

**SEDIMENTOLOGY OF PLIO-PLEISTOCENE
GRAVEL BARRIER DEPOSITS
IN THE PALAEO-ORANGE RIVER MOUTH, NAMIBIA:
DEPOSITIONAL HISTORY AND DIAMOND MINERALISATION**

VOLUME 1

A thesis submitted in fulfilment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

of

RHODES UNIVERSITY

by

RENATO IGINO SPAGGIARI

March 2011

VOLUME 1

Chapters 1 to 7

References

VOLUME 2

All figures

Appendices A to E

ABSTRACT

The largest known marine diamond placer, the Namibian mega-placer, lies along the Atlantic coast of south-western Africa from the Orange River mouth 1,000 km northwards to the Namibian–Angolan border. The most economically viable portion of the Namibian mega-placer (>75 million carats recovered at >95% gem quality) comprises onshore and offshore marine deposits that are developed within ~100km of the Orange River outfall. For much of the Cainozoic, this long-lived fluvial system has been the main conduit transporting diamonds from kimberlitic and secondary sources in the cratonic hinterland of southern Africa to the Atlantic shelf that has been neutrally buoyant over this period. Highly energetic marine processes, driven in part, by southerly winds with an attendant northward-directed longshore drift, have generated terminal placers that are preserved both onshore and offshore.

This study, through detailed field sedimentological and diamond analyses, investigates the development and mineralisation of gravel barrier deposits within the ancestral Orange River mouth area during a major ~30 m regional transgression ('30 m Package') in the Late Pliocene. At that time, diamond supply from this fluvial conduit was minimal, yet the corresponding onshore marine deposits to the north of the Orange River mouth were significantly diamond enriched, enabling large-scale alluvial diamond mining to take place for over 75 years.

Of the entire coastline of south-western Africa, the most complete accumulation of the '30 m Package' is preserved within the palaeo-Orange River mouth as barrier spit and barrier beach deposits. Arranged vertically and laterally in a 16 m thick succession, these are deposits of: (1) intertidal beach, (2) lagoon and washover, (3) tidal inlet and spit recurve and (4) storm-dominated subtidal settings. These were parts of larger barrier features, the bulk of which are preserved as highstand deposits that are diamond-bearing with varying, but generally low grades (<13 stones (diamonds) per hundred tons, spht). Intertidal beach and spit recurve deposits have higher economic grades (12–13 spht) due to the energetic sieving and mobile trapping mechanisms associated with their emplacement. In contrast, the less reworked and more sandy subtidal, tidal inlet and washover deposits have un-economic grades (<2 spht). Despite these low grades, the barrier deposits have the largest average stone (diamond) size (1–2 carats/stone, cts/stn) of the entire Namibian mega-placer, given their proximity to the ancestral Orange River outfall.

This study demonstrates that barrier shoreline evolution at the fluvial/marine interface was controlled by: (1) a strong and coarse fluvial sediment supply that sustained shoreline growth on a highly energetic coast, (2) accommodation space facilitating sediment preservation and (3) short-duration, high-frequency sea-level cycles superimposed on the ~30 m regional transgression, promoting hierarchal stacking of progradational deposits. During these sea-level fluctuations, diamonds were 'farmed' from older, shelf sequences in the offshore and driven landward to accumulate in '30 m Package' highstand barrier deposits. In spite of the large supply of diamonds, their retention in these deposits was poor due to an incompetent footwall of ancestral Orange River mouth sediment and the inherent cobble-boulder size of the barrier gravels. Thus the principal process controlling diamond entrapment in these barrier deposits was kinetic sieving in a coarse-grained framework. Consequently, at the marine/fluvial interface and down-drift for ~5 km, larger diamonds (1–2 cts/stn) were retained in low-grade (<2 spht), coarse-gravel barrier shorelines. Smaller diamonds (mostly <1 cts/stn) were rejected into the northward-driven littoral sediments and further size-sorted along ~95 km of Namibian coast to accumulate in finer, high-grade beach placers (>100 spht) where bedrock footwall promoted such high concentrations.

The gravel-dominated palaeo-Orange River mouth is considered to be the 'heart' of the Namibian mega-placer, controlling sediment and diamond supply to the littoral zone further north. Although coarse gravel is retained at the river mouth, the incompetence of this highly energetic setting to trap diamonds renders it sub-economic. This ineffectiveness at the fluvial/marine interface is thus fundamental in enriching the coastal tract farther down-drift and developing highly economic coastal placers along the Atlantic coast of south-western Africa.

THESIS DECLARATION

I declare that the material presented in this thesis is a result of my own independent research and all assistance and sources of information have been fully acknowledged or referenced in the text. This work has not been presented to any other university for the purpose of a higher degree.

A handwritten signature in black ink, appearing to read 'R. Spaggiari', written in a cursive style.

Renato Igino Spaggiari

1 March 2011

*Pencil, ink marks and
highlighting ruin books
for other readers.*

TABLE OF CONTENTS

ABSTRACT	i
THESIS DECLARATION	iii
CONTENTS.....	iv
ABBREVIATIONS AND ACRONYMS.....	ix
ACKNOWLEDGMENTS	xii
CHAPTER 1 – INTRODUCTION	1
1.1 BACKGROUND	1
1.2 LOCALITY	3
1.3 PRESENT COASTAL REGIME	4
1.4 DEPOSITIONAL SUB-ENVIRONMENTS OF BARRIER BEACHES	6
1.4.1 Coastal lagoon.....	7
1.4.2 The backshore	8
1.4.3 The foreshore	10
1.4.4 The shoreface.....	12
1.5 OBJECTIVES OF STUDY	15
1.6 PREVIOUS WORK.....	16
1.7 METHODS	18
1.7.1 Trench excavations	19
1.7.2 Field measurements	19
1.7.3 Palaeontological sampling.....	22
1.7.4 Diamond data.....	22
CHAPTER 2 – GEOLOGICAL SETTING	25
2.1 REGIONAL SETTING	25
2.1.1 Diamond supply	25
2.1.2 The Orange River conduit	27
2.1.3 The Atlantic sink.....	28

2.2 GEOLOGICAL FRAMEWORK OF MINING AREA 1 (MA1).....	33
2.2.1 Proterozoic lithologies.....	33
2.2.2 Mesozoic lithologies.....	34
2.2.3 The Cainozoic sequence.....	34
CHAPTER 3 – SEDIMENTARY FACIES	39
3.1. INTRODUCTION	39
3.2 GENERAL ASPECTS OF THE SEDIMENT COMPOSITION	42
3.2.1 Gravel	42
3.2.2 Sand	43
3.3 FACIES A.....	44
3.3.1 General.....	44
3.3.2 Distribution and thickness	44
3.3.3 Lithology and structure.....	44
3.3.4 Interpretation of Facies A	51
3.3.5 Summary and depositional setting of Facies A	58
3.3.6 Age and correlation.....	60
3.4 FACIES B	61
3.4.1 General	61
3.4.2 Distribution and thickness	61
3.4.3 Lithology and structure.....	61
3.4.4 Interpretation of Facies B	63
3.4.5 Summary and depositional setting of Facies B.....	66
3.4.6 Age and correlation.....	68
3.5 FACIES C	69
3.5.1 General.....	69
3.5.2 Distribution and thickness	69
3.5.3 Lithology and structure.....	69
3.5.4 Interpretation.....	77
3.5.5 Summary and depositional setting of Facies C.....	88
3.5.6 Age and correlation.....	90

3.6 FACIES D.....	90
3.6.1 General.....	90
3.6.2 Distribution and thickness	91
3.6.3 Lithology and structure.....	91
3.6.4 Interpretation of Facies D	96
3.6.5 Summary and depositional setting of Facies D	107
3.6.6 Age and correlation.....	109
CHAPTER 4 - DEPOSITIONAL MODELS AND STRATIGRAPHY.....	110
4.1 INTRODUCTION	110
4.2 PRESERVATION OF COASTAL SEQUENCES.....	114
4.2.1 Coastal stratigraphic sequences	114
4.2.2 Sediment supply.....	115
4.2.3 Sequence preservation during transgression.....	117
4.3 DEPOSITIONAL MODELS AND STRATIGRAPHY	118
4.3.1 Conceptual depositional models	121
4.4 GENESIS OF THE STRATIGRAPHIC ARCHITECTURE	131
4.5 SUMMARY.....	139
4.5.1 Problems with the depositional models	140
CHAPTER 5 – DIAMOND MINERALISATION.....	142
5.1 INTRODUCTION	142
5.2 FACIES MINERALISATION	147
5.2.1 Facies A: Barrier spit.....	147
5.2.2 Facies B: Transgressive lag	148
5.2.3 Facies C: Barrier beach.....	150
5.2.4 Facies D: Storm gravel sheet.....	153
5.3 ECONOMIC POTENTIAL OF FACIES	154
5.4 MINERALISATION MODELS.....	157
5.4.1 Seaward facing intertidal deposits	160
5.4.2 Back-barrier and spit recurve deposits	162
5.4.3 Subtidal deposits.....	164

CHAPTER 6 – DISCUSSION OF RESULTS	166
6.1 STRATIGRAPHIC MODEL.....	166
6.2 SEA-LEVEL AND PRESERVATION MODEL.....	169
6.3 DIAMOND EMPLACEMENT MODEL.....	173
6.3.1 Diamond delivery to barrier deposits.....	177
6.3.2 Preservation of diamond cache.....	178
6.3.3 Diamond retention.....	178
6.3.4 Diamond-rich sediment pulses.....	179
6.3.5 Sediment dispersal related to diamond concentration.....	180
CHAPTER 7 – CONCLUSIONS AND FUTURE RESEARCH	181
7.1 CONCLUSIONS.....	181
7.1.1 Palaeo-Orange River mouth setting.....	181
7.1.2 Diamond potential of barrier deposits.....	183
7.1.3 Diamond emplacement model.....	184
7.2 FUTURE RESEARCH.....	185
REFERENCES	187

LIST OF TABLES

1.1 Previous work on gravel beaches.....	17
1.2 Previous work on diamond mineralisation in gravel beaches.....	17
2.1 Variability in diamond concentration within Orange River terraces through time.....	27
3.1 Classification of sedimentary environments and facies for the ED Area deposits.....	41
3.2 Palaeo-current data of Sub-facies A1.....	46
3.3 Palaeo-current data of Sub-facies A2.....	47
3.4 Palaeo-current data of Sub-facies A3.....	49
3.5 Palaeo-current data of Sub-facies C1.....	73
3.6 Palaeo-current data of Sub-facies C2.....	76
3.7 Palaeo-current data of Sub-facies D1.....	92
3.8 Palaeo-current data of Sub-facies D2.....	94
3.9 Palaeo-current data of Sub-facies D3.....	96

3.10	Horizontal orbital velocities (U_d) at depths greater than 30 m during normal wave conditions	99
5.1	Overall diamond results for barrier spit from the G25 trench	148
5.2	Overall diamond results for transgressive lag	149
5.3	Descriptive statistics for the transgressive lag diamond data	150
5.4	Overall diamond results for barrier beach	152
5.5	Descriptive statistics for barrier beach grade data (spht)	152
5.6	Descriptive statistics for barrier beach stone size data (cts/stn)	152
5.7	Overall diamond results for storm gravel sheet.....	153
5.8	Descriptive statistics for the storm gravel sheet diamond data	154
5.9	General ranking of facies according to diamond potential.....	157

ABBREVIATIONS AND ACRONYMS

%	percent
Σ	sum
$\sqrt{\quad}$	square root
©	copyright
<i>phi</i>	logarithmic transformation of the Wentworth grade scale. The diameter value of particles (in mm) is transformed using the expression $-\log_2 d$, where d is the grain diameter in millimetres.
2-D	two-dimensional
3-D	three-dimensional
π	π = ratio of the circumference of a circle to its diameter = 3.14159
σ	standard deviation
a	a-axis of pebble
b	b-axis of pebble
BB	barrier beach
BBC	barrier-beach complex
BCB	beach cusps and berms
BP	before present
BS	barrier spit
BSC	barrier-spit complex
BT	beach toe
c	c-axis of pebble
C	velocity
CBF	coarse basal fabric
CD	compact disk
CF	coarse framework
cm	centimetre(s)
cos	cosine
cpht	carats per hundred ton
CSI	Cory Shape Index
ct	carat (1 ct = 0.2 g)
cts/m ²	carat(s) per square metre
cts/stn	carats per stone

cts/ton	carats per ton
CV	coefficient of variation
D	grain diameter
d	water depth
DMS	dense medium separation
DRI	Disc Rod Index
ED	estuarine delta
<i>et al.</i>	and others
FBF	fine blinding fabric
g	gravity constant = 9.81 m/s
g/cm ³	gram(s) per cubic centimeter (= density)
GEBCO	General Bathymetric Chart of the Oceans
H	wave height
IC	infill clasts
IUGS	International Union of Geological Sciences
Jr	Junior
km	kilometre(s)
L	wavelength
L%	vector magnitude
Ltd	Limited
m	metre(s)
m/a	metre(s) per annum
m/s	metre(s) per second
m ³	cubic metre(s)
m ³ /yr	cubic metre(s) per year
Ma	million years ago
MA1	Mining Area 1
MHW	mean high water
ML 43	Mining Licence 43 (= study area)
ML	mining licence
MLW	mean low water
mm	millimetre(s)
msl	mean sea-level
n	number of readings

NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
ppm	parts per million (1 ppm = 1 gram per ton)
Pty.	proprietary
R	resultant vector length
R.	River
RC	rejected clasts
RJP	rejected diamond population
RTP	retained diamond population
s	second(s)
SACS	South African Committee for Stratigraphy
SAMREC	South African Resource Committee
sin	sine
sinh	hyperbolic sine
SIO	Scripps Institution of Oceanography
<i>sk</i>	skewness
SL	sea-level
spht	stones per hundred ton
Sr	Strontium
ST	subtidal
t	ton(s)
T	wave period
tanh	hyperbolic tangent
TGL	transgressive lag
U_d	horizontal orbital velocity
U.K.	United Kingdom
U.S.A.	United States of America
US\$	United States dollar
US\$/ct	United States dollar per carat
US\$/ton	United States dollar per ton
Var	variance
Xv	vector mean

ACKNOWLEDGEMENTS

This dissertation accumulated enough voyager miles to embark on a final journey towards a book shelf. Its beginnings in Oranjemund (Namibia) saw a journey through Centurion (RSA), Johannesburg (RSA), Kinshasa (DRC), Tshikapa (DRC), Central African Republic, Western Cape and a final return to Namibia (Windhoek). Many people have willingly provided guidance and shared their knowledge with the author throughout this journey – either in the field, over the telephone, via e-mail or over a casual cup of coffee. In particular my mentors and supervisors, Prof. Brian Bluck and Dr. John Ward, are thanked for my introduction to the 'clattering pebbles' of the Atlantic, the many discussions and their continued support and guidance through the project. I'm indebted to John 'Sensi' Ward for his endless interaction, whether it was in the ED Area trenches (with his frayed and faded overalls) or thereafter wading through swamps in the DR Congo (similar frayed and faded overalls). Brian gave generously of his time to review this dissertation from cover to cover, providing stimulating and invaluable comments. Both inspired me through this undertaking and without their encouragement, I never would have completed this dissertation.

The guidance and input from my principal supervisors, Prof. John Moore and Dr. Emese Bordy is greatly appreciated. Their view on the study came from a completely different angle and provided new and different ideas that vastly improved the manuscript. Emese, who adopted the role of principal supervisor at a later stage of the study, made a brief transition from her preferred carbon form that fires power stations to this other that 'fires' sparkle, is singled out for her rigorous sedimentological approach, thought-provoking suggestions and meticulous review of the work. Her comments and approach added a new dimension to the presentation of sedimentological aspects.

Dr. Mike de Wit is thanked for his interest in the study, helpful recommendations and the several cups of coffee consumed at Cafe' Mozart in Kinshasa during our afternoon discussions. His incredible dexterity in rescuing the first draft from a cup of coffee he showered over the author is also appreciated – the fact that the rescue was directed towards the manuscript before its author, did not go unnoticed.

I have also benefited from many fruitful discussions with various people, as well as their assistance with references. They are:

- Drs. Koos Reddering (clast shape analysis and the Robberg gravel spit), Derek Robinson (Namibian diamonds), Jurgen Jacob (Orange River deposits), Lisa Fink (for the *South African Journal of Science* paper), Gerhard Diedericks (Atlantic wave energy and boulder movement), Piet Gresse (palaeo-shorelines along the Namaqualand coast), John Rogers (Atlantic wave energy), Bob de Decker (megaripple forms in the offshore), Ian Corbett (West Coast geology) and Prof. Andrew Cooper (for the papers on estuaries);
- Mr. Dick Barker and Assie van der Westhuizen for sharing their Orange River knowledge. Dick is particularly thanked for his discussion on the Orange River Meso-deposits and other diamondiferous alluvial deposits;
- Messrs. Alastair Baumann, Mike Millad, Leonard Apollus, Richard Gray, Bob Liddle, William Macdonald, Lourens Myburg, Richard Hall, Gottfried Grobelaar, Moss Botha (on diamond-rich sediment pulses), Geoff Smith (Atlantic wave energy and boulder movement) and Mrs. Jana Jacob;
- Mr. Sean Duggan is especially thanked for discussions and reviewing the diamond mineralisation chapter, especially on the statistical aspects thereof.

Southern Areas Sampling Plant (SASP), in particular, Marais Loubser, Manie Klassen and Desmond Olivier are thanked for supervising the bulk sample collection and treatment thereof. The micro- and macro-fossil identification by Dr. Ian McMillan, Dienne Dale and John Pether is greatly acknowledged, as is the diamond sorting and result compilation by Debbie Bowen, Elana Groenewald and Ronel Fourie.

Surveying of trench sections were undertaken by surveyors, Koos O' Kennedy, Andre Fourie, Johan Mall, Dave Devine and Jorrie Jordaan. Their assistance in both the field and during data compilation is appreciated. Ralph Scholz, Christa Keyser, Lou Maritz, Annette Schoeman, Johan Langenhoven, Lodewyk du Plessis, Gloudina Brand, Dawn Jones and Martin Ockhuizen are also thanked for their assistance with historical data, Microstation and GIS training.

Wayne Schablinski and Lourens Venter proved to be skilled field assistants and sacrificed their weekends for sedimentological adventures in MA1. These adventures lead to the serendipitous discovery of the 'lost treasure' – a pile of fossiliferous boulder conglomerates. Thanks, guys! I'm also indebted to Ella Scholtz for her unwavering support and encouragement throughout my stay in Oranjemund.

Namdeb Diamond Corporation (Pty.) Ltd and managers, as well as ex-managers, Rob Smart, Bob Burrell, Mike Lain, Graham Wheelock, and Alan Ashworth are thanked for the generous use of equipment throughout the field study and for granting permission to use Namdeb's data. Funding for the study was provided by the De Beers Research Committee and Drs. Mike de Wit, John Ward and Ian Corbett (committee members at that time) are thanked for organising this support and for the vote of confidence. De Beers Marine Namibia is thanked for the use of their printer, as are Leonard Apollus for arranging this generous opportunity and Christa Keyser for assisting with the printing.

Profs. Brigitte Senut and Martin Pickford are thanked for the lively discussions on Sperrgebiet fossil ages and their continuous encouragement. Such encouragement and support also came from my neighbours in Somerset West. The 'Joneses' (Mike & Noreen) and 'van Niekerks' (Johan & Elaine) are particularly thanked for the copious meals and red wine that maintained my energy levels and fired the geological imagination. Mike certainly demonstrated that red wine is the fruit-of-the-gods, but forget to remind me that you have to be a god to survive the morning after.

At Rhodes University, Ashley Goddard is sincerely thanked for her guidance and assistance with registration and logistical arrangements for my visits to Grahamstown, and the many giggles over a cup of tea.

A special word of thanks goes to my parents for their words of encouragement that were relayed from the 'side lines' in Sydney and to my partner, Carole Roberts. Her endless support and the numerous journeys from Windhoek to Somerset West, giving extra encouragement, often with biltong in hand, has been a lifeline during my 'gloomy' times. Her review of the dissertation, recommendations and assistance with the final layout is most appreciated.

And so life is a beach – it's gravelly and at times treasured with diamonds.

CHAPTER 1 – INTRODUCTION

'A place where pebbles are polished and diamonds are dimmed' - Robert Green Ingersoll (1833-1899)

1.1 BACKGROUND

Known diamond marine placers are rare and the only occurrences of economic importance occur in sub-Saharan Africa along the west coast of South Africa (over a distance of 370 km) and the Namibian coast (over a distance of 1,400 km in length). Together these placers have yielded exceptional production levels since their discovery in the early 1900s. Approximately 120 million carats have been mined from these deposits and it has been estimated that a combined diamond resource of approximately 30 million carats remain (Bluck *et al.*, 2005). More importantly, more than 95% of the diamonds mined are gem quality (Hallam, 1964). Given the appreciable production levels, the size of the placers and the quality of the diamonds, Bluck *et al.* (2005) have defined both placer deposits as mega-placers.

The Namibian mega-placer, situated in the most south-western corner of the country along the Atlantic coastline and immediately north of the Orange River (Figure 1.1A), is Namibia's main diamond producer. Here the most economical deposits that continue to be the mainstay of Namibia's diamond industry are the Quaternary onshore gravel beaches of the Alexander Bay Formation (SACS, 1980). Testimony to their economic value lies in the fact that they have been mined for over 75 years, producing more than 75 million carats making this the world's richest marine diamond mega-placer (Schneider & Miller, 1992; Corbett, 1996; Corbett & Burrell, 2001; Corbett, 2002; Oosterveld, 2003; Spaggiari *et al.*, 2006).

The development of this mega-placer is attributed to a combination of processes. Among these, the Orange River is seen as the fluvial 'conveyor'. It supplied consistently vast quantities of predominantly coarse-grained sediment, together with diamonds to the Atlantic coast. At the terminal point of this 'conveyor' system, the outfall of diamond-bearing sediment accumulated at an interface representing the end of the fluvial delivery and the start of the marine dispersion processes (the marine 'conveyor'). It is at this interface that the role of the Atlantic Ocean was fundamental in developing the Namibian mega-placer.

The combined effect of a vigorous wind-wave system, northward-directed longshore current and a shallow buoyant shelf created a natural gigantic ‘jig’ to separate the Orange River outfall by grain size and re-distribute them to different depositional areas (Bluck *et al.*, 2007). This energetic ‘jig’ ensured that the fine-grained sediments are removed, whilst only the gravel fraction is capable of remaining at, and building up, the coastline (Bluck *et al.*, 2007). The finest material is dispersed into the offshore as thick mudbelts and the sand fraction is moved onshore to accumulate in the Namib Sand Sea and as dune belts. The gravel fraction is retained along the coastline as a series of different beach types to form a continuous palaeo-littoral wedge tapering northwards for approximately 110 km from the Orange River mouth. This is the marine mega-placer.

In the proximal setting of this littoral wedge at the interface of the fluvial and marine ‘conveyor’ systems, gravel barrier spits and barrier beaches predominate for approximately 5 km (Spaggiari *et al.*, 2006). These are replaced in a down-drift direction (northwards) by linear beaches for approximately 70 km, that in turn, grade farther northwards into pocket beaches (Spaggiari *et al.*, 2006). The last typifies the distal end of the littoral wedge (Figure 1.1B; Apollus, 1995; Spaggiari *et al.*, 1999; Bluck *et al.*, 2001; Spaggiari *et al.*, 2002; Spaggiari *et al.*, 2006).

The process of sediment segregation is highly significant for placer development as the coarser diamonds follow the gravel fraction and are therefore retained in gravel beaches (Bluck *et al.*, 2005). The largest gravels are confined to the interface, which in turn, yield the coarser diamonds. North of this interface, the diamond size decreases in a down-drift direction (Sutherland, 1985; Schneider & Miller, 1992) and is significantly smaller, as much as 75%, within pocket beach deposits that represent the down-drift part of the dispersal system.

It is, however, only the linear and pocket beach deposits that have the highest concentrations of diamond and form the principal mining targets (Hallam, 1964; Apollus, 1995; Jacob, 2001). These deposits are floored by marine-bevelled bedrock platforms with a variety of trapsites such as potholes and gullies, which enhance diamond concentration. In contrast, the gravel barrier spits and barrier beaches closest to the Orange River mouth rest on unconsolidated fluvial sediments that do not promote the development of trapsites. Significantly and unsurprisingly, these deposits have lower diamond concentrations and their

contribution to mining production is relatively small. It thus follows that the introduction and retention of diamonds in such river mouth settings is governed by depositional processes.

This study focuses on the proximal setting of the palaeo-littoral wedge where the interaction between marine and fluvial processes has created a complex arrangement of barrier spit and barrier beach deposits within the Orange River valley. The sedimentological framework of these deposits and associated diamond mineralisation models are thus considered. The deposits within the study area are correlative to the 30 m Package (Plio-Pleistocene; Pether, 1986) of the Alexander Bay Formation (SACS, 1980). Along the Namaqualand coast in South Africa and the Namibian coastline, palaeo-shoreline sediments occurring at a transgressive maximum of 30 m above msl and contain the biostratigraphic zone fossil *Donax rogersi*, are referred to as the 30 m Package (Pether, 1984). In Namibia, marine sediments of the 30 m Package are best preserved within the study area, whilst isolated occurrences are recorded farther north along the Namibian coastline at and immediately north of Walvis Bay (Rooikop gravels; Miller & Seely, 1976; SACS, 1980; Miller, 2008) and along the Skeleton Coast (Hallam, 1964; Miller, 2008; Figure 1.1A).

1.2 LOCALITY

Along part of its lower course, the Orange River forms a natural border between Namibia and South Africa before entering the Atlantic Ocean. The coastal tract immediately north of the Orange River mouth in Namibia, extending northwards for some 300 km to Lüderitz, falls within the *Sperrgebiet* ('forbidden territory') – an area that was proclaimed in 1908 after the discovery of diamonds within this region (Pallett, 1995; Figure 1.1A).

The study area is situated in the most southern end of the *Sperrgebiet* coastal tract within the mining licence (ML 43) held by Namdeb Diamond Corporation (Pty.) Ltd. This area, locally known as Mining Area 1 (MA1), is the main centre of Namdeb's mining operations (Figure 1.1B). The mining targets near to the present Orange River mouth where the littoral deposits are at their widest, representing some 3 km of gravel beach accretion is investigated. This part of MA1 is known locally as the ED Area (Figure 1.1B), an informal acronym used by the mining company for 'Estuarine Delta' Area.

Although Terrace Bay, situated within the Skeleton Coast Park, some 1,000 km north of the Orange River (Figure 1.1A), was not part of the study, the modern gravel beaches at Terrace Bay were visited to gain a better understanding of modern gravel beach formation, processes and structures. These modern beaches are formed under similar wave and tidal conditions envisaged for the palaeo-beaches in the study area (Spaggiari *et al.*, 2006; Bluck, in press).

Geologically, MAI contains an accumulation of Late Cainozoic sediments covering Precambrian and Mesozoic rocks (Figure 1.2). Chapter 2, Section 2.2, considers the geological framework in more detail.

1.3 PRESENT COASTAL REGIME

A brief discussion of the modern coastal regime is presented here as a prelude to gain an understanding of the coastal energy that has ostensibly remained unchanged since at least the Neogene (de Decker, 1988). The Atlantic coastline of south-western Africa is recognised as the most energetic in the world (Hay & Brock, 1992) where it is dominated by persistent high-energy waves (Davies, 1972) that are driven by strong southerly winds. The South Atlantic Anticyclone, an offshore high-pressure cell, is responsible for generating these onshore-directed winds (Rogers, 1977; Figure 1.3).

In summer, the high pressure system occupies a more southerly position centred at about 30° S, but shifts some 6° northwards in the winter months due to the development of low-pressure cells in the Southern Ocean (Tchernia, 1980, pg. 104; Tyson & Preston-Whyte, 2000). Consequently, strong anticyclonic southerly winds are experienced along the coastal tract during summer where the South Atlantic trade winds predominate (Tchernia, 1980), whilst a reduction in their magnitude is experienced in winter months (Rogers, 1977).

The northward shift of the high-pressure cell allows periodic eastward-migrating circumpolar cyclones of the Southern Ocean to move closer to South Africa (Woodborne, 1991). This creates north-westerly and westerly gale force winds that regularly induce stormy seas and high swells during winter months (Woodborne, 1991). It thus follows that long period swells generated by the circumpolar cyclones ('roaring forties') contribute to the wave energy regime in winter and generally constitute the major storm waves, whilst the shorter

wave periods generated by the southerly gales contribute most of the energy to the summer wave regime (Smith, 2002).

The wave-dominated setting offshore of the Orange River is characterised by wave heights that fall mainly (90% of the waves) in the range of 0.75-3.25 m, averaging 1.75 m for winter and 1.5 m for summer (de Decker, 1988). The attendant wave periods are between 11 and 15 seconds for all seasons, with the longest occurring in winter where it averages 12.5 seconds (Rogers, 1977; de Decker, 1987). Wave heights exceeding 5 m during periodic storms are not uncommon and have been recorded in all seasons (de Decker, 1988; Smith, 2002, pg. 3). In fact, wave heights of greater magnitude exceeding 9 m (Didenkulova *et al.*, 2006, see pg. 1011) and at times 16 m (Jury *et al.*, 1986; Brundrit & Shannon, 1989) have been documented along the west coast of South Africa, particularly during winter storms. It is also alleged that the grounding of the diamond mining vessel, *Barge 77* onto the rocks at Chameis Bay some 110 km north of the Orange River mouth in 1963 was due to an unsuspected 25 m wave (Williams, 1996, pg. 90). Although this eyewitness account was not scientifically recorded, such waves do make an appearance along the west coast of South Africa. Apart from those mentioned earlier, a wave height of 20 m was recorded at a popular surf spot, the ‘Dungeons’ in Cape Town during 2004 (Pisces Environmental Services, 2008).

Driven by distant storms (winter cyclones) in the ‘roaring forties’, which migrate west to east, these deep-water waves intensify as they head eastward from Cape Horn (Tierra del Fuego archipelago, offshore Chile) towards South Africa (Wavescape, 2004). More significantly, it has been demonstrated that deep-water waves have the greatest wave length and longest wave period and therefore travel faster than waves with shorter periods (Brown *et al.*, 1989), given that velocity (C) can be expressed as $C = \sqrt{gL/2\pi}$, where g is the gravity constant of 9.81 m/s and L is the wave length (Bascom, 1964). Thus, with wave base equivalent to half the wave length (see Brown *et al.*, 1989), sea floor interference will seemingly be considerably deeper as wave base is lowered well beyond the depths normally reached during local summer storms or fair weather conditions. Closer to the shoreline, the waves begin to touch bottom as they propagate across the shallow shoreface where they becoming steeper and are refracted towards a more shore-normal direction. This is the shoaling zone (Reinson, 1984). Here the waves oversteepen as they continue to approach the shoreline and ultimately break up in the breaker zone (Niedoroda *et al.*, 1985). Offshore of the Orange River, the area encompassing the shoaling and breaker zone can be recognised by

current-induced bedforms from sonographs where it has been demonstrated that this area can be as much as 300 m wide at depths from 10-25 m below msl (de Decker, 1988). This indicates that the distance between the shoaling zone and beach face is considerable and hence sediment movement takes place over an extremely broad zone (Bluck, 2005, 2007).

Seasonal differences in the present wave regime are also reflected in the direction of wave approach. The majority of waves approach from the south-west (Rogers, 1977; de Decker, 1988). During summer a southerly approach is predominant due to the strong summer southerly winds, whilst in winter a south-westerly to south-south-westerly approach is a reflection of the predominate swell originating in the low pressure belt of the Southern Ocean (Rogers, 1977; de Decker, 1988; Smith, 2002). Coupled with the persistent high wave energy, the predominance of south-westerly waves incident on the Atlantic coastline at the Orange River mouth results in a strong northward-directed longshore drift with an estimated volume of $1.4 \times 10^6 \text{ m}^3/\text{yr}$ (Swart, 1984) that intensifies during winter months (de Decker, 1988). It has also been demonstrated that waves originate from the north-western quadrant, but these are quantitatively insignificant (de Decker, 1988). However, they are highest during spring and winter, and during these periods the northward-directed longshore drift is absent or even reversed (Gurney *et al.*, 1982 in de Decker, 1988). In contrast to the extreme wave energy, the tidal range is only 1.8 m off the Orange River mouth, making this a micro-tidal coast (Davies, 1972). In these wave-dominated settings, the tidal energy is overwhelmed by the persistent wave energy (Davis Jr & Hayes, 1984). Consequently, tidal effects on sediment dispersion along the present coastline and adjacent shelf are negligible and largely governed by wave-induced currents (de Decker, 1988).

1.4 DEPOSITIONAL SUB-ENVIRONMENTS OF BARRIER BEACHES

The aim of this section is to introduce the different sub-environments for modern beaches and their depositional processes, to serve as background to the terminology used for interpreting the various sub-facies recognised within the study area. The sub-environments, including the general beach morphology, sedimentary processes and structures are graphically summarised in Figures 1.4 & 1.5. From landward to seaward, the sub-environments that are discussed in this section are coastal lagoons, backshore, foreshore, shoreface and offshore. Although the terminology used in these figures is not universal, it is a generalised compilation from various sources (Reineck & Singh, 1975; Elliott, 1978, 1986; Harms *et al.*, 1982;

Reinson, 1984; Davis Jr, 1985; Leeder, 1988; Reading & Collinson, 1996; Nichols, 1999; Bluck 1999; Boggs Jr, 2001; Carter, 2002). Note that this general compilation presents 'classic' examples of beach sub-environments, but these are in places not a representation of what was recorded in the study area. This divergence in correlation is briefly discussed in this section and expanded on in Chapter 3. In addition, given that this study focus primarily on gravel beaches, the terminology used for describing their sub-environments differs to that of sand beaches. Based on the Wentworth (1922) grain scale, gravel is hereinafter defined as a particle that is greater than 2 mm (-1ϕ). The terminology used in this study for gravel beach description is based on research that has focused mainly on modern settings in Europe (mainly the United Kingdom), America (mainly Canada) and New Zealand. This body of research, like those of Bluck (1967, 1999), Orford (1975), Carr (1983), Carter & Orford (1984), Williams & Caldwell (1988) and others, form the basis to understanding gravel beach sedimentation.

1.4.1 Coastal Lagoon

In general, the term 'lagoon' is nonspecific and loosely used to describe a body of shallow water that is landward of a protective barrier and connected to the open sea with an outlet (Reineck & Singh, 1975; Kirk & Lauder, 2000; Davis Jr & Fitzgerald, 2004). Lagoons may develop in a variety of geological settings provided that there is some form of embayment from the open marine environment and a mechanism to isolate it, such as the growth of a barrier beach or barrier spit (Davis Jr & Fitzgerald, 2004). Given that a lagoon is impounded by some form of barrier structure and occurs landward of the backshore environment (see Section 1.4.2), it represents the back-barrier setting.

Generally, back-barrier sediments are mixtures derived from multiple sources such as rivers or the sea (Nichols & Boon III, 1994). Tide-dominated back-barrier settings are sinks to marine sediments through flood-tidal processes at the tidal inlet, whilst fluvial sources dominate those that are river-dominated (Cooper, 2001). In addition to these sediment sources, marine sediment is also introduced during storms where waves transfer sediment over the barrier structure into the lagoon. Such washover sedimentation in both tide- and river-dominated settings is confined to the landward margins (backshore; see Section 1.4.2) of barrier structures.

Lagoons in micro-tidal settings are generally low-energy environments and are thus good sediment traps. They fill rapidly with marine and fluvial deposits, resulting in a progressive decrease in depth, volume and areal extent (Reineck & Singh, 1975; Nichols & Biggs, 1985). The infill process is accelerated on enclosure of the lagoon by growth of a barrier beach or spit, coupled with late stage development of tidal flats and marshes (Nichols & Biggs, 1985). Sedimentation in a lagoon, therefore, comprises mostly mud, silt and fine sand and is largely controlled by sediment influx and hydrographic conditions (Reineck & Singh, 1975). The sand fraction is confined to more energetic environments such as mid-channel islands and tidal inlets where current ripples dominate (Reineck & Singh, 1975), whereas marshes, floodplains and deeper parts of the lagoon are low-energy environments favourable for the deposition of mud and silt. Generally these deposits are finely laminated, but their structures are commonly obliterated where bioturbation is extensive (Reineck & Singh, 1975; Elliott, 1978). Other back-barrier deposits include tidal channel and flood-tidal delta sediments that are sand dominated with lag gravels. Bi-directional planar and trough cross-stratification are diagnostic sedimentary structures. In addition, tidal-flat deposits that are developed landward of the barrier consist of mud and fine- to medium-grained ripple-laminated, flaser- and lenticular-stratified sands (Boggs, 2001).

The present Orange River back-barrier setting, however, has estuarine characteristics and is defined by Cooper (2001, 2002) as a river-dominated estuary. He notes that the inlet (within a micro-tidal regime) is maintained by fluvial discharge. In addition, flood-tidal deltas are small or absent as a result of weak tidal currents and limited accommodation space in the estuary. One significant feature of river-dominated estuaries is that fluvial sediments extend to the landward margin of a barrier beach in the form of floodplains, mid-channel islands or subtidal deposits and therefore the back-barrier area is seen as an extension of the inflowing river (Cooper, 2002). Here sedimentation is dominated by fluvial processes (Cooper, 2001, 2002) with a small marine contribution from washovers and weak tidal incursions. In this study back-barrier deposits of palaeo-Orange River origin will be defined as estuarine-lagoon; a term also applied by Barnes (2001) for estuarine settings in Britain that have been sealed off by a barrier deposit, but still receive small amounts of seawater through washovers.

1.4.2 The backshore

This extends from the highest berm landward into the hinterland. The backshore generally remains dry and therefore represents the supratidal zone. This zone is only

subjected to wave action under unusually high-water conditions that are associated with storms. The highest berm, representing the most elevated part of the beach, is usually built during these periods and thus is referred to as a storm berm (Harms *et al.*, 1982; Hayes *et al.*, 2010). However, a broad range of definitions are used to describe storm berms. These include berm crest (Reinson, 1984; Reading & Collinson, 1996; Boggs Jr, 2001), berm ridge (Otvos, 2000), beach ridge (Orford, 1986; Meldahl, 1995; Otvos, 2000), beach crest (Lorang, 2002) and storm ridge (Davis Jr & Fitzgerald, 2004). Consequently, the definition and use of the aforementioned terms in the literature is confusing and at times the terminology is broadly interchanged (see Hesp *et al.*, 2005; Hesp, 2006). For example, Otvos (2000) combines berms, beach ridges, foredunes and cheniers into a single type where beach ridges are of wave (berm ridge), wind (backshore foredune) or chenier in origin (see Hesp *et al.*, 2005).

For simplicity and using Hesp's (2006) definition to ensure consistency, beach ridge is applied in this study. Beach ridges (*sensu stricto*) are persistent swash and storm wave built ridges, forming typically at or above the normal spring high tide level (King, 1972 in Hesp, 2006). Whereas berms are non-persistent ridges or terraces that are wave built at the limit of swash run-up (Hesp, 2006). Therefore, beach ridges are fingerprints of storm swash surges and are semi-permanent features that are only reworked by the next, more severe storm. In gravel beaches, they are typified by an accumulation of predominantly large disc- and blade-shaped clasts which are well imbricated on the immediate seaward slope of the ridge, whereas on the immediate landward side the discoidal clasts are flat lying (Bluck, 1967; Orford, 1975; Williams & Caldwell, 1988; Bluck *et al.*, 2001; Pascucci *et al.*, 2009; Figure 1.4B). The preferential accumulation of discs and blades at the beach ridge is a function of their hydrodynamic characteristics. Disc- and blade-shaped clasts can be easily lifted in the water column and remain elevated longer than any other shape due to their greater surface area and are thus entrained further landward during swash uprush. In addition, unlike rollers and spheres, discs and blades are also less pivotable and therefore difficult to move during backwash (Bluck, 1967; Hayes *et al.*, 2010).

Sand-dominated beach ridges consist of a range of grain sizes from fine to coarse sand and gravelly sand (Reineck & Singh, 1975; Otvos, 2000). Sedimentary structures on either side of the ridge include landward and seaward dipping stratification (Figure 1.5).

In profile, the backshore has, therefore, a landward-sloping surface. This geomorphological feature in gravel beaches helps differentiate between a beach and barrier beach (Figures 1.4 & 1.5). The presence of a rear landward slope is typical of the latter, whereas the absence thereof defines a beach (Orford *et al.*, 2001). Sediments that form the landward-sloping surface represent storm deposition. These are washover deposits (Figure 1.5). Once a beach ridge has been breached or overtopped by waves during a storm surge, washover sediments are moved landward into a topographically lower area, such as a lagoon (Carter & Orford, 1981; Bluck, 1999; Sedgwick & Davis Jr, 2003). Like their sandy counterparts (see Sedgwick & Davis Jr, 2003; Figure 1.5), landward-dipping stratification is a diagnostic feature of gravel washover deposits. Low-angle stratification, which is the predominant structure, typifies washover sheets, whilst steeper angles represent washover deltas. The last is a function of subaqueous deltaic deposition (Carter & Orford, 1981; Orford & Carter, 1982). In this study the washover deposits are considered part of the back-barrier setting, given that their distal portions interfinger with fine-grained lagoon sediments,

1.4.3 The foreshore

The foreshore environment, situated between the low and high tide levels, is the intertidal zone and may display a variety of configurations (Elliott, 1978; Davis Jr, 1985). The simplest of these is a steep beach face that extends seaward from the beach ridge (Elliott, 1978; Kirk, 1980; Davis Jr, 1985; Figures 1.4A & 1.5). Generally, the intertidal zone is flooded and exposed during normal tidal cycles where swash and backwash consistently sweep the beach face (Reinson, 1984; Boggs Jr, 2001). In gravel beaches it comprises three main settings, notably the upper, middle and lower beach face.

Generally, the upper beach face will include remnant features recording the last highest storm event (Davis Jr, 1985; Single & Hemmingsen, 2001). These are the beach ridges as discussed in the aforementioned section (Figure 1.4B). They mark the boundary between the foreshore and backshore (Reinson, 1984). In gravel beaches seaward-imbricated discs occur immediately below the beach ridge forming the uppermost part of the foreshore.

Below this boundary, in the middle part of the beach face (Figure 1.4B), morphological change is greatest with swash berms and cusps as diagnostic features (Kirk, 1980; Davis Jr, 1985; Bluck, 1999; Carter, 2002; Austin & Masselink, 2006). Swash berms will move landward across the beach face with successively higher swash excursions and are

ephemeral in nature compared to the more permanent beach ridges (Otvos, 2000; Austin & Masselink, 2006). Like swash berms, tiers of beach cusps can occur at different levels and these are indicative of reflected beaches where the beach face is steeply inclined (Carter & Orford, 1984; McKay & Terich, 1992; Sherman *et al.*, 1993; Forbes *et al.*, 1995; Masselink & Pattiaratchi, 1998; Carter, 2002; Austin & Masselink, 2006). Ranging from a few centimetres to approximately 50-70 m in length and up to 2-3 m in height, beach cusps are rhythmic patterns characterised on surface by prominent horns that taper seaward, separated by broad landward curving bays (Carter, 2002; Coco *et al.*, 2003; Figure 1.4C). Their mode of formation has not been satisfactorily addressed. Rhythmic standing edge waves have been advocated as a process of cusp formation (Sherman *et al.*, 1993; Pye, 2001), whilst self-organisation models are proposed as alternative explanations (Masselink & Pattiaratchi, 1998; Coco *et al.*, 2003; Austin & Masselink, 2006).

On gravel beaches, the middle sector of the beach – given its highly dynamic nature – is subjected to aggressive sorting through a process of clast acceptance and rejection, resulting in effective clast size and shape sorting. Here a variety of shapes are sorted, but this part of the beach is commonly dominated by seaward-imbricated discs (Carter, 2002). Graded beds with steeply seaward-dipping foresets are products of swash berm and beach cusp deposition (Bluck, 1999). Noteworthy is that complete cusp structures are seldom preserved in the rock record due to erosion, making it difficult to differentiate them from swash berm structures (Bluck, 1999).

The lower part of the beach, below the active ‘sweep zone’, has a gently inclined surface and may be stable for long periods compared to the highly dynamic, steep middle sector (Bluck, 1999; Pye, 2001; Figures 1.4 & 1.5). This gently inclined area at the base of the beach may comprise erosional rock platforms, depositional sand aprons or accumulations of cobble and/or boulder lags (Forbes *et al.*, 1995). Bluck (1999) has termed these gently inclined surfaces in gravel beaches as ‘selection pavements’ (Figure 1.4B). These consist of gently inclined sheets of well-sorted gravel that has been sourced from the landward parts of the beach during erosion of swash berms and cusps, and seaward during swash excursions (Bluck, 1999; Bluck *et al.*, 2001). In microtidal regions where the wave energy is significantly high with a small tidal range, as in the case of the study area, selection pavements are poorly developed (Bluck *et al.*, 2001). Contiguous with selection pavements and forming the most seaward end of the beach face is an accumulation of large spherical

clasts that can reach boulder size (Bluck, 1967; Orford, 1975; Williams & Caldwell, 1988; Bluck, 1999). The predominance of spheres is a result of their greater mobility and thus can roll easily down the beach face for long distances to accumulate at the beach toe (Bluck *et al.*, 2001). This accumulation produces a gentle seaward-inclined, thin gravel sheet (clast thick) and is defined as the outer frame by Bluck (1967).

Given their grain size, sand beaches in micro-tidal settings obviously yield different bedforms and structures. In most instances, many of the surface features are rarely preserved due to their impervious nature, coupled with high swash and backwash energy levels in the foreshore. The most notable sedimentary structures preserved in the rock record are parallel laminae, dipping gently seaward (Elliott, 1978; Boggs Jr, 2001; Figure 1.5). Here heavy mineral laminae consisting of minerals such as garnet, ilmenite, magnetite, zircon and others are commonly present where they alternate and are overlain by coarser-grained quartz-rich sand (Boggs Jr, 2001). These heavy minerals represent a lag concentration where grain segregation is achieved under conditions of plane-bed sedimentation (Davis Jr, 1985). In contrast, low-angle, landward-dipping laminae represent antidune migration that has formed during backwash (Davis Jr, 1985; Boggs Jr, 2001).

Where foreshore bars are preserved, they are recognised by their steep landward-dipping stratification (Elliott, 1978; Davis Jr, 1985; Boggs Jr, 2001; Figure 1.5). These bars originate from the shoreface and migrate landward during fair-weather conditions to weld onto the beach face, thereby inducing beach growth (Davis Jr, 1985). However, such foreshore bars are absent where shorelines are highly reflective, as in the case of gravel beaches (Reading & Collinson, 1996; Carter, 2002).

1.4.4 The shoreface

The shoreface is always submerged and thus represents the subtidal zone (Figures 1.4 & 1.5). It extends from mean low water (MLW) to the lower limit where normal waves begin to affect the seabed; this is fair-weather wave base (Reading & Collinson, 1996). Hence, it corresponds to a region of shoaling where wave shape is altered to a more peaked crest, increased height (shoaling effect) and change in propagation toward a shore-normal direction (wave refraction; Niedoroda *et al.*, 1985). This occurs once wave base comes into contact with the seabed and the effect increases as waves propagate over the shoreface towards the foreshore. When fair-weather wave base is considered, the depth at which wave base begins

to touch the seabed is dependent on the wave climate in that coastal area and the gradient of the shoreface. Obviously, steeper gradients favour greater depths at which fair-weather wave base occurs, whilst the opposite holds true for more gentle gradients. However, it has been estimated that fair-weather base is generally shallower than 20 m, a depth where sand-sized material is not commonly moved (Elliott, 1978; Harms *et al.*, 1982; Reinson, 1984; Niedoroda *et al.*, 1985; Walker, 1985, pg. 256; Nichols, 1999). Fair-weather wave base for highly energetic coasts, as in the case of the study area (noted in Section 1.3), is considerably deeper. Here average wave conditions are capable of moving very coarse sand at depths of 30 m (de Decker, 1988). It therefore follows that the movement of finer sand would occur at a greater depth. Consequently, shoreface processes and sediment characteristics in such dynamic settings are different to most ‘classic’ shoreface examples gleaned from various literature sources.

For simplicity, the shoreface is divided into the three broad zones as described by Boggs Jr (2001), namely the upper, middle and lower (see Figure 1.5).

The upper shoreface is the energetic surf zone (Boggs Jr, 2001). Here sediment size ranges from fine- to medium-grained sand with gravel also occurring (Boggs Jr, 2001). Shore-normal currents generated by waves are superimposed on shore-parallel wave-driven currents giving rise to complex sedimentary sequences exhibiting multi-directional structures. These are dominated by trough cross-stratification formed due to the migration of ripples and dunes, but low-angle planar-stratification can occur (Reinson, 1984; Boggs Jr, 2001). Bioturbation is common, but not abundant (Boggs Jr, 2001).

The middle shoreface is also a highly energetic area and encompasses the breaker zone where fine- to medium-grained sand, silt, shell material and gravel accumulate (Boggs Jr, 2001). In addition to rip currents, longshore-bar development is commonly associated with this part of the shoreface, with the latter predominating. (Boggs Jr, 2001). Similar to the upper shoreface, sedimentary structures are complex, ranging from landward-dipping ripple cross-lamination through seaward-dipping, low-angle planar-stratification to trough cross-stratification (Boggs, Jr, 2001). Bioturbation is also common (Boggs Jr, 2001).

The lower shoreface is seaward of the surf and breaker zone and is subjected to oscillatory wave currents during fair-weather. These are important in agitating the seabed, but

will generally not produce net sediment transport (Swift & Niedoroda, 1985). Sediments in this zone consist predominantly of fine sand interbedded with silt and mud. These exhibit variable structures, but are dominated by near horizontal lamination, landward migrating ripples and hummocky cross-stratification that may contain hydraulically light particles such as mica flakes and plant debris (Boggs Jr, 2001). High levels of bioturbation tend to obliterate sedimentary structures (Boggs Jr, 2001).

Effective sediment entrainment in this part of the shoreface only takes place during storms where wave base is significantly lowered to scour and modify the seabed deposits. Here the sediment is aggressively agitated into suspension and re-deposited farther seaward in the offshore-transition zone and/or beyond as the storm wanes (Reinson, 1984). Coarser sediment, ranging from coarse sand to gravel, can also be injected into the lower shoreface during storm periods to be deposited as thin storm lag sequences. Sourced from the foreshore and upper shoreface, the coarse sediment is moved seaward in strong offshore-directed rip-channels (see Reineck & Singh, 1975; DeCelles, 1987; Leckie, 1988; Cheel & Leckie, 1992).

Seaward, the lower shoreface grades into the deeper water environment of the offshore-transition zone where mud and silt deposition dominates. This zone extends from fair-weather wave base to storm wave base and is contiguous with the offshore (Figure 1.4; Elliott, 1986; Reading & Collinson, 1996). Deposition is characterised by low- and high-energy conditions where suspension settling takes place during fair-weather, whilst seafloor agitation and coarse sediment deposition is governed by storm conditions associated with oscillatory wave processes (Elliott, 1986; Reading & Collinson, 1996). Consequently fair-weather mud deposits will alternate with storm-generated sands. These storm deposits are characterised by hummocky cross-stratification, which typically represent storm-dominated settings where wave base is lowered beyond fair-weather wave base (Reading & Collinson, 1996; Boggs Jr, 2001). The depth to which this occurs is variable for different coastal areas (Nichols, 1999). Similar to the lower shoreface, rip currents and storm-generated density currents are one of the mechanisms for introducing coarser sediment (sand to fine gravel) to the offshore-transition zone. These introduced sediments are reworked into hummocky cross-stratification (Johnson & Baldwin, 1986; Reading & Collinson, 1996).

1.5 OBJECTIVES OF STUDY

There is a substantial body of work on gravel beaches, but this stems mainly from European, American and Australasian studies. More significantly, these studies have focused primarily on understanding gravel beach structures, sedimentary process and beach behaviour in view of implementing and improving coastal management techniques. Here, gravel beaches play a significant role in the natural protection of coastlines. Thus the management of such coastlines is not only an essential requisite in maintaining a robust defence against sea flooding, it also ensures habitat conservation (Pye, 2001; Orford, 2001; Buscombe & Masselink, 2006). The beaches in sub-Saharan Africa are equally important, but there are also specific gravel beach deposits that are fundamental to the mining industry. These are the diamond-bearing beaches of southern Africa.

In comparison to the body of research on European, American and Australasian deposits, little work has been done on the diamond-bearing gravel beaches of sub-Saharan Africa and, more importantly, none on diamond-bearing gravel barrier beaches and barrier spits. Given that these barrier deposits of economical significance are only known, to date, from southern Namibia, this study is the first of its kind to examine the anatomy and diamond mineralisation of such deposits within a palaeo-river mouth setting (Figure 1.6A & B). With a dearth of gravel beach studies in southern Africa, most of the gravel beach data used in this study as comparative examples originate from countries outside of Africa.

Mining operations within the study area have exposed these deposits both in mining faces and sample trench sections. This provided an opportunity to examine the internal structure and, in places, the forms of gravel beach accumulation at the interface. Thus, the objectives of the thesis are to:

- 1) Describe the gravel accumulations deposited under highly energetic wave conditions and a low tidal range. Deposits built under these conditions, particularly in sub-Saharan Africa, are not well documented in the geological literature.
- 2) Examine the stratigraphic architecture of the entire marine sequence from beach to shoreface. Given that the energy conditions are known, it is of interest to determine the gradual change in structure and form of the deposits when one moves from the backshore

to the shoreface. The genesis of these deposits under such highly energetic conditions is interpreted.

- 3) Examine the general stratigraphy of the deposits, paying particular attention to the effects of sea-level change during the 30 m Package transgressive event and variation in sediment supply. Noteworthy is that the beach deposits have accumulated within a palaeo-river mouth setting where accommodation space has allowed unrestricted beach growth and preservation during times of fluctuating sea-levels and sediment supply.
- 4) Develop a diamond distribution model. Results from sampling campaigns undertaken by the mining company to test the diamond potential of the interface provide an unprecedented opportunity to appraise and interpret the diamond mineralisation patterns of each facies. This has not been done before given the rarity of such deposits. The number of diamonds retained and their size is documented. Consideration is also given to the various processes in which this might occur in a setting where classic fixed trapsites are absent. Moreover, the bulk of diamonds introduced mainly from the offshore during the Plio-Pleistocene contrasts with conventional mechanism whereby river input governs diamond nourishment in placer deposits. In view of this, the process of diamond introduction during transgressions and subsequent recycling will be described.
- 5) Examine the fluvial and marine interface. That the study area represents the interface between fluvial ('supply') and marine ('dispersion') processes, the importance of this interface is considered given that it is a sink to the fluvial discharge where coarse gravel has accumulated and a reservoir to the marine realm, particularly to the highly diamondiferous linear and pocket beaches farther down-drift.

1.6 PREVIOUS WORK

Since their discovery in 1928, and subsequent mining from 1935, the MA1 onshore palaeo-beach deposits received considerable attention due to their economic significance. Paradoxically, apart from the confidential reports regarding their exploration, evaluation and exploitation, little has been published. For ease of appraisal, discussions on the previous work are tabulated in two parts, notably, the aspects of MA1 gravel beaches in Table 1.1 and their diamond mineralisation in Table 1.2. Mention must be made that these past studies encompassed the entire MA1 beaches. More recent studies on the study area will not be discussed here, but considered in the relevant sections, namely, Chapter 3 (facies association)

and Chapter 5 (diamond mineralisation). Publications on the study area by the author are presented in Appendix A.

Table 1.1: Previous work on gravel beaches

Author(s)	Study
Stocken (1962), Hallam (1964)	Formulated a regional stratigraphic framework for MA1 gravel beaches based on fossil occurrences. Recognised a series of beach terraces stepping seaward at progressively lower elevations from the oldest and highest in the east to the youngest and lowest in the west.
Hallam (1964)	Was the first to recognise unique sedimentological characteristics of the gravel beaches in MA1. Noted that the gravel beds dip steeply seaward with different clast shapes confined to specific areas of the beach. Egg-shaped clasts (discs and blades) were found at the beach ridge, whilst a combination of well-rounded and flattened clasts accumulated seaward of the ridge.
Fowler (1976, 1982)	Provided the first brief description of the interface within the ED Area. Noted that the sequence consisted of complex marine and fluvial sediments that were intertwined. He concluded that the marine deposits represented a continuum of gravel beach environments from the most landward backshore environment through the foreshore and shoreface settings to the most seaward offshore environment – each characterised by a distinctive set of structures. He also noted that the older gravel beaches were characterised by the occurrence of <i>Donax rogersi</i> – a fossil that was absent in the younger beach sequences.
Corvinus (1983)	Investigated the archaeological potential of the onshore palaeo- beaches to augment the stratigraphic correlation. Significantly, Early Stone Age artefacts of an Acheulian culture were recovered from the older beaches close to the Orange River mouth. They occurred within the surface calcrete that was capping the littoral succession. The beaches were therefore considered to be older than 0.8 Ma.

Table 1.2: Previous work on diamond mineralisation in gravel beaches

Author(s)	Study
Hallam (1964)	Showed that diamonds are likely to occur in two main areas; immediately seaward of the beach ridge and at the base of the beach slope (the beach toe) close to or in contact with the bedrock footwall. Hence, an irregular bedrock footwall comprising gullies and potholes was recognised as a favourable area for diamond concentration.
Apollus (1995)	Noted that pocket beach deposits formed at the most distal end of MA1 yielded high diamond concentrations in beach sequences that were dominated by sand and shell. This is in contrast to the general view that sand dominated sequences are poorly mineralised, whilst beaches with good gravel fabric are considered to have the best potential.

Jacob (2001)	Demonstrated that diamond concentration within linear beaches developed on bedrock north of the ED Area was linked to the depth of gulley incision into the bedrock footwall. The deepest incisions were confined to the seaward end of marine-cut platforms and thus areas of higher diamond concentration were recorded at the interface of bedrock platforms.
--------------	--

Past studies considered the ED Area deposits as part of the linear beach stratigraphy and thus were seen as the southern continuation of linear beach deposits. Although this view is not erroneous, Fowler's (1976) work on identifying the ED Area as a complex setting of marine and fluvial sediments was not investigated further. Consequently, a stratigraphic framework in the context of a palaeo-Orange River mouth setting where accommodation space affords the development and preservation of different beach types, particularly during sea-level fluctuations, was not fully examined.

Aspects of the diamond mineralisation were also not taken to a level of better understanding. Whilst there is a clear appreciation of the bedrock influence on diamond distribution, there is a need to further investigate the conditions of diamond retention and distribution in the ED Area deposits where the influence of a competent footwall is absent. Hence, the depositional history of this dynamic interface and the controls on diamond distribution has not hitherto been fully appraised and is a major focus of the work presented here.

1.7 METHODS

This study stems from a Namdeb Diamond Corporation project to appraise the economic potential of the ED Area in view of extending the life of mining operations. A programme of trenching, trial mining and diamond sampling was initiated during 1994, and on conclusion in 1998, over 300,000 carats were added to the company's diamond resource inventory. The beach deposits were therefore sequentially sectioned and well exposed; presenting an opportunity to examine the different depositional environments.

Being the first comprehensive study of the ED Area, the main emphasis was placed primarily on fieldwork where the stratigraphy and depositional settings were considered. Consequently, laboratory work, gravel clast and diamond analyses (such as surface features) were kept to a minimum. Only trench sections that exhibited the full spectrum of beach

environments were examined in detail; these were key to understanding the sedimentological characteristics of the ED Area.

Visits to the Terrace Bay gravel beaches along the Skeleton Coast helped to gain insight on the aspects of modern gravel beach formation and their structures. These cursory visits were part of Namdeb Diamond Corporation (Pty.) Ltd. field training excursions. Thus, the Terrace Bay deposits did not constitute a comprehensive study of modern processes. Such a study is beyond the scope of this thesis.

1.7.1 Trench excavations

Trenches of 1-2 km in length and approximately 1.5 m wide were excavated perpendicular to the present shoreline and strike of the palaeo-beach ridges. Besides the trench excavations, mine faces created during gravel extraction supplemented field data as it permitted a three-dimensional view of the marine sequences (see Appendix B, Section 1.1).

Bulk samples, ranging in size from 200-1,000 tons, were collected from the excavated material that was stockpiled in windrows for diamond sampling. In places, it was impractical to sample individual facies separately and in many instances the samples comprised a mixture of depositional environments or sediments of different time frames. Nonetheless, discrete sampling results were also sourced from historical sampling data where the bulk sample size ranges from 20 tons to approximately 4,000 tons.

1.7.2 Field measurements

Palaeo-current measurements

Palaeo-current azimuths were determined using two techniques designed for unconsolidated sand- and gravel-sized sediments. In sand-dominated strata, sections were cut into the face to obtain a reasonable three-dimensional view of the cross-strata. The foresets were measured using a home constructed inclinometer based on Dasgupta's (1995) design. Improving on earlier models, Dasgupta (1995) designed a simplistic but effective inclinometer to enhance the measurement capabilities, particularly where bedding planes were awkwardly exposed. The design and application of the inclinometer constructed by the author is presented in Appendix B, Section 1.2.

Although three-dimensional exposures were excavated for measuring trough cross-stratification, erroneous readings can result if trough limbs are treated as planar foresets (DeCelles *et al.*, 1983). Consequently, to ascertain the magnitude of error, some measurements were verified using stereographic projections. A similar technique to that of DeCelles *et al.* (1983) was used where opposing limbs of a trough structure were plotted stereographically using GEORient © 2009 (version 9.4.4; Holcombe, 2009). The results of using this technique are illustrated in Appendix B, Section 1.2.

Measurement of gravel foresets was more difficult as they collapsed easily if any excavation was attempted to gain a three-dimensional view. However, two techniques proved useful in obtaining measurements. The first focused primarily on recognising the same gravel foreset in both faces of the trench. Once corresponding points were established, two poles were wedged in place between the trench walls along the foreset, at a distance from each other, to create an imaginary plane. A wooden board was then placed on the poles and held firmly in position (Figure 1.7). This created a plane from which the attitude of the foreset could be established using a Brunton compass. The second technique was used only where sand could be seen interbedded with the gravel foresets. At the contact, the sand was removed to expose the gravel foreset plane on to which the sand was deposited. A wooden board was placed on the exposed gravel surface and measurements were determined with a Brunton compass.

All palaeo-current results are presented using rose diagrams. A software, GEORient © 2009 (version 9.4.4; Holcombe, 2009) was used to generate the graphic presentations. The number of readings (n), the vector mean (X_v), the length of the resultant vector (R) and the vector magnitude ($L\%$) for each sub-facies are tabulated. These are calculated using GEORient © 2009 (version 9.4.4; Holcombe, 2009). Note that (X_v) is an expression of the average direction in degrees, (R) represents the length of the vectors describing the directional values ($R = \sqrt{(\sum n \sin x)^2 + (\sum n \cos x)^2}$) and ($L\%$) is a measurement of dispersion as a percentage ($L = R/n \times 100$) where values close to 100% represent a cluster of data around the vector mean, whilst lower values reflect a greater scatter (Lindholm, 1987; Graham, 1988).

Trench and mine section mapping

Exposures were mapped in detail and the thickness of sedimentary units was measured with a tape, as were sedimentary structures. Elevation measurements of the surface

topography, marker units and, in places, lithological boundaries were determined by a qualified surveyor using a Leica digital theodolite. In addition, old records and mine plan sections dating from 1952 were sourced from the Mineral Resource Department archives in Oranjemund. Although this extensive dataset did not record all the sedimentological aspects, it was nevertheless used to supplement the field mapping.

The terminology used for describing sedimentary structures are after Collinson & Thompson (1989), whilst symbols used for illustrating graphic logs and the format of presentation are based on Johnson (1992).

Grain size description is based on the Udden-Wentworth grain scale, (Udden, 1914; Wentworth, 1922), whilst grain class terminology is according to Friedman & Saunders (1978; in Packham & Neal, 2001; see Appendix B, Section 1.2.4 for grain scale chart). Infield grain size estimation for sediments less than 4 mm (-2ϕ) was achieved with the use of a grain-size comparator (classes of 1 ϕ) in conjunction with a 10X magnification hand lens. However, for gravel-sized material, a Vernier caliper was used mainly for clasts up to cobble size, whereas boulder-sized gravels were estimated using a tape measure.

Clast shape discrimination

Clast morphology was established using the largest clasts. Note that the term morphology, as per Blott & Pye's (2008) description, is a general expression of an object's shape and surface texture. Particle shapes have been described in various ways (see Blott & Pye, 2008; pg. 34), but descriptive terms such as sphere, disc, blade and rod is favoured in this study as it allows ease of visualisation of such geometric shapes.

The three orthogonal axes of each clast, notably the long (a), intermediate (b) and short (c) as described by Krumbein (1941; cited in Pettijohn, 1975), were measured in centimetres using a Vernier caliper. Clast indices were plotted using a Microsoft © 2003 Excel-based Folk diagram designed by Graham & Midgley (2000) sourced from the internet. While it has been shown that errors in measuring clast axes using a caliper can be as much as 2.8% (Blott & Pye, 2008), a test plot of the raw data demonstrated that if a 2.8% underestimation is corrected, no appreciable difference is noted when the 'corrected indices' are plotted. Thus, it is viewed that the clast data is sufficiently accurate to provide an adequate measure of shapes.

The Folk form triangle modified by Blott & Pye (2008) was used in this study for shape discrimination. Considering that their eight classes represent different degrees of equancy (sphericity) and the descriptive terms make it difficult to envisage the geometric implications, these eight classes were grouped into four broad categories for this study so that an easy appreciation of particle shape is gained. These are spheres, discs, blades and rods. This grouping is elaborated on and illustrated in Appendix B, Section 1.2.5.

Gravel clast roundness was visually estimated using the classification scheme of Powers (1982; in Graham, 1988). Mention must be made that the gravels within the study area are all well-rounded and thus no further reference is made on their degree of roundness when describing sedimentological characteristics in Chapter 3.

1.7.3 Palaeontological sampling

Fossil molluscs were collected and submitted to the De Beers Marine Mineral Resource Laboratory in Cape Town for identification by Pether (2003). In addition, samples from selected depositional environments were taken to establish their foraminifera content and these were also submitted to the De Beers Marine Mineral Resource Laboratory in Cape Town for processing and identification by Dale & McMillan (1996, 2003). Note that the fossil molluscs could not be dated using strontium isotope ratios due to calcite overgrowth (calcretisation). Consequently, age relationship is based primarily on the association of fossil assemblages. The fossil assemblage for the study area is presented in Appendix C.

1.7.4 Diamond data

Diamond data were derived from the different sampling phases that tested various sedimentary beach environments. This dataset also included results from past sampling campaigns during the 1950s and 1970s. The data from the last two were used extensively for determining the mineralisation patterns of beach deposits, given that the entire spectrum of beach environments were *in situ* at that time of sampling. Data from the later phases of sampling during the 1990s were mostly used for diamond size frequency distribution analyses (see Appendix B, Section 1.3). The data are included on a compact disc (CD) accompanying the abstract volume.

Sample treatment process

Samples generated from the trench excavations were treated on the mine site through a dedicated Dense Medium Separation (DMS) plant equipped with an X-ray facility. The capacity of the DMS plant used is 30 tons per hour. All bulk samples were weighed at the head-feed bin with an Economy Process Automation weightometer before processing. To prevent sample contamination, both the DMS plant and X-ray unit were flushed after the completion of each sample.

Final sorting of the X-ray concentrate was conducted at Namdeb's Geological Laboratory where the diamonds were sorted, counted, weighed and photographed. Thus, each sample pertaining to a specific depositional environment or a mixture thereof has a discrete result comprising the sample weight, total diamond weight and number of diamonds. Only the diamonds falling within a size range that is greater than 2 mm and less than 25 mm were recovered. The processes relating to DMS and X-ray separation are briefly described in Appendix B, Section 1.3. Also included is a sample flow diagram in Figure B5.

Sample results – diamond data

All diamond results from the earlier and later phases of prospecting were used to gain an appreciation of the mineralisation patterns. With the later phases of sampling, physical logging of the sedimentary sequences from where the samples were extracted ensured that results correlated to sedimentary facies. Sampling results from the earlier phases were gleaned from the 1950s and 1970s geological cross-sections on which prospecting data for each different lithological unit were recorded, but these lacked detailed recordings of sedimentological characteristics.

It must be noted that the objective of the diamond study was not to evaluate the resource using geostatistical computations, but rather to establish any geological control where distinct patterns were evident by simply applying the raw data in geographic space despite the variance in results and sample size. Pertinent to this study is the degree of diamond concentration (grade) and the average diamond size. The terminology and the basic statistical methods applied to calculate diamond concentration (grade) and average diamond size are adapted from Oosterveld *et al.* (1987) and Rombouts (1995).

The raw data from the sampling campaigns, presented in geographic space, are displayed as broad contours that were visually estimated for average grade and average diamond size. The relative position of each sample, based on their co-ordinates (surveyed using a Leica digital theodolite), was plotted using ArcGIS © Version 9.1. The derivation of average grade and average diamond size for this study is discussed in Appendix B (Section 1.3), whilst diamond results are tabulated in Section 1.3.3 and included on a compact disc (CD) accompanying the appendix volume.

Diamond mineralisation trends are presented in either two-dimensional or three-dimensional diagrams. The latter displayed better the mineralisation trends for three-dimensional bodies such as the barrier beach (Facies C; see Chapter 3, Section 3.5), whilst two-dimensional representations suited sheet-like sedimentary bodies, such as the transgressive lag (Facies B; see Chapter 3, Section 3.4) and storm gravel sheets (Sub-facies D3; see Chapter 3, Section 3.6).

CHAPTER 2 – GEOLOGICAL SETTING

The first part of this chapter summarises a regional perspective of the marine and continental processes that were active since the Late Cretaceous in developing the diamond palaeo-beach placers along the Atlantic coastline. The second part discusses briefly the geological framework of MA1, with greater emphasis on the Quaternary marine deposits. Their stratigraphic relationship and distribution are also considered here. An illustrated summary of the stratigraphic framework for the Cainozoic deposits is presented in Figure 2.1, whilst a summarised perspective of the regional geological setting is depicted in Figure 2.3.

2.1 REGIONAL SETTING

2.1.1 Diamond supply

It is widely accepted that the diamonds along the Atlantic coast of Namibia have been transported principally by an ancestral Orange River from a southern African hinterland source restricted to the Kaapvaal Craton (Kaiser, 1926; Stocken, 1962, 1978; Hallam, 1964; van Wyk & Pienaar, 1986; Corbett, 1996; Ward & Bluck, 1997; de Wit, 1999; Jacob *et al.*, 1999; Ward *et al.*, 2002; Bluck *et al.*, 2005; Jacob, 2005).

Post-Gondwana erosion during the Cretaceous rapidly stripped the interior of South Africa (Partridge & Maud, 1987; Brown *et al.*, 1990; Partridge, 1998) and while the precise amount of erosion remains unresolved, estimates of 3,000-1,400 m (Brown *et al.*, 1998; Brown *et al.*, 2002), 2,700-1,000 m (Hanson *et al.*, 2009) and 7,000- 2,000 m (de Wit, 2007) have been suggested. Most of the diamond-bearing kimberlites within the Orange River drainage basin are between 80 Ma and 140 Ma (Smith *et al.*, 1985; Gurney *et al.*, 1991; Brown *et al.*, 1998) and would have thus been extensively eroded during this strip-out phase releasing their diamonds into secondary deposits. These deposits, termed pre-assembled proximal placers by Bluck *et al.* (2005), would have accumulated within or near to the drainage network of the Orange River as an intermediary source of diamonds to be tapped by the evolving Orange River at the right time (Bluck *et al.*, 2005; this is discussed in Section 2.1.2).

However, the severe denudation declined rapidly by the end of the Cretaceous or Early Tertiary. This is evident from the reduced offshore deposition rates during the Tertiary

(Dingle *et al.*, 1983; Dingle 1993 cited in Miller, 2008, pg. 23-7; Partridge, 1998) and from apatite fission-track analyses of key geomorphological surfaces (Brown *et al.*, 2002; de Wit, 2007). Also the occurrence of un-eroded Late Cretaceous olivine-melilitite/alkaline intrusions in Namaqualand and Bushmanland containing crater-lake deposits (Scholtz, 1985; Moore & Verwoerd, 1985; Smith, 1986; de Wit *et al.*, 1992) further support minimal lowering of the landscape during the Cainozoic. It has been estimated that less than 1,000 m of rock was removed during the Cainozoic (de Wit, 2007). Consequently, the supply of diamonds to these pre-assembled placers would have declined in concert with decreasing erosion of kimberlites.

So when was the right time for the introduction of diamonds to the Atlantic coast of Namibia? The onshore marine deposits at Bogenfels and Buntfeldschuh some 150 km north of the present Orange River mouth are diamondiferous (see Figure 2.2 for locality; Kaiser, 1926; Stocken, 1978; Ward & Bluck, 1997; Bluck *et al.*, 2005; Jacob, 2005). These deposits comprise a unique clast assemblage dominated overwhelmingly by yellow chalcedony and agate, with lesser, but notable, amounts of jasper and quartz lithologies. This assemblage is similar to the Late Cretaceous Mahura Muthla gravels (de Wit, 1996; Partridge, 1998, pg. 172; de Wit *et al.*, 2009); a pre-assembled proximal placer located in the interior of South Africa. Whilst the marine deposits at Bogenfels are considered as Middle to Upper Eocene in age (Siesser, 1977; Siesser & Salmon, 1979; Pickford & Senut, 1999), the undated Buntfeldschuh deposits are suspected to be of a similar age based on their clast assemblage similar to that at Bogenfels. Mention must be made that diamondiferous onshore marine and fluvial deposits younger than Eocene age lack the predominance of yellow chalcedony and agate, but their presence is still evident. Therefore the Bogenfels and Buntfeldschuh deposits suggest that the earliest introduction of diamonds to the Atlantic coast was by at least Eocene times.

Diamond supply to the Atlantic coast continued as the Orange River evolved throughout the Cainozoic, but a decreasing input through time, with a cessation by at least the Holocene, is apparent (van Wyk & Pienaar, 1986; Bluck *et al.*, 2005). Mining operations along the lower Orange River valley have shown that different terrace suites demonstrate varying degrees of diamond concentration (measured in carats per 100 ton; reported as cpht). This is summarised in Table 2.1.

Table 2.1: Variability in diamond concentration within Orange River terraces through time

Terrace suite	Age	Diamond concentration
Pre-Proto Orange	Not adequately dated. Assigned a Late Oligocene age (Bluck <i>et al.</i> , 2005; Jacob, 2005).	Highest at 35 to 55 cpht (Jacob <i>et al.</i> , 1999; Bluck <i>et al.</i> , 2005).
Proto-Orange	Middle Miocene (Arris Drift Gravel Formation <i>sensu</i> SACS, 1980; Corvinus & Hendey, 1978; Fowler, 1976; Jacob <i>et al.</i> , 1999; Pickford & Senut, 1999, 2003; Jacob 2005).	Lower at 1 to 10 cpht (van Wyk & Pienaar, 1986; Jacob <i>et al.</i> , 1999; Bluck <i>et al.</i> , 2005).
Meso-Orange	Undated, but assigned a Pliocene age (Fowler, 1976; Jacob <i>et al.</i> , 1999; Pickford & Senut, 1999; Jacob, 2005)	Poor at less than 0.5 cpht (van Wyk & Pienaar, 1986; Jacob <i>et al.</i> , 1999; Bluck <i>et al.</i> , 2005).
Modern River	Holocene to Recent	Barren. Not targeted for mining (Jacob, 2005).

Based on the above, it appears that there was an early flush of finer-grained diamonds to the Atlantic coast during the Middle Eocene, followed by an accelerated supply during Pre-Miocene times (possibly Late Oligocene) and thereafter (from Middle Miocene) a diminishing input, but with coarser diamonds (see Bluck *et al.*, 2005).

2.1.2 The Orange River conduit

Offshore records show that by Late Cretaceous times an ancestral, free-meandering Orange River (Kalahari River *sensu* de Wit, 1993) entering the Atlantic Ocean fed a large fine-grained (mud and silt) delta (Dingle *et al.*, 1983; Ward & Bluck, 1997; Aizawa *et al.*, 2000; Bluck & Ward, 2000). The delta was well established as a major depocentre in the Late Cretaceous, located approximately offshore from its current position (Aizawa *et al.*, 2000; Cartwright *et al.*, 2008). It therefore suggests that the Late Cretaceous Orange River – a suspended-load fluvial system (Cartwright *et al.*, 2008) – was not only positioned near to the course it follows today, but that such a distal fluvial system is also unlikely to have debouched coarse clastics, including diamonds into the Atlantic Ocean. However, by Middle Eocene times, predominantly siliceous gravels were being supplied to the coastal zone via a more energetic, bed-load dominated fluvial system. The marine gravels at Bogenfels and Buntfeldschuh, noted in Section 2.1.1, are testament to this input of substantially coarser sediment. Agates measuring 10 cm in diameter have been recorded from these deposits. These agates, as noted in Section 2.1.1, are characteristic of a Vaal-Orange River clast assemblage derived from the interior of southern Africa (Ward & Bluck, 1997; Macdonald,

1999). The change in fluvial character from suspended to bed-load dominated at the continental margin is a response to a rejuvenation of the ancestral Orange River through regional sub-continental uplift. In the absence of more accurate records, a Late Cretaceous/Early Tertiary age is assigned broadly to this epeirogenic uplift (Dingle *et al.*, 1983; Aizawa *et al.*, 2000).

In addition to the increase in fluvial energy, the Late Cretaceous/Early Tertiary uplift also invoked superimposed fluvial incision through the Phanerozoic cover and into Precambrian country rock, steeping channel gradients. During incision, the Orange River yielded an impressive and progressively coarser bed-load as shown by Ward & Bluck (1997) and Jacob (2005).

Studies have also shown that by Early Tertiary times the gross arrangement of the Orange River drainage system had established itself more or less as it is today (Dingle & Hendey, 1984; de Wit, 1999). In fact, by Early Miocene times the Orange River was unequivocally bedrock confined and not far from its present course (van Wyk & Pienaar, 1986; Fowler, 1976; Jacob *et al.*, 1999, Jacob 2005).

In summary, it can be concluded that an ancestral Orange River was debouching sediment into the Atlantic Ocean not too far from its present position since the Late Cretaceous. The change of river character to a gravel-bearing system as a consequence of epeirogenic uplift in Late Cretaceous/Early Tertiary times is the most significant event in the evolution of the Orange River. This not only introduced diamonds tapped from pre-assembled proximal diamond-bearing deposits in the hinterland to the Atlantic coast, but also provided coarse gravels to the Orange River and coastal systems that were integral to trapping diamonds.

2.1.3 The Atlantic sink

Wave climate

The highly energetic wave climate of today's Atlantic coast, as discussed in Section 1.3, has remained remarkably unchanged since the Neogene (de Decker, 1988). The strong southerly winds were certainly in existence during Middle Miocene times. In Namibia, aeolianites of this age, notably the Tsondab, Elizabeth Bay, Andoni, and Rooilepel Sandstone

Formations (Pickford & Senut, 1999; Miller, 2008) were emplaced under a southerly palaeo-wind regime (Ward, 1988; Corbett, 1989; Ward & Corbett, 1990; Besler, 1996; Ward, 2000). It has also been argued that the wind regime has greater antiquity. Aeolianites with a southerly palaeo-wind signature are present in Cretaceous sediments some 130 km offshore from Oranjemund (Kudu borehole 9A-3; Wickens & McLachlan, 1990) and at Buntfeldschuh (some 150 km north of Oranjemund) where they are coeval with Middle Eocene marine sediments forming a regressive package (Corbett, 1989; Ward & Corbett, 1990).

An additional significance of the Buntfeldschuh marine sediments is that the shoreface cross-strata exhibit palaeo-current flows to the offshore (west) and alongshore (north; Corbett, 1989). The first was interpreted as being due to rip currents that transported storm gravel sheets (seen in the same section) where clasts of 12 cm were recorded (Corbett, 1989), whilst the northward-directed palaeo-flows suggest longshore drift. If the Eocene Orange River was positioned in its present location during the Tertiary, as noted in Section 2.1.2, gravel emplacement at Buntfeldschuh some 150 km to the north could have only been possible through powerful longshore drift transport. Noteworthy is the absence of any chalcedony and agate-bearing river input of Eocene age south of the Buntfeldschuh deposit. Alternatively, the channel of the Eocene Orange River could be deflected northward by the longshore drift dispersing sediment along the coast (see Bluck *et al.*, 2007). A modern analogue is the Senegal River where the channels and attendant delta plain are deflected along the coast for a considerable distance (Bhattacharya & Giosan, 2003; Coleman & Huh, 2004). If this were the case, then a significant gradient is needed to ensure energetic river transport of coarse gravel up to 12 cm in diameter. This is unlikely for that distance in a coast parallel setting at constant sea-level. In view of the above, the Buntfeldschuh marine settings are no different to those seen at the present day and in Plio-Pleistocene sections within the study area.

From the above discussion, it can be argued that the present Atlantic wave climate, notably a combination of a southerly quadrant wind, northward-directed longshore drift and high wave energy, has been in existence since the Middle Eocene. This combination of processes was critical in fractionating and redistributing the Orange River sedimentary outfall.

Sediment dispersal

Since the Late Cretaceous/Early Tertiary uplift there has been little or no subsidence of the shelf and thus accommodation space for sediment input from the Orange River has been lacking (Aizawa *et al.*, 2000; Bluck *et al.*, 2007). The combination of a neutrally buoyant shelf and the energetic wave climate has consequently enabled wave base to engage the sediment outfall from the Orange River more aggressively since the Eocene. The thin Tertiary cover in the offshore (Dingle *et al.*, 1983; Aizawa *et al.*, 2000), is not only a testament to this (see Aizawa *et al.*, 2000), but also suggests that shallowing of the shelf region through significant sediment build up has been prevented, despite continued input from the Orange River (Bluck *et al.*, 2007). Evidence of this is seen in the present offshore where extensive areas of exposed bedrock and gravel deposits at depths of 70 m and 120 m, respectively, have been recorded during exploratory dives with the *JAGO* mini-submersible offshore of the Orange River mouth and farther to the north (observations by the author, 1997, dive nr. 532; J. Ward, pers. comm., 1999). It is therefore evident that the shelf region off the Orange River mouth is an area of sediment bypass through efficient redistribution as seen today (see Bluck *et al.*, 2007).

The present coastal redistribution system, active since at least the Eocene, has dispersed the coarser and finer sediment fractions from the Orange River outfall to separate regions of the continental shelf and shoreline (Figure 2.2; Bluck & Ward, 2000; Spaggiari *et al.*, 2006; Bluck *et al.*, 2007). The mud is believed to move offshore where it accumulates as an extensive mud belt at the continental edge away from wave energy influence. According to offshore studies, the shoreward boundary of the mud belt varies, but averages approximately between 40-65 m below msl (de Decker, 1987). It has also been proposed that the majority of suspended sediment, like the mud and silt fraction, is removed from the middle shelf southward by the south-directed de Decker current (in Birch *et al.*, 1991)

Driven by longshore drift, the sand which is mostly retained within the breaker zone, moves northwards along the coast in a belt that is usually not more than 3 km wide. Where the coastal configuration changes to embayments ('J'-shaped bays; Hallam, 1964; Corbett, 2002) and the gravel fraction runs out, the sand is returned onshore to accumulate on beaches, particularly in areas of lower wave energy where waves are refracted around headlands (Figure 2.2). Under a strong southerly wind regime, the sand is removed from these bays and transported inland, in the form of barchan dunes, via well-defined valleys termed aeolian

transport corridors (Corbett, 1989) to accumulate in the main Namib Sand Sea under desert conditions (Rogers, 1977; Corbett, 1989, 1996; Ward *et al.*, 1998; Corbett, 2002).

Through the removal of the finer sediment, a southern ‘head’ of residual gravel is thus left behind to accrete as a series of narrow beaches, which in their various forms, have built up the coast for over 150 km north of the Orange River mouth (Hallam, 1964; Ward *et al.*, 1998; Bluck *et al.*, 2001; Spaggiari *et al.*, 2006; Figure 2.2).

From past studies of the Pleistocene gravel beaches, a distinct northward change in beach type and gravel size is evident (Bluck *et al.*, 2001, 2005, 2007; Spaggiari *et al.*, 2006). As noted in Section 1.1, close to the Orange River mouth, boulder to large cobble-bearing gravel barrier spits predominate, whilst pebble-bearing pocket beaches form the most northern accretion (Apollus, 1995; Spaggiari *et al.*, 1999, 2002, 2006; Bluck *et al.*, 2001; Bluck *et al.*, 2007). This northward change is thought to be a result of decreasing sediment supply under the influence of a vigorous longshore drift (Bluck *et al.*, 2001). A northward decrease in diamond size is also evident as a consequence of longshore drift sorting (Hallam, 1964; Sutherland, 1982; Schneider & Miller, 1992).

In summary, the debouched Orange River sediments have been fractionated and redistributed since the Middle Eocene through a combination of a buoyant shelf, extreme wave energy, longshore drift and powerful southerly winds. This fractionation into gravel, sand and mud, ensures that the coarse material (>2 mm) forms the host framework into which pebble- and granule-sized diamonds accumulate through mechanical concentration in diamond-bearing beaches.

Sea-level changes

Sea-level changes had a profound influence on the supply and distribution of the coarse sediment, as well as the diamonds over the continental shelf. Old high-level shorelines and submerged terraces of Cainozoic age along the southern Namibian coast show that the sea-level has fluctuated considerably in the past.

Relative sea-level estimates are difficult to measure due to the earth moving constantly in response to various factors (Kendall & Lerche, 1988) and thus there is at times little correlation in the eustatic events when results are compared on a global scale. For

example, there is hardly any correlation between the Neogene sea-level curves inferred for South Africa and Western Australia (Pickford, 1998). Despite this, there is a strong agreement that global scale events have occurred. Of these, a major transgression was recorded in the Eocene (Siesser & Dingle, 1981; Dingle *et al.*, 1983; Dardis & Grindley, 1988; Pickford, 1998). The Buntfeldschuh littoral deposit occurring at 180 m above msl is evidence for this. Also, there is good correlation for two major global regressions. The first, a protracted lowstand, occurred during the Oligocene (Vail & Hardenbol, 1979; Dingle *et al.*, 1983; Dingle & Hendey, 1984; Pickford, 1998) and whilst estimates on the amount of sea-level fall are not precise, 200 m is considered a best estimate. A number of deeply incised valleys have been recorded in the Sperrgebiet and it is thought that their incision is a response to the Oligocene regression. These are the Proto-Kaukasib, Proto-Langental, Proto-Glastal, Kerbehuk and Uubvlei valleys (Pickford & Senut, 1999).

While multiple sea-level falls occurred globally throughout the Pleistocene, the last lowstand of significance occurred during the Last Glacial Maximum some 18,000 years ago where sea-level fall ranging from 120-150 m has been estimated (Guilcher, 1969; Dingle *et al.*, 1983; Dingle & Hendey, 1984). Off the Orange River mouth, a submerged palaeo-delta occurs at depths of some 120 m (*JAGO* dive observations by the author, 1997, dive nr. 532; J. Ward, pers. comm., 1997; see Gray 2002). This is correlated to a possible Pleistocene lowstand (Corbett & Burrell, 2001). It thus follows that sea-level variation for the southern Namibian coast is significant in that it ranges from 180 m above to 200 m below msl.

This would mean that the shelf has been occupied at different levels throughout the Cainozoic. Diamond-bearing sediment deposited at each of these levels are therefore available for reworking, particularly when previous levels are reoccupied as sea-level fluctuated. By, implication, the shelf is seen as a fertile area for diamond 'farming' during sea-level fluctuations. More significantly, the shelf remained an area of sediment bypass where dispersion of the mud (to an offshore mudbelt), sand (into the main Namib Sand Sea) and gravel (forming coastline beaches) was sustained (see Figure 2.2). Evidence for this is unequivocally provided by the numerous raised and submerged beaches developed at different elevations. In addition, the recovery of aeolian ventifacts during offshore sampling campaigns in water depths exceeding 100 m (Corbett, 1996) and reports of wind fluting in Precambrian dolomites at depths of 70 m (*JAGO* dive observations; L. Apollus, pers. comm., 1999) indicate an ancestral wind dispersal system similar to that of the present day. Therefore,

diamoniferous sediment deposited at the marine/fluvial interface during earlier sea-level stands would be subjected to the same dispersal process as today and the resultant gravel beaches, under the influence of longshore drift, would each have a northward decline in gravel clast and diamond size. In addition to the diamond contribution from the offshore where the shelf is ‘farmed’, it is highly likely that higher-lying, older gravel beaches representing earlier highstands would have also contributed where sheetwash and ephemeral streams erode the beaches (see Figure 2.3 for secondary diamond pathways).

From the above discussions, it can be concluded that the continental shelf has been raked by marine processes during periods of sea-level fluctuations since the Eocene. Hence, diamoniferous sediment introduced by the Orange River during that time will be ‘farmed’ for its diamond and gravel content at different intervals over the shelf area to be incorporated into younger gravel beaches during either a transgression or regression. A complex interplay of shelf ‘farming’ and erosion of higher-lying, older beaches would be seen as secondary, reworked sources for diamond supply. Thus, each gravel beach at a particular interval will retain a pre-sorted population of diamonds and gravel. The Plio-Pleistocene beaches within the study area, which is the focus of this study, are just one of many such beaches.

2.2 GEOLOGICAL FRAMEWORK OF MINING AREA 1 (MA1)

This section summaries briefly the geological framework of MA1 only. The general distribution of the different geological units is shown in Figure 1.2.

Broadly, the geology in MA1 can be summarised as:

- 1) Proterozoic rocks, principally of the Gariiep Supergroup;
- 2) Mesozoic dolerite dykes; and
- 3) Cainozoic fluvial, marine and aeolian sediments.

2.2.1 Proterozoic lithologies

The oldest rocks within MA1 belong to the Oranjemund Group of the Pan-African Gariiep Belt (Frimmel, 1995, 2008; Jacob, 2001). Essentially, the Gariiep Belt is a record of tectonic stages linked to the opening and closure of an oceanic basin during Proterozoic times (Frimmel, 2008). Each of these stages is recorded by characteristic successions of

sedimentary, volcanic and plutonic rocks. The Oranjemund Group is a tectonic sub-unit of one such tectonic stage, the Marmora Terrain (Frimmel, 2008).

The Oranjemund Group consist of mostly chlorite schist, minor carbonate, and abundant arenitic rocks. Volcanic and intrusive rocks are absent (Frimmel, 2008; Jacob, 2001). These rocks form the ‘bedrock benches’ on which the younger Cainozoic marine deposits rest. In many instances they are gullied and potholed by siliceous coarse gravels acting as an abrasive medium in the vigorous littoral zone (Jacob *et al.*, 2006). There are no exposed Proterozoic rocks within the ED Area, save for a small island of bedrock rising through unconsolidated fluvial sediments that have accumulated within the palaeo-Orange River channel during the Pliocene (Hallam, 1964; Fowler, 1976; see Figure 1.6). Consequently, the younger marine cover in the southern part of MA1 steps southward off a bedrock footwall onto incompetent fluvial sediments that, although only planed at the same level as the juxtaposed bedrock platforms, lack the ubiquitous gullies and potholes that is characteristic of the bedrock-floored palaeo-linear beaches farther north.

2.2.2 Mesozoic lithologies

The only rocks of Mesozoic age are Karoo dolerite dykes striking predominantly in a north-west to south-east direction. These are the only magmatic rocks to be found within MA1. Although undated, a Karoo age is tentatively inferred from their stratigraphic relation with the Proterozoic Oranjemund Formation they intrude. The only other dyke swarm they could represent is the Gannakouriep Suite, which is interpreted as a syntectonic intrusion during Gariiep times (Tankard *et al.*, 1982). However, the Gannakouriep dykes are older than the Oranjemund Formation (Frimmel, 1995, 2008) and it therefore implies that the dolerite dykes in MA1 are probably Karoo in age. A younger alternative could be Kudu volcanic equivalents of Lower Cretaceous age (Dingle *et al.*, 1983) intersected in boreholes offshore the Orange River mouth (Kudu 9A-2 & 9A-3; see Wickens & McLachlan, 1990). Unfortunately, attempts to date the MA1 dolerites have been thwarted by preferential weathering along these dykes.

2.2.3 The Cainozoic sequence

The cover is mainly an accumulation of Late Cainozoic aeolian, fluvial and marine sediments. The last are correlatives to the Alexander Bay Formation (SACS, 1980). In Namibia, this Formation is best represented within MA1 that extends from the Orange River

mouth to Chameis (Figure 1.1). Other isolated occurrences of marine sediments correlating to the Alexander Bay Formation are found farther north at Walvis Bay and along the Skeleton Coast (Hallam, 1964; Miller & Seely, 1976; SACS, 1980; Pether, 1994; Miller, 2008).

As this study focuses mainly on these marine sediments, the associated aeolian and minor fluvial deposits are not discussed. Nonetheless, the more prominent fluvial settings are summarised.

Pre-Pleistocene fluvial channels

Fluvial deposits infilling bedrock-bounded channels that are either coast parallel or perpendicular represent the oldest Cainozoic sediments. Although undated, these sediments are overlain by the younger Plio-Pleistocene marine deposits, providing a minimum age for the fluvial aggradation. The most prominent of these channels is the palaeo-Orange River, which constitutes the footwall to the overlying marine sediments within the study area as noted in Section 2.2.1. Drilling results have shown that the fluvial succession can be as thick as 80 m comprising predominantly coarse sand with minor interbedded gravel. A feature that is diagnostic of these fluvial sediments is the high abundance of zeolite pebbles within both the sand and gravel components. Only the north bank of this channel has been delineated, whereas its opposite bank is believed to have been either eroded away by younger Orange River channels or occurs south of the present Orange River mouth across the international border in South Africa (Hallam, 1964). The fluvial sediments, although undated, are considered to be Pliocene in age (5-2 Ma; Jacob *et al.*, 1999; Jacob, 2005).

Other smaller channel features, notably the Uubvlei Clay channel and the Kerbehuk channel, occur some 20 km and 70 km, respectively, north of the study area. They have an infill of locally derived quartz rubble and silt with no indications of a clast assemblage that characterises an Orange River provenance (see Macdonald, 1999 for Orange River exotic suite) and are thus believed not to be associated with the Orange River drainage network. However, as with the palaeo-Orange River, these smaller channels have incised deeply (>50 m) into the Proterozoic basement and have been bevelled at the same level as their host bedrock by subsequent marine processes. As noted in Section 2.1.3, the incision of these channels is thought to have taken place during the Oligocene regression, whilst the infill sediments are considered to be Early Miocene; deposited as a response to sea-level rise during the Early Miocene (Pickford & Senut, 1999).

Pre-Pleistocene gravel beaches

Outcrops of older beaches, given the assumption that deposits occurring at higher elevations have greater antiquity, are sporadically found at 35-50 m above msl and occur as terrace remnants some 50 km north of the study area where they are preserved within bedrock depressions (Figure 1.2). These have not been found within the ED Area. Although they have not been adequately dated due to a lack of fossil material, they are tentatively correlated to the 50 m Package of Late Miocene/Early Pliocene age (based mainly on elevation) in Namaqualand (Pether, 1994; Pickford & Senut, 1999).

A prominent vestigial break in slope, cut into highly weathered Proterozoic Gariiep rocks, is located some 3 km inland (east) of the 50 m Package remnants (Figure 1.2). This geomorphic feature persists roughly for 25 km and parallels the present-day shoreline with its upper-scarp edge occurring some 100 m above msl. No marine sediments have been found on top or at the base of this feature. Consequently, the timing of its development is unknown. Although inconclusive, it is assumed that the geomorphic feature is a preserved cliff line cut during a transgression. Being stratigraphically higher than the 50 m Package remnants, it is tempting to correlate the cliff line to the 90 m Package of Early to Middle Miocene age in Namaqualand (Pether, 1986).

Early Pleistocene gravel beaches

The beach stratigraphy recognised by Stocken (1962) and Hallam (1964) comprises six beach sequences successively decreasing in elevation from the eastern part of MA1 to the present coastline (Figure 2.4). The general consensus is that the easternmost three sequences can be clearly differentiated from their younger western group of terraces based on molluscan fauna. Thus, the terraces were grouped into two main suites – the older ‘Upper Terrace’ and younger ‘Lower Terrace’. These were further subdivided and assigned an alphabetical code in order of increasing age and elevation. Beaches ‘A’, ‘B’ and ‘C’ thus form part of the ‘Lower Terrace’ suite, with ‘C’ being the oldest. Whereas beaches ‘D’, ‘E’ and ‘F’ constitute the ‘Upper Terrace’, with ‘F’ being the oldest (Figure 2.4; Stocken, 1962; Hallam, 1964; Fowler, 1976). Only the beach sequences relevant to this study, notably the ‘Upper Terrace’ suite, will be considered further in this Section.

Upper beach terraces ('D', 'E' and 'F')

Despite the lack of faunal differences, the sub-division of the 'Upper Terrace' suite, to distinguish the 'D', 'E' and 'F' beaches, was based on geomorphic features; these being elevation differences of beach ridges and wave-cut bedrock platforms (Fowler, 1976). However, these geomorphic linkages, notably the beach ridge height and bedrock platforms, become less distinctive farther south in the ED Area. This is primarily due to the absence of a bedrock footwall and the complex stacking arrangement of gravel beaches. Consequently the lateral relationship of the ED Area sequences with those to the north is still not fully understood.

The most striking feature of the 'Upper Terrace' beaches is a bedrock cliff ('F' cliff) that backs the 'F' beach and thus marks the position of maximum transgression achieved during 'Upper Terrace' times (Murray *et al.*, 1970; Figure 2.4). The 'F' cliff loses its continuity in the ED Area where unconsolidated fluvial sediments form the footwall and to the extreme north of MA1 where pocket beach settings predominate. Hallam (1964) and Fowler (1976) demonstrated that the elevation of the cliff base diminishes in a northerly direction from 25 m in the south to roughly 8 m above msl over a distance of 90 km. This translates to a gradient of approximately 0.019%. Uplift and tilting has been advocated as the primary cause for this elevation discrepancy (Hallam, 1964; Fowler, 1976).

As previously mentioned, the sub-division of the 'Upper Terrace' beaches is difficult to determine due to the lack of faunal differences. A fossil that is common to all three older terraces and is distinctly absent in the younger 'Lower Terrace' beaches (Hallam, 1964; Fowler, 1976), is *Donax rogersi* (Pether, 1986). South of the Orange River along the Namaqualand coast in South Africa, *Donax rogersi* is considered a key species in differentiating the 30 m Package – a marine sequence developed between 22 m and 30 m above msl – from the older 50 m (*Donax haughtoni*-bearing) and 90 m Packages (*Isognomon gariesensis*-bearing; Tankard, 1975; Pether, 1986, 1994, 2000; Gresse, 1988). Consequently, the 'Upper Terrace' beaches are correlatives of Pether's (1986) 30 m Package as initially invoked by Murray *et al.* (1970).

The age of the 30 m Package is not well constrained (Pether, 2000). Based primarily on sea-level curves, palaeo-climate data and other beaches of similar elevation along the Atlantic coast of Africa as correlatives, an Early Pleistocene age was advocated by earlier

workers (Hallam, 1964; Carrington & Kingsley, 1969; Pether, 1986). However, recent biostratigraphic investigations of the Namaqualand littoral deposits by Pickford & Senut (1999) suggest a late Pliocene age (3.5-2.5 Ma) based on the presence of un-eroded remains of *Equus* in association with *Donax rogersi* mollusc fauna. This fossil mammal discovery indicates that the 30 m Package ('D', 'E' and 'F' beaches) corresponds more closely to the Meso-Orange River deposits of presumably Pliocene age (5-2 Ma; Jacob *et al.*, 1999).

The succession of vertically stacked beach sequences, more specifically barrier beaches, within the study area differ to their 'Upper Terrace' linear and pocket beach counterparts that are developed northwards as follows (see also Figure 2.5):

- 1) The 'D', 'E' and 'F' beaches within barrier settings are condensed sequences that are vertically stacked and not laterally contiguous as shown in Figure 2.5, making it difficult to correlate beach sequences along the coast. In fact, the alphabetical code, notably 'D', 'E' and 'F', is incorrectly applied to the study area. This is demonstrated in Chapter 4;
- 2) As mentioned earlier, the stacked sequences are not developed on bedrock, they rest on unconsolidated fluvial sediments;
- 3) The cumulative gravel thickness within the barrier settings reach 16 m, whilst an average gravel thickness of no more than 3 m is characteristic of the linear and pocket beaches;
- 4) Given that there is no bedrock cliff, the accommodation space afforded by the palaeo-Orange River mouth setting favoured the development of barrier beaches. These are typified by shoreface, foreshore, backshore (washovers and lagoonal) sub-environments. The beaches fringing the bedrock cliff have no accommodation space on their landward side and thus their geometry is typified by shoreface and foreshore sub-environments only;
- 5) Diamond mineralisation is significantly lower than that in the linear and pocket beaches.

There are also differences in the sedimentological character and diamond mineralisation within the vertical succession of stacked barrier beaches. It has been recorded that the most seaward barrier beach representing the last phase of vertical stacking (Figure 2.5) – now removed by mining – yielded the coarsest gravel (J. Ward, pers. comm., 2010), highest grade and largest diamond size within the entire vertical succession. The sampling data shows that the average grade was six times more, whilst the average diamond size was twice as large.

CHAPTER 3 – SEDIMENTARY FACIES

3.1. INTRODUCTION

The concept of sedimentary facies is a fundamental tool for the description and interpretation of ancient sedimentary rocks (Nichols, 1999). These are used to interpret the environments in which the sediments were deposited. Each sedimentary environment is characterised by physical, chemical and biological processes that generate a body of sediment which is distinguished by identifiable features such as the dimensions, sedimentary structures, grain sizes and types, colour and biogenic content (Nichols, 1999; Boggs Jr, 2001). Such a distinctive body of sediment is therefore referred to as a facies (Boggs Jr, 2001). By studying groups of facies that occur together and are genetically or environmentally linked (commonly referred to as facies association), the interpretation of sedimentary environments is greatly improved (Boggs Jr, 2001).

Sedimentary environments have been defined and classified in a number of ways. Generally there are those environments on a local scale responsible for a particular body of sediment or sequences of such sedimentary bodies and there is the broader realm relating to the nature and tectonics of the greater basin in which sedimentation has occurred (Pettijohn, 1975). For example, a non-marine realm represents the broader environment where on a local scale fluvial environments are deposited. Obviously both are characterised by a particular geomorphic setting in which specific physical, chemical and biological processes operate (Reineck & Singh, 1975; Boggs Jr, 2001). A sedimentary environment, therefore, as per Reineck & Singh's (1975, pg. 4) definition, is 'a geomorphic unit in which deposition takes place'. The classification of sedimentary environments would include, in various ways, the broader primary realm, the major sedimentary environments and their sub-environments. For example, a delta is a major sedimentary environment comprising a number of transitional non-marine to marine sub-environments. These include delta plain, delta front and prodelta (after Boggs Jr, 2001); each are in turn recognised by a number of environments. For example, distributary channels, floodplains, swamps, tidal flats and oxbow lakes represent a delta plain sub-environment.

Reading & Levell (1996) have shown that although the use of the word facies is primarily descriptive, it is applied in different ways to portray:

- 1) Products of a process under which sedimentation has occurred. For example ‘turbidite facies’ for sediments produced by turbidity currents;
- 2) An environment on a broad scale in which the sediments or a suite of mixed sediment types have thought to have formed such as ‘shallow marine facies’ or ‘fluvial facies’; or
- 3) An environment on a more local scale in which the sediments or a suite of mixed sediment types have thought to have formed, such as ‘shoreface facies’ for an inferred shoreface environment within a shallow marine setting.

Therefore the terms ‘facies’ and ‘environments’ can be used in various ways, but their use in any combination is justified provided that the reader is aware of the sense in which the word is being used (Reading & Levell, 1996). The scale of sub-divisions, as noted by Walker (1984), is obviously dependent upon one’s objectives of the study, but it should also have a degree of flexibility and generality (Pettijohn, 1975).

Thus, for reasons of simplification, a facies classification scheme using examples from Boggs Jr (2001) with slight modifications to incorporate depositional time frames is used in this study. This will relate in some meaningful way to the stratigraphy of the study area (as described by Pettijohn, 1978). The classification (Table 3.1) shows that the major sedimentary environments are assigned an alphabetic code (Facies A, Facies B, etc.). While some of these environments, such as the transgressive gravel sheet, are easily identifiable from a single facies, others are recognised from an association of sub-environments. Here the term ‘sub-facies’ is applied and each is given an informal alpha-numerical code (Sub-facies A1, Sub-Facies A2, etc.).

Detailed mapping of the sedimentary sequences has shown that the marine succession, which consists primarily of gravel and sand, has a complex internal stratigraphic hierarchy of four different sedimentary facies referred to here as A, B, C and D. Note that this facies nomenclature is separate from, and not to be confused with, the older terminology used to describe the beaches ‘A’, ‘B’, ‘C’ and ‘D’, *sensu* Stocken (1962) and Hallam (1964). Each facies is, in turn, characterised by a distinct arrangement of sub-facies which are differentiated by their unique internal sedimentary structures. These are either vertically or laterally arranged as depicted in the block diagram of Figure 3.1.

Table 3.1: Classification of sedimentary environments and facies for the ED Area deposits

Primary realm	Major environment	Sub-environment	Main characteristics
Marine	Shallow-marine (Facies D)	Upper shoreface (Sub-facies D1)	Medium to coarse sand interbedded with gravel sheets. Sand is highly bioturbated; crude tabular cross-stratification. Lenticular strata of interbedded pebble gravel and very coarse sand. Trough cross-stratification.
		Upper/middle shoreface (Sub-facies D2)	Coarse sand to granule strata with isolated lensoid gravel sheets. Trough cross-stratification.
		Lower shoreface (Sub-facies D3)	Tabular cross-stratified fine- to medium-grained micaceous-rich sand.
	Barrier-beach (Facies C)	Foreshore (Sub-facies C1)	Gravel dominated. Extreme clast shape and size sorting with vertically stacked discs at most landward end of deposit and horizontal sheet of large spheres forming most seaward margin. Wedged between the above two are steeply inclined, normal graded strata with foresets dipping steeply seaward. Seaward-imbricated discs.
		Back-barrier (Sub-facies C2)	Gently inclined, ungraded gravel strata; foresets dip landward. Poor clast shape and size sorting. Clay rafts present. Foresets interfinger with finely laminated clay and silt that are horizontally interbedded.
	Transgressive lag (Facies B)	Identified as a single facies	Gravel sheet dipping slightly seaward. Dominated by spherical boulders. Sheet truncates a variety of sediment types.
	Barrier-spit (Facies A)	Foreshore (Sub-facies A1)	Normal graded, inclined strata; foresets dip steeply seaward. High degree of clast shape and size sorting with discs imbricated seaward.
		Tidal inlet (Sub-facies A2)	Herringbone cross-laminated sand with interbedded gravel sheets and stringers. Poor clast shape and size sorting.
		Spit recurve (Sub-facies A3)	Normal graded, inclined strata; foresets dip landward with radial geometry. Moderate degree of clast shape and size sorting.
		Estuarine-lagoon (Sub-facies A4)	Finely laminated clay and silt deposits. Horizontally interbedded. Desiccation cracks, root casts and plant fragments.

These four main sedimentary facies are discussed individually in their order of deposition from oldest to youngest and consideration is given to:

- 1) General introduction with reference to stratigraphic position. Note that a loose copy of Figure 3.1 is included with locality maps as Appendix D in the map folder to facilitate correlation during reading of the thesis.
- 2) Distribution and thickness. The discussions will focus mainly on key sections. Although the distribution and thickness of each facies is schematically illustrated in this chapter, a reconnaissance map showing basic stratigraphic sections for ease of referencing is included in the map folder as Appendix E.
- 3) Lithology and sedimentary structures based on field observations. Their description and interpretation are considered.
- 4) Age and correlation. Although the facies are *Donax rogersi*-bearing, a lack of faunal variation makes it difficult to ascertain the sequence of deposition. Consequently, age variation is based primarily on stratigraphic relations.

Mention must be made of the informal stratigraphic beach nomenclature used by previous workers (Hallam, 1964; Stocken, 1962). Although, these are still informally used, they will not be applied in this chapter, as mentioned earlier. Also, given that the present wave climate has remained unchanged since the Neogene, as discussed in Chapter 2, it is proposed for this and other reasons to emerge later, that the configuration of the palaeo-shoreline was not significantly different to that of today.

3.2 GENERAL ASPECTS OF THE SEDIMENT COMPOSITION

3.2.1 Gravel

An ancestral Orange River, notably the Meso-Orange of Plio-Pleistocene age, was the main source of the ED Area marine gravel and thus clast characteristics within the study area such as rounding, sphericity and shape have, to some degree, been inherited. Noteworthy is that spheres, blades and discs are common components within Meso-Orange River sediments with the last two accumulating at bar heads, whilst spherical shapes form part of the bar tails (Jacob *et al.*, 1999). Thus disc- and blade-shaped clasts are not necessarily indicative of shape modification by beach processes.

The range of gravel size is from granules to large boulders and these were largely derived from Precambrian rocks through which the river incised, generating lithologies that typify the Meso-Orange River (Jacob, 2005). Consequently, the marine gravels within the study area as examined by Jacob (2005) have a composition of quartzite, banded ironstone, riebeckite, vein quartz, chert, granite, schist, felsic and mafic volcanic rocks, agate, feldspar and zeolite. Jacob (2005) demonstrated that the cobble to boulder size range is generally dominated by quartzite, with only quartzite found in the boulder fraction. The remaining lithologies are confined to the smaller gravel fraction, more appreciably in the pebble size range. When clast roundness is compared, the gravels within the study area have higher values of rounding than those from the Meso-Orange River deposits (Jacob, 2005), suggesting that clast rounding was augmented in the littoral environment.

3.2.2 Sand

Similar to the gravel component, the marine sand was derived from the Meso-Orange River and is generally quartzo-feldspathic rich with lesser amounts of zeolite, mica, lithic fragments and heavy minerals such as zircon, ilmenite, magnetite, garnet and rutile (Fowler, 1982; Dale & McMillan, 1996). Clay is absent from all sand fractions.

Sand coarseness is variable, ranging from fine to very coarse with the coarser fractions containing abundant quartz, feldspar, zeolite grains that reach granule size, minor biotite and lithic fragments of quartzite and basalt. Heavy minerals are rare in the coarse to very coarse sand fractions, as are glauconite and shell fragments.

The quartzose finer sand (fine to medium fractions) as described by Dale & McMillan (1996) has lesser amounts of feldspar and zeolite, but contains higher amounts of heavy minerals and mica (biotite and muscovite). Flakes of mica can be significantly coarser than the host sediment reaching 0.4 cm in length. In addition to these minerals, glauconite and chrysoberyl, as well as agate and jasper occur in minor quantities. Shell fragments of unknown origin also form a minor part of the finer sand fractions (Dale & McMillan, 1996).

3.3 FACIES A

3.3.1 General

Facies A forms the base of the entire marine sequence and is overlain by sediments of Facies B, C and D (Figures 3.2 & 3.3, Appendix D(4)). More significantly, at the most southern end of the study area (G9 sampling trench, Figure 3.2A & C), the marine package of Facies A is attached to a bedrock high of schistose composition. Here the sediments are truncated by a boulder bed at an elevation of some 10 m above msl (see Figure 3.3). This truncation surface is level with the top of the bedrock island suggesting that it and Facies A were part of the contemporary shoreline prior to the emplacement of the boulder bed. The type section for Facies A is the G25 trench (see Figure 3.2A for locality) and although the other sampling trenches (G19 and G15) provide good exposures, the geometry and relationship of distinct sub-facies can be best seen in this trench that has been retained as a witness section.

3.3.2 Distribution and thickness

The sediments of Facies A extend northwards from the bedrock high for some 2 km. It is thinnest – approximately 2.4 m – at the bedrock island and thickest (approximately 5 m) in the north. At the type section in G25 trench, the sediments extend down-dip (south-west to north-east) for a distance of approximately 400 m and maintain a consistent thickness of 5 m throughout the entire length of the exposure.

3.3.3 Lithology and structure

Facies A is dominated by coarse rudaceous sediments where resistant clast types such as quartz and quartzites constitute the bulk of the gravel. These sediments may contain a matrix of either coarse sand or gravel that is finer than the coarser framework, but in most instances they are matrix free. Four lateral interconnected sub-facies, designated A1 to A4, have been recognised at G25 (Figure 3.4). The south-western (seaward) part of the trench is dominated by cross-stratified gravel of Sub-facies A1 with steep seaward-dipping foresets. Cross-stratified gravel of Sub-facies A3 is restricted to the most north-eastern (landward) part of the exposure and their foresets dip in the opposite direction, landward. Wedged between these two sub-facies are cross-laminated sands with interbedded gravel sheets of Sub-facies A2. Marking the landward termination of Facies A are extensive silts and clays of Sub-facies A4 (also summarised in Figure 3.2B).

Sub-facies A1: Cross-stratified gravel

This sub-facies occupies the most south-western part of the exposure where it is developed with remarkable consistency over a distance of 120 m and is predominantly gravel. These sediments are brown and in places black in colour; the latter is mainly due to a manganese coating on the gravel clasts with some accumulation in the voids between clasts. The manganese precipitation is a post-depositional product from ground water, preferentially developed in the more porous and permeable sediments.

Stratum attributes

Cross-stratified sets of approximately 1.8 m in thickness are stacked vertically in a 5 m thick package. Their boundaries are marked by near-horizontal truncation surfaces comprising predominantly large cobble blade-shaped gravel lags, which can also be traced a short distance up the toe of each individual foreset that are tangent to the set boundary (Figure 3.5A). Note that where clasts larger than the background size form a residual layer that is no thicker than the gravel clast size, it is here defined as a lag.

Textural attributes

The gravels are well-rounded, clast-supported, large cobble to fine pebble in size. A range of shapes are present with discs and blades predominating. These dominant shapes show imbrication with their long axes dipping seaward. Clast size and shape sorting is evident in the gravel strata, as is extreme porosity where in most instances the voids between clasts remain visibly open due to the absence of infilling sand or smaller gravel particles. Although clast shape sorting is present, the degree thereof is not significantly high in comparison to that of the Facies C deposits where distinct zonation of shapes is evident. However, there is a considerable degree of clast size sorting in Facies A1 gravels. Rounded clay rafts of pebble to large cobble size are found within the gravels. These rip-up clasts occur throughout the vertical section and are mainly reddish-pink in colour and sphere-shaped.

Structural attributes

The tabular cross-stratification in Sub-facies A1 has the longest foresets within the entire study area. A single foreset can be traced down-dip over a distance of more than 7 m. The foresets are tangential, exhibiting slight concave-up geometries with some merging at their distal ends to give wedge-shaped geometries. They dip at steep angles, up to 28°,

towards the south-west (on average 229° ; Table 3.2). This dip direction is similar to the gravel beds of the same sub-facies seen in the G19, G15 and G9 trenches, where they dip towards 239° , 223° and 243° respectively (Figure 3.5B). The most conspicuous feature of the Sub-facies A1 gravels, besides the openwork framework, is the normal grading of foreset strata where a large cobble base grades upward into granule-sized sediment. The sediment in each of these graduations exhibit extreme sorting. These are laterally stacked to form a continuous succession of alternating normal graded foreset strata, each approximately 40 cm thick.

Table 3.2: Palaeo-current data of Sub-facies A1

n	Xv	R	L(%)	Structure	Sediment
11	229	10.93	99	Tabular cross-stratification	Gravel at G25
12	239	10.91	91	Tabular cross-stratification	Gravel at G19
4	223	3.98	100	Tabular cross-stratification	Gravel at G15
11	243	10.21	93	Tabular cross-stratification	Gravel at G9

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

Fragments of the 30 m Package mollusc, *Donax rogersi*, were recovered.

Sub-facies A2: Cross-laminated sand

The principal sediments of Sub-facies A2 are brown, coarse cross-laminated sand and granule with interbedded gravel. In section, which is perpendicular to the present coastline, the Sub-facies A2 package is approximately 50 m in length. On the most seaward side (south-west), these sediments are sharply truncated by gravel strata of Sub-facies A1, producing a steep erosion surface inclined seaward as much as 25° (see also image in Figure 3.10). At the base of this erosion surface, the cross-stratified sand deposits of Sub-facies A2 pinch out in a seaward direction and interfinger with coarse to very coarse, planar cross-stratified subtidal sand that have foresets dipping towards the north-east. Although the excavation was not deep enough to intersect the base of this sand, the exposure in the south-western part of the trench clearly shows that this subtidal sand forms a sheet onto which Sub-facies A1 and A2 have been deposited.

Stratum attributes

The coarse-grained sand is characterised by opposing thick cross-laminae, each less than 0.5 cm thick. Cross-lamination sets are approximately 15-20 cm thick with cosets

reaching 1.2 m (Figure 3.6A). Set bounding surfaces are inclined towards the north (coast parallel) and are accentuated by pebble lags lining these surfaces. The interfingering gravel occurs either as stringers of clasts or sheets of gravel that can be as much as 2-3 m thick. These have a parallel geometry and are gently inclined northwards having sharp contacts with the sand units.

Textural attributes

A bimodal sediment population is present comprising coarse to very coarse sand and fine pebble to large cobble gravel. The latter is a constituent of the interfingering gravel stringers and sheets. When the coarse sand is considered, an abundance of rounded to well-rounded granules comprising lithologies of low specific gravity such as quartz and zeolite are in places aligned along opposing foresets, further accentuating the sedimentary structures. As regards the gravel sheets, they have a clast-supported framework with a matrix of sand and granule to fine pebbles. This sand matrix is zeolite-rich and is therefore, no different from the cross-stratified sand. Gravel sorting is poor where the degree of clast shape and size sorting is far lower than that of Sub-facies A1 and A3. Clasts are well-rounded with discs and blades lacking imbrication. Manganese coating is absent due to the lower porosity and permeability of these sediments given that the gravel framework has a matrix fill of sand.

Structural attributes

The main characteristic feature of the coarse sand is the opposing cross-lamination, exhibiting bipolar orientation directed towards the south-west and north-east (Figure 3.6B). Foresets dip on average 20° . Surfaces bounding the cross-laminated sets dip, on average, 20° in a northerly direction (see Table 3.3).

Table 3.3: Palaeo-current data of Sub-facies A2

n	Xv	R	L(%)	Structure	Sediment
13	353	12.77	98	Bounding surfaces	Cross-stratified sand

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

A single foraminiferal specimen of marine affinity was recovered from the coarse, cross-stratified sand, but was not identified.

Sub-facies A3: Cross stratified gravel

These are the coarse gravel deposits which occupy the entire north-eastern (landward) section of the exposure and consist exclusively of gravel that is developed over a distance of 70 m. Like Sub-facies A1, these are in places coated with a manganese film giving them a black colour. The most seaward (south-western) end of these deposits interfinger and envelop sediments of Sub-facies A2.

Stratum attributes

Cross-stratification is in a direction opposite to that measured in Sub-facies A1; that is landward. The gravel is vertically stacked into a 5 m thick package, but unlike Sub-facies A1, cross-stratified set boundaries could not be determined.

Textural attributes

Sub-facies A3 is distinguished by its tabular cross-stratification and textural maturity where clast shape and size sorting is notable, but not to the same degree of sorting as seen in Sub-facies A1 (Figure 3.7A and cross-section in Figure 3.10). However, a similar clast-supported, open-work framework is also present with well-rounded clasts. Where disc- and blade-shaped clasts are imbricated, they dip landward. Gravel size ranges from fine pebble to large cobble; the latter forms the base to each normal graded foreset stratum and grades upward to either granules or pebbles. Where the grading includes granule-sized sediment, an abundance of zeolite is confined to these finer sediment layers. Similarly, where the clast-supported framework has a matrix of sand and granule- to pebble-sized sediment, zeolites are in abundance as part of the matrix fill. Such an occurrence of zeolites is totally absent in Sub-facies A1.

Structural attributes

The tabular cross-stratification differs to that of Sub-facies A1 in that the foresets are not only angular, but also the direction of dip is opposite and inconsistent. Here foresets dip landward and exhibit a radial growth pattern spreading from the north-east through to the south-east (see cross-section in Figure 3.4, 3.7B and Table 3.4). The foresets dip on average at 18°, but can reach 27° in places. Despite the textural maturity, normal grading of the foreset strata that are approximately 30-40 cm thick is not as prevalent and extreme as that seen in Sub-facies A1.

Table 3.4: Palaeo-current data of Sub-facies A3

n	Xv	R	L(%)	Structure	Sediment
9	95	8.71	97	Tabular cross-stratification	Gravel at G25
6	148	5.46	91	Tabular cross-stratification	Gravel at G25
4	48	3.98	99	Tabular cross-stratification	Gravel at G19

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Soft sediment deformation structures have been observed where the gravel foresets of Sub-facies A3 are slumped into a concave fold-like structure (Figure 3.8). The vertical orientation of the gravel clasts and opposing imbricate dips clearly demonstrate that this imbricate fabric is not primary, but induced by sediment slumping. The presence of dis-dominated clasts further aided the slumping process where the gravel particles have a greater propensity to slide over each other. The normal grading in the foreset strata is, however, still maintained. The degree of flexure decreases towards the top of the gravel sequence; a feature expected of slumping. Although the mode of deformation is not clearly understood, an *in situ* section at the base of the trench showed that the gravel sequence overlies a clay deposit. It is assumed that displacement of the clay due to contemporaneous loading of the gravel possibly caused the deformation.

Reddering (1993) noted soft sediment folding in the Cretaceous Robberg Formation where marine conglomerate rests on palaeo-channel deposits comprising shale and sand. He illustrated that the base of the gravel sequence occurs on a slope and the folding, therefore, was not only induced by loading, but also by drag as the gravel bed slid down slope. Field observations in the ED Area show that the deposits of Sub-facies A3 were emplaced on a horizontal surface and thus precludes down slope drag as a contributing factor.

Palaeontological attributes

No micro- or macro-fossils were recovered from the Sub-facies A3 gravels.

Sub-facies A4: Laminated clay and silt

Comprising clay and silt (Figure 3.9A), Sub-facies A4 is confined to the most north-eastern part of the G25 section. Drilling results show that the sediments are laterally persistent over distances of 1 km along strike (north-west to south-east direction) and can reach a

thickness of 4 m. The clay exhibits variable colours from reddish pink to green, whilst the silts are orange-yellow.

Stratum attributes

Alternating cosets of planar-parallel, finely laminated clay and silt to very fine sand predominate throughout the sequence. These cosets vary considerably in thickness for both the clay and silt, ranging from approximately 1-50 cm. Their contacts are gradational. Although unlithified, the clay displays fissility, splitting into exceptionally thin plates due to compaction.

Structural attributes

The clay exhibits, in places, desiccation cracks and where interbedded with very fine sand, asymmetrical wave ripples are developed within the very fine sand layers (Figure 3.9B). These bedforms have a gentle inclined stoss side of 15° followed by a steeper lee side dipping in the opposite direction (seaward) at 25° . Measurements of their geometry show that the crests are spaced 15 cm apart and the ripples have a length and height of 22 cm and 3 cm, respectively. This translates to a ripple index (L/H) of 7.3, which falls within the range between 6 and 8 for asymmetrical wave ripples (Reineck & Singh, 1975, pg. 25). The internal structure of these ripples exhibits fine tabular foreset laminae with tangential bases, dipping in a single direction at 15° towards the south-west.

The green coloured clay lithology has a distinct absence of interbedded silt layers, desiccation cracks and biogenic structures. These clays are generally overlain by the red-pink clays.

Palaeontological attributes

Rare pedotubes, approximately 1 mm in length and 0.3 mm in diameter, occur within the red-pink coloured clays. These are highly friable and red-brown in colour possibly due to oxidation. Small plant remains were found by Hallam (1964) and Corvinus (1983) within similar clay laminae at G19, but these were not identified. In addition, burrows confined mainly to the clayey silt layers have also been recorded from the same trench. They have a horizontal, branching geometry with an average diameter of 5 mm (Figure 3.9C). In contrast, the green-coloured clays are organic free and have no biogenic structures.

3.3.4 Interpretation of Facies A

The relationship between the four main sub-facies and the geometry of the entire exposure in the G25 trench are consistent with gravel barrier spit accumulations described by Bluck *et al.* (2001) and Spaggiari *et al.* (2006). Consequently, the recognition of gravel barrier spits, as opposed to barrier beach settings rests on the identification of the sub-facies as described in Section 3.3.3 and their lateral stratigraphic disposition. This lateral relationship is illustrated in the Figure 3.10 cross-section, as well as in block models in Figures 3.11 & 3.12.

Sub-facies A1: Cross-stratified gravel

The gravel deposits of Sub-facies A1 are characteristic of beach face sediments and thus reflect a foreshore setting (Reddering, 1993; Bluck, 1999; Bluck *et al.*, 2001; Neal *et al.*, 2001; Jol *et al.*, 2002; Spaggiari *et al.*, 2006). In such settings the hydrodynamics of open coast swash and backwash facilitate gravel sorting whereby a process of clast acceptance and rejection (Bluck, 1999; Buscombe & Masselink, 2006) generate super-mature fabrics. The normal graded strata of Sub-facies A1 are a product of such sorting. However, the lower degree of shape sorting is not unusual and has been recorded by Carter *et al.* (1990) at Fisherman's Beach, a modern gravel barrier spit in Nova Scotia. They note that cross-beach sorting patterns were not distinctive and attributed the phenomenon to either a high sediment supply to preclude such sorting or there had been extensive reworking of the barrier spit. The former is more applicable to the study area considering that the gravel barrier spit of Facies A developed within a palaeo-river mouth setting where sediment supply was considerably high. Its position near to the sediment outfall is supported by the presence of clay rafts within the gravel beds. Sourced from flood plain or estuarine-lagoon deposits, these clasts were ripped from their sediment hosts during river floods and debouched into the coastal setting.

The foreshore processes under which Sub-facies A1 accumulated and the associated bedforms are discussed in more detail in Section 3.5 (Facies C) given that Sub-facies A1 bedforms are identical to those recorded in Sub-facies C1.

With a copious yield of gravel supplied to the foreshore by the Orange River, a sequence of laterally, seaward-stacked, steeply inclined accretionary foresets would have developed during seaward progradation of the beach face as described by Martini (1975), Massari & Parea (1988), Postma & Nemeč (1990, their unit II) and Blair (1999, his facies C).

This would account for the lateral persistence of Sub-facies A1 over a distance of 120 m where growth was roughly perpendicular to the palaeo-coastline. The last is evident from the palaeo-current measurements. The surface expression of this growth would be in the form of a beach-ridge plain where successive barrier spit ridges develop seaward during progradation (Dominguez *et al.*, 1987; Orford *et al.*, 2002).

Sub-facies A2: Cross-laminated sand

The Sub-facies A2 sand and granule are interpreted as herringbone (bipolar) cross-laminated, shallow subtidal deposits. Its position landward of the Sub-facies A1 gravel foreshore and the presence of herringbone cross-lamination precludes an open coast subtidal setting.

Herringbone cross-lamination is widely reported in shallow subtidal and intertidal settings (Reineck & Singh, 1975; Casshyap & Aslam, 1992, pg. 983) and is commonly accepted as a criterion for the recognition of current reversals in tidal environments (Boothroyd, 1985, pg. 472; Collinson & Thompson, 1989), including tidal inlets. Barwis & Makurath (1978) also noted that bipolar lamination in such sediments is consistent with barrier inlet settings. Tidal inlets are also a feature of wave-dominated coasts where swash platforms are predominantly developed in the inlet throat (Boothroyd, 1985). It is well documented that these inlets allow the passage of tidal water between the open sea and the protected lagoonal area, but this exchange of water does not necessarily require a vigorous tidal setting. Van Heteren & van de Plassche (1997) demonstrated that during the evolution of the Sandy Neck barrier spit (Massachusetts, U.S.A.) within a wave-dominated setting, the development of a tidal inlet channelled the displaced water – driven by high wave energy – into the lagoon.

A similar setting is proposed for the deposition of Sub-facies A2, where these subtidal sediments have accumulated at the spit head (see Bluck *et al.*, 2001) under high wave energy conditions. This ensured sufficient displacement of coastal waters into the lagoon, as seen in the present Orange River mouth where strong waves drive coastal waters through an inlet into a back-barrier setting. The presence of a marine foraminiferal specimen recovered from the sand-dominated sediments of Sub-facies A2 supports such an exchange of coastal waters.

Similar to unit 2A of Nielsen *et al.* (1988), the deposits of Sub-facies A2 are thought to have been deposited as 3-D megaripples on a sub-aqueous platform. Hine (1979) demonstrated that such platform deposits are developed where the spit head curves away from the ocean into the inlet (referred to as a spit recurve). Here the breaker angle increases with a concomitant decrease in longshore drift power, inducing rapid sedimentation in an area of reduced wave energy. This energy deficit is due to the decreased wave height created by the strong wave refraction. The reduction in wave height can be significant, as much as 92% (see King & Mc Cullagh, 1971). At this point where wave energy dissipates, the more readily longshore entrained sediment, namely the sand fraction, enters into the tidal inlet (Carter *et al.*, 1989) to accumulate as a broad, shallow subtidal platform. The accumulation of clast lithologies having a low specific gravity, such as zeolites, is a reflection of this energy dissipation where refracting waves have the inability to winnow out these clasts.

In many respects, sedimentary structures associated with 3-D megaripples are typically tabular or trough cross-stratified (Reineck & Singh, 1975; Boothroyd, 1985; Lindholm, 1987; Collinson & Thomson, 1989). However, it is not uncommon to find herringbone cross-laminations in such bedforms, as discussed by Nichols (1999, pg. 138) and reported by Boothroyd (1985, pg. 472) who observed these sedimentary structures in cusped megaripples. More importantly, high sedimentation rates are required to preserve the cross-lamination (Nichols, 1999).

Palaeo-current measurements from the herringbone-dominated laminae of Sub-facies A2 indicate a north-east to south-west exchange of coastal water, which is similar to the inlet setting of today's Orange River mouth. More importantly, the palaeo-current measurements of the bounding surfaces between cross-laminated sets show a northward growth. This clearly suggests that these subtidal platform deposits prograded northward with a northerly (down-drift) migrating spit head.

The gravel sheets of Sub-facies A2 are thought to have derived from the spit head where slumping of the intertidal beach face would have introduced gravel into the inlet environment (Spaggiari *et al.*, 2006) and armoured the platform surface prior to the next depositional event. Given that wave energy is lowered at the spit head, sorting of the introduced gravel would be limited as described by Hiroki & Masuda (2000) for the spit platform of a Pleistocene gravelly spit deposit in Japan and thus accounts for the northerly dip

of the beds, which is in the direction of barrier spit elongation. Such gravel armouring has been described by Carter *et al.* (1990, pg. 126) at Fisherman's Beach in Nova Scotia. Here gravel-armoured platforms occupy the inlet portions where the gravel spit has been breached and segmented into three parts.

Sub-facies A3: Cross-stratified gravel

Although the gravel foresets of Sub-facies A3 dip in a direction opposite to that of Sub-facies A1, the degree of clast shape and size sorting with a distinct lack of clay rafts and sand layers negate a washover fan setting (Figure 3.10). Similar to Sub-facies A1, the normal grading and textural maturity of the gravel strata suggest a beach face that is consistent with the foreshore. Sub-facies A3, therefore, represents an intertidal setting on the landward side of the gravel spit at the point where the terminal recurve arcs away from the coast into the protected back-barrier lagoon (see Bluck *et al.*, 2001).

This is at odds with a typical lagoon where the energy regime is significantly lower than that of a foreshore environment. However, in this context, the degree of sorting exhibited by Sub-facies A3, although not as extreme as that of Sub-facies A1, implies considerable wave refraction around the growing tip of the spit (see Bird, 1972; Bluck *et al.*, 2001; Spaggiari *et al.*, 2006). Wave refraction sorting can only have been achieved if wave height and energy conditions were significant. Such conditions are not uncommon along the present Namibian coast and as noted in Section 1.3, wave heights exceeding 5.0 m in all seasons were reported by de Decker (1988). The pattern of inconsistent dip directions depicted in Figures 3.4 & 3.7, which are so characteristic of Sub-facies A3, further supports the spherical radial growth of beds at the recurved end of the barrier spit (Bluck *et al.*, 2001; Spaggiari *et al.*, 2006).

There are two possible depositional models for Sub-facies A3, both of which would generate deposits having similar structures:

- 1) reworking of washover sediments; or
 - 2) reworking of welded swash bars.
-
- 1) Washover deposits transfer sediment from the foreshore into the lagoon (see also Section 3.5 on Sub-facies C4) through breaching of the spit ridge during periods of storm. Here, the displaced sediments spread out landward of the barrier spit into the lagoonal

environment in the shape of small fans. Continued washover events, if the same breach point is exploited, will sustain the sediment supply to the washover setting inducing fan growth. If the washover fans are further subjected to high wave energy refracting around the spit head, it is likely that size sorting of the gravel-dominated sediment is highly active and the sand fraction is removed. The variation in dip direction of the gravel foresets are retained as a consequence of their original curved, fan-shaped disposition.

- 2) In contrast to washover sedimentation, swash bar welding has been identified as a mechanism for spit head progradation (Hine, 1979; Nielsen *et al.*, 1988; Carter *et al.*, 1990; Morales, 2001). Under wave refraction, it is thought that swash bars migrating alongshore or emerging from the shoreface will travel across the tidal-inlet (Sub-facies A2) to weld onto the spit head and merge with intertidal deposits in the back-barrier, displaying landward-dipping, tabular cross-stratification (Nielsen *et al.*, 1988; Morales, 2001). Consequently, a considerable amount of gravel must pass around a sharp angle at the spit head as noted by King & Mc Cullagh (1971) to sustain growth of these ‘recurved’ intertidal deposits. Apart from wave refraction, high wave energy and sediment supply are therefore seen as fundamental controls for spit recurve growth as described by King & Mc Cullagh (1971) and Firth *et al.* (1995). In addition to a longshore and shoreface source, the spit platform with its armoured gravel surface may have also been a sediment reservoir for the spit recurves as documented for the Buctouche Spit in New Brunswick, Canada (Ollerhead & Davidson-Arnott, 1995). Here, cycles of scavenging the armouring gravel followed by collapse of the spit head would have been repeated as waves fronts refracted into the inlet.

Washover sediments have their provenance in the foreshore (see Section 3.5.3, Sub-facies C2, cross-stratified gravel) and thus their average diamond size is similar to that in the foreshore (see Chapter 5 on diamond mineralisation and size trends). However, the average diamond size within Sub-facies A3 is significantly smaller, by as much as three to five times, than that in the foreshore. This disparity would favour swash bar welding (model (2) in the above) as a more likely depositional model for Sub-facies A3.

When the direction of barrier spit growth is considered, based on palaeo-current data, it was towards the north. Refraction of waves originating from the dominant south-westerly quadrant would be expected to have lower energy on entering the inlet. Wave power would

dissipate on contact with the prograding spit platform preventing complete wave refraction around the spit head. Reworking of spit recurve gravels would thus be limited. However, examples of wave refraction along the present-day coast of Namibia demonstrate that this is not necessarily the case. Here, complete wave refraction has been observed around protuberances that are orientated in a northerly direction (see Figure 3.13C). Therefore, periods of high storm surges such as those noted in Chapter 1, Section, 1.3, are likely to augment not only the wave refraction and associated energy levels, but also induce greater reworking of spit recurves. Equally, storm-driven waves originating from the north-west, although infrequent (1.6% in spring and 1.4% in winter, de Decker, 1987), may have exerted a greater impact with a propensity to maintain higher energy levels and wave heights (see Figure 3.13B). They would have also driven sediment from the shoreface landward into the inlet to build up the spit recurves whilst longshore drift was absent or reversed (see Chapter 1, Section 1.3 on changes to longshore drift).

Energy levels during wave refraction must have been inconsistent with higher levels allowing effective sorting of the recurve gravels followed by waning periods under which zeolite clasts accumulated. This is in contrast to the direct wave attack in open coast conditions where aggressive wave energy is consistently maintained and for this reason, the Sub-facies A1 gravels are free of zeolite clasts.

Sub-facies A4: Laminated clay and silt

The finer sediments of Sub-facies A4 typify an estuarine-lagoon and are similar to those described by Blair (1999, his facies E), Bluck *et al.* (2001, their unit C) and Neal *et al.* (2001, their facies B-3). Coastal lagoons are most characteristic of microtidal regions (Barnes, 2001) and are partially or completely enclosed by a depositional barrier beach or barrier spit (Bird, 1972). These barriers have a greater preponderance to completely isolate impounded regions from the sea as opposed to their sandy counterparts where seasonal closure of estuaries and lagoons are encouraged by the accumulating sand (Barnes, 2001). At barrier spit/river mouth complexes, estuarine-lagoons are impounded by the evolving barrier spit and the only coastal water exchange is through an inlet at the spit head. Estuarine-lagoons can therefore be extensive and generally deeper than 2 m (Barnes, 2001); a setting typifying the present Orange River back-barrier. The depositional environment of Sub-facies A4 would have thus been similar, given the lateral extent and thickness of the sediments.

Features such as desiccation cracks and oxidation that typify the red clays of Sub-facies A4 are unequivocally indicators of exposure and therefore negate a lower shoreface or offshore setting. The size of the wave ripples further support this. Generally, for equivalent grain sizes, the wave ripples from deeper water tend to be larger than those confined to shallower settings (Reineck & Singh, 1975). In addition, the biogenic structures are indicative of low-energy settings and their preservation in sediments that are landward of a gravel spit recurve (Sub-facies A3) further support an estuarine-lagoon.

The present estuarine-lagoon at the Orange River mouth is defined as a river-dominated estuary and as such, the fluvial sediment extends to the landward margin of the coastal barrier (Cooper, 2001, 2002). The back-barrier area is, therefore, seen as an extension of the inflowing river which is attributed to high fluvial sediment supply from the hinterland (Cooper, 2001). It thus follows that the predominant sedimentary facies are fluvial sediments such as floodplains, channels, inter-channel bars and salt marshes. These are vegetated to various degrees and although the estuarine-lagoon is river-dominated, evidence of estuarine fauna (trace fossil and fossil assemblages) may be present (Cooper, 2001). Given its fluvial dominance the estuarine-lagoon acts as a conduit for river sediment to the sea rather than a sink for marine sediments (Cooper, 2001).

That the Orange River back-barrier is viewed as a modern analogue of Sub-facies A4, the asymmetrical ripples recorded in the Sub-facies A4 silt layers is thus a reflection of the dominant river flow, directed seaward towards the south-west, as it occurs today. Noteworthy, is that this direction is similar to that of the tidal inlet deposits of Sub-facies A2 where a north-east to south-west bimodal palaeo-flow was recorded.

The red clay lithologies would have accumulated along the fringes of the spit environment as exposed elevated clay banks. Stabilisation of these areas was promoted by vegetation growth which is evident from the plant remains and root casts recovered from the red-pink clays. In turn, the vegetation acted as traps for clay during overbank deposition allowing the banks to accrete above normal flow levels. In contrast to the shallower back-barrier fringes, the deeper part of the estuarine-lagoon was the main depocentre of the green clays during low river flow. Obviously, these would be scoured out during high-flow events (Cooper, 2001).

3.3.5 Summary and depositional setting of Facies A

The sedimentological processes for the deposition of Facies A are discussed in this section. Figure 3.14 encapsulates the salient features of each sub-facies and a summarised interpretation thereof.

Orford *et al.* (2001) noted that gravel dominated coasts require specific driving mechanisms for the development of gravel beaches. Amongst others, coarse sediment supply and the presence of energetic waves are crucial requirements to sustain the growth of coastal landforms and actively transport, as well as sort, the heterogeneous sediment into a spectrum of gravel beaches. The Namibian coast is no exception and the persistence of high-energy conditions throughout most of the year makes this wave-dominated coastline a most vigorous regime (de Decker, 1988; Hay & Brock, 1992). Thus, with a continued supply of sediment from the Orange River, albeit a diminishing contribution, it is no surprise that these conditions have modelled the sediment outfall of the Orange River into distinct coastal landforms.

Facies A is a clear expression of this consequence in the form of gravel barrier spit accumulations where discrete depositional environments have evolved together. Spaggiari *et al.* (1999, 2006) and Bluck *et al.* (2001) have shown that the recognition of gravel barrier spits in the geological record depends on the presence of discrete environments. They include intertidal gravel sediments with seaward, as well as landward dipping foresets and subtidal sediments with bipolar cross-stratification (see Figures 3.11 & 3.12). The intertidal deposits with landward divergent dips interfinger with extensive lagoonal clays. These conditions are satisfied in Facies A and thus support the interpretation of gravel barrier spit accumulations. A modern equivalent of Facies A is depicted in Figure 3.11 illustrating the distribution of depositional environments.

Gravel barrier spits have been recorded from Cretaceous (Reddering, 1993), as well as modern (Eddison *et al.*, 1983; Firth *et al.*, 1995) settings and are the extreme case of drift-aligned barriers (Davies 1972; Orford *et al.*, 1991; Bluck *et al.*, 2001) that are fed from a discrete source under a set of conditions that can facilitate the transfer of sediment alongshore from source to sink (Orford *et al.*, 1991). These barrier forms are known to grow at extremely high rates. In his study of the Orford spit in England, Carr (1969) has shown that although the growth was irregular, rates of 183 m/a for the period 1804 to 1812, 69 m/a (1867 to 1880)

and 64 m/a (1962 to 1967) were recorded from early cartographic sources (see also Randall & Fuller, 2001). Growth rates of this kind require a substantial supply of gravel and for this reason, the fact that Facies A occurs immediately north of the Orange River mouth and nearest to the sediment supply, they are regarded as the fastest growing barrier forms in the entire study area. A proposed model for the depositional style of the Facies A barrier- spit is illustrated in Figure 3.13.

Where there is a copious supply of sediment, the barrier spit grows in the direction of longshore sediment transport (Bird, 1972) with a concomitant thickening and extension of the distal section through gravel accumulation, often in the form of recurved ridges (Orford *et al.*, 1991; Firth *et al.*, 1995; Anthony & Dolique, 2001). This is clearly seen in the geometry of the gravel and sand units of Facies A. The internal structures of the sub-facies demonstrate spit growth to the north (down-drift), west (seaward) and east (landward).

Van Heteren & van de Plassche (1997) highlighted the importance of seaward migration during spit accretion, most likely through rapid welding of intertidal sediments to the ocean side of the barrier spit. These are the swash bars described by Hine (1979), Carter *et al.* (1990) and Orford *et al.* (1991) that migrate alongshore and weld onto the beach face. These pulses of sediment, also termed ‘nesses’ by Orford *et al.* (1991), may originate from increased river outfall such as flooding or an erosion event on the up-drift side of the barrier spit. A ‘ness’, as described by Orford *et al.* (1991, pg. 93), is a pulse of sediment produced by a discrete erosion event, intermittent offshore to onshore sediment exchange or spasmodic release of sediment drift from a barrier in erosion. It is thought that the intertidal deposits of Sub-facies A1 prograded seaward in a similar fashion to swash bar welding. Down-drift, where the transport power is reduced at the point of barrier spit curvature and where wave refraction is considerable, the refracted bars will accumulate in a spit-like sink forming distal recurves (Carter *et al.*, 1990; Forbes *et al.*, 1995) giving rise to intertidal gravel deposits on the landward side of the barrier spit with an internal structure comparable to that of Sub-facies A3. Spit recurve growth was possibly similar to that of the Hurst Castle Spit in Hampshire, England (King & Mc Cullagh, 1971) and Buctouche Spit in New Brunswick, Canada (Ollerhead & Davidson-Arnott, 1995) where variable wave approach is refracted around the spit head with a particular direction having a greater effect on the recurve deposits. Wave refraction and reworking was enhanced by intense storm-driven waves where, under such conditions, sediment was also transported from the shoreface and spit platform into the

back-barrier setting. It thus follows that the spit recurve gravels of Sub-facies A3 are storm-generated deposits and their growth, as well as textural maturity is dependent on the storm intensity and its duration, wave approach and degree of refraction, as well as sediment supply.

At the leading edge of the spit head, the tidal inlet platform of Sub-facies A2 occupied a non-restrictive, open inlet setting through which waves and tidal currents were channelled. These platform sediments are built northwards ahead of the spit terminus, which is growing in the same direction. However, the bipolar cross-lamination of Sub-facies A2 also suggests that the subtidal body grew seaward and landward at a slower rate than that of the down-drift (northerly) growth. Consequently, the geometry of Sub-facies A3 has a northerly elongation. The barrier spit with its northerly growth accreted over these subtidal deposits partly incorporating them into its structure. This theme of deposition would generate a vertical sequence similar to that described by Nielsen *et al.* (1988) where tidal inlet platform sediments are overlain by top-set beds (Sub-facies A2), which are in turn overlain by coarse spit head gravel beaches (Sub-facies A3).

As barrier spit growth continues, large parts of the mainland are cut off from the sea, encouraging the formation of a lagoon where clay, silts and fine sand are deposited. This is clearly apparent in the Facies A barrier spit sequence where the gravel beaches of Sub-facies A3 interfinger landward with extensive estuarine-lagoon sediments (see Figures 3.11 & 3.12).

3.3.6 Age and correlation

Facies A rests upon and is therefore, younger than the fluvial footwall of meso-Orange age presumed to be 2-5 Ma (Jacob *et al.*, 1999; Jacob, 2005). It also pre-dates the boulder lag of Facies B that truncates the upper part of the barrier spit sequence. In Section 3.4.6, it is demonstrated that the boulder lag is assigned an Earliest Pleistocene age, but due to the absence of diagnostic age fossils from Facies A, it is difficult to establish the depositional hiatus between Facies A and the truncating boulder lag of Facies B. Consequently, the best age determination that can be assumed for the barrier spit sequence is Latest Pliocene/Earliest Pleistocene.

3.4 FACIES B

3.4.1 General

Of all the sedimentary facies recorded, the unconsolidated boulder bed of Facies B is the most laterally persistent. Besides the bedrock high in the most southern part of the study area, the boulder bed also rests unconformably on a variety of marine to estuarine-lagoon sediment. It, thus, truncates the underlying marine sequence of Facies A and grades landward (north-eastward) into the stacked gravel sequence of Facies C. On the most seaward side (south-western) of the study area, the sand-dominated deposits of Facies D overlie the boulder bed. (see Figure 3.15 B & C, Appendix D(4)).

3.4.2 Distribution and thickness

Facies B is restricted to the most western part of the study area and is a laterally extensive, sub-horizontal gravel sheet, traceable along strike and down-dip for 4.5 km and 1.8 km, respectively (Figure 3.15). Dipping slightly seaward (south-west), the boulder sheet rises from an elevation of approximately 2 m above msl in the south-west (seaward) to 10 m above msl to the north-east (landward), truncating a footwall of pre-existing unconsolidated marine and estuarine-lagoon sediments, as well as bedrock (Figure 3.16). Note that the most seaward end of the boulder lag has not been established given that mining has removed part of the deposit. From the exposures, the average thickness of the boulder bed (1.0 m) remains remarkably consistent throughout the study area.

3.4.3 Lithology and structure

Apart from its areal extent, the most striking feature of Facies B is the predominance of boulders confined to a single stratum that persists throughout the entire length and width of the stratum.

Stratum attributes

The stratum dips slightly seaward with a gradient of 0.004 (grade = 0.04%) and is horizontal along strike showing – in contrast to the ‘F’ bedrock-cliff (see Chapter 2, Section 2.2) – no inclination towards the north. Stratum thickness is approximately one metre and exhibits little change in either a down-dip (seaward) or along strike direction. Its basal contact is sharp, truncating pre-existing sediments of variable origin and bedrock. Although not erosive, the upper surface is equally sharp with the overlying Facies D sand. In places where

the basal surface is in contact with estuarine-lagoon clay of Facies A, sediment loading is evident from the protrusion of boulder gravel into and distorting the underlying clay.

Textural attributes

Facies B gravel is poorly-sorted comprising a coarse framework of well-rounded, small to large spherical boulders set in a matrix of well-rounded small pebbles and medium to very coarse sand. Zeolite granules also form part of the matrix fill. Boulder surfaces are scarred with percussion rings. The length of these crescentic indentations, i.e. the length between their ends, can be as much as 4 cm.

Boulder size is variable, ranging from 0.3-1.5 m in length (a-axis). The occurrence of large boulders greater than a metre is relatively low, whilst small- to medium-sized boulders generally predominate. Clasts are dominated by highly resistant lithologies such as quartzite, vein quartz and chert; the first being most abundant. More conspicuous, but less common, are conglomerate boulders containing marine fossils. These are less rounded than the boulder clasts of quartzite, vein quartz and chert. The sub-rounded to rounded conglomerate boulders consist of well-rounded granule to cobble gravel set within a sand matrix and are cemented by highly ferruginous calcite. They represent older consolidated marine units reworked into the sediment of Facies B (see Section 3.4.6 for age relationship). Compositionally, two varieties of conglomerate boulders are evident; those with an abundance of zeolite clasts and those that are zeolite poor. Besides these compositional differences, the macro- and micro-fossil variation is also evident (see Section 3.4.6).

Apollus (1993) studied the distribution of the boulders along strike (south-east to north-west; parallel to present coastline) within the study area to gain an appreciation of the geological controls that may have governed diamond concentration. He noted that the average boulder size forming the coarse framework decreased slightly to the north over a relatively short distance of some 4.5 km. The larger clasts (maximum length of 1.5 m) were found to the south in close proximity to the present Orange River (trenches G9 to G4, see Figure 3.15). In contrast to the decrease in clast size to the north, there appears to be no apparent change in the boulder size in a south-west to north-east direction (along dip), which is perpendicular to the present coastline.

In addition to the quartz-rich lithologies, sub-rounded to rounded red and green clay boulders are also present. These are confined to the most landward edge of the boulder sheet and boulders range in size from 0.3-0.5 m.

Structural attributes

Sedimentary structures are scarce and due to the predominance of spheres, obvious clast orientation is lacking (Figure 3.16). Consequently, a sense of transport direction cannot be established from the gravels. Sediment loading is, however, evident where the boulders overlie estuarine-lagoon clay deposits. The gravel protuberance distorts the clay laminae, depressing the layers downward.

Palaeontological attributes

Isolated fragments of marine shells, notably *Donax rogersi*, have been recovered from the matrix. In addition, the conglomerate boulders that form part of the coarse framework yield a number of well-preserved foraminifera and fragments of molluscan shells (Dale & McMillan, 2003; Pether, 2003), the last comprising an assemblage of bivalves and gastropod casts. In places, clusters of disarticulated bivalves were found, but generally the shell fragments are sparsely disseminated throughout the conglomerate.

Both the micro- and macro-fossil assemblages indicate that all of the species lived in a shallow marine environment, notably the intertidal and subtidal settings (Dale & McMillan, 2003; Pether, 2003). A rocky shoreline habitat is advocated for some foraminifera species such as *Lobatula lobatula* and *Pararotalia nipponica* where they were attached to a substrate in life and washed off into adjacent beach environments once deceased (Dale & McMillan, 2003). A list of the fossil assemblages for both the zeolite-rich and poor conglomerate boulders is presented in Appendix C, whilst Figure 3.17 illustrates their age relationship.

3.4.4 Interpretation of Facies B

Although, the features described in Section 3.3.3 are consistent with a transgressive lag similar to those described by Clifton (1981), DeCelles (1987), Massari & Parea (1988) and Dickinson & Woolfe (1997), two possible interpretations are considered for the boulder-gravel sheet:

- 1) storm generated lag sheet; and
- 2) transgressive lag.

1) Boulder-bearing gravel sheets generated by severe storms have been recorded in the rock record by Pether (1994). He argued that the cobble to boulder gravel (his unit 2) basal to the 50 m Package sequences in Namaqualand ('A' block section exposures) is typical of proximal lower shoreface, storm-deposited gravels (tempestite deposition) rather than transgressive lags. Tempestite deposits in the geological record are a signature of storm processes where sediment is mobilised from the shoreline into the immediate offshore (see Myrow & Southard, 1991) and often exhibit a scoured base with the particle size decreasing in the direction of the current, that is offshore (Nichols, 1999). Pether (1994) based his interpretation on the presence of lower shoreface cross-stratified sand of storm origin, overlying the gravel sheet. In addition, where gravel imbrication was observed, he noted that the clasts dipped towards the palaeo-shoreline and thus seaward transport was advocated for the emplacement of his 'unit 2' basal gravel facies.

Further evidence that boulders can be transported into the offshore during severe storms is afforded by Gruszynski *et al.* (1993; in Mathers & Zalasiewicz, 1996) who reported that boulders of 1 m can be transported seawards for 0.5 km by rip currents. Hartley & Jolley (1999) described similar boulder-sized gravel deposits enclosed in rip-channel features that cut into cross-stratified shoreface sediments of Pliocene to mid-Pleistocene age. As with most rip-channels, the areal extent of these features is limited, widths of 40-70 m and thicknesses up to 2.9 m were recorded.

If storm-generated gravel sheets are considered, the source of the gravels is a gravel-dominated foreshore setting where a mixture of clast shapes would be moved offshore into the shoreface (see also interpretation of Sub-facies D3). This, however, is in contrast to the textural maturity of Facies B where spherical clasts dominate the coarse framework and infilling particles. More significantly, storm-generated beds that are rip-channel derived are coeval with the sediment they incise and exhibit a chaotic arrangement of gravel and sand as described by Hartley & Jolley (1999).

2) Transgressive lags are the preserved record of a landward migrating shoreline under a sea-level rise (Reinson, 1984, pg. 131) and are associated with a ravinement surface that can be traced as a laterally extensive, single erosional feature (DeCelles, 1987, pg. 253; Nummedal & Swift, 1987, pg. 245; López-Blanco *et al.*, 2000, pg. 50). In coarse-grained depositional environments, these ravinement surfaces are armoured by a thin layer of

coarse gravel (Postma, 1995), also termed a lag, which can be, in most instances a single clast thick. Similar transgressive lags have been described by Clifton (1981, his facies A), DeCelles (1987, his facies 1), Massari & Parea (1988) and Dickinson & Woolfe (1997; the Boulder Bank platform gravels). They reported boulder beds no thicker than 0.5 m and clast sizes ranging from a few centimetres to over 2 m, with the coarsest clasts concentrated at or near the base, thus reflecting some degree of normal grading.

Besides the dominance of spherical clasts, the principal characteristic of Facies B is its lateral persistence along strike and down-dip. This can be traced for several kilometres (Figure 3.15A). In addition, the ravinement surface on which the boulders rest demonstrates net erosion of pre-existing deposits as the shoreline migrated landward. Hence, the truncation of older estuarine-lagoon (see Section 3.3.3 for estuarine-lagoon) and gravel barrier spit deposits provide the most fundamental evidence that Facies B is a transgressive lag rather than an accumulation of storm deposits (Figure 3.18A). In fact, the boulder-armoured ravinement surface separates these shallow water deposits from the overlying deeper shoreface deposits of Facies D (see Section 3.6.4 for interpretation of Facies D), which is a diagnostic feature of ravinement surfaces (Catuneanu, 2002; Cattaneo & Steel, 2003)

River flooding is regarded as the main mechanism of introducing the Facies B boulders into the Atlantic Ocean. It has been demonstrated by Bluck & Ward (2000) and Jacob (2005) that the Plio-Pleistocene Orange River (Meso-Orange) was capable of delivering large boulders to the coast during that time. Boulder roundness and percussion scarring was therefore inherited from these vigorous fluvial events. Once deposited, reworking of these outfall sediments and boulder entrainment by wave energy occurred, more particularly during storm periods. Although not quantified, there are several lines of evidence that boulder movement was accomplished. These are:

- 1) The fact that the boulders decrease in size down-drift (in a northerly direction) as noted by Apollus (1993) suggests longshore sorting.
- 2) The absence of encrusting organisms on the boulders shows that not only were the boulders mobile, but also the smaller gravel population that infills the boulder framework. The movement of these smaller clasts over the boulders would preclude the growth of encrusting organisms such as barnacles and polychaetes (Dickinson & Woolfe, 1997).

3) Wave-generated boulder deposits of Neogene age along the Atlantic Coast of South Africa are not uncommon and have been documented by Gresse (1988; Alexander Bay Formation), Roberts & Brink (2002; possible Varswater Formation) and of Quaternary age by Hendey & Volman (1986). Boulder-sized clasts have also been observed by the author along the Skeleton Coast in Namibia where they accumulate at the most seaward edge of gravel beaches (Figure 3.18B). In addition to this observation, alongshore sorting is also evident in boulder beach occurrences between Gordons Bay and Rooiels Bay, South Africa. Although the clasts have derived through reworking of alluvial fan deposits, boulder sorting is clearly apparent where large boulders of approximately 0.9 m (average size = $(a+b+c)/3$) decrease in size alongshore to an average of 0.3 m ($((a+b+c)/3)$) over a short distance of 120 m (Figure 3.18C).

The presence of large boulders along a shoreline, which were derived from a river source, is an obvious expression of the threshold wave energy that can move such clasts to a shoreline position. This was pointed out by Hartstein & Dickinson (2006) for boulder clasts in the Nelson Boulder Bank deposits, New Zealand.

Considering all of the above, it suggests that the boulder component, once injected into the Atlantic Ocean during high-energy fluvial events, would have been driven towards the foreshore over time by vigorous wave energy to finally weld onto and form part of a gravel shoreline. It is, however, during a transgression that the boulders are separated from the shoreline to accumulate in the offshore as a gravel platform. As the shoreline advances landward and being too large to be transported on a rising sea-level (Clifton, 1981), the boulders are left behind in the shoreface as a wide trail of oversized spheres (Massari & Parea, 1988; López-Blanco *et al.*, 2000). The Facies B boulders are, therefore, equivalent to Bluck's (1967) outer frame (coarse sphere-rich gravel sheet of Sub-facies C1 in Section 3.5) and have their origin in the most seaward part of a gravel foreshore setting, which contains the largest spherical clasts where shape and size sorting is ubiquitous. Consequently, such clast shape and size sorting is unlikely to be the result of rapid sedimentation into the offshore as in the case of rip currents.

3.4.5 Summary and depositional setting of Facies B

A conceptual model for the deposition of Facies B is presented in Figure 3.18, whilst the general characteristics of Facies B are summarised in Figure 3.19.

In sections where sediment variability reflects a mix of non-marine to marine-transitional deposits, as in the case of the study area, subaerial and subaqueous sequences are separated by either a landward single ravinement surface or by multiple erosive surfaces, both of which are armoured by gravel lags (Postma, 1995; López-Blanco *et al.*, 2000). The boulder lag of Facies B illustrates this relationship and is a clear record of a barrier shoreline advancing under a rising sea-level. The barrier migrated landward in a ‘rollover’ fashion, a process of constant barrier reworking whereby the material is recycled from the foreshore over the beach ridge into the backshore and returned to the foreshore as the shoreline moves landward (Carter & Orford, 1980; Orford *et al.*, 1991). Clasts that are too large to be moved in the recycling process, as in the case of the outer frame boulders, are left behind as a lag trailing the migrating barrier. Sea-level rise was slow enough to facilitate aggressive sorting at the leading edge of transgression, but the wave and current energy at the sea floor decreased as water depth increased (see Nummedal & Swift, 1987; Figure 3.18A). Consequently, the finer sediment within wave base was aggressively winnowed by shoaling waves and driven onshore, whilst the boulder clasts of Facies B – too large to be transported – were abandoned on the ravinement surface to be drowned *in situ* (see also Clifton, 1981). De Decker (1988) demonstrated that small cobbles and medium pebbles can be transported during storms at depths of 15 m and 30 m, respectively. Thus sediment movement over static boulders at these depths was likely to have prohibited the growth of encrusting organisms.

Variability in boulder lithology, particularly the change to clay, reflects variation in the underlying sediments over which the barrier shoreline migrated. Both the red and green clays originated from a back-barrier setting where clay rafts were ripped from an estuarine-lagoon and incorporated into the ‘rollover’ process. Given their lower specific gravity when compared to the quartz-rich lithologies, the clay rafts would have been entrained further landward during the transgression. The estuarine-lagoon clay over which the shoreline migrated was not consolidated and allowed the boulders to distort the underlying clay that was hydroplastic in nature. The source of the quartz-rich lithologies was, however, the Orange River. The introduction of these clasts into the littoral was during fluvial events where flow competence was at a considerable level to inject boulders into the surf zone. The boulders were driven shoreward and along shore during storms when wave and longshore drift energy levels were significantly raised. This not only facilitated some degree of size sorting, but it also added a boulder component to the shoreline forming the outer frame of a gravel foreshore setting.

The boulder roundness, to some degree, also reflects different source areas. Orange River derived boulders are well-rounded; an inherited texture from river abrasion during transport over great distances. In contrast to the well-rounded boulders, the clay and conglomerate boulders that are locally derived from estuarine-lagoon settings and older calcified beaches occurring at higher elevations (see Section 3.4.6), show less rounding and tend to be sub-rounded to rounded.

3.4.6 Age and correlation

The boulder lag post-dates the accumulation of Facies A as evidenced from its stratigraphic position where it truncates barrier spit sediments. Also, the two fossiliferous conglomerate boulders have yielded different ages based on their foraminifera and macro fauna assemblages (Dale & McMillan, 2003; Pether, 2003; Figure 3.17). The zeolite poor conglomerates are assigned a Late Miocene/Early Pliocene age, correlative to the 50 m Package (Pether, 1986), whilst a Plio-Pleistocene age, corresponding to 30 m Package (Pether, 1986) has been assigned to the zeolite-rich conglomerate boulders.

Dale & McMillan (2003) further point out that the foraminifera from the Late Pliocene conglomerate boulders are indicative of an intertidal setting, suggesting an older calcified gravel beach source. As discussed in Chapter 2, older beaches along the Namibian and Namaqualand Coast are generally found at successively higher elevations (Hallam, 1964; Pether, 1986; Gresse, 1988) and the Pliocene age deposits – the 50 m Package (Pether, 1986) – have the maximum transgressive unit some 50 m above present sea-level. It is, therefore, envisaged that these Pliocene conglomerate boulders were introduced into the littoral during Facies B times through sheetwash action or ephemeral streams reworking an older raised shoreline. Compared to the littoral and Orange River environments, lower energy levels are associated with ephemeral streams and thus such reworking would account for the lower degree of boulder rounding. Whereas, the 30 m Package conglomerate boulders, although older than the enclosing Facies B sediments by virtue of its stratigraphic relationship, fall within the same time frame; that is within 3.5-2.5 Ma that typifies 30 m Package deposits.

In summary, the deposition of Facies B is no older than Late Pliocene/Early Pleistocene and correlates to the 30 m Package (Pether, 1986).

3.5 FACIES C

3.5.1 General

The gravel-rich deposits of Facies C are the primary targets for mining operations and collectively constitute the most eastern part of the marine package within the study area. The most striking feature is the preservation of the almost original geomorphological surface by fossil pedogenic calcrete where distinct topographic ridges, seen in section, are parallel to the present coastline in a south-east to north-west direction. From the trench exposures, two main sub-facies have been recognised and their sedimentary units are combined in various ways that typify Facies C. Although, trench sections may exhibit varying proportions of each sedimentary unit, the type section for Facies C is the G29 trench.

3.5.2 Distribution and thickness

Along strike (parallel to present coastline; south-east to north-west), Facies C extends over a distance of some 3.2 km, with the thickest part of the sequence confined north of the G14 sample trench; it thins abruptly southward of G14. Down-dip (perpendicular to present coastline) it is developed over a distance of approximately one kilometre where it grades westward (seaward) into the deposits of Facies D (Figure 3.20, Appendix D(4)). From the type section at G29, it is apparent that the sub-facies of Facies C are either stacked into an 11 m thick marine package where they are vertically duplicated or, in places, arranged laterally to form a complete gravel sequence (Figure 3.21, Appendix D(4)).

3.5.3 Lithology and structure

Gravel, sand and clay constitute the bulk of Facies C, with gravel being dominant. From the type section, two main sub-facies, designated C1 and C2 have been recognised. These consist of various sedimentary units, notably:

- 1) Completely preserved coarse gravel sheet, rich in spherical shapes of Sub-facies C1;
- 2) Partially preserved cross-stratified gravel and laminated sand of Sub-facies C1;
- 3) Poorly preserved coarse gravel sheet with abundant disc- and blade-shaped clasts of Sub-facies C1;
- 4) Completely preserved cross-stratified sand and gravel of Sub-facies C2; and
- 5) Completely preserved laminated clay and silt deposits of Sub-facies C2.

Sub-facies C1

Sedimentary units with distinct textural and structural differences make up Sub-facies C1 in various combinations. These are either arranged vertically or laterally, but the units are more commonly vertically stacked. In most instances not all of the sedimentary units are preserved and thus their lateral and vertical arrangement can be described as follows (see also Figure 3.22):

- 1) Laterally, the coarse sphere-rich gravel sheet is replaced landward by cross-stratified gravel and laminated sand. These are in turn replaced by the coarse gravel sheet rich in discs and blades;
- 2) Vertically, the coarse sphere-rich gravel sheet is overlain by cross-stratified gravel and laminated sand, which is in turn replaced upward by the coarse disc- and blade-rich gravel sheet, if the last is preserved. However, where the last is absent, the coarse sphere-rich gravel sheet is overlain by a combination of cross-stratified gravel and laminated sand. This stacking arrangement, which is the more common geometry seen in section, is repeated throughout the 11 m section.

Similar to Facies A, the gravels are in places stained black by a manganese coating, but are commonly grey-brown in colour. The gravels are unconsolidated, but the sediments in the uppermost part of the 11 m marine package that forms the geomorphic surface is cemented by calcium carbonate as a result of pedogenic processes. Although dominated by gravel, sand units do occur. These are, however, briefly considered given their poor diamond-potential and are thus viewed as non-economic deposits.

*Coarse sphere-rich gravel sheet**Stratum attributes*

These form the most seaward part of laterally arranged sedimentary units or at the base where they are vertically stacked (Figures 3.20B & 3.22). The sub-horizontal strata dip gently seaward at 2° and are distinct in that they are relatively thin, reaching a thickness of approximately 0.7 m. The gravels are coarse, up to large boulder size and predominantly sphere-shaped. The upper surface of the strata has a sharp contact with overlying sediments, whilst the lower surface truncates the underlying sediments.

Textural attributes

The strata are characterised by a bimodal population of clast size. Large cobble to large boulder (0.5 m in length) clasts, predominantly sphere-shaped, constitute the original framework, whereas finer gravel with a range of clast sizes and shapes infill the coarser framework (Figure 3.23A & B). The gravels are matrix-supported with the coarser framework displaying considerable shape sorting maturity, whilst the overall character of the sediment with its infilling gravel matrix has an appearance of a poorly sorted deposit. Sediment grading is absent. Shape measurements of the largest framework clasts show a high proportion of rods and spheres (Figure 3.23D). In addition, the surfaces of these large clasts are scarred with percussion rings which, in places, are 4 cm in length. Clast orientation is not only absent due to the predominance of spheres, but also the infill disc- and blade-shaped clasts show no preferential orientation. They are either vertical or imbricated seaward and landward. Similar to the Facies B boulders, the larger gravels forming the coarse framework consist mainly of quartzite and quartz lithologies.

Structural attributes

The gravel strata are structureless.

Palaeontological attributes

No fossils were recovered from these sediments.

*Cross-stratified gravel and laminated sand**Stratum attributes*

Landward of or overlying the sub-horizontal strata are cross-stratified sets of approximately 1-1.2 m thick that are vertically stacked throughout the 11 m thick marine package (see also Figures 3.20B & 3.22). Set boundaries are well defined by sub-horizontal strata comprising coarse spherical gravel sheets that truncate the upper surfaces of the cross-stratified sets.

Textural attributes

The textural attributes of the gravel is remarkably distinct and besides the sand deposits, there are two gravel types; those that are clast-supported with distinctive structures and fabrics, and the matrix-supported gravels where sand has infiltrated the intergrain spaces.

Both gravel types have well-rounded clasts and range in size from granule to small cobble. The fabrics exhibited by the clast-supported gravels distinguish these sediments from the other Facies C deposits. These are:

- 1) An openwork framework where the voids between the clasts remain visibly open (Figure 3.24A & B). The larger pore spaces are consistently associated with the coarser framework. A carpet of smaller clasts (small pebble to granule size) overlying this framework partly penetrates the upper portion and becomes tightly wedged between the larger gravel clasts. This forms a barrier to further infiltration by either sand, finer gravel or diamonds into the coarser framework;
- 2) An abundance of imbricated discs and blade-shaped clasts which dip seaward, on average, towards the west-south-west at steep angles;
- 3) A notable absence of zeolite clasts in coarser gravels, but occur more prominently in matrix-supported gravels.

It is also not uncommon to find clay clasts within the sand and gravel strata. These usually occur randomly throughout the sequence or are aligned along the foresets as in the case of gravel-dominated deposits. Although disc-shaped clasts have been observed, the clay clasts are invariably equant, generally reddish-pink in colour (with minor green clay occurring) and usually measure from 5-30 cm in length.

In contrast to the highly porous gravel strata, the matrix-supported gravel shows less order and poorer sorting where sand constitutes the matrix infill. These strata often exhibit a lateral (down-dip) seaward transition into laminated beach sand. Heavy mineral laminae often occur in these sand units comprising garnet, magnetite and minor ilmenite grains. The laminae are sub-horizontal, dipping slightly seaward towards the west-south-west.

Structural attributes

Similar to Sub-facies A1, well-defined tabular cross-stratification is a characteristic feature of these gravels. Tangential foresets dip steeply seaward towards the south-west and west-south-west at angles ranging from 15°-25° (Table 3.5; Figure 3.24C). Foreset strata of approximately 60 cm show normal grading. Here a basal layer of cobbles grade through a coarse pebble layer to a small-pebble/granule upper layer. The last, locally referred to as a blinding fabric, represents the final accumulation of a gravel sheet before the emplacement of the next coarse basal layer (see Figure 3.24A). Each foreset demonstrates a high degree of

clast-size and clast-shape sorting. The basal cobble layers, dominated by spheres or blades (Figure 3.24B), are overlain by coarse pebble layers which have a mixture of discs and spheres; the latter shapes also predominate in the uppermost blinding fabric. In places, clasts significantly larger than the well-sorted background size occur as ‘floating’ oversized clasts. These are not confined to strata of specific size fractions, but occur randomly in all strata.

In addition, soft deformation features are best represented in the G29 section. These are fold-like structures, similar to those seen in Sub-facies A3, where disc and blade clasts are imbricated in opposite directions, accentuating the opposing fold limbs.

Table 3.5: Palaeo-current data of Sub-facies C1

n	Xv	R	L(%)	Structure	Sediment
2	240	1.95	98	Tabular cross-stratification	Gravel at G19
2	208	1.97	98	Tabular cross-stratification	Gravel at G25
6	252	5.54	92	Tabular cross-stratification	Gravel at G29
5	261	4.73	95	Near-horizontal laminae	Sand at G29

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

Mollusc fragments of *Donax rogersi* have been recovered from the gravel strata, as were small fragments of unidentified shell from the sub-horizontal laminated sand in size fractions < 1 mm.

Coarse disc-rich gravel sheet

Stratum attributes

The cross-stratified gravel is replaced landward by horizontal strata comprising coarse disc- and blade-shaped gravel. Where preserved, the latter forms the most landward and uppermost unit of laterally arranged and vertically stacked sedimentary units of Sub-facies C1, respectively. Generally, these strata are not preserved and are usually removed by the coarse spherical gravel sheets (Figures 3.20B & 3.22). Strata thickness, where preserved, varies and can be as thick as one metre (Figure 3.25A).

Textural attributes

These strata consist largely of well-sorted, clast-supported pebble to small cobble discs and blades that are not orientated in any particular direction; they generally lie flat, at times are vertical or have opposing dips where the clasts are imbricated landward or seaward (Figure 3.25B). Smaller isolated gravel clasts forming the gravel matrix are lodged tightly within the coarser framework, but more commonly the gravels have an openwork framework. Reverse grading is evident from the upward increase in gravel size from pebble to small cobble. A high degree of blade- and disc-shape sorting (Figure 3.25D) and the lack of stratification is the most distinguishing feature of these deposits, which is absent in the other gravel deposits of Facies C.

Structural attributes

The strata are structureless and unstratified.

Palaeontological attributes

No fossil material was recovered from these deposits.

Sub-facies C2

Like Sub-facies C1, the deposits of Sub-facies C2 comprising gravel, sand, clay and silt are either arranged horizontally or are vertically stacked (Figure 3.21). Within a vertical sequence these sediments are more commonly wedged between those of Sub-facies C1 (see Figure 3.26). The lateral continuity of Sub-facies C2 deposits can be as much as 100 m and the textural character is consistently maintained over this distance.

*Cross-stratified gravel and sand**Stratum attributes*

Cross-stratified sets are approximately 1.5 m thick with either sharp or gradational lower contacts. Where the gravels overlie silt and clay deposits, the lower contact surfaces are sharp, whilst gradational contacts in lateral sequences occur more commonly at the contact with cross-stratified gravel deposits of Sub-facies C1. The upper contacts are sharp and defined by a truncation surface generated by the coarse sphere-rich gravel sheets of Sub-facies C1.

Textural attributes

Gravel size ranges from granule to small cobble and is generally well-rounded, displaying poor shape and size sorting. Disc and blades are the predominant shapes with cobble-sized gravel forming the base of each foreset strata. Here the cobbles are clast-supported and well-sorted, whilst the overlying gravels are finer, matrix-supported and poorly sorted. Normal grading is thus evident by this upward decrease in gravel size. Coarse sand to small pebbles with a distinct absence of zeolite clasts form the matrix fill in the matrix-supported gravels. Disc- and blade-shaped clasts are imbricated landward; a direction opposite to the imbrication measured from the Sub-facies C1 cross-stratified gravel. Cohesive clay rafts that exhibit little to no rounding are also present and these can be 0.8 m in length, often occurring as oversize rafts. The gravel deposits are replaced landward by coarse cross-stratified sand with foreset strata that dip towards a similar direction. This change from gravel to sand is gradational with inter-dispersed pebble stringers occurring throughout the sand deposits.

Structural attributes

The tabular cross-stratification differs to that observed in Sub-facies C1 in that the foresets dip in the opposite direction; that is, landward and at lower angles of 10°-20° (Figure 3.26A). Field measurements show that the tangential foresets with concave geometries are approximately four metre in length and have radial dips directed towards the north-west through to the north-east, therefore implying that they are fan-shaped (Table 3.6; Figure 3.26C). Foresets in gravel often grade, more particularly at the distal ends, into very fine sand or silt. This gradation into sand or silt is prevalent in the upper part of the foreset strata, giving an appearance of normal grading from cobble gravel upward through to sand or silt. These last two fine sediments interfinger landward with horizontal strata of laminated silt and clay deposits. In places, the foresets, in fine sand, have a convex geometry at their distal ends where they bend downward towards and interfinger with the horizontal clay and silt sediments.

Table 3.6: Palaeo-current data of Sub-facies C2

n	Xv	R	L(%)	Structure	Sediment
7	342	6.73	96	Planar cross-stratification	Gravel at G19
3	31	2.94	98	Planar cross-stratification	Gravel at G39.5
24	30	22.95	96	Planar cross-stratification	Sand at G25

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

No fossil material was recovered from the gravel or sand. However, the red-coloured clay rafts, in places, yielded fragmentary leaf and twig mash of unknown origin (Dale & McMillan, 1996).

Laminated clay and silt

Stratum attributes

Laminae sets of interbedded clay, silt and fine sand extend along strike (parallel to the present coastline) and down-dip (perpendicular to the present coastline) for approximately 1 km and 100 m, respectively. These maintain a sub-horizontal geometry over these distances, dipping gently landward. Coset thickness is seldom one metre; it is usually on average 0.5-0.8 m. Set boundaries are gradational, whilst coset boundaries (upper and lower) in contact with gravel and sand are sharp.

Textural attributes

These deposits differ considerably to all the others of Facies C in that they comprise predominantly fine sediments. In addition to fine sand, the key sediment types are interbedded clay and silt. Their textural attributes are, however, no different to those observed in Sub-facies A4. Consequently the interbedded clay and silt deposits of Sub-facies C1 will be briefly considered in this section; a more detailed description is offered for Sub-facies A4 in Section 3.3.3. The clay and silt sediments of Sub-facies C2 are finely, parallel-laminated and commonly red to pink in colour, whilst the fine sand has an orange-brown colour with fine parallel laminations.

Structural attributes

In places, symmetrical wave ripples are preserved within the fine sand layers that are interbedded with clay and silt. Both the stoss and lee sides of these bedforms have similar angles of approximately 15° . The approximate height and length of a ripple is 3 cm and 15 cm, respectively, giving a ripple index (L/H) of 5 and are thus comparatively smaller in size to those ripples in Sub-facies A4. The internal geometry exhibits fine tabular foreset laminae that are tangential-based. These dip seaward in a single direction at low angles of 4° - 12° .

In addition to the wave ripples, load structures have been observed where the cross-stratified gravels of Sub-facies C2 directly overly the clay and silt deposits. The unequal loading of larger clasts, in this case a large cohesive clay raft, illustrated in Figure 3.27(A) has distorted the underlying clay beds creating flame structures that have extended upward into the overlying silt layer. This indicates penecontemporaneous deposition of the cross-stratified gravel prior to the consolidation of clay sediments. More significantly, the ponding of flame structures, as depicted in Figure 3.27(B2), to 'mushroom' out beneath the overlying upper clay unit, clearly suggests that the clay strata were saturated with water to be sufficiently hydroplastic prior to the emplacement of the overlying cross-stratified gravels.

3.5.4 Interpretation

The architecture of Facies C and the internal structures of the sub-facies (see Figures 3.21 and 3.28) are comparable to the foreshore (intertidal) and backshore (supratidal) settings described from modern and ancient gravel barrier beaches by Bluck (1967, 1999), Hobday & Banks (1971), Orford (1977), Carter & Orford (1984), Nemeč & Steel (1984), Massari & Parea (1988), Williams & Caldwell (1988), Orford *et al.* (1991), Postma & Nemeč (1990), Reddering (1993) and Hayes *et al.* (2010). Such deposits are the most complex in a gravel barrier beach sequence, having a diverse range of both texture and structure. However, Bluck (1967, 1999), Orford (1975), Caldwell & Williams (1985) and Williams & Caldwell (1988) have shown that these deposits exhibit remarkable clast shape segregation into distinct zones, producing unique sedimentary structures that characterise the various foreshore settings. Figure 3.28 provides a schematic representation of such settings in a gravel barrier beach environment.

The modern gravel beaches, composed entirely of gravel, at Terrace Bay along the Skeleton Coast of Namibia provide excellent analogues of Facies C, exhibiting similar

structural and textural features at the surface. As with most modern gravel beaches, a distinct down-beach zonation of the various settings within the foreshore is recognisable at Terrace Bay. Given this comparability to the study area, the gravel barrier beaches within the ED Area are compatible to Jennings & Shulmeister's (2002) 'type 1 pure gravel' of their classification scheme of gravel beaches.

Sub-facies C1

Coarse sphere-rich gravel sheet

These gravels, which are composed mainly of cobble and boulder spheres, are consistent with the deposits representing the most-seaward margin of the foreshore (intertidal) and are thus equivalent to Bluck's (1967) outer frame, representing the base or toe of a gravel barrier-beach sequence (Figure 3.28A). During swash incursions, spherical clasts are thrown a shorter distance on to a beach face due to their higher settling velocity and roll down the slope with ease to accumulate at the most seaward margin (Bluck, 1967; Bluck *et al.*, 2001). These are thus the largest, most mobile clasts within a beach sequence. As they are coarser than the surface over which they move during the backwash stage, they are able to bridge the open pore space of the finer gravel framework and travel farther down beach than any other clast type. Hence, the existing gravel fabric over which they move encourages a sorting process whereby large misfit clasts are rejected, a process referred to as 'overpassing' (Buscombe & Masselink, 2006). Coupled with gravity, the steep beach face would have facilitated the mobilisation of these coarse spherical clasts to roll down slope, particularly when the backwash effect is limited as it percolates rapidly through the permeable slope of the beach face.

Kirk (1975) has shown that on mixed sand and gravel beaches, backwash flow has lower velocities than their swash counterparts – an indication of the degree of water percolation through the sediment. Consequently on beaches, such as those at Terrace Bay on the Skeleton Coast in Namibia, that are coarser and comprise a greater component of gravel than the beaches described by Kirk (1975), the percolation rate and difference in flow velocities between swash and backwash would consequently be greater and of a magnitude predicted for the Facies C beaches. Such swash asymmetry on gravel beaches has been demonstrated by Masselink & Li (2001), Austin & Masselink (2006) and Buscombe & Masselink (2006).

The larger spherical clasts constituting the main framework would have accumulated at the beach toe prior to the arrival of the finer gravel infill. These would therefore act as receptors to clasts rejected from gravel fabrics forming elsewhere farther up the beach face (see Bluck, 1967). This implies deposition of a well shape- and size-sorted primary fabric before infiltration of finer gravel assemblages. The final accumulation of sediment is thus a cumulative record of grain size sorting through a process of rejection and filtering as discussed by Buscombe & Masselink (2006). Such bimodal fabrics have been described by Haslett & Curr (2001) from Quaternary beaches in France and also observed in the modern gravel beaches along the Skeleton Coast in Namibia.

With beach face slopes greater than 14° (see cross-stratified gravel interpretation) – a minimum angle that is necessary for boulders and cobbles to roll down slope (McLean & Kirk, 1969 in Dickinson & Woolfe, 1997) – the outer frame clasts would have accumulated preferentially on the seaward platforms with lower slopes of 2° . It has been argued in Section 3.4.4 that the outer frame is the precursor to the transgressive boulders of Facies B and the northerly decrease (down-drift) in boulder size seen in that facies points to longshore sorting within a restricted zone. It also suggests that swash incursions could conceivably push boulders up the beach face, more competently during storm periods where wave heights exceed 5 m. Such storm conditions with wave heights of 5 m and wave periods of 20 seconds do occur presently off the study area, approximately 1% of the time as documented by de Decker (1988). Boulders of an approximate mass of two tons, equating to an average clast size of one metre $((a+b+c)/3)$ for quartzite, can be moved during such storms, but the boulders must be in shallow water conditions where it is subjected to direct wave attack (G. Diedericks, pers. comm., 2010; G. Smith, pers. comm., 2010).

Boulder movement on a gravel beach is not unusual and has been documented in Australia. A study at Kiama, south of Sydney, by Oak (1984), where boulder movement was monitored for a period of two years, revealed that upslope movement of such clasts was achieved only during storms, as one would expect. For example, she notes that where a significant wave height of 4.3 m (equating to breaker height of 5.6 m) and wave period of 14 seconds was measured, a boulder of 2.2 tons (equating to an average size of 1.1 m for a quartzite clast in the study area) was pushed upslope. Following on Oak's (1984) study, Lorang (2000) came to a similar conclusion based on field observations and using statistical computations that incorporated a range of parameters. He concluded that boulder movement

was accomplished by increased wave power as a result of increasing wave period. Given that present-day storm waves of 5 m high (and more) with attendant wave periods of 20 seconds occur off the study area, it is reasonable to infer that the outer frame boulders of Sub-facies C1 would have been mobilised onto the beach face.

Being at the most seaward margin of the beach and the coarsest material, the outer frame clasts are consistently raked by wave energy. They are the first to receive wave or swash uprush where energy is highest, whereas on the backwash, the outer frame clasts are subjected to the maximum return of water lost through percolation. On highly permeable beaches, the uprush will at some point – usually coinciding with the ‘dry’ middle to upper part of the beach face – percolate through the coarse sediment (Butt & Russell, 2000). The percolated water will eventually exit seaward at the beach toe. Obviously this exit point will move up and down the beach face in concert with rising water levels, either during storms or tidal differences (Butt & Russell, 2000). However, unlike the middle and upper part of the beach, water loss as a function of percolation is far less in the lower part, leading to slopes with lower angles (Butt & Russell, 2000). Consequently, the outer frame deposits represent a winnowed lag where gravel accumulation rarely takes place.

Cross-stratified gravel and laminated sand

The sedimentary structures of these deposits are consistent with the middle sector of the foreshore environment, which has been described in detail from modern gravel beaches by Bluck (1967, 1999), Orford (1986), Postma & Nemeč (1990), Sherman *et al.* (1993) and Austin & Masselink (2006). Dominated by swash berm, cusp and selection pavement features, this is the section landward of the sphere-rich outer frame deposits and contains the majority of sedimentary structures where the largest morphological changes occur (Figure 3.28B).

The sedimentary characteristics of the cross-stratified deposits of Sub-facies C1 are comparable with those of swash berms and cusps, representing Bluck’s (1999) imbricate zone. Kirk (1980) describes this zone as the ‘engine-room’ of the foreshore in gravel beaches and it is the site of vigorous swash and backwash energy that generates extreme clast shape and size sorting in either spheres/rods or disc/blades (Bluck *et al.*, 2001). Here gravel is more mobile than any other part of the foreshore and the process of clast selection and rejection is

highly active under constant wave attack. It is therefore not surprising that clast lithologies with low specific densities such as zeolites, are absent within this part of the barrier beach.

Gravel is either sourced from the erosion of the upper beach face or directly from swash-derived sediments thrown onto the beach. Various processes of gravel clast mobilisation have been advocated such as saltation, traction bed-load and sheetflow (Buscombe & Masselink, 2006). While a combination of these may occur, saltation is seen as an important process aside from clasts simply being ‘rolled’ upslope during swash uprush. Here a population of swash-derived gravel is ejected onto the beach face through violent particle collision (Orford *et al.*, 1991; Isla & Bujalesky, 1993; Lorang, 2002). This process of saltation associated with plunging breakers (see Orford, 1977, pg. 383) was commonly observed on the modern gravel beaches at Terrace Bay (see Figure 1.1 for locality) along the Skeleton Coast of Namibia.

Plunging breakers are thought to be the dominant wave-breaking process on steep gravel beaches. Here wave impingement ‘jets’ water into the beach face, increasing sediment mobility during swash incursions (Carter, 2002; Pedrozo-Acuña *et al.*, 2008). It has been shown that the strength of the beach face is related primarily to the geometric arrangement of interlocking grains and their intergranular friction. Therefore when waves are not present, the pore water pressure between the gravel particles (below the surface) equals the hydrostatic pressure (e.g. Pedrozo-Acuña *et al.*, 2008). This effect, however, is reduced when a sudden rise of pore water pressure is ‘jetted’ into the sediment during wave impingement, causing the effective stresses that bind the particles to decrease and a resultant weakening of the sediment under increasing magnitude of wave impact. The particles consequently become ‘supported’ by water and are transported up beach by a turbulent bore that moves ahead of the collapsed wave-front as swash uprush (Pedrozo-Acuña *et al.*, 2008).

Swash uprush and backwash are therefore obviously integral to mobilising and sorting gravel, with swash incursions having greater competence to transport more sediment than backwash as shown from field experiments by Austin & Masselink (2006). However, given that gravel beaches are highly permeable due to their openwork framework – a function of sediment size (Butt & Russell, 2000; Pye, 2001; Everts *et al.*, 2002; Austin & Masselink, 2006; Buscombe & Masselink, 2006, 2008) – swash competency decreases landward, generally during the latter stages of uprush when the velocity is no longer sufficient to retain

sediment in transport (Buscombe & Masselink, 2006). This inefficiency coincides with the infiltration or percolation of the swash incursion, resulting in material being stranded on the beach face (Buscombe & Masselink, 2006). On steep gravel beaches, as those within the study area, stranded spherical clasts roll down slope towards the beach toe and although percolation losses have reduced backwash flow over the beach face, some fine material would have been downcombed by a thin layer of backwash.

During this limited backwash flow, clasts are moved over a stationary carpet of gravel. If the mobile clasts are smaller than those in the gravel carpet, they are likely to lock into the pore space of the stationary gravel and remain wedged. Where clasts are significantly finer than the pore space, these have a greater propensity to filter through the sediment pile back into the energetic surf zone; a process known as kinetic sieving (Buscombe & Masselink, 2006; Figure 3.29A). However, clasts larger than those in the gravel carpet will bridge the pore space (referred to as ‘overpassing’; Buscombe & Masselink, 2006) to be rejected as misfit clasts and return to the beach toe (outer frame; see Figure 3.29A). Therefore as the pore space of the original framework is filled with inter-locking clasts, the pore space of this infill phase is, in turn, filled with finer clasts and by progression normal grading is developed that culminates in a blinding fabric (Figure 3.29A, B & C). This process of extreme clast segregation was also observed by Rasmussen (2000; his facies B1) in an Eocene gravel beach from the Sant Llorenç del Munt fan-delta complex in Spain. He described normal grading where layers of pea-sized spheres (comparable to the blinding fabric) alternate with layers of pebble or cobble disc-shaped clasts.

However, the displacement of misfit clasts may not always be achieved. In some instances, where isolated clasts are significantly larger than the background size as seen in the study area (Figure 3.29D), they will sink into the finer gravel mass and become immobile (Orford *et al.*, 1991). With continued turbulence around the larger clasts they become buried by the mass of finer gravel, but the surface will continue to grow with little or no change in the modal clast size, provided that the supply of finer gravel is sustained (Bluck, 1999; Figure 3.29D & E).

Unlike their modern counterparts, the distinction between accretionary cusps and berms in the study area is difficult, since complete structures are not always preserved. In many instances, only the steeply seaward-dipping foresets are seen in section; a feature that is

diagnostic of the imbricate zone and common to both cusps and berms, but are nevertheless key in determining the direction of beach growth.

The laminated sands with heavy mineral laminae are interpreted as intertidal beach sand and correspond to the beach facies described from the Palaeozoic (Cheng, 1982, his facies 6), Mesozoic (Davies *et al.*, 1971), Late Pleistocene (Nishikawa & Ito, 2000, their facies FA6) and modern beach deposits (Clifton, 1969; Reineck & Singh, 1975).

Besides the heavy mineral constituent seen in section, clay balls also occur as isolated oversized clasts. These are not only restricted to the beach sands (Figure 3.30A), but are also found within the gravel sequences as noted in Section 3.5.3. Clay clasts within a littoral environment are not uncommon. Eroded balls and boulder-sized clasts of indurated clay containing lacustrine plant remains have been recorded from a gravel beach face at Cansore Point in south-east Ireland, particularly after onshore storms (Carter & Orford, 1980; Orford & Carter, 1982). Clay balls have also been observed on the sand-dominated barrier beach (personal observation, 2001) immediately north of the present-day Orange River mouth where they occur on the beach face as isolated, well-rounded pebble to cobble clasts – either disc- or equant-shaped (Figure 3.30B). The mud banks exposed in the estuarine-lagoon behind the modern sand-dominated barrier are the source areas for the clay. During floods or increased flow of the Orange River, clay is ripped from the banks and washed into the Atlantic Ocean where it is returned to the foreshore and fashioned into clasts under highly energetic swash and backwash. The clast preservation in the beach environment is further afforded by a coating of sand, armouring them against further attrition. The presence, therefore, of clay clasts in the cross-stratified gravels and laminated sands of Sub-facies C1, implies that Facies C was proximal to a river mouth where clay was derived from a local back-barrier source during a period of river flooding or possibly through coastal erosion. It thus follows that their preservation in the rock record suggests an increased supply of sediment to the barrier beach environment where high accretion rates are facilitated through rapid sedimentation.

Invariably, the sandy matrix-supported gravels are associated with sand beaches and in laterally sequences, the gradational change from matrix-supported gravel to sand or vice versa suggests that both components were contemporaneously deposited. This deposition took place either during a phase of increasing sand supply with a progressive decline in gravel to produce a gradational change from matrix-supported gravel to sand, or during an increasing

gravel supply with an associated decline in sand to give the reverse sequence. However, where gravel beaches in lateral sequences truncate their sandy counterparts, although clast-supported, the gravel beds closest to the contact have a sand matrix. This suggests an introduction of sand into an openwork gravel framework rather than contemporaneous deposition of sand and gravel. By charging the gravel framework with sand, the stability of a gravel beach is greatly reduced as a consequence of diminishing hydraulic conductivity (swash and backwash infiltration) due to decreasing permeability (Everts *et al.*, 2002). The beach is thus easily eroded during the backwash stage where water percolation is considerably impeded and backwash flow over the beach face is consequently increased. It is therefore likely that the build up of these types of beaches occurred often during Facies C times, but few have been preserved compared with the openwork framework beaches.

Coarse disc-rich gravel sheet

Field observations of the modern gravel beach at Terrace Bay along the Skeleton Coast in Namibia show that the most landward part of the foreshore is represented by a prominent beach ridge demarcating the limit of swash run-up during storm periods (Figure 3.28C). Furthermore, the accumulation of gravel at this ridge is dominated by large flat-lying, disc- or blade-shaped clasts; a feature that has also been recorded from other modern gravel beaches by Bluck (1967), Hobday & Banks (1971), Loureiro & Granja (2001), Single & Hemmingsen (2001) and Orford *et al.* (2002). Such a gravel assemblage of Sub-facies C1 is distinctly similar to the beach ridge accumulation at Terrace Bay and therefore represents Bluck's (1967) large disc zone.

The beach ridge is an area where the least amount of reworking takes place since it is the most landward accumulation of gravel and is linked to storm-generated swash processes. Successive higher waves will modify the beach profile and move the ridge further landward. Therefore ridge elevation is equal to the maximum height of swash run-up. Storms are advocated as the main mechanism for beach ridge building; a process known as overtopping (see Orford, 1977; Orford & Carter, 1982; Carter, 2002). During storms, discoidal and blade clasts are transported further than any other particle shape onto and beyond the beach face as result of their larger surface area that allows greater suspension (Bluck, 1967). Coupled with the reduction in backwash strength at the beach ridge due to high percolation rates through the permeable gravel, the clasts are left stranded to accumulate, provided that sediment supply is sustained (Bird, 1972; Orford, 1977; Orford & Carter, 1982; Carter, 2002). This mechanism

of ridge nourishment differs to overwashing; the latter is an extension of overtopping that reduces ridge height and moves sediment well over the beach ridge into a back-barrier setting during washover events (Carter & Orford, 1980, 1981; Orford & Carter, 1982; Carter, 2002; Sedgwick & Davis Jr, 2003).

Storm intensification is manifested at the beach ridge through overwashing, but also by an increase in gravel size at the ridge. The latter leads to reverse grading where a progressive increase in gravel size is a result of increasing transport competence as the storm intensifies. Thus, the largest disc- and blade-shaped clasts are delivered to the beach ridge at the peak of the storm. Such reverse grading has also been observed by Wells (1996) in the Santa Beach Ridge Complex, Peru, and the change of gravel size is interpreted as a function of changing energy levels.

Although, plunging breakers are considered as the dominant wave type for clast mobilisation (Carter, 2002; Pedrozo-Acuña *et al.*, 2008) on a steep gravel beach face, Orford (1977) argued that spilling breakers are the dominant mode during storms, which are essential for overtopping and beach ridge construction. He proposed that breaker types evolve during storm periods and the resultant breaker variations on a gravel barrier beach are achieved in association with breaker height and changing beach profiles. Thus, according to Orford (1977), plunging breakers will be replaced by spilling forms at upper beach levels. However, when conditions are conducive to downcombing, clast mobility during this breakdown phase is greatest at the beach face, rather than at the beach ridge given that the clasts are stranded at the highest elevation on highly permeable sediments that are relatively flat lying. Here, instead of returning over the gravel surface, the backwash percolates rapidly through the openwork framework and, in its passage, entrains finer gravel particles seaward. The size and shape of the smaller clasts entrained is dependent on the geometry of the gravel pore space. Thus, the large disc zone can be regarded as a lag deposit due to a sieving action induced by a combination of pore size and shape created by the gravel fabric and incessant backwash flow (Bluck, 1967, 1999).

*Sub-facies C2**Cross-stratified gravel and sand*

These deposits are similar to the washover fans described by Carter & Orford (1980, 1981), Orford & Carter (1982), Gresse (1988), Massari & Parea (1988), Orford *et al.* (1991), Wells (1996), Blair (1999, his facies D) and Bluck *et al.* (2001, their sub-facies B6). They are the products of washover during storms where sediment is transferred from the foreshore landward into a topographically lower area such as a back-barrier to form washover fans (Figure 3.28D). It thus follows that the washover gravels have their provenance in the beach ridge, supplying a particular shape such as discs and blades to produce downslope fan imbrication (Carter & Orford, 1981). With individual foresets representing a thin layer of overwash material produced by a surge of water across the barrier – as observed in modern washovers at Oranjemund (personal observation, 2001) – variations in hydraulic conditions throughout washover events will be reflected in the foreset strata (see Sedgwick & Davis Jr, 2003). Consequently, a progressive decline in washover flow velocity is expected to produce normal grading. This is seen at the G29 trench where the coarse basal gravel lag, sourced directly from the beach ridge, represents peaked energy levels, as does the presence of large clay rafts of lagoon origin. Plant remains found in such rafts support such an origin. As washover energy levels progressively decline during the final surge stages, finer sandy gravel followed by sand are deposited. Such normal grading is not an unusual textural feature in washover deposits and has been recorded elsewhere (e.g. Andrews, 1970 in Sedgwick & Davis Jr, 2003).

The low-angle cross-stratification represents proximal to mid-fan reaches, whilst the distal parts are characterised by foreset interfingering with clay and silt deposits of lagoon origin (e.g. Barwis & Hayes, 1984, pg. 908). The convex geometry of the foreset terminus at the point of interfingering, possibly represent small deltaic lobes.

In contrast to washover on a gravel barrier beach, Gresse (1988) recorded washover sedimentation landward of a bedrock-barrier in Pleistocene marine deposits south of the study area, along the Namaqualand coast in South Africa. He notes an accumulation of cobble- to boulder-sized gravels behind bedrock highs, with foresets interfingering with back-barrier sand and clay. The last is no different to that observed within the study area at G29.

The degree and frequency of washover is dependent on, *inter alia*, antecedent beach face geometry (Carter *et al.*, 1989) and an absence of tidal passes or inlets (Carter & Orford, 1984). In many respects, the former is paramount in directing the sediment-charged swash flows into the back-barrier via breach points along the beach ridge (Carter & Orford, 1980). The breaching, amongst others, has been ascribed as a function of local wave focusing; a process possibly controlled by beach cusps that act as templates for directing and amplifying swash run-up (Orford *et al.*, 1991). Once the beach ridge has been breached, the washover sediments enter the back-barrier setting as a fan-shaped body to generate foresets with radial orientations and, more significantly, there is no return of this material to the foreshore setting. Consequently, there will be an absence of vigorous fan reworking to produce well-sorted fabrics. The only reworking that would take place is along the distal fringes of the washover fan where the deposition may be sub-aqueous (Carter & Orford, 1981). Here these marginal sediments, mainly fine-grained, are reworked by less-energetic, wind-generated waves in a back-barrier setting.

Laminated clay and silt deposits

Lithologically, these finer sediments are no different to those of Sub-facies A4 and thus typify a back-barrier setting. However, the limited areal extent and thickness that typifies Sub-facies C2 suggests a setting different to the estuarine-lagoon of Sub-facies A4. The clay and silt of Sub-facies C2 was likely to have been deposited in water that was significantly shallower, possibly a pond-like feature, considering that sediment thickness is less than one metre. The small, interfingering deltaic lobes of the washover fans also reflect the shallow nature of the pond-like setting.

A small enclosed body of water behind the present sand barrier beach at the Orange River mouth in Namibia (Figure 3.31) is a modern analogue that best illustrates this depositional setting. Here, a small pond of water extends north to south for about 400 m and is some 70 m wide. It is wedged between the modern sand barrier beach and an older Holocene sand barrier sequence. Water depth is less than one metre and there is no direct exchange with coastal waters; the pond is fed by estuarine-lagoon water entering through a restricted opening and during washover events.

Red clays are developed along the fringes of the lagoon and in places are partly vegetated. Tidal exchange ensures that the area is flooded during high tide periods, whilst on

the low tides the clay banks are exposed and their surfaces become desiccated. Apart from roots, a lack of animal biogenic activity is notable in the red clay; a feature which is also evident in the Sub-facies C2 silt and clay sediments. Washover incursions into the narrow enclosure not only agitate the sediment to induce re-suspension, but also introduce sand into the enclosure. These are moulded into ripple bedforms during tidal variances and wind influence. It is therefore envisaged that the depositional setting of Sub-facies C2 clay and silt was a shallow pond-like body between an inactive and evolving gravel beach barrier having little or no direct interaction with coastal waters.

3.5.5 Summary and depositional setting of Facies C

The spatial relationship between the different sub-facies together with their internal structures, demonstrate a foreshore and backshore (back-barrier) origin of a barrier beach (see Figure 3.32). The salient features of Facies C are summarised in Figure 3.33.

Using the present-day gravel beaches at Terrace Bay as an analogue, it is apparent that these modern beaches have a distinct profile characterised by a composite foreshore slope. This slope extends from a prominent beach ridge seaward to the low tide mark and is made up of a steep upper part, followed by a middle and gently-inclined lower part. The beach ridge (modern equivalent of Sub-facies C1 coarse disc- and blade-rich gravel sheet) marks the most landward margin and highest point on the beach where it forms a topographic ridge. This the most upper and stable part of the foreshore sequence; its preservation is dictated by the limit of extreme swash run-up induced by storm conditions, which is in turn dependent on the magnitude of the storms. Consequently, growth at the beach ridge is at its greatest during storm periods as noted by Everts *et al.* (2002) and Orford (1977) and is therefore a semi-permanent feature.

Immediately seaward of the beach ridge, the seaward-dipping slope is the beach face (modern equivalent of Sub-facies C1 cross-stratified gravel) and represents the most dynamic part of the foreshore where a high degree of sorting takes place through a process of size-related clast acceptance or rejection on a steep slope (see also Isla, 1993; Orford *et al.*, 2002, Buscombe & Masselink, 2006). This is the area where the sediment is frequently re-mobilised under normal and storm conditions, but the magnitude of change is dependent on tidal variations, as well as wind and wave conditions (Pye, 2001). This part of the foreshore is characterised by the predominance of constructional features such as swash berms and cusps

(Sub-facies C2), which are bedforms typical of reflective beaches (Short, 1979; Carter & Orford, 1984; Masselink & Pattiaratchi, 1998; McKay & Terich, 1992, pg. 824; Carter, 2002; Buscombe & Masselink, 2006).

It has been shown that steeper slopes increase wave reflection, which increases the potential for cusp development (Ilman & Guza, 1982; Sherman, 1991; Sherman *et al.*, 1993). Here, incident wave energy will be reflected from the shoreline and the nearshore will become excited by second- or third-order waves in the form of standing edge waves. These propagate normal to the shoreline and create periodic flow patterns responsible for cusp formation (Ilman & Guza, 1982; Sherman, 1991; Sherman *et al.*, 1993). Although this is the general view, others for example Masselink & Pattiaratchi (1998), Coco *et al.* (2003) and Austin & Masselink (2006) advocate the self-organisation model for the development of these rhythmic features where standing edge waves are not necessarily a prerequisite. They argue that beach cusps are initiated by positive feedback between swash flows and morphology; the developing beach morphology affects the swash flow and the swash flow feeds back on sediment transport and change in morphology.

The steep gradient of the beach face is maintained due to the high permeability of the gravel; a function of particle size (increasing slopes are related to increasing grain size) and sorting (Masselink & Li, 2001; Jennings & Shulmeister, 2002). This governs swash infiltration or hydraulic conductivity and consequently the beach face gradient increases with increasing infiltration, which in turn, reduces the influence of backwash to return sediment to the littoral. The beach face, therefore, resists erosion. However, the stability of the beach face is greatly reduced if the gravel fabric is charged with sand, which decreases sediment permeability (Everts *et al.*, 2002).

The most seaward margin of the modern Terrace Bay foreshore is an accumulation of the most mobile clasts. This is the relatively stable outer frame (modern equivalent of Sub-facies C1 coarse sphere-rich gravel sheet), which consists predominantly of spherical clasts. Here they remain stationary for long periods allowing their pore space to be filled with smaller clasts derived from the beach face or offshore, but sediment build up is short lived due to the consistent winnowing by the more energetic swash and backwash events leading to the development of an armouring lag.

In contrast to the foreshore deposits, the backshore deposits of Sub-facies C2 represent deposition landward of the beach ridge. The washover deposits are responsible for the transfer of gravel from the beach face landward into a back-barrier setting during storms that cause the beach ridge to fail under extreme wave conditions. Thus, similar to the beach ridge, washovers are storm deposits and represent the extension of overtopping. Repeated gravel accumulation at the beach ridge due to overtopping, followed by subsequent failures of the ridge, allow the washover fans to build up and extend into the back-barrier where the distal parts of the fans interfinger with clay and silt. Penecontemporaneous deformation features seen in section also serve as evidence for loading of washover gravel onto unconsolidated back-barrier sediments that are hydroplastic, as evident from the continuous distortion of clay laminae exhibiting no fracturing. In addition to the washover loading, soft sediment deformation is also notable in the foreshore gravels where a barrier beach sequence has accumulated onto pre-existing back-barrier sediments.

3.5.6 Age and correlation

Considering the high energy conditions during the deposition of Facies C, particularly the gravel-dominated foreshore environment, only shell fragments of *Donax rogersi* have been recovered from the Sub-facies C1 cross-stratified gravels. As shown in Section 2.2.3, this 30 m Package zone fossil has been tentatively assigned a Late Pliocene/ Early Pleistocene age (Pether, 1986). This would suggest that there was no significant hiatus in the deposition of Facies B and C as discussed in Section 4.4. In fact, their deposition may be penecontemporaneous (see also Figure 3.17 for age relationship with other facies)

3.6 FACIES D

3.6.1 General

Unlike the other facies consisting mainly of gravel, Facies D is predominantly a sand sequence with minor gravel interbeds. These sediments are confined to the most western (seaward) part of the study area and grade laterally eastward (landward) into the sediments of Facies C (Figure 3.34A, Appendix D(4)). This gradual transition was not always discernable due to the collapse of trench exposures, but its lateral relationship with Facies C sediments was also recorded in past geological face logs during the earlier bulk sampling campaigns.

The G39.5 mine face, orientated roughly perpendicular (north-east to south-west) to the present coastline, was used as a key section from which the sedimentological characteristics

of Facies D were established. Here, the exposure clearly exhibits a vertically stacked marine package.

3.6.2 Distribution and thickness

Facies D extends along strike (south-east to north-west) for some 4.5 km and down-dip (north-east to south-west) over a distance of 1.2 km. On the basis of current exposures and past geological logs, the sequence was approximately 8 m at its thickest between sample trenches G45 and G19 (a distance of approximately 2.5 km). However, south of trench G19 to G4, Facies D thins rapidly to approximately one metre or less over this 2 km distance (Figure 3.34).

3.6.3 Lithology and structure

At the G39.5 key section, the vertically stacked marine package comprises three distinct sub-facies (Figure 3.35). These are:

- 1) Basal tabular cross-stratified sands of Sub-facies D1;
- 2) Trough cross-stratified sands with minor gravel lenses of Sub-facies D2; and
- 3) Upper, highly bioturbated, tabular cross-stratified sands with interbedded gravel sheets of Sub-facies D3.

Apart from surface pedogenic calcrete that cements the sediments at surface and incipient calcretisation of some gravel, the sediments of Facies D are largely unconsolidated. More significantly, the entire spectrum of the Facies D sediment types observed at the G39.5 section and elsewhere is devoid of silt and mud, as layers or a matrix fill.

Sub-facies D1: Tabular cross-stratified sand

Stratum attributes

These sediments have tabular cross-lamination in sets no thicker than 0.3 m. Laminations are defined by an abundance of mica flakes. Set boundaries are marked by curved, undulating erosional contacts that scour the underlying sediments. These surfaces, although erosive, have a gently inclined geometry. The thickness of Sub-facies D1 shows a slight thickening (laterally) towards the south-west (seaward), but this is not significant and strata thickness remains relatively thin throughout the section, seldom reaching one metre.

Textural attributes

This sub-facies, consists wholly of unconsolidated fine- to medium-grained sand and immediately overlies the boulder bed of Facies B. A characteristic feature of the sand is the distinct yellow-brown colour and an abundance of mica flakes, which is macroscopically visible in outcrop. The mica flakes, reaching approximately 0.4 cm in size, are concentrated along laminations. In a similar fashion, fine pebbles comprising mostly zeolite clasts (0.9 cm in length) with a lesser component of quartz-rich clasts (2 cm in length) are, in places, aligned along low-angle foresets with their longest axes (a-axis) parallel with the forest laminations, and also fill shallow depressions that scour underlying cross-sets (Figure 3.36A). Within scours, the pebbles are clast-supported and closely packed, but clast orientation is lacking. The abundance of these pebbly foresets is greatest towards the lower contact boundaries and decrease upward away from boundary surfaces.

Structural attributes

The cross-lamination in Sub-facies D1 is characterised by inclined foresets at low angles that are tangential at the base and dip at 5° - 12° with an average direction towards the north-east (Figure 3.36B; Table 3.7). Scours are shallow, up to 3 cm deep and deepen in the direction of foreset dip. Scour lengths are approximately 10-15 cm (Figure 3.36A).

Table 3.7: Palaeo-current data of Sub-facies D1

n	Xv	R	L(%)	Structure	Sediment
38	44	34.22	90	Tabular cross-lamination	Fine sand

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

No fossils have been recovered from the Sub-facies D1 sediments, but a moderate degree of bioturbation is present, occurring throughout the vertical section.

Sub-facies D2: Trough cross-stratified sand with minor gravel lenses*Stratum attributes*

Sub-facies D2 thins laterally seaward towards the south-west from 1-3 m over a distance of 150 m and truncate the underlying sediments of Sub-facies D1. The truncation surface is distinctly erosive with scouring in places. At some localities, the scour depressions

are filled with small pebbles which, in turn, grade upward into either coarse sand or granules. Granule strata only make an appearance towards the most seaward (south-western) end of the section where they are approximately 0.5 m thick (Figure 3.35). The transition from granule into sand or vice versa is gradational. Foreset laminae in both sand and granule are defined by differences in alternating sediment size. In contrast to these sediments, isolated gravel lenses occur as 'floating' bodies that have erosive lower contacts, whilst their upper surfaces are undulating and have sharp contacts. These lenses are only confined to the central portion of the section and thus have limited distribution (Figure 3.35). Lengths range from 2- 2.5 m with varying thicknesses of 0.2-0.4 m. In places, these lensoid gravel bodies show a landward thickening towards the north-east and thus have crude wedge-shaped geometries.

Textural attributes

The sediment colour differs to that of Sub-facies D1 in that it is grey-brown in colour with coarse to very coarse sand – averaging in the coarse range – and granule dominating. Minor gravel is present, but is confined to lensoid-shaped bodies. Here the gravel is poorly sorted and clast-supported with a matrix fill of granule and coarse sand. Clasts are pebble size (maximum size is 3 cm), rounded to well-rounded and predominantly spherical in shape, exhibiting no specific orientation with a hint of normal grading. Generally, these gravel lenses are moderately cemented by calcium carbonate. Similar to these gravels, the scour filling gravels are equally fine and pebble-sized (maximum size recorded is 3 cm), but are matrix-supported with a sand matrix fill. Clast orientation and grading is absent.

Structural attributes

The coarse to very coarse sand is trough cross-stratified with foresets inclined at 10°-28°. In section the troughs are near symmetrical, approximately 1-1.2 m in length and 0.2 m deep, with foreset laminae tangential to the base of the trough. Foresets have variable dip directions, but are largely confined to the north-west and north-north-east quadrants, with their average towards the north-north-west (Figure 3.37C, Table 3.8). The gravel-filled scours at the contact with and eroding Sub-facies D1 are shallow with depths of 7 cm and their lengths are approximately 45 cm (Figure 3.37B).

The granule beds also exhibit trough cross-stratification with foresets inclined 12°-30°, dipping predominantly in a north-north-west direction (Table 3.8; Figure 3.37D). Similar to those found in the coarse sand, the troughs measure 0.7-1.0 m long and roughly 0.2 m deep,

floored with fine pebbles that can be traced upward along the foreset laminae. In contrast to the sand and granule sediments, a hint of cross-stratification is noticeable in the lensoid gravel beds and although only three palaeo-current readings were measured from an isolated exposure, foresets dip at 10° - 20° towards the north-east (Figure 3.38 A to C; Table 3.8).

Table 3.8: Palaeo-current data of Sub-facies D2

n	Xv	R	L(%)	Structure	Sediment
18	349	16.52	92	Trough cross-stratification	Coarse sand
6	340	5.6	93	Trough cross-stratification	Granule
3	26	2.91	97	Tabular cross-stratification	Gravel

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

Fossils or biogenic structures are absent.

Sub-facies D3: Cross-stratified sand with interbedded gravel sheets

Comprising couplets of grey-brown coloured, cross-stratified sand interbedded with sub-horizontal lenticular gravel strata, Sub-facies D3 represents the uppermost part of the Facies D sequence (Figure 3.35). The gravel strata alternate vertically with the sand units, which they truncate with sharp, erosive contacts. This relationship, coupled with the abundance of gravel differentiates Sub-facies D3 from the other two sub-facies. In this vertical alternation, a change in the sediment character is notably different from the base to the upper part of the sediment pile.

Stratum attributes

Gravel strata with interbedded sand, which thin slightly seaward to the south-west from 0.8-1 m, form the base of Sub-facies D3 and truncate the underlying sediments of Sub-facies D2 with sharp, erosive contacts. The interbedding sand at the most north-eastern (landward) part of the exposure is approximately 0.45 m thick, whilst at the south-western part (seaward), thins to 0.20 m. In contrast, the gravel strata thicken in the same direction.

The uppermost portion of Sub-facies D3 is characterised by well-defined gravel sheet couplets interbedded with sand (Figure 3.35). These gravel sheets dip gently seaward and are developed uninterrupted over a distance of 200 m. Although mining has removed much of the

exposure, the gravels appear to grade landward (north-east) into the barrier beach deposits of Facies C. Some of the gravel sheets thin from 1.5 m at the north-eastern (landward) end to approximately 0.2 m at the south-western (seaward end). In addition, this attenuation of the strata thickness can also be seen in a north-westerly direction (parallel to present coastline), thinning from some 1.5 m in the south to 0.3 m in the north. Thus, the gravel sheets are seen as series of westerly and northerly thinning wedges. Their lower boundary surfaces truncate the underlying interbedding sand, whilst their upper contacts are sharp; defined by a change in sediment size and not by an erosion surface.

The entire Sub-facies D3 sequence thickens towards the south-west (seaward) from approximately 3-4 m.

Textural attributes

The basal portion of the sequence is dominated by coarse to very coarse sand, whilst the upper most section is characterised by medium to coarse sand. In contrast, the gravels in both the basal and upper part of the sequence have similar textures. Here, gravel size ranges from granule to cobble (largest recorded is 20 cm) and show a decrease in average clast size $((a+b+c)/3)$, which is more obvious in the upper gravel couplets, from 12 cm in the north-east (landward) to 5 cm in the south-western (seaward) part of the exposure. Note, however, that the landward measurements do not represent the most north-eastern part of the sub-facies where it grades into Facies C. Collapse of the trench face and mining of sections has made it impossible to gain an appreciation of the average gravel size at the most north-eastern end.

The gravels in both the basal and upper parts of the exposure are rounded to well-rounded, poorly sorted and matrix-supported with coarse sand to granule forming the matrix fill. There is no preferential shape sorting in any direction; a mix of clast shapes occurs throughout the gravel strata over a distance of some 130 m (see Figure 3.39E for clast shapes). In places, imbrication is noticeable in disc- and blade-shaped clasts, but grading in the sediments is lacking.

Structural attributes

Both the gravel and coarse to very coarse sand in the basal part of the exposure are characterised by trough cross-stratification (Figure 3.39). The former rarely exhibits crude trough cross-stratification with foresets dipping at 16° - 25° towards the west-south-west and north-west, whilst trough cross-stratification is well-defined in the sand lenses with foresets

dipping at 10° - 25° towards the west-south-west and north-west (Figure 3.39D, Table 3.9), a direction similar to that of the gravel. With lengths of 0.50 m and heights of 0.15 m, the troughs are smaller than those observed in the underlying sand deposits of Sub-facies D2. In places, fine pebbles and granules line the base of the troughs.

These trough cross-stratified sediments are replaced upwards in the section by planar cross-stratification which typifies the upper portion of the section. Although highly bioturbated, crude foresets are evident with a dip orientation towards the north-west at 15° - 20° (Figure 3.39C, Table 3.9). Stratification is rare in the gravel sheet couplets that occupy the upper part of the G39.5 section, but in some places, a hint of cross-stratification can be recognised with the foresets dipping at 18° - 20° in a south-west direction (Table 3.9). In addition, imbricated clasts with their long axes dipping landward at angles of 30° , towards the north-east (average direction), suggest a palaeo-flow towards the south-west (Table 3.9).

Table 3.9: Palaeo-current data of Sub-facies D3

n	Xv	R	L(%)	Structure	Sediment
8	265	7.08	89	Trough cross-stratification	Gravel (basal section)
14	306	10.85	78	Trough cross-stratification	Coarse sand (basal section)
8	314	7.94	99	Planar cross-stratification	Coarse sand (upper section)
2	233	1.93	97	Planar cross-stratification	Gravel (upper section)
10	241	9.49	95	Flow direction from clast imbrication	Gravel (upper section)

n = number of readings, Xv = vector mean (degrees), R = length of resultant vector, L(%) = vector magnitude

Palaeontological attributes

Only the sand deposits of the upper part of the exposure have yielded fragments of molluscan shell. These deposits are also highly bioturbated and despite the preservation of crude cross-stratification, much of the sedimentary structures have been obliterated.

3.6.4 Interpretation of Facies D

Many of the features of Facies D observed in the G39.5 trench section are consistent with shoreface deposition within a wave-dominated setting and are similar to those described by Vos & Hobday (1977), Dupré (1984), Leithold & Bourgeois (1984), DeCelles (1987), Massari & Parea (1988), Simpson & Eriksson (1990), Yagishita (1994) and Hartley & Jolley (1999).

Sub-facies D1

The sand-dominated deposits of Sub-facies D1, which are interpreted as shoreface sediments, similar to those described by Vos & Hobday (1977, their facies 1), Clifton (1981), Dupré (1984), Bose & Das (1986, their facies B) and DeCelles (1987) reflect two products of transportation and deposition; one for a medium-grained sand forming the bulk of the sub-facies and the other, low-density granules to small pebbles that are concentrated along foreset laminae or lining scoured surfaces.

The morphology of the cross-stratified beds, notably the cross-set thickness (>0.1 m) and geometry, indicate that the cross-stratification was likely to have been produced by the migration of 2-D dunes (Lindholm, 1987; Collinson & Thomson, 1989; Nichols, 1999) that were shoreward driven as evidenced from the palaeo-current measurements. The foreset-aligned pebbles would reflect higher velocity flow regimes, which is in agreement with Dupré's (1984) interpretation for lower shoreface sediments that contain scattered pebbles, but lack ripple-drift stratification. The latter is distinctly absent in Sub-facies D1.

It is envisaged that scouring of the sediment and movement of small pebbles would have occurred as bottom energy conditions intensified during storm events. Under such conditions, the bottom currents are initially non-depositional – more likely to be erosional – and deposition would have only commenced during a time of diminishing velocity (Myrow & Southard, 1991). Consequently, progressive waning conditions generate winnowed pebble-lined scours, which are subsequently filled with finer sediment. The suspended sediment that was agitated by the passage of storm-induced waves, would have settled out with the mica particles accumulating on the rippled surface.

Bose & Das (1986) have also reported foreset aligned pebbles in fine- to medium-grained cross-stratified sand (their facies B) from the Cretaceous Nimar Formation in India. They conclude that the sand and pebbles did not move simultaneously, but were entrained under separate hydrodynamic conditions. Accordingly, the pebbles were moved under higher energy flows during storms, whilst the sand was agitated into suspension and removed. As flow intensity declined, pebble movement halted, but sand deposition and ripple migration continued. The resultant is a gradational change from gravelly sand (pebble-aligned foresets) into sand only, which is characteristic of Sub-facies D1. Therefore, the energy regime during Sub-facies D1 times was decelerating and each cross-set separated by an erosional contact

displaying a progressive upward change from gravelly to sand cross-strata is a product of numerous spasmodic high-energy pulses as described by Bose & Das (1986).

Medium- to coarse-grained dunes, which are possible modern equivalents of Sub-facies D1, have been recorded from the modern inner shelf off the Orange River at depths of 15-30 m below sea-level (de Decker, 1988). However, subaqueous dunes have been observed at greater depths during reconnaissance dives with the *JAGO* mini-submersible. These were observed at depths up to 60 m off the coast of Lüderitz, Namibia, situated approximately 300 km north of the present Orange River mouth and 5 km west of the present coastline (J. Ward, pers. comm., 1999; Figure 3.40; Halifax dive site, 1999). By aligning the mini-submersible parallel to the ripple crests, an appreciation of the strike was obtained using the mini-submersible's compass. Corrected readings show that the ripple crests strike sub-parallel with the present coastline and possibly migrate shoreward towards the north-east to north-north-east, a direction similar to the palaeo-current measurements of Sub-facies D1. This is also in agreement with the side-scan sonar image off that area depicted in Figure 3.40C.

De Decker (1988) has shown that present-day average wave conditions where the median (50% exceedance) significant wave height for winter is 1.75 m and maximum wave period is 12.5 seconds, which is skewed towards the higher energy spectrum, can transport very coarse sand (0.15 cm) and gravel (1.5 cm) at water depths of 30 m and 15 m, respectively. By inference, subaqueous dunes in medium-grained sand can be expected to form at depths deeper than 30 m during such wave conditions.

The Airy or linear-wave theory has been used by de Decker (1988) to establish wave conditions that are capable to transport sediment at depths of 15 m, 20 m and 30 m offshore the study area. The linear-wave theory is seen to treat waves as sinusoidal forms and regarded as a simple application to provide acceptable approximations of measured orbital diameters and near-bottom maximum velocities for real waves in shallow water (Le Mehaute *et al.*, 1969; in Clifton & Dingler, 1984). Following on this, wave conditions for depths of 40 m, 50 m and 60 m were calculated using the horizontal orbital velocity (U_a) equation to gain an appreciation of what sediment size would be moved at these depths. The horizontal orbital velocity equation is expressed as follows:

$$U_d = \frac{\pi H}{T \sinh \left(\frac{2\pi d}{L} \right)} \quad (1)$$

Where H is the wave height, T is the wave period (in seconds), d is the water depth and L is the wave length. The wave length (L) can be determined from the following equation:

$$L = \frac{gT^2}{2\pi} \tan H \frac{2\pi d}{L} \quad (2)$$

Where g is a gravity constant of 9.8 m/s² and can be simplified to:

$$L = \frac{gT^2}{2\pi} \quad \text{for deep to intermediate water} \quad (3)$$

$$L = T\sqrt{gd} \quad \text{and for shallow water} \quad (4)$$

Using the median (i.e. 50% exceedance) significant wave height (H) of 1.75 m for winter which, as mentioned earlier, has the highest wave period (T) of 12.5 seconds, to represent average wave conditions that are more energetic during winter, the wave orbital velocities for the various depths are given in Table 3.10.

Table 3.10: Horizontal orbital velocities (U_d) at depths greater than 30 m during normal wave conditions

H (m)	T (secs)	U_d (m/s) 30 m depth*	U_d (m/s) 40 m depth	U_d (m/s) 50 m depth	U_d (m/s) 60 m depth
1.75	12.5	0.52	0.36	0.26	0.20

Note that the average wave conditions (50% exceedance) for winter includes T values between 12.5 seconds and 15 seconds

(de Decker, 1987). * From de Decker (1987).

Komar & Miller (1975) established various wave parameters required to transport quartz-density sand of variable diameter and produced a set of curves from which orbital velocity values can be determined for a given grain size. Considering the U_d values shown in

Table 3.10, the grain diameter is determined from the curves assuming that the sediments occurring at such depths are quartz-rich (Figure 3.41). As previously noted, de Decker (1988) demonstrated that very coarse sand can be transported at depths of 30 m during average wave conditions. The assumed grain sizes that will be transported at greater depths, notably 40 m, 50 m and 60 m are 0.85 mm (coarse-grained), 0.35 mm (medium-grained) and 0.17 mm (fine-grained), respectively. This would suggest that medium-grained sediment can be engaged under average conditions to a depth of 50 m, whilst fine-grained sediment corresponds to a depth of 60 m. Noteworthy is that present wave base in the Atlantic Ocean off the study area is assumed to be in the region of 40 m with mud and fine silt accumulating beyond this depth (de Decker, 1987; Smith, 2006). Wave base is thus deeper than the assumed average depth of 20 m for most coastal systems (see Section 1.4.3).

The depth at which fine sand can be transported as per Table 3.10 coincides with modern subaqueous dunes observed during *JAGO* dive surveys at depths of 60 m (Jacob, 1999). The geometry of these bedforms was estimated using the submersible where a laser-mounted apparatus illuminated points that were exactly one metre apart. Ripple heights were difficult to determine, whilst crest spacing was better established and recorded to be approximately 0.5-1 m apart (*JAGO* dive nr. 592; Jacob, 1999). It was also observed that the crests are symmetrical. Using the diagram of Komar & Miller (1974; in Clifton, 1976) for grain movement initiation, the resultant plot for fine-grained sand demonstrates that present average wave conditions can initiate a ripple bed at a 60 m depth for more than 50% of the time (Figure 3.42). Note, however, that the average wave periods for a 50% exceedance includes a range from 12-5 seconds and thus average conditions are skewed towards the higher wave periods that are associated with higher energy levels. This implies that ripple formation and possibly migration occurs when the wave energy is higher and ripples remain static when conditions are calmer. This is borne out by the ripple crest symmetry and the fact that they are stationary as recorded during *JAGO* dive nr. 592. In addition to this, mud drapes within ripple troughs were documented (*JAGO* dive nr. 592; Jacob, 1999) and therefore add credence to the view that ripples are only formed during higher-energy levels, whilst a shift towards calmer conditions allowed the mud to settle out.

The depositional theme of Sub-facies D1, as interpreted from the sedimentary record, approximates that of the modern subaqueous dunes at 60 m depths where a combination of higher and lower energy events occurred. The resultant plot for medium-grained sand in

Komar & Miller's (1974; in Clifton, 1976) diagram for grain movement initiation as illustrated in Figure 3.43, also confirms that the Sub-facies D1 dunes can be formed (more than 50% of the time) at depths of 50 m. In addition, the presence of detrital mica supports calmer conditions, which would have settled out from suspension in accordance to energy levels. However, Sub-facies D1 is devoid of silt and mud suggesting that although conditions were favourable for mica deposition, they were not for mud and clay.

Samples taken by de Decker (1987) from the modern sea-bed offshore and south of the study area up to depths of 20 m, which is within the breaker zone, showed a similar relationship in that a high percentage of mica was present, but the percentage of mud was significantly less. A similar trend was also documented by Dias *et al.* (1984) from the wave-dominated coast of northern Portugal where they noted a high abundance of mica in nearshore fine to coarse-grained sand. Obviously, the fact that mica occurs in Sub-facies D1 where clay and silt is lacking, is a reflection of contrasting hydraulic equivalence. Due to its flaky appearance, which will affect its settling characteristics, sand-sized mica has consequently assumed to be hydraulic equivalent to clay and silt (Doyle *et al.*, 1983). However, based on results derived from settling experiments, Doyle *et al.* (1983) were able to demonstrate that contrary to previous views, mica in the coarse-silt to fine-sand size is not in hydraulic equivalence with mud, but is instead hydraulic equivalent to silt and fine quartz spheres. Note that their experiments did not include mica flakes that were granule to pebble-sized. Therefore, by inference and the fact that mica flakes within the study area is considerably coarser (up to small pebble size), it is reasonable to conclude that energy conditions were suitable for settling out mica, but were too energetic for mud and silt deposition.

In view of the foregoing discussions, it is envisaged that the sediments of Sub-facies D1 is a preserved record of storm-induced sedimentation in a palaeo-depositional setting comparable to that of today at depths associated with a lower shoreface/inner shelf environment that is deeper than 30 m, but possibly shallower than 50 m (Figure 3.44). More importantly, the abundance of mica flakes within the sediment indicates that Sub-facies D1 was positioned not too far from the palaeo-Orange River outfall. In the present day offshore, de Decker (1987) demonstrated that the percentage of mica in sediments is highest at the Orange River outfall/mouth, with a steady decrease southwards along the Namaqualand Coast of South Africa. This relationship of mica abundance and river mouth proximity was also noted by Dias *et al.* (1984) from shelf sediments in northern Portugal. They noted that the

coarser the mica fraction, the more proximal the setting is to a river mouth. As mentioned before in Section 3.6.3, very coarse mica, up to small pebble size is a characteristic feature of Sub-facies D1 and thus serves as an indication of the close proximity to the palaeo-river mouth.

Sub-facies D2

The coarser Sub-facies D2 sequence is interpreted as middle shoreface sediments where the abundance of trough cross-stratification suggests deposition by 3-D dunes within a high-energy environment driven by unidirectional currents (Leithold & Bourgeois, 1984; DeCelles, 1987; Pether, 1994; Figure 3.44). It is envisaged that they were medium-sized bedforms based on their geometry which correspond to that recorded by Collins & Thompson (1986, pg. 78).

The palaeo-current measurements indicate that the ripple migration was obliquely shoreward, driven by wave currents as opposed to orbital flows under which Sub-facies D1 was deposited. Massari & Parea (1988) have shown that the migration of 3-D dunes can be achieved through powerful longshore flows, possibly active under storm conditions or during the waning stages to generate longshore-directed cosets of large-scale trough cross-stratification. Intuitively, it seems obvious that such sedimentary structures are consistent with deposition in longshore troughs (Dupré 1984; Leithold & Bourgeois, 1984; DeCelles, 1987; Els & Mayer, 1992), but the palaeo-current direction of Sub-facies D2 (oblique to shoreline) is at odds with such an interpretation as coast-parallel palaeo-directions would be expected, assuming that the coastal configuration and wave climate was similar to that of today.

Pether (1994) also pointed out from his interpretation of sections along the Namaqualand coast in South Africa that the large composite bedforms such as bars, have migrated oblique to the shoreline under oblique wave approach, generating an abundance of trough cross-stratification due to the shifting of bars with changing wave conditions. The coarse-grained sediments of Sub-facies D2 are thus likely to represent a similar depositional style where the sediments were emplaced into the upper shoreface and fashioned into bars. These migrated obliquely onshore under normal wave conditions, corresponding to depths where very-coarse sand is transported at approximately 30 m and shallower, based on de Decker's (1988) study of the present-day inner shelf. Increasing flow energy is evident from

pebble-filled scour features at the base of cross-sets and the presence of cross-stratified granules; a testament of storm driven events. Similar to Sub-facies D1, the transport of granules and fine pebbles with a concomitant scouring of underlying sediments is therefore storm-related, whilst the progressive winnowing of pebble lags at the base of scours and attendant deposition of coarse to very coarse grained ripples takes place during storm decay. Consequently, the deposits reflect similar pulses of higher energy events followed by waning periods. With scours deeper and larger than those recorded in Sub-facies D1, energy levels were unsurprisingly more intense throughout the deposition of Sub-facies 2, given the shallower depths.

Not only do the sand and granule deposits reflect storm deposition, but the lensoid gravel deposits also indicate such perturbations. Their limited extent as lensoid bodies and isolated distribution are convincing indicators of storm emplacement, but at much higher magnitudes. This is borne out by the size of the gravel clasts and expected depths at which they can be moved. In the present offshore, pebbles (1 cm in diameter) and cobbles (10 cm in diameter) can be transported under storm conditions in water depths of 30 m and 15 m, respectively, where wave heights (H) of 3.25 m and wave periods (T) of 14.8 seconds occur 50% of the time (de Decker, 1988).

From the palaeo-current measurements, although limited, it is proposed that the gravels were probably transported shoreward immediately after a storm peak (Clifton, 1981; Cheel & Leckie, 1992), whilst the sand was agitated into suspension by the high energy event. As conditions returned to normal, depth and velocity conditions became suitable to mould the coarse-grained sand into migrating subaqueous dunes, but were not apt to drive the gravel fraction shoreward. This produced winnowed 'post-storm' gravel lags (DeCelles, 1987) that can only be set in motion during the next storm event. The above theme of deposition may account for the normal grading seen in the gravel lenses as result of diminishing energy levels and the wedge-shaped geometry of the gravel lenses that thicken in a landward direction. The last is possibly an expression of gravel build up into a crude ripple during migration. The spatial segregation of the gravel lenses seen in outcrop would thus have an irregular lensoid appearance when viewed in plan.

This style of deposition for Sub-facies D2 is also inferred from various literature where similar features in the rock record have been documented. For example, Clifton's (1981)

facies C in the Miocene Branch Canyon Sandstone, California, U.S.A., comprise lenses of coarse-grained sand within a sequence of fine-grained sandstone. Notwithstanding the different wave energy regimes, the architecture is similar to Sub-facies D2 where coarse-grained sediments are interbedded with, and truncate underlying, finer sand. A similar relationship was also noted by Bailey *et al.* (1990) for his shallow marine facies (Zandfontein Quartzite Formation) in the Archaean Witwatersrand Supergroup, South Africa. In addition to these, comparable descriptions of the Sub-facies D2 gravel lenses have also been noted from ancient shoreface sediments by Leithold & Bourgeois (1984, their unit A, Miocene age), Leckie (1988, Cretaceous Gates and Cardium Formations) and Cheel & Leckie (1992, Cretaceous Chungo Member).

Apart from the ancient rock record, modern equivalents of the Sub-facies D2 gravel lenses on present-day continental shelf and shoreface settings are not uncommon. These have been recorded from the inner shelf of Nova Scotia at depths from 15-65 m (Forbes & Boyd, 1987) and along the Namibian coast where migrating pebble gravel ‘wave trains’ have been observed at depths of 15-20 m by divers and are characterised by sinuous crests that are aligned sub-parallel with the present coastline (W. Macdonald, pers. comm., 2002).

It is difficult to predict the palaeo-depth of Sub-facies D2 to a reasonable degree of accuracy with the current dataset, but although speculative, depths up to 30 m could approximate the depositional setting based on the arguments above. In view of this and assuming depths of 20-30 m, it would imply that the sea-bed was possibly most of the time in motion and would preclude the deposition of clay, silt and mica which are absent in Sub-facies D2.

Sub-facies D3

The depositional theme of Facies D ends with the accumulation of Sub-facies D3 sediments, which are consistent with a proximal upper shoreface setting (Figure 3.44) reflecting storm and post-storm recovery events (Leithold & Bourgeois, 1984; Massari & Parea, 1988). The cross-stratification of both the gravel and sand of Sub-facies D3, indicate two predominant transport directions; that is an offshore and alongshore component, respectively. The former attests to offshore transport by storm-generated rip currents, whilst the latter indicates reworking by longshore drift as conditions normalised.

The alternating gravel and interbedded sand arrangement therefore suggests that each gravel/sand couplet may represent the record of a single storm event and subsequent recovery stage (Massari & Parea, 1988). This 'multi-storied' arrangement of strata has also been documented from other deposit types by Vos & Hobday (1977), notably their facies 2 in Ecca Group sediments of Palaeozoic age within the Bothaville area, South Africa, and they afforded a similar interpretation.

The cross-stratification of the interbedded coarse sand sequences of Sub-facies D3 would have been generated by subaqueous dunes migrating alongshore under a northward-directed littoral drift after the passage of a storm. If the modern day longshore current off the study area is considered, current velocities are variable with extremes as much as 2 m/s, but more typically it averages between 0.3 m/s and 0.5 m/s (Swart, 1984). More significantly, its magnitude varies across the breaker zone from zero at the shoreline to a maximum that is approximately two-thirds of the way towards the breaker zone, after which it drops to zero at some distance after the breaker zone (Swart, 1984). Given that the seaward extent of the breaker zone lies close to a depth of 15 m – evidently coincident with subaqueous dunes, as reported by de Decker (1987) – the depth where the magnitude of longshore drift is highest can be speculated to approximate ten metres; obviously depending on wave conditions. It thus follows that these zones of different conditions will be reflected in the sediments that accumulate there. Higher flow conditions are recorded in the trough cross-stratified sands seen at the base of Sub-facies D3, whilst the sedimentary features in the upper sands reflect lower velocities to allow biogenic activity. This also suggests that deposition of the upper sands was within an area away from the higher energy zone where basal trough cross-stratified sands accumulated, but not necessarily in calmer conditions that are unfavourable for bedform migration. This inference is based on the fact that biogenic activity can occur in high energy environments. Droser & Bottjer (1989) documented bioturbation in high-energy nearshore deposits (beach, littoral and shoreface) and noted that sedimentary structures are not always completely destroyed by the biogenic activity. Clifton (1988, his table 1, pg. 512) also documents the presence of bioturbation in cross-stratified deposits of high energy environments, these being nearshore surf zone and zone of longshore and rip currents.

In contrast to the sand units, the gravel sheets represent exceptionally strong currents that were capable of entraining large gravel clasts (up to cobble size) into the upper parts of the shoreface, which could only be induced by extreme storm conditions. DeCelles (1987),

Mathers & Zalasiewicz (1996) and Hartley & Jolley (1999) demonstrate that sheets of ungraded to partially graded gravel in the upper shoreface were deposited by severe storm-generated rip currents that were capable of transporting large cobble- to boulder-size clasts. A similar interpretation is proposed for the gravel sheets of Sub-facies D3. The seaward-decreasing gravel size (to the south-west, i.e. offshore), clast imbrication signifying an offshore transport direction and the palaeo-current direction of cross-strata – which is offshore – lend support to this view. Adding further credence to this interpretation is the recognition of similar rip current features by Yagishita (1994) from Upper Cretaceous sediments in north-east Japan where clast size variation as described above and offshore-directed palaeo-flows from cross-strata and clast imbrication were noted. The lenticularity, sheet-like geometry with erosive bases and orientation of the Sub-facies D3 gravel couplets which is normal to the palaeo-shoreline, can be interpreted as rip current channels similar to those described by Mathers & Zalasiewicz (1996).

The variable clast shapes in the gravel sheets suggest a provenance in a gravel-dominated shoreline, particularly the presence of disc- and blade-shaped clasts. These are commonly found in gravel foreshore settings where such shapes predominate (Bluck, 1967; Nemeč & Steel, 1984; Section 3.5). Consequently, their transportation into the shoreface can only be achieved under storm conditions. More significantly, the decrease in clast size in an offshore direction reflects some degree of clast-size sorting related to changing flow velocities, whereas the mix of clast shapes throughout the storm sheets, demonstrates the inability to shape sort in these rapid depositing events.

Although exposures near to the foreshore facies as described in Section 3.5 were removed by mining, no boulders (outer frame – Sub-facies C1) were observed in the gravel sheets or recorded in historical geological records. Worthy of mention is the record by Pether (1994) of storm-deposited cobble to boulder gravels in palaeo-shoreface deposits along the Namaqualand coast in South Africa (see also Section 3.4.4). In addition, Gruszynski *et al.* (1993; in Mathers & Zalasiewicz, 1996) and Hartley & Jolley (1999) document boulder-size clasts as a component of rip-channel deposits. These observations clearly demonstrate the competence of rip currents to remove such gravel size from a shoreline. Coastal conditions must, therefore, favour the development of strong rip currents. These would be best developed during exceptional storms driven by long period waves (Cook, 1970). Such storms do occur offshore of the study area as noted in Section 1.3 where wave heights (H) and wave

periods (T) of 5 m and 20 m/sec, respectively, are recorded 1% of the time and would seemingly generate rip currents that are capable of moving boulders offshore over a short distance. The infrequency of these storms would also allow greater preservation of the boulder clasts; they will remain static until a storm of greater magnitude, which is considerably more infrequent, moves the clasts further offshore. The lack of these large gravels in Sub-facies D3 is not fully understood given that they do occur at the toe of the foreshore environment and, as such, are a source of boulder clasts. It may be that these were removed by mining operations and were also possibly not recognised in the past as a component of the storm gravel sheet deposits.

3.6.5 Summary and depositional setting of Facies D

Many of the features preserved in Facies D closely resemble those in modern coastal sediments along the Namibian coast and because of its extreme energy, this coast serves as a good analogue to work from. Figure 3.44 serves as a schematic reconstruction of the depositional settings for the different sub-facies, whilst the salient features of each sub-facies and their interpretation are summarised in Figure 3.45.

The west coast of southern Africa has been classified as a storm-dominated coastline (Davies, 1964) with a present wave climate that has remained unchanged since the Neogene (de Decker, 1988). These attributes are therefore reflected in the sediments of Facies D where depositional processes demonstrate great depths, which typify storm-dominated shoreface deposition. More significantly, the processes that engender sediment transport and deposition in the shoreface are distinctly different to those in the surf zone (Niedoroda *et al.*, 1984). One aspect of this is that near the coast, wave-induced oscillatory currents are the main agents, whilst farther seaward and at greater depths, storm-induced unidirectional currents generally govern sediment transportation and erosion. Thus storm-related sedimentation dominates the lower shoreface, whereas fair-weather signatures are reflected in upper shoreface sediments (Immenhauser, 2009).

Equally important is the sediment exchange between the foreshore and shoreface. Sediment is sourced from the foreshore during storms and its deposition can extend across the entire shoreface into the adjoining inner shelf (Niedoroda *et al.*, 1984). Those that are deposited within lower shoreface and inner shelf areas may consequently not be returned to the foreshore, whilst deposition onto the upper shoreface will see a return of the sediment

during normal conditions (Niedoroda *et al.*, 1984; Héquette *et al.*, 2001). Using calibrated storm erosion models for exposed coasts such as the modern beach just north of the Orange River mouth, it has been estimated that the volume of sand approximating 50-100 m³ per linear meter of beach can be eroded during storms and moved offshore (Smith, 2006). This will obviously lead to significant deposition in the shoreface and has been demonstrated from profile measurements to be in the order of 0.1-2 m in thickness at depths up to 18 m (Smith, 2006). While this deposition may take place over a period of hours or days, the return of eroded sediment to the shoreline under calm conditions is envisaged to be considerably slow, over a period of months or years (Smith, 2006). It therefore follows that the upper shoreface is a reservoir to the foreshore, which in turn is depleted and replenished during normal and storm conditions, respectively (Niedoroda *et al.*, 1984). An important part of this replenishment which also governs net deposition in the shoreface is river flooding (Wiberg, 2000). Besides sediments deriving from the Namaqualand coast in South Africa (south of the study area) through longshore transport, which is negligible (Smith, 2006), and also from foreshore settings during storm scavenging, river-derived sediments from the Orange River is seen to be a major source for shoreface sedimentation during Facies D times.

Evidence from modern oceans suggests that the lower shoreface is roughly equivalent to or slightly deeper than normal wave base, and it varies between 2 m and 20 m (Walker, 1985). Here, normal waves do not reach bottom and thus sand deposits are moved only during storm events. The sediments of Facies D, however, reflect contrasting settings where lower shoreface sands (medium-grained) are moved during average wave conditions at depths greater than 30 m. This is borne out by de Decker's (1988) findings that coarse to very coarse sand entrainment is effective at depths of 30 m during the present-day under such conditions (more than 50% of the time), whilst pebble gravel can be transported at depths of 30 m during storm conditions (5% of the time). Thus, sedimentary features ascribing to tidal cycles (see Simpson & Eriksson, 1990; Winn, 1991), notably, the repetitive variation in cross-sets, mud drapes and tidal bundling of cross-stratification, is expected to be absent in Facies D, as is hummocky cross-stratification. Although the last mentioned is indicative of storm-induced bedforms (see Leckie, 1988; Southard *et al.*, 1990; Walker & Bergman, 1993; Midgaard, 1996; Nichols, 1999, pg. 140), its absence from facies D does not necessarily negate a storm-dominated sequence, but simply implies the inability of these bedforms to form in such coarse sands; they are commonly found in fine- to very fine-grained sediments (Harms *et al.*, 1982). The predominance of coarser grained sediments in Facies D is testament to the highly

energetic nature of the shoreface environment where it is estimated by de Decker (1988) that more than 50% of the time wave heights and wave periods of 1.7 m and 12.5 seconds, respectively, occur with a bias towards winter that is more energetic. Therefore such conditions do not favour the deposition and preservation of finer sediments such as clay and silt, particularly at depths up to 50 m, as evidenced from the total absence of these clay and silt in Facies D.

Immenhauser (2009) discusses the difficulties of reconstructing palaeo-water depths from the rock record, which evidently can prove difficult given that sedimentary features have limitations as proxies for palaeo-depth estimation. By using the modern Atlantic Ocean as an analogue to supplement the field data, crude depth estimates were derived for Facies D, but obviously further work is required to gain better estimates. Nonetheless, what the Facies D sediments do reflect, as seen from the vertical distribution of each sub-facies, is a shallowing succession. The deeper, lower shoreface sediments (Sub-facies D1), which record sea floor perturbations during storm events, as evident from the scouring and entrainment of pebble clasts, are overlain by shallower, coarse-grained bar deposits (Sub-facies D2) and winnowed gravel ‘wave trains’ of the middle shoreface setting where the energy regime was comparatively higher. This is also reflected in the change from planar (in Sub-facies D1) to tough cross-stratification (Sub-facies D2), which is related to upward shoaling with increased current and wave velocities as illustrated by Harms *et al.* (1975; pg. 110) for the Shannon Sandstone Sequence in Wyoming, U.S.A. Sub-facies D2, is in turn overlain by gravel rip-channel features interbedded with cross-stratified sand (Sub-facies D3) reflecting high-energy, storm-induced deposition and post-storm recovery events in the proximal upper-shoreface. The abundance of gravel in Sub-facies D3, in contrast to the sand-dominated sequences of Sub-facies D1 and D2, further supports a shallower setting that is closer to a gravel foreshore source. In addition, Facies D demonstrates that the shoreface sediments form part of the offshore continuum of the barrier beach environment of Facies C.

3.6.6 Age and correlation

The recovery of shell fragments of the zone fossil *Donax rogersi* (Earliest Pleistocene) correlated to the 30 m Package farther south along the Namaqualand Coast in South Africa (Pether, 1986) points to contemporaneous deposition with the sediments of Facies C and D of similar age.

CHAPTER 4 - DEPOSITIONAL MODELS AND STRATIGRAPHY

4.1 INTRODUCTION

It is evident from the facies relationship that two principal episodes of deposition occurred in the study area, these being the emplacement of a gravel barrier spit followed by the deposition of a gravel barrier beach complex. Both took place within the confines of a palaeo-Orange River mouth, where the development of barrier forms took place. In addition to the recognition of these principal episodes, it has also emerged from Chapter 3 that the barrier beach complex is represented by a stacked arrangement of barrier beach deposits preserved in various forms. The degree of preservation is obviously related to a combination of depositional processes, which is discussed in Section 4.2, but complete preservation is at most times rare within the ED rock record.

Figure 4.1 illustrates broadly the stratigraphic framework of the ED Area and it is clear from the diagram that complete preservation has occurred during the evolution of the barrier beaches. The surface expression of this preservation is the beach ridges that are partly seen in the field as topographical ‘humps’ and represent the final accumulation of beach forms before sea-level abandoned the study area during a regression. Both ridges that are shown in Figure 4.1 form part of separate barriers. Traditionally, these were informally classified as the ‘F’ and ‘E’ beaches, the latter being recognised as the oldest in the Plio-Pleistocene beach stratigraphy of MA1 (see Section 2.2 for beach classification and Figures 1.2 & 2.4 for stratigraphic illustration). However, for reasons to emerge later, deposits of the ‘F’ barrier beach are absent in the ED Area and thus the alphabetical codes ‘D’ and ‘E’ are more correct and shall henceforth be applied.

Although the two barriers (‘D’ and ‘E’) obviously comprise similar facies, their gross morphology is dissimilar in the following ways:

- 1) The ‘D’ barrier is positioned seaward and at a lower elevation in comparison to the more landward and higher position of its ‘E’ counterpart.
- 2) Deposition of the ‘E’ barrier is seen as a vertical build-up through episodic accumulation of barrier beaches, culminating in a completely preserved barrier complex. In contrast to

this depositional style, the ‘D’ barrier beach is more indicative of a single emplacement event, also completely preserved.

- 3) The size of the gravel clasts in the ‘D’ barrier beach as discussed in Chapter 2 (Section 2.2) is considerably coarser and the deposits proved to be highly economic, considering that it was the principal mining target. Vestiges of these coarse gravels, mainly the beach ridge and outer frame deposits are still *in situ*. Figure 3.23 (A & B) show such an outer frame deposit. Note that outer frame and beach ridge clasts of boulder size are absent in the ‘E’ barrier.

Although these differences are obvious, a more striking feature that is applicable to both the ‘D’ and ‘E’ barrier deposits, which is clearly seen in Figure 4.1, is their shore parallel (to the modern shoreline) configuration and sudden disappearance towards the south-east in the direction of the bedrock high. Consequently, with an absence of barrier forms in the south-eastern part of the study area, the barrier beaches, along strike, only occupy approximately 75% of the ED Area. This contrasts with the extent of the transgressive lag, which occupies the entire study area. It has been argued in Chapter 3 that the transgressive boulders were derived from a landward migrating shoreline, sourced from the outer frame setting (beach toe). Therefore, the most landward end of the transgressive lag should culminate at a barrier beach. This raises the question as to why the barrier beaches do not extend throughout the study area in concert with the transgressive lag. It is conceivable that the most south-eastern extremities of the barrier forms were eroded away by river flow. In Figure 4.1 it is equally clear that the barrier beach ridges increase in elevation and thickness towards the north-west (down-drift). By contrast, the south-eastern end (up-drift) of the barrier beaches was possibly thinner and at lower elevations. River energy levels during river migration and passage to the Atlantic Ocean may have been sufficiently powerful to erode the thinner barrier structure, but not that energetic to remove the largest boulders of the transgressive lag.

It is also evident that both the barrier beach and barrier spit deposits extend northwards towards the highly diamondiferous bedrock-floored linear beaches, but their relationship with the latter could not be ascertained due to the complete removal of large areas by mining. Historical records also fail to illustrate clearly the contact relationship between the ED deposits and linear beaches, showing an indistinct boundary. The northward transition of the ED deposits is therefore not clear; it could be either a gradual transition

(smearing) into linear beach forms or they may terminate at the bedrock boundary that forms the north bank of the palaeo-Orange River. A fundamental aspect of this relationship seen from Figure 4.2A is that the barrier beach ridges, more particularly the most landward (i.e. 'E' barrier), are positioned at lower elevations than the base of the 'F' bedrock-cliff. Assuming that the latter represents a transgression and is time equivalent to the emplacement age of the barrier beaches, the base of the cliff and that of the barrier beaches should have similar elevations (Figure 4.2B(1)). However, the 'F' cliff base is approximately 25 m above msl, whilst the elevation of the highest ridge (at G39.5) is lower at approximately 23 m above msl (Figure 4.2A). In addition, the transgressive lag that leads to the barrier beaches is positioned 15 m below the base of the 'F' cliff (Figure 4.2A & B(2)). This difference in elevation intuitively suggests that the bedrock platform, representing a transgressive surface on which the 'F' cliff is developed, cannot be correlated to the transgressive boulder lag. Thus, these transgressive events are seemingly unrelated.

The 'F' cliff is also not laterally (coast parallel) contiguous with the ED Area barrier beach deposits, but is positioned slightly landward (see Figure 4.2A). It is therefore reasonable to assume that the 'F' cliff was cut earlier than the emplacement of the ED Area barrier beaches. This would also imply that 'F' cliff time-equivalent barrier beaches are farther landward of the study area; a function of higher barrier migration rates within a palaeo-river mouth setting as compared to that of a bedrock-dominated setting (Figure 4.2B(3 & 4)). This is discussed in Section 4.3.1. Beach correlation along strike at the palaeo-river mouth/bedrock interface is consequently disjointed with the barrier beaches developed more landward (Figure B (3 & 4)). It therefore follows that the 'F' cliff and its associated bedrock platform were developed prior to the emplacement of the ED Area barrier deposits. If this reasoning is permissible, the transgression responsible for depositing the latter would have thus reached an elevation that is lower than the 'F' cliff (Figure 4.2B (4)). The 30 m Package ED deposits would therefore represent only the 'D' and 'E' informal beach stratigraphy of Stocken (1962) and Hallam (1964; see also Chapter 2, Section 2.2 for discussion on the beach stratigraphy).

In view of the above, one aspect that is also not readily appreciated is subsidence through sediment compaction. Soft sediment deformation features have been recognised in some of the facies as described in Chapter 3 and these are mainly due to penecontemporaneous loading of barrier beach deposits onto unconsolidated sediments.

Hence, subsidence of the barriers due to the compaction and dewatering of the underlying sediments is not inconceivable. For example studies such as those by Törnqvist *et al.* (2008; Mississippi Delta, U.S.A.) and Long *et al.* (2006; West Winchelsea, England) on peat compaction within coastal wetlands, either through a process of autocompaction (compaction due to its own body mass) or compaction due to loading by estuarine or deltaic sediments, validate the views that these processes contribute to landscape subsidence and consequential inundation of coastal waters. Long *et al.* (2006) concluded that the peat in coastal wetlands of West Winchelsea, England, compacted at least 3 m due to loading by 5 m of fine tidal sand. Obviously, peat can be compressed to a greater degree than other sediment types such as sand, silt or clay. Nonetheless, the concept of compaction is a fundamental mechanism in coastal evolution as demonstrated by Rosati *et al.* (2010). Through the application of model-induced simulations for sand-dominated barriers that were correlated to field data, they concluded that barrier migration over a soft substrate (either of marine or estuarine origin) will result in the compaction of underlying sediments over time due to loading. The consequential response, albeit delayed, is a lowering of the barrier elevation, volumetric adjustment of the barrier and increased washover sedimentation when the barrier ridge is lowered to a critical level that encourages frequent overwashing (Rosati *et al.*, 2010).

Comparatively, the magnitude of loading and attendant compaction in gravel barrier beach settings would expectedly be higher due to their greater weight. However, as in the case of the study area, the amount of compaction in the underlying clay, sand and gravel would be far less than that in peat or marsh sediments, but the consequential effect cannot be ignored. Perhaps equally important is the compaction of the unconsolidated palaeo-channel fill sediments of the Meso-Orange River (80 m in thickness) of predominantly sand with minor gravel that are footwall to the marine deposits. Although untested, it is assumed that these Meso-Orange River sediments would have compacted during their accumulation to possibly create an already subsided surface onto which the barrier deposits were emplaced. The degree of subsidence within the ED Area has not been quantified, but may have contributed to difference in elevation heights between the barrier beaches and linear beaches as discussed earlier. Further work will be required to test this hypothesis.

In summary, the ED Area palaeo-shoreline of Plio-Pleistocene age, confined to a river mouth setting, is characterised by barrier beach and barrier spit deposits that have accumulated through variable sea-level and river processes. The vertical stacking of

sedimentary facies is therefore an indication of sea-level changes. Coupled with coastal subsidence, it is the behaviour of these processes that has promoted the preservation of a coastal stratigraphic sequence, capturing the evolutionary pathways of barrier deposits. Background to such coastal processes and the evolution of the study area are presented hereafter in Sections 4.2 and 4.3.

4.2 PRESERVATION OF COASTAL SEQUENCES

The development and preservation of coastal sequences are unequivocally dependent on several factors; the dominant being sea-level changes, sediment accumulation and wave and tidal processes (Davis Jr & Clifton, 1987; Cooper & Pilkey, 2004). It has been demonstrated in preceding chapters and by de Decker (1988) that the Atlantic wave climate has not changed since the Neogene and similarly the shelf remained relatively buoyant since the Late Cretaceous (Aizawa *et al.*, 2000; Bluck *et al.*, 2007). Given the persistence of a micro-tidal regime and a shelf with minor subsidence, the accumulation and preservation of thick sedimentary sequences in such settings, alone, is considered unlikely. Consequently, changes in sea-level and rate of sediment supply are recognised as the primary controls for the development of the ED Area stratigraphy. The signature of these, notably regressive and transgressive, as well as progradational events is imprinted in the sedimentary record. There are, however, various combinations of sea-level and sedimentation models that can explain different styles of coastal stratigraphic sequences and their preservation. The general aspects of these will be discussed to serve as a prelude to understanding the genesis of the ED Area stratigraphy. The intention is not to review sequence stratigraphy applications, but merely to present basic principles that have relevance to the study area and design of the depositional models. Consequently, sea-level changes in this study are considered to be independent of tectonism (uplift and subsidence) given the assumption that the area has remained relatively stable throughout Plio-Pleistocene times. Additionally, behaviour patterns and resultant sequences of the Meso-Orange River will not be reconstructed, but where applicable to the ED stratigraphy, river influence will be briefly discussed.

4.2.1 Coastal stratigraphic sequences

Davis Jr & Clifton (1987) note that transgressive sequences involve the landward migration or a retreat of a shoreline as an obvious result of sea-level rise (tectonic subsidence is excluded from the equation). The response to this migration as documented by Catuneanu

(2002) is a landward shift of facies and deepening of the marine water in the vicinity of the shoreline. The result is stacked retrogradational patterns (Catuneanu, 2002).

Regressive patterns are commonly associated with a sea-level fall inducing a seaward migration of the shoreline. This induces a seaward shift of the facies, as well as shallowing of the marine water in the vicinity of the shoreline (Catuneanu, 2002). However, a regression may also occur during a stable or rising sea-level where sediment supply is in surplus resulting in shoreline progradation (Davis Jr & Clifton, 1987). Note, however, where sea-level fall is independent of sediment flux and the shoreline is forced to regress by falling base level, it is termed a forced regression. Whereas a static or rising sea-level accompanied by a sediment supply rate that outpaces the rate of accommodation space at the shoreline is referred to as a normal regression (Helland-Hansen & Martinsen, 1996; Muto & Steel, 1997; Nichols, 1999; Catuneanu, 2002). Normal regressions occur during the early and late stages of a transgression; that is, lowstand and highstand, respectively (Catuneanu, 2002).

During either of the above scenarios, sediment is deposited in the space between the sea floor and base level; the latter for simplicity approximates sea-level in a marine context, although in reality it is below sea-level due to the erosion of waves and currents (Catuneanu, 2002). The space that is generated between the sea floor and base level is referred to as accommodation space. This is where sediments potentially accumulate and the amount of space will vary according to the degree of base level change (Posamentier *et al.*, 1988; Catuneanu, 2002). Note that during transgressions the newly created accommodation space outpaces sediment accumulation, whereas the opposite occurs in normal and forced regressions where the newly created accommodation space is consumed by sedimentation and thus encourages progradation (Catuneanu, 2002).

4.2.2 Sediment supply

The sustainability of barrier spit and barrier beach growth is dependent on sediment supply (Orford *et al.*, 1991; Firth *et al.*, 1995; Soons *et al.*, 1997; Orford *et al.*, 2001; Pye, 2001). An adequate supply will maintain growth, while sediment starvation will lead to breakdown through a process of cannibalisation or reworking of the barrier sediments (Orford *et al.*, 2001). Consequently, river behaviour during base level fluctuations controls sediment supply, which in turn is central to the fate of the shoreline.

Rivers adjust to newly established base levels to maintain equilibrium; that is, they adjust to their graded longitudinal profile. They either aggrade ('back-filling' *sensu* Schumm, 1993) during a transgression where base level has been raised, or degrade (fluvial incision) on a forced regression when base level is lowered. In both circumstances, the impact of base level change is, amongst others, influenced by the magnitude, duration and rate of change (Schumm, 1993). Once equilibrium has been achieved, however, the river is able to transport the sediment without aggradation or degradation (Catuneanu, 2002). Base level adjustment, however, has limited upstream extent and is usually confined to the downstream reaches of the river. Beyond this upstream limit, the river is influenced primarily by a combination of climate and tectonic factors (Catuneanu *et al.*, 2005). At the downstream reach, the river mouth moves according to base level change where it keeps the adjusting river profile connected to changing base levels, either through seaward extension during regressions or landward retreat during transgressions (Catuneanu *et al.*, 2005). Where seaward extension occurs on a forced regression, the river extends across the newly exposed shelf with a concomitant incision into previously deposited highstand sediments (Blum & Törnqvist, 2000). With the onset of aggradation during the early stages of transgression (i.e. lowstand), the river, once in equilibrium, will have the capacity to migrate laterally across the exposed shelf with the river mouth responding in concert.

Where base level fall at the shoreline is small during forced regressions, river adjustments are slight such as minor down cutting, but where the regression is significant with base level falling beyond a major topographic break such as the shelf, the magnitude of incision is greater (Catuneanu, 2002). It is at this time that river competence is highest to transport a coarse bed-load, up to boulder size, to the coastline (see Posamentier *et al.*, 1988; Postma, 1995; Nichols, 1999). Noteworthy, is that sediment supply is initially locked up in terrace deposits and gradually released over a protracted period as the new base level migrates upstream during a regression (B. Bluck, pers. comm., 2010). For example, it has been demonstrated that rivers do exhibit an imbalance in sediment production and sediment yields at the basin mouth, which is attributed to a source-to-sink time lag and alluvial storage (Phillips & Slattery, 2006). By contrast, coastal aggradation during a transgression lowers the slope gradient of the downstream reach, encouraging river aggradation and a reduction in fluvial energy (Catuneanu *et al.*, 2002). Sediment supply to the coast, however, continues but the bed-load size is generally finer than that delivered during a forced regression. The fining-upward trends in aggradational profiles are an expression of this energy reduction. Obviously

this reduced flow will be punctuated by river flooding that will result in the delivery of coarser sediment to the coast.

Apart from river supply, reworking of delta deposits during transgressions is also another source of sediment. A modern example of this is seen along the Skeleton Coast, south of Terrace Bay in Namibia (Figure 4.3.A; see also Figure 1.1 for locality of Terrace Bay). Here, Cainozoic fan-delta sediments form the Uniab Fan and its seaward edge is represented by a steep, wave-cut cliff (van Zyl & Scheepers, 1992; Krapf, 2003). Through extrapolation of the surface gradient, Krapf (2003) demonstrated that the fan-delta extended some 6-7 km offshore of the present coastline and thus its present position, notably the wave-cut cliff, is a relict feature of sea-level rise. At the base and fringing the wave-cut cliff, a modern gravel beach forms the shoreline (Figure 4.3B). Although, it is likely that the modern fan-delta distributaries may have supplied sediment to the shoreline during flood periods, it was probably negligible given the ephemeral nature of the drainage system. The gravel is sourced principally from the fan-delta. This not only supplied coarse sediment to the modern gravel beaches fringing the Uniab Fan, but also modern deposits farther north at Terrace Bay where the delivery of sediment is through longshore transport.

4.2.3 Sequence preservation during transgression

Demarest II & Kraft (1987) note that not all sedimentary environments are likely to occur in a single vertical sequence since the preservation potential of some depositional environments is higher than others. During a transgression, as the shoreline shifts landward, the combination of wave erosion of the foreshore and upper shoreface with a concomitant deposition in the lower shoreface is required to maintain the bathymetric profile (Catuneanu, 2006). This transgressive wedge deposited in the lower shoreface known as 'healing-phase' deposits (Catuneanu, 2006), has the greater preservation potential. Landward of the shoreface, in close proximity to the foreshore, sediments that are proximal to the barrier beach and at a lower level, such as those filling deep estuarine-lagoons and tidal inlet channels, as well as washover deposits (see also Sedgwick & Davis Jr, 2003) will also have a propensity to survive erosion during shoreline retreat (Demarest II & Kraft, 1987; Nummedal & Swift; 1987).

However, a rapid sea-level rise will induce maximum preservation (Davis Jr & Clifton, 1987). Here *in situ* drowning of a barrier beach is accomplished when barrier

migration rates fall behind the rate of sea-level rise (Orford *et al.*, 1991). Such submerged barriers have been recorded by Forbes *et al.* (1991) at depths of about 5 m offshore Story Head, Nova Scotia and by Gray (2002) at depths of 90-119 m offshore the ED Area. It has been shown by Forbes *et al.* (1991) that during submergence of the Nova Scotia barrier, a remnant of the barrier feature was left behind in the shoreface, whilst its upper part migrated with sea-level rise.

When sea-level rise decelerates (highstand), shoreline progradation and aggradation is encouraged with sedimentation outpacing the rate of sea-level rise (normal regression; Catuneanu, 2006). Coastal settings that are dominated by aggradation thus have a propensity to preserve estuarine and backstepping beach facies in the rock record, but their preservation can be precluded by sub-aerial and marine erosion that are associated with a subsequent forced regression (Catuneanu, 2006). In such instances, only partial preservation of gravel beach progradational sequences is thus expected where the large disc zone is removed, whilst swash and berm, as well as outer frame (beach toe) deposits survive the erosion. Note that gravel beach progradational sequences, when completely preserved, are characterised by a layer of large discs (beach ridge) overlying an extension of steeply inclined foresets (cusps and swash berms), which in turn rest on a layer of large, spherical clasts (outer frame; Bluck, 1999; Bluck *et al.*, 2001),

4.3 DEPOSITIONAL MODELS AND STRATIGRAPHY

The lower reaches of palaeo-fluvial deposits and palaeo-coastal remnants along the Atlantic coastline, north and south of the Orange River, record sea-level fluctuations that are best imprinted in Neogene and Quaternary age deposits. It has been advocated that these fluctuations are primarily glacio-eustatic driven due to the waxing and waning of high latitude ice sheets (Hallam, 1964; Tankard *et al.*, 1982; Dingle *et al.*, 1983; Gresse, 1988; Pickford & Senut, 1999). Geological evidence for glacio-eustatic sea-level fluctuations – linked to climate changes – is widespread and gleaned mainly from marine oxygen isotope and ice rafting records that are used as proxies for sea-level changes (Lambeck *et al.*, 2002; Pillans & Naish, 2004).

Nonetheless, the Cainozoic coastal stratigraphy within individual mining areas in South Africa (Namaqualand) and Namibia (Sperrgebiet) is fragmentary and problematic to

correlate due to difficulties in dating and characterisation of the deposits. As regards the latter, variances in elevation heights of nearshore sediments of similar age cannot be satisfactorily correlated and continue to fuel speculation of tectonic influences (see Figure 4.4A). Although, tectonism is to some degree suspected as one of the contributing factors for the deposition of coastal deposits, it is yet to be satisfactorily proven. In fact, a reappraisal of MA1 stratigraphy within the Sperrgebiet in terms of elevation heights and age relationship has not been attempted since the work of Pickford & Senut (1999). However, unique depositional patterns have emerged from recent studies on both the coastal and fluvial deposits. For examples, Jacob (2005) has shown that the Meso-Orange River during Plio-Pleistocene times was capable of transporting boulder-grade sediment to the coastline. This was facilitated by a combination of river competence (also a function of steep gradients) and tributary input with the last playing a critical role in delivering coarse gravel to the main channel. The resultant pattern is an unconventional coarsening of the lower reaches of the Meso-Orange River and thus typical downstream fining is lacking. Moreover, Jacob (2005) and Ward *et al.* (2002) also noted that the aggradational profiles of the Meso-Orange deposits do not fine upward, but the coarse gravel component is retained in the upper units of the aggradational sequences.

The Meso-Orange River outfall and its associated dispersal system, as discussed in Chapter 2, is also unique within the context of delta deposits and difficult to classify as pointed out by Bluck *et al.* (2007). The highly energetic wave climate and vigorous sediment dispersal system, as discussed in Chapter 2 (Section 2.1), active since the Eocene precluded the formation of a classic delta deposit. Bluck *et al.* (2007) demonstrate that the Orange River outfall compares with smaller gravel-dominated fan-deltas and wave-dominated deltas; the main difference, amongst others, being the scale of the delta and the persistent coastal energy. Thus the Orange River outfall is an extreme case of a wave-dominated delta and although it does not conform to typical delta settings, Bluck *et al.* (2007) suggested that its classification as a delta should still hold; a definition that will be hereinafter applied.

When the Meso-Orange River deposits (Plio-Pleistocene) are considered, the influence of sea-level control is apparent from the seaward thickening wedge of fluvial sediments in the lower reaches of the Orange River valley that extend upstream for some 250 km (Ward *et al.*, 2002). The aggradational sequences and incised bedrock profiles with deep scours are testament to periods of transgressions and regression, respectively (Jacob, 2005). More

significantly, Jacob (2005) demonstrates that the suite of Meso-Orange deposits represent shorter periods of aggradation and incision compared to their older counterparts. This could possibly reflect high-frequency sea-level oscillations.

Sea-level fluctuations have been equally recognised within the palaeo-coastal settings where palaeo-shoreline remnants are developed at descending elevations with decreasing age (Stocken, 1962; Hallam, 1964; Carrington & Kingsley, 1969; Murray *et al.*, 1970; Keyser, 1972; Tankard, 1975; Pether, 1986, 1994; Gresse, 1988). Taking cognisance of only Neogene and Quaternary deposits and ignoring the offshore sector, generally the most landward and oldest marine deposits of Early Miocene age occur approximately 90 m above msl (Pickford & Senut, 1999; Pether, 2000), whereas the youngest and most seaward at 2 m above msl has been dated (Sr isotope) at 5,000 BP (Millad, 2004; Figure 4.4A). This stratigraphic evolution spanning approximately 20 million years points to an overall regression, but another cycle within this regressive hierarchy has also been recognised. Pether (1994) identified single cycles of transgression and regression within Neogene and Quaternary deposits along the Namaqualand coast in South Africa. He notes that the deposition of each seaward thickening wedge, such as the 50 m (Early Pliocene) and 30 m (Plio-Pleistocene) Package deposits, were emplaced under a cycle of transgression and subsequent regression, but only the highstand sequences were preserved. These cycles correlate to Haq *et al.* (1987) third-order cycles (Figure 4.4B).

In addition to these aforementioned cycles, a third component has been identified within the study area. Here, cycles of transgressions and regressions within the bounds of the 30 m Package interval are responsible for the emplacement and building of the barrier spit and barrier beach deposits (Figure 4.4B). Simply put, the 30 m Package deposits within the palaeo-river mouth reflect numerous sea-level changes; a contrast to previous assumptions that a single cycle of transgression and subsequent regression was responsible for their deposition.

Catuneanu (2002) describes various pros and cons regarding the use of sequence hierarchy systems that are used to separate stratigraphic sequences and surfaces into different orders of importance. Although the systems are in vogue, he notes that there is no universal hierarchy system in place that can be applied to all stratigraphic case studies, but instead the development of a system should be on a case by case basis where hierarchal orders are

assigned to sequences based on their importance. In view of this, the overall regression as discussed above is considered least important for the study area and is thus considered low order, possibly correlating to the Haq *et al.* (1987) second-order cycle. The sequences that were deposited by a single cycle of transgression and regression are of moderate importance (Haq *et al.*, 1987; third-order cycles), whereas the building of the barrier beach and barrier spit sequences through high-frequency transgressive and regressive cycles are considered more important for the overall development of the study area and are considered to be fourth-order cycles (Figure 4.4B).

4.3.1 Conceptual depositional models

In this section consideration is given to barrier beach and barrier spit behaviour as a backdrop to understanding the stratigraphic framework of the study area. Conceptual models are presented for both barrier types, but note that sea-level influence has been omitted in this discussion and thus only a simplistic view on barrier behaviour will be presented. Sea-level changes and the development of the associated barrier stratigraphy will be discussed separately in Section 4.4.

Barrier spit

The fact that the barrier spit is bedrock-attached implies that the bedrock island was at some point in time a disruption to wave propagation and sediment transport along the coast. Also, given the absence of washover deposits as indicated by the available exposures, the barrier spit was a great deal wider to preclude overwash. It was also considerably longer relative to its width. Hence, the deposits seen in section are only a relic of its much larger geometry. Therefore, barrier spit evolution in the study area is not adequately clear, but there are several indications that point to cycles of progradation and subsequent erosion.

Deposition at some point in the spit history would have been influenced by the presence of the bedrock island. This bedrock feature, in excess of a kilometre in length, was probably a large island. Such protuberances are known to disrupt the incident waves, which dissipate the energy to form a wave-sink on the down-drift end (Carter & Orford, 1988). This induces rapid deposition of the entrained sediment, forming an anchor point for sediment growth. With a continued supply of sediment fed from the Orange River outfall, the anchored spit had the competence to extend down-drift and isolate large parts of the mainland from the wave energy to form an estuarine lagoon. The relic recurve features (spit tips) preserved at

trenches G19 and G25, as well as the estuarine-lagoon clay at G29 and 39.5, marks the progressive down-drift growth (see Anthony & Dolique, 2001, pg. 134). Note that as the barrier spit lengthened down-drift, the estuarine-lagoon equally extended in a similar direction. In such sediment surplus environments, barrier lengths greater than 2 km can be attained such as those recorded in the Orford Shingles (Randall & Fuller, 2001) and even greater lengths as seen in Patagonia, Argentina, where 33 km length has been documented (Kokot *et al.*, 2005).

Once bedrock-attached, the initial stage of spit accumulation would have seen the deposition of a subtidal, skeletal framework (Orford *et al.*, 2001). With an adequate supply of sediment, the subtidal body would have developed in advance of the gravel spit filling the accommodation space; this being the platform onto which the gravel spit was contemporaneously emplaced (Nielsen *et al.*, 1988; Soons *et al.*, 1997; Mäkinen & Räsänen, 2003). Persistent sediment supply encouraged the emergence of the gravel spit in a barrier form which, with time, developed a significantly steep-beach face extending to a prominent ridge. In addition, it also induced seaward and landward progradation of the beach. This is clearly seen in the seaward-facing beaches at the G25 trench where a part of the progradation, some 120 m, has been preserved. Also, the direction of seaward growth towards the southwest, demonstrates that spit alignment was roughly parallel to the present-day shoreline; an indication that the direction of wave propagation and longshore drift has remained unchanged since the Quaternary, as noted by de Decker (1988). Spit alignment would not have been completely straight, but instead a curve-linear configuration was possibly prevalent. Given that the preserved deposits are relict features, the extent of progradation and overall length of the barrier spit is unknown. However, the fact that growth was in perpetuation provides an indication that sediment supply was adequate and the resultant surface expression of such growth would be in the form of amalgamated beach ridges (beach-ridge plain; Figure 4.5).

Sediment supply was primarily from the Meso-Orange River. It has been demonstrated by Ward *et al.* (2002) and Jacob (2005) that the fluvial deposits of that age reflect an ephemeral character related to episodic flow rates. This is no different to the present flow regime, which although less energetic, is highly variable even though the river is perennial as pointed out by Hughes & Brundrit (1995). Obviously, human intervention in terms of dam construction has played a major part in the modern river system. Nevertheless,

data prior to the construction of large dams show that their smaller equivalents had played a lesser role (van Heerden, 1986), implying that the Orange River flow is inconsistent.

Nonetheless, a high sediment flux to the coast during floods would be rapidly dispersed as described in Chapter 1. Being a wave-dominated coast, river influence (such as delta deposition) would be inferior to the coastal processes that modify the shoreline as described by Hughes & Brundrit (1995) and Bluck *et al.* (2007). Such rapid dispersion of outfall sediment is described by Cooper (2002) where the 1988 Orange River flood, delivering approximately $1.4 \times 10^6 \text{ m}^3$ of bed-load sediment to the Atlantic Coast, was deposited in an ephemeral delta and redistributed by wave energy and littoral currents within three to four years during the post-flood adjustment phase. By contrast, the Plio-Pleistocene Orange River is assumed to have been more energetic and active to supply a greater quantity of coarse sediment. Here the resultant product from wave and current dispersion of a magnitude that was equally aggressive during post-flood readjustment would be in form of gravel barrier spits.

Therefore barrier spit growth was at times rapid and episodic, with increased growth rates where copious sediment was available by flood introduction; the last is evidenced from clay rafts found in the beach sequences. These were ripped from the estuarine-lagoon and flood plain settings. During periods of low river flow, however, barrier spit growth progressively waned when sediment availability was reduced and a process of cannibalisation was provoked. Here, the barrier spit reworks itself at the proximal end to feed the spit terminus thereby maintaining barrier integrity (Orford *et al.*, 1991). However, continued sediment decay would induce segmentation of the barrier spit into distinctive cells leading to final barrier breaching where a series of islands are formed (Orford *et al.*, 1991). The barrier spit remnant within the study area is thought to be one such feature.

Sediment supply was thus episodic, but there is uncertainty as to where the outfall was positioned during barrier spit times. Field evidence shows that the Meso-Orange River was undoubtedly bedrock confined in its lower reaches and occupied a position near to the present course as evidenced from the terrace deposits (Jacob, 2005). At the palaeo-mouth, however, the river course would not have been bedrock incised and probably held a different position to that of today. Within a wave-dominated setting where longshore drift is relatively strong, delta and river mouth behaviour would thus be influenced by coastal processes. Bluck *et al.*

(2007) describe these influences for the Orange River and as mentioned earlier, they note that the Orange River delta typifies an extreme-wave delta setting where sediment storage is precluded. In these settings and under the influence of longshore drift, there is a propensity to deflect the river mouth down-drift so that river flow is sub-parallel with the coastline (Bhattacharya & Giosan, 2003). Several examples of such river mouth deflection have been described, for example the Senegal and Saloum deltas in West Africa (Bhattacharya & Giosan, 2003), the Mahanadi delta in India (Bhattacharya & Giosan, 2003) and the Rhone Delta in France (Rey *et al.*, 2009). Such river deflection is associated with river discharge rates that cannot compete with the dominance of longshore drift, resulting in the rapid removal of outfall sediments (Bhattacharya & Giosan, 2003). Therefore, delta storage capacity is limited and the sediments are consequently moulded into a barrier spit feature that separates the deflected channel from the open ocean (Figure 4.6). With the protection afforded by the spit, the river channel has the ability to extend alongshore in concert with spit growth, but to a point where a reduction in hydraulic competence is reached due to a loss in gradient. The channel thus begins to ‘backfill’ causing river avulsion and the spit is consequently breached to promote the growth of a new spit feature (Bhattacharya & Giosan, 2003; Rey *et al.*, 2009; Figure 4.6). By contrast, where river discharge can compete with the longshore drift, the discharge behaves like a groyne at the mouth encouraging up-drift retention of sediment that is moving alongshore, such as in the case of Paraibo do Sul and São Francisco deltas in Brazil (Dominguez *et al.*, 1987; Bhattacharya & Giosan, 2003). As river discharge decreases and becomes inefficient to produce a groyne effect, the river mouth is deflected entirely down-drift as discussed earlier (Bhattacharya & Giosan, 2003; Figure 4.6).

It is difficult to invoke which of these characteristics (as discussed above) the palaeo-Orange River mouth adopted; it may have been a combination of both, but the persistence of longshore drift power cannot be discounted and it is likely that river mouth deflection did occur given the limited storage of delta sediments as described by Bluck *et al.* (2007). With a sediment load comprising coarse gravels (up to boulder size), the deflection would, however, be difficult to sustain for any length of time since the gravels would be exceptionally coarse for river transport that parallels the coastline where the channel has a minimal gradient. In addition to river deflection, there may have been a number of active distributary channels within the estuary feeding the outfall; either at different times or simultaneously. Van Heerden (1986) and Cooper (2001) describe the present Orange River estuary as being river-dominated where high rates of channel extension and bifurcation are symptomatic of such

settings. By inference, the palaeo-estuary setting during barrier spit times was probably similar to that of today. While it is difficult to reconstruct the position(s) of outfall(s) given the absence of their signatures due to erosion, the fact that a barrier spit remnant (as seen in section) is bedrock-attached and having a down-drift growth as evidenced from palaeo-current directions, implies that the palaeo-outfall was to the south of the bedrock island at that time of spit deposition.

The dominance of gravel in the barrier spit as seen in section at G25 and G19 implies sediment segregation under a longshore drift with gravel and sand separating out along the spit length. The finer sediment would have moved ahead of the gravel, whilst at most times, the latter is moved as a traction carpet. However, during sediment outfall the gravel component would not have been debouched far from the shoreline as compared to the finer sediment. With an assurance of a sediment budget provided by the river, growth rate was rapid and sustainable. Therefore, the barrier spit would have grown at a remarkable rate.

Growth rates in gravel spits are impressively high, despite being irregular, as shown by Carr (1969) and Randall & Fuller (2001) for the Orford Shingles in the U.K. (see also Chapter 3; Facies A) where a maximum of 183 m/a was recorded during the early 1800s, whilst more recent (1969-1970) annual rates of 88 m/a were measured. Noteworthy, is that the source for the gravel was mainly from the offshore – supplied when sea-level was lower – and from eroded glacial cliffs (Carr, 1965; Randall & Fuller, 2001). By comparison, a greater sediment load supplied directly from the Meso-Orange River would in contrast encourage higher growth rates in the study area. Within the present Orange River setting, a sand barrier impounds the estuarine-lagoon from the Atlantic Ocean. It has been demonstrated by van Heerden (1986) that the estuarine inlet has migrated down-drift and up-drift with time. To establish migration rates and hence barrier growth, the position of the inlet was surveyed by the author during 1999 and again in 2003 and showed a down-drift (northward) migration for some 1.2 km during the five-year period. This equates to an average annual shift of 240 m/a. In view of this and with the assumption that the Meso-Orange River was more active than that of today, barrier spit growth rates during the Plio-Pleistocene could have ostensibly been of equal magnitude, but certainly higher than those reported for the Orford Shingles; that is, in excess of 180 m/a.

However, at some point during its evolution, the G25 spit was abandoned when it became isolated from the wave energy by another barrier growing seaward of it. The extensive estuarine-lagoon clays seen in section at the G19 trench, which is positioned seaward of the barrier spit sequence at the G25 trench (see Figure 4.1; Appendix E), is the back-barrier setting to the new emerging barrier. Continued growth of the new barrier would have encouraged the G25 spit to progressively deactivate in concert with a diminishing supply of gravel. The supply was instead redistributed to nourish the new seaward barrier. While there is a tendency for a sediment-starved spit to become destabilised through a process of reworking itself and eventually segment into cells (Orford *et al.*, 1991), parts of the deactivated G25 spit was – at some point during its erosive state – preserved as a result of the protection by the new emerging barrier. More significantly, the new barrier would have grown rapidly, as discussed above, thereby affording maximum protection from the wave energy. The preservation of some 120 m (and possibly more given that sections were mined away) of prograded beach face at the G25 trench is a testament to this. A modern analogue of this deactivation and subsequent protection by a younger seaward barrier is seen in the modern Orange River mouth (Figure 4.7). Although, the deposits are sand-dominated, the overall nature of such a process is envisaged to have been similar during Plio-Pleistocene times.

In summary, the perpetual supply of sediment, albeit episodic, from the palaeo-Orange River outfall and a concomitant accommodation space within the palaeo-mouth provided the impetus for barrier spit growth in a wave-dominated setting. Although the history of spit development is fragmentary due to the removal of their evolutionary signatures and the reconstruction remains, at best speculative, some conclusions can be presented. The rate of barrier spit growth within the study area was envisaged to be high, in concert with a copious sediment supply by the Meso-Orange River. However, growth periods were likely to be punctuated by stages of erosion where sediment supply was in decay and hence coastal features were ‘trimmed’ back. Consequently, the coastal morphology had a complex history that alternated between the development of extensive beach-ridge plains and fragmented barrier spit remnants (or cells *sensu* Orford *et al.*, 1991). On renewed and increased sediment delivery, the breaches separating cell remnants would have possibly ‘healed’ – provided it remained within the sediment delivery corridor – and thus barrier spit growth was reinitiated when cell remnants were linked (Orford *et al.*, 1991).

In addition to episodic sediment supply, constant shifting of outfall positions through time changed the loci of sedimentation and therefore a number of gravel barrier spits could have developed, each being deactivated when channel avulsion occurred. The last is a function of gradient adjustment and this process also leads to barrier fragmentation when a new inlet is breached. The portion down-drift of the new inlet would be in sediment surplus, whilst the up-drift equivalent being outside of the sediment delivery corridor would be sediment starved (for example, Rey *et al.*, 2009).

There are a number of evolutionary combinations that could be invoked for the ED Area barrier spit history, but only a window of this is recorded in the rock record. The more notable of these is the bedrock attachment and subsequent growth as described earlier, but thereafter the evolutionary path is vague until the emergence of a younger, more seaward barrier feature that encouraged a progressive deactivation of its older, landward counterpart. This led to abandonment of the older barrier spit that was already in a stage of erosion and thus only a remnant of its configuration was preserved once cut off from the Atlantic Ocean and protected by the younger barrier spit.

Barrier beach model

The most striking feature, amongst others, of the barrier beaches seen in section, is the well-developed boulder lag that leads to the barrier complex, implying that it was emplaced on a transgression. However, the bulk of the preserved sediments demonstrate that the emplacement and growth of these barrier deposits is more likely to be a result of numerous transgressions and normal regressions on an overall transgressive system to build a barrier beach complex of some 11 m thick. This is considered in more detail in Section 4.4.

In comparison to the barrier spit deposits, the overall gravel size – on a visual basis – is smaller in the barrier beaches and the presence of sand is comparatively more abundant. Bluck *et al.* (2001) demonstrate that the wedge of littoral sediment along the Atlantic Coast tapering down-drift in a northerly direction from the Orange River mouth represent different gravel beach types as discussed in Chapter 1. This progressive change in beach type, accompanied by a thinning in the width of coastal accretion, is by inference ascribed to a diminishing supply of sediment (Bluck *et al.*, 2001). Therefore the vertical change from barrier spit to barrier beach deposits with an associated change in sediment character is a representation of this decline in sediment supply. If this is considered, the model whereby

barrier spits undergo a morphological change due to sediment decay is invoked as a plausible, although inconclusive, explanation for the emplacement of the ED Area barrier beaches.

Orford *et al.* (1991) demonstrated that without adequate supply of sediment, there is a tendency for barrier spits to segment into cells through a process of reworking the existing barrier. With continued reduction in sediment supply, the ultimate fate of each segmented cell is to become totally isolated and reorganise itself into some structure. In some cases the segmented cell will convert to a cohesive free-standing, solitary barrier, which will inherently have the potential to migrate landward (Carter & Orford, 1984). Obviously, the tempo of migration is dependent on several factors – the rate of sea-level rise being the main driving force, amongst others. For example, mean migration rates for the Story Head barrier in Nova Scotia, of less than 1 m/a have been recorded, whilst maximum rates of 8 m/a are not unusual (Forbes *et al.*, 1991).

Within the study area, the transgressive lag leading to the barrier beach complex is a relict manifestation of barrier migration on a sea-level rise and given the accommodation space within a palaeo-river mouth setting, the passage and development of the barrier was unimpeded. Barrier migration was in the form of ‘rollover’ – a process of constant barrier reworking whereby the material is recycled from the beach face over the ridge crest into the back-barrier and returned to the beach face as the barrier structure moves landward (Carter & Orford, 1980; Orford *et al.*, 1991). Clasts that are too large to be moved in the recycling process, as in the case of the outer frame (beach toe) boulders, are left behind as a lag trailing the migrating barrier. This is the transgressive lag of Facies B as discussed in Chapter 3. The rate of sediment supply to the study area was considerably reduced at that particular time to allow the development of a thin transgressive boulder sheet.

‘Rollover’ rates are dependent on a number of imposing factors, but can be remarkably fast. For example, it has been shown that barrier beach migration at Story Head, Nova Scotia was rapid with one ‘rollover’ completed in five to six years (Orford *et al.*, 1991). Comparatively, barrier migration in southern Ireland was recorded to be considerably slower where one ‘rollover’ is accomplished in four to five thousand years (Orford *et al.*, 1991). The rate of sea-level rise obviously influences ‘rollover’ rates, but the barrier’s passage is equally manipulated by the underlying geology over which it migrates. Where unconsolidated fluvial sediments form the floor of the migration path, such as that within the study area – where

landward space is also made available within a palaeo-river mouth setting – barrier migration would be unimpeded as discussed above. In contrast, a bedrock floor would slow the rate of sea-level rise. The transgressive front would be obstructed during erosion of more competent rock, encouraging bedrock planation and cliff cutting. Consequently, rates of sea-level rise can differ along the same coastline, leading to laterally disjointed sequences as in the case of the study area. For example, the beaches fronting the ‘F’ cliff are not laterally (coast parallel) contiguous with the barrier beaches of the same age that are developed within the palaeo-Orange River mouth. The latter are developed farther inland due to their unimpeded advance (see Figure 4.2B(3 & 4)).

There are several lines of evidence suggesting that the barrier beaches were at some point stationary to perpetuate growth and more importantly to enter into a process of self-organisation once positional stability was achieved (Forbes *et al.*, 1995; Orford *et al.*, 2002). Beach progradation and the textural maturity reflected by the high degree of cross-beach clast size- and shape-sorting into distinct zones are manifestations of barrier stability (Forbes *et al.*, 1995). It also implies that there was renewed, adequate sediment supply to encourage progradation. The rate of sediment supply, however, was sufficient to maintain the correct level of self-organisation. An insufficient supply of sediment may favour the breakdown of existing features, whilst excessive amounts will saturate the beach limiting the potential for self-organisation (Forbes *et al.*, 1995). By inference, the sediment supply rate during barrier beach evolution was therefore not as aggressive as that during barrier spit times. Moreover, the textural maturity of barrier-sediments (size- and shape-sorting) is also a proxy to barrier migration behaviour. Slow migration rates allow the development of discrete cross-beach sorting zones, whereas the propensity for cross-beach zonation is reduced during rapid rates of migration (Orford *et al.*, 1991; Forbes *et al.*, 1995).

Once positional stability was achieved, growth of the shoreline was perpetuated through renewed sediment supply. Fringing the bedrock-cliff, linear beach growth had no accommodation space to yield barrier forms and thus the deposits were ‘fixed’ as described by Carter & Orford (1984), whereas barrier beach growth was unobstructed during their migration. The bedrock-cliff edge may have possibly formed an anchor point, similar to a headland, to which the barrier beaches attached.

The abundance of sand in the form of sand beaches implies that a flux of excessive sand was injected into the foreshore to accrete as a sand bar, only to be later veneered and stabilised by gravel (Bluck, 1999). However, field evidence shows that sand beach progradation was considerable and thus their persistence in the depositional record is primarily due to substantial volumes (Orford *et al.*, 2003). More significantly, sand deposition in a gravel-dominated system suggests a switch from reflective (gravel deposition) to possibly dissipative conditions (Orford *et al.*, 2003). While a reflective regime can be maintained during sand deposition when sand volumes are low and in deficit (Orford *et al.*, 2003), the sand beaches seen within the study area demonstrate sediment surplus and therefore dissipative conditions were, at times, possibly prevalent. Reflective conditions would return during renewed gravel influx, which is evident in the trench sections. Consequently, the change from reflective to dissipative and a return to reflective conditions with associated changes in sediment deposition will have an obvious effect on diamond concentration.

Inasmuch as there is conjectural evidence for a declining sediment supply, the wave climate has conversely remained the same. Similar to the modern Terrace Bay beaches along the Skeleton Coast, the ED Area barrier beaches have a morphological predominance typical of reflective conditions, suggesting that neither the wave energy nor the relative tidal range has changed (see Wells, 1996, pg. 11). This is further supported by the alignment (north-east to south-west) of the barrier beaches (beach ridges of the 'E' and 'D' sequences in Figure 4.1), which are similar to the present-day coastal configuration and also by the direction of beach face progradation, that is, predominantly towards the south-west. These, as in the case of the barrier spit, indicate that the direction of wave propagation was similar to that of today.

In summary, the ED Area barrier beach complex has originated, in part, from the atrophy of a barrier spit that segmented into a free-standing barrier due to a diminishing sediment supply during a sea-level rise. Through a process of 'rollover', the barrier beach migrated landward leaving in its wake a trail of boulders that were too large to be transported. Barrier coherency (see Orford *et al.*, 2001) was still maintained by virtue of volume sustainability during landward migration. With space afforded by the palaeo-river mouth setting, the landward advance of the barrier would have continued unimpeded and once maximum transgression was reached, the barrier beach entered into a state of positional stability. Here, renewed sedimentation promoted progradation and self-organisation where textural maturity was achieved.

4.4 GENESIS OF THE STRATIGRAPHIC ARCHITECTURE

Despite the lack of control dates which make it difficult to integrate the detailed mapping with regional sea-level curves, a depositional time frame can nevertheless be roughly estimated. If a maximum age, although inconclusive, of 3.5 Ma is considered for the ED Area deposits based on Pickford & Senut's (1999) work (see Chapter 2, Section 2.2), then a minimum age can be ascertained from the younger 'Lower Terrace' suite. Here, the oldest beach of the 'Lower Terrace' suite, notably the 'C' beach, has eroded into the ED Area shoreface deposits. The 'C' beach was tentatively dated as 0.40 Ma (Rogers *et al.*, 1990, see Chapter 2, Section 2.2). These estimates are obviously conjectural, but they give an indication of the time frame in which the ED Area deposits evolved (some 3 Ma).

Six main stages have been recognised from the key sections and demonstrate how sea-level behaviour has controlled the evolutionary paths of the ED Area deposits within this time frame. A degree of caution is applied in the development of these models as only a window of the entire MA1 beach stratigraphy is considered and more significantly, there is no detailed linking to either the offshore and Orange River fluvial geology.

Stage 1: Barrier spit growth

It is difficult to reconstruct the coastal configuration during this stage, but there is conclusive evidence that during the evolution of the study area, a barrier spit became attached to a bedrock promontory. This is the G25 barrier spit. There may have been a number of barrier spits separated by back-barrier environments and their lengths may have extended considerable distances. The signatures of these deposits have been removed and the only expression of barrier spit growth at that time is the bedrock-attached remnant (BS1 in Figure 4.8), which records progradation before the coastal system entered into a state of erosion where the spit feature was trimmed back. Thus, the extent of the beach-ridge plain (width of progradation) of 120 m as seen in section was likely to have been a remnant of a formerly extensive sheet of spits. Reworking and segmentation of the spit feature into cells would have occurred on a diminishing supply of sediment leading to the formation of type D2 barriers (Forbes *et al.*, 1995) that have entered into a breakdown phase. The segmented remnant (BS1 in Figure 4.8) at the G25 sample trench is not only a product of this phase, but also marks the most landward position of a barrier spit within the study area.

Stage 2: Barrier spit abandonment

The main feature of this stage is a change in position of sediment delivery to induce barrier spit abandonment. It is envisaged that the locus of sediment delivery shifted farther south through channel avulsion and with renewed sediment supply, a new barrier spit (BS2) emerged seaward of the older landward barrier (BS1; Figure 4.8). With sediment now directed to and bolstering the down-drift growth and seaward extension of the new barrier (BS2), erosion of the older de-activated spit feature (BS1) continued to a point where it became impounded and protected from wave attack by the down-drift growth of the new barrier spit (BS2). Once completely cut off from the ocean, the older barrier remnant (BS1) remained inactive indefinitely. The emergence and growth of the new barrier spit took place during the same progradational phase as that of the older barrier spit (BS1). It is thus envisaged that growth of barrier spits BS1 and BS2 were during a normal regression and they represent only part of the highstand record, whilst the subsequent forced regression and lowstand signatures have been removed by a transgression during Stage 3.

Stage 3: Barrier spit erosion

An erosion surface can be seen in the G25 trench section where it occurs at approximately 8 m above msl, approximately 2 m above the base of the barrier spit (Figure 4.8 (1)). This surface cannot be traced throughout the study area, but is apparent only in the foreshore gravels at G25 where it is, for a limited distance, marked by a horizontal layer of large blade- and sphere-shaped clasts (see Figure 3.5A). The fact that these clasts are an extension of the overlying foresets (see Chapter 3) indicate a beach toe environment and consequently, the erosion surface separates two vertically stacked foreshore environments. More importantly, assuming that clast shape sorting was present, the sub-aerial, large disc zone of the foreshore environment below the erosion surface and belonging to BS1 has been removed, supporting an erosional event (Figure 4.8 (3)). The stacking of two foreshore environments into a five metre or possibly thicker sequence (Figure 4.8) within a micro-tidal coastal setting with an approximate tidal range of 1.8 m is a reflection of a transgression. In such coastal settings, Bluck (in press) demonstrates that the height of a gravel beach (the vertical distance between the beach toe and beach ridge) is related to the tidal range, and heights of less than 2 m typify the Namibian Coast. In this setting, however, gravel beach thickness of 2.2 m can be at times slightly greater than the tidal range due to the overprint of storm wave activity (Bluck, in press).

The transgressive event culminated in the emplacement of barrier spit BS3 and growth of this coastal feature was perpetuated during the highstand stage (normal regression). Noteworthy is the lack of conglomerate clasts within the BS3 sediments, indicating that the interval between Stages 1 and 3 was possibly short and thus pedogenic processes, such as calcretisation to cement the gravels at surface, were thwarted.

Stage 4: Barrier spit breakdown and emplacement of barrier beach

This stage correlates to a major perturbation, provoking a change in depositional style from barrier spit to barrier beach. This change can be progressive where a continuum of deposits evolves in response to various perturbations (see Orford *et al.*, 2001). Two perturbations leading to and driving the evolution of the barrier beach are evident in Stage 4. The first corresponds to a forced regression allowing the coastline that is dominated by barrier spits to shift seaward with an associated development of coastal features at successively lower elevations, resembling a tier of ridge plains. Evidence for estimating the distance of seaward shift has been removed by subsequent sea-level changes, but it is likely that the most seaward shoreline was offshore of the present study area. A key response to such a regression was the introduction of boulder gravel during river incision as a means of adjusting to the new base level. The boulders would have accumulated as outer frame clasts to form a platform over which the beach-ridge plains extended as the shoreline grew seaward. In addition to this boulder input, erosion of older higher-lying beach terraces, more specifically those correlating to the 50 m Package, allowed the introduction of conglomeratic material of that age into the regressing system when the ephemeral drainage network was rejuvenated.

The second and more significant perturbation correlates to a subsequent transgression. This is recorded in the ravinement surface that truncates pre-existing barrier spit deposits and the bedrock island. Armoured by a boulder lag, its most landward end (as seen from available exposures) occurs approximately 10 m above msl. A deficit in sediment budget would have accompanied the transgression thereby causing active barrier spit features to enter into a phase of progressive atrophy and finally fragment into a cohesive free-standing barrier beach (BB1 in Figure 4.9). With a rising sea-level, the barrier (BB1) migrated landward, reworking pre-existing barrier spit deposits into the “rollover” process. Estuarine-lagoon clays found in washover deposits at the G19 trench attest to the process of ‘roll-over’ reworking whereby washover is the driving mechanism (Leatherman, 1983). If gravel sediment is in surplus, sourced from pre-existing barriers, the transgression is consequently at

times punctuated by periods of stability and progradation. However, the sediment source is rapidly consumed with a concomitant leakage to the littoral and thus with an exhausted sediment supply, barrier migration is reinitiated. Therefore, the landward migration is seen as alternating phases of 'roll-over' during sediment starvation and temporary periods of barrier stability during sediment recharge. The manifestation of these evolutionary changes is the development of multiple beach ridges as a result of progradation (beach-ridge plain) and a solitary ridge when the barrier is in a 'rollover' state (Orford *et al.*, 2002). The latter typifies the culmination of Stage 5 leading to barrier development in Stage 6.

The platform of outer frame clasts, being a source of pre-sorted boulders from the preceding forced regression, would have possibly been reworked to a point where they became too large for further entrainment and are left behind in the wake of the migrating barrier as a trailing lag. However, a large part of their depositional character such as the down-drift size sorting was likely to have been inherited from the forced regressive deposits. In addition to these inherited clasts, the 30 m Package conglomerate boulders (see Chapter 3, Facie B) were sourced from the pre-existing barrier spits. These boulders thus support the assumption that the beach-ridge plains of these pre-existing deposits were exposed and inactive for a protracted time allowing pedogenic calcretisation of their sub-aerial parts before the onset of sea-level rise. This is in contrast to the shorter duration of Stages 1 to 3.

Planation of the bedrock island as sea-level migrated landward did not produce bedrock clasts due to the weathered nature of the schist. This is evident from the lack of such clasts within the transgressive lag (Facies B). However, despite the bedrock incompetence, poorly developed gullies and potholes were cut preferentially along joint and fracture plains, similar to the mechanisms discussed by Jacob (2001). It is important to note that once bedrock planation was completed, the influence of bedrock in the development of the barrier beaches (Stages 5 to 7) was inconsequential.

Transgressive lags are a reflection of a sediment-starved system (Carter *et al.*, 1989) and more importantly, they also signify aggressive sorting with a concomitant removal of sediment to leave no evidence of previous shoreline positions. This is best achieved during a slow rate of sea-level rise (Davis Jr & Clifton, 1987). It therefore brings into question the survival of barrier spit and associated estuarine-lagoon remnants seen in exposures below the transgressive lag. Although a sea-level rise is advocated as the main mechanism to create

accommodation space for their preservation, subsidence due to compaction as discussed in Section 4.1 is suspected, but definite evidence thereof is lacking. In addition, it can be argued that the rate of sea-level rise may have accelerated. However, the armoured ravinement surface displays no change in its steady landward projection, indicating that sea-level rise remained constant. For whatever reason to induce their preservation, two end members were generated at the point of sea-level deceleration into a highstand. These are the preserved barrier spit deposits (BS1, BS2 and estuarine-lagoon of BS3) below the transgressive lag and a barrier beach (BB1) that reached a point of positional stability where growth of the 'E' barrier complex was initiated.

Stage 5: Growth of the 'E' barrier beach complex

This stage records the vertical growth of the barrier complex through sequential transgressions, normal regressions and forced regressions. Each cycle of normal regression is bounded by an erosion surface where approximately two metres of sediment have been preserved below these surfaces. The last occur at some 12, 14 and 16 m above msl. Similar to the barrier spit sequence, only the sub-aerial parts of the barrier beaches, notably the large disc zones, were removed resulting in the preservation of the middle (swash berms and cusps) and lower beach (outer frame; BB1 to BB3 in Figure 4.9) faces, save for the topmost barrier beach (BB4 in Figure 4.9) where the entire foreshore and backshore deposits have been preserved.

The development of the vertical succession in Stage 5 can be explained using Donselaar's (1989) model for the stacking of transgressive barrier deposits recorded in the Cliff House Sandstone in New Mexico, U.S.A. Although, the scale of these deposits is significantly larger and comprising fine-grained sediments, the concept of vertical stacking or 'stepping-up' can be simplistically applied to Stage 5. The 'step-up' begins with a landward shift of the barrier shoreline (BB1) that was initiated during the Stage 4 transgression where a ravinement surface was cut (Figure 4.9). At some point in time, the barrier's (BB1) migration slowed down as sea-level rise decelerated into a highstand, allowing the barrier to achieve positional stability and enter into a phase of progradation. An ensuing forced regression, followed by a lowstand saw the shoreline shift seaward to a position offshore of the study area. However, the deposits related to these regressive events were removed during the next transgressive phase of landward barrier translocation (BB2), which also eroded the upper parts of barrier BB1 (Figure 4.9). The emplacement and growth of barrier beaches BB3 and

BB4 were encouraged through similar sea-level and sedimentation cycles, thereby building up the barrier beach complex to culminate in a fully developed barrier feature (BB4).

The stratigraphically highest exposure (BB4 in Figure 4.9 (3)) of Stage 5, characterised by its solitary geomorphic 'barrier-hump' reaching approximately 21 m above msl and the complete preservation of the barrier beach environments, marks the end of the 'stepping-up' process. Its preservation thus reflects a major perturbation rather than regressive/transgressive spasms that are recorded in the overall transgressive build-up. In fact the complete preservation of the BB4 barrier beach marks a turnaround from a transgression to a rapid forced regression leading to the abandonment of the entire study area. It is clear from the gravel fabric, where clast size and shape sorting is evident, that the barrier (BB 4) remained static prior to its abandonment and is therefore an example of a completely preserved transgressive S2 type barrier beach of Forbes *et al.* (1995). This transgressive signature is also evidenced from the washover deposits and the development of a single ridge structure (see Orford *et al.*, 2001). Noteworthy, is that transgressive barrier shorelines are characterised by a dominance of overwashing that drives the 'roll-over' process and hence the presence of washover deposits (Carter & Orford, 1981; Orford & Carter, 1982; Sedgwick & Davis Jr, 2003). The survival of the BB4 beach ridge structure during 'roll-over' where overwashing is highly active, suggests that sediment was in supply during barrier retreat and in doing so, a sufficient volume of sediment was maintained in the 'roll-over' process to sustain a coherent barrier structure that is elevated in relation to rising sea-level (Orford *et al.*, 2002). On the subsequent forced regression, pedogenic calcretisation of the surface gravels prevented sub-aerial erosion of the surface deposits, thereby preserving the original geomorphic 'barrier-hump' of BB4.

The history of sea-level movement during Stage 5 is then one of continuous rise, punctuated by high frequency regressive/transgressive pulses. As shown by Donselaar (1989), the shoreline in such a setting thus remains within a narrow belt where vertical stacking of foreshore and backshore environments takes place, which is clearly seen in the G29 key section. More significantly, only a portion of each highstand accumulation is preserved and these accumulations are bounded by transgressive erosion boundaries, save for the stratigraphically highest barrier where the topographic ridge is preserved (Figure 4.9). It also envisaged that the forced regressive pulses were possibly minor (i.e. they may have not extended beyond the shelf edge) to preclude the introduction of large boulder-grade material,

which is evidently lacking within the 'E' barrier beach complex. In addition to this, gravel delivery by the palaeo-Orange River may have not been as vigorous as that during barrier spit times (Stages 1 to 4) and a greater sand component is more characteristic of the barrier beach evolution, suggesting a change in the Orange River sediment delivery.

Considering that the build-up of the barrier beach complex was a result of high-frequency sea-level oscillations, the lack of conglomeratic clasts within the entire barrier complex is a reflection of a rapidly evolving coastline, preventing pedogenic calcretisation of surface deposits during the development of barrier beaches BB1 to BB3 (Figure 4.9). Correlation of the shoreface sequence (ST1 and ST2 in Figure 4.9) to the 'E' barrier beach complex proved difficult given the poor preservation potential of shoreface deposits where high energy waves lower wave base to a great depth, as recorded in the present Atlantic Ocean. Here shoreface erosion is operative at depths of 20-30 m (see Chapters 1 and 3). Given that the accommodation space between the transgressive boulder lag and the stratigraphically highest barrier beach (BB4) is well within this depth range at some 10 m, the shoreface sediments were recycled continuously on each transgressive event into the shelf bypass system where it was removed by longshore drift. The result is that no shoreface sediments of the 'E' barrier beach complex were preserved. Deeper water sediments are, however, likely to be found farther seaward (west) of the key trench section. The sedimentary sequences below the transgressive lag, which are still within the depth range of shoreface erosion, were preserved due to the boulder lag armouring the surface (Figure 4.9). Although wave energy at this depth of approximately 10 m would have been greater than that recorded for depths of 15 m in the modern shoreface where small cobbles are moved in storm conditions (de Decker, 1988), and given that the wave energy has not changed significantly through time, it is unlikely that the transgressive boulders up to one metre in diameter would have been moved.

The preservation of deeper shoreface sediments (Sub-facies D1 in Chapter 3 and ST1 in Figure 4.9), which were correlated roughly to depositional depths greater than 40 m, cannot be explained. The possibility that these sediments are correlative to an older shoreline that was emplaced further inland of the study area is unlikely, as they would be stratigraphically positioned below and truncated by the transgressive boulder lag.

Stage 6: Emplacement of the 'D' barrier beach

This stage represents the last depositional episode of the ED Area Plio-Pleistocene deposits. Orange River incision accompanied the rapid forced regression that caused abandonment of the 'E' barrier beach complex in Stage 5. It is envisaged that the magnitude of the forced regression was significant to sub-aerially expose shelf sediments and allow river incision to deliver coarse gravel to the shoreline. As sea-level, once again, entered into a transgressive phase, it did not rise to the same height as that of the previous transgression in Stage 5; it was at least approximately 3 m lower, depositing barrier beach BB5 (the last of the 30 m Package barriers; Figure 4.9(1)). This evolutionary path is in contrast to the transgressive events in Stage 5 where successively higher transgressions built up the barrier beach complex.

The Stage 6 transgressive event 'bulldozed' the coarse gravel regressive shorelines, incorporating the sediments into the 'roll-over' process and thus removed all signatures of earlier regressive events as the shoreline shifted landward. The gravel character of the barrier beach (BB5 in Figure 4.9; 'D' barrier beach) is strikingly coarse with boulder clasts making up the large disc zone (beach ridge) and outer frame (beach toe) environments. Field evidence demonstrates that the base of the barrier beach, which is demarcated by boulder-grade outer frame spheres, rests at some 13 m above msl, approximating the stratigraphic position of the transgression (Figure 4.9(1)). Noteworthy, is that the transgression eroded into and reworked part of the 'E' barrier beach complex, removing the entire suite of shoreface sediments.

On reaching stability during the highstand, barrier progradation ensued, but this was not significant as evident from the length of outer frame growth, which is approximately 100 m. The barrier crested to 18 m above msl, producing a typical geomorphic 'barrier-hump' (Figure 4.9(1)). However, unlike the 'E' barrier beach complex, the entire 'D' shoreline, notably its barrier beach and parts of the shoreface which extend for some 1.4 km, have been preserved. This degree of preservation could have only been possible when the entire shoreline was abandoned on a rapid sea-level fall. The fact that foreshore deposits do not extend seaward over their shoreface equivalents, lends support to a rapid forced regression. Such a rapid sea-level fall has the propensity to promote the formation of detached, forced regressive deposits (Posamentier & Morris, 2000). Here, a zone of significant separation exists between regressive wedges so that the shoreface sediments are not immediately attached to preceding highstand deposits (Posamentier & Morris, 2000). Therefore the 'D'

barrier beach (BB5 in Figure 4.9) is a preserved product of a highstand event that preceded the formation of seaward stepping, detached forced regressive deposits. Only the sediments that accumulated during the normal regression (highstand) were preserved. Here progradation of the shoreface sediments generated a shallowing and coarsening-upward succession (ST 1 & 2 in Figure 4.9; see also Chapter 3). This is typical of a normal regressive stack (Walker, 1984; Helland-Hansen & Martinsen, 1996; Nichols, 1999).

Although not forming part of this study, mention must be made that next transgressive phase, namely the ‘C’ barrier beach, dated at roughly 0.4 Ma, eroded into the ‘D’ shoreface sediments, but did not rise to the same level as the ‘D’ barrier beach (BB5 in Figure 4.9); it was approximately eight metres lower. Worthy to mention is that the gravel make-up of the younger ‘C’ beach was also impressively coarse with large-cobble to boulder-sized clasts occupying the beach ridge and outer frame foreshore environments. Mention has been made in Chapter 3 that the ‘C’ beach is assigned to the younger ‘Lower Terrace’ suite of Stocken (1962) and Hallam’s (1964) informal beach stratigraphy, which contains the zone fossil *Donax serra*.

4.5 SUMMARY

The architectural stacking of the ED Area barrier deposits are a result of high frequency sea-level oscillations of small amplitudes over short time spans. It is envisaged that these were a combination of spasmodic minor and major transgressions-regressions that promoted the development of barrier deposits. Major regressions also encouraged the introduction of coarse gravel, up to boulder size, to the shoreline. Whereas older marine deposits reworked during the transgressions, were a secondary source of gravel material. These high-frequency (fourth-order) cycles are superimposed on an overall transgressive cycle (third-order cycles) that was responsible for depositing the 30 m Package shoreline along the entire west coast of South Africa and the Namibian coast. The abandonment of the 30 m Package shoreline is a result of a rapid major regression, as evidenced from the architectural character of the ‘D’ barrier beach. In addition to this, the accommodation space afforded by the palaeo-river mouth allowed unrestricted landward migration of shorelines and also enhanced the preservation potential of barrier deposits. Only remnants of highstand deposits (normal regressive packages) are preserved in a 16 m thick sequence. Besides coastal subsidence through sediment compaction or tectonism, it can be argued that the hyper-arid

climate where surface pedogenic processes (calcretisation) and the deposition of aeolian dunes onto the barrier-deposits, in part, aided this degree of preservation. Mention must be made that 30 m Package remnants elsewhere along the Namaqualand and Namibian coasts, outside of the study area, rarely reach a thickness of six metres (see Chapter 6).

4.5.1 Problems with the depositional models

Stages 1 to 3: Barrier spit

A minor transgression is interpreted during these stages where the landward translocation of the shoreline (BS3) has eroded earlier barrier spit deposits (BS1 & BS2). The erosion surface (erosion surface 1 in Figure 4.8 (1) & (3)), characterised by a near-horizontal layer of large sphere- and blade-shaped clasts (see also Figure 3.5A), is seen as a hint of sea-level rise that removed the large disc zone of BS1, which is commonly confined to the barrier ridges, assuming that there was some degree of clast shape sorting. The erosion surface, however, cannot be traced throughout the trench section and is only confined to part of the foreshore gravels (see Figures 4.8 (1) & 4.10). This limited extent does not lend much support to a transgressive event and the only conclusive evidence for a transgression is the vertical stacking of foreshore environments into a five metre thick sequence where the coastal regime is micro-tidal (Figure 4.8 (1) & (3); Figure 4.10).

Once sea-level rise reached a standstill (highstand in BS3 times; Figure 4.8 (5)), a normal regression saw the BS3 shoreline prograde seaward. Therefore foreshore deposits of BS3 are expected to extend over deposits of earlier barriers (BS1 and BS2 in Figure 4.8 (5)), which includes the estuarine-lagoon clays of BS2 (Figure 4.8 (5)). There is, however, no evidence for the latter and in fact, the remnant of estuarine-lagoon clay of BS2 has a total thickness similar to that of the entire stacked foreshore deposits (stacking of BS1 & BS3); that is, five metres. This would suggest that the topmost barrier (BS3) would have also been cut off from open coast conditions by a seaward emerging barrier (BS4 in Figure 4.10D), leading to the deposition of back-barrier clays that front older barrier spit deposits (BS3) and in turn overlie older estuarine-lagoon of BS2 (Figure 4.10D). However, in view of the latter, there is no indication (such as an erosion surface) to separate the two estuarine-lagoon sequences belonging to BS2 and BS4 that are not time-equivalents (Figure 4.10D)

Stage 6: Emplacement of the 'D' barrier beach

Gravel in the 'D' barrier beach is exceptionally coarse where, for example, boulders constitute the outer frame component. It has been interpreted that a forced regression provided the impetus for renewed river incision to deliver such coarse material to the coastline (as envisaged for Stage 4). Therefore, it would be expected for the subsequent transgressive event to cut a boulder-armoured ravinement surface. Such a lag is, however, lacking and its absence remains unexplained. It therefore could be argued that the 'D' barrier beach represents a detached regressive sequence, following the 'E' barrier beach highstand deposition. If this is considered, shoreface sediments of the latter would be preserved between the two barriers. Field evidence, however, suggests a different architecture where 'E' barrier shoreface sediments have been eroded by a landward migrating 'D' shoreline. This adds credence to a transgressive event.

CHAPTER 5 – DIAMOND MINERALISATION

5.1 INTRODUCTION

Resource estimation of placer deposits is complicated due to the heterogeneity of the deposits and the patchy mineralisation patterns. Note that a placer deposit is defined as, ‘Surficial mineral deposits formed by mechanical concentration, commonly by alluvial, but also by marine, aeolian, lacustrine and glacial agents, of heavy mineral particles such as gold from weathered debris’ (Hails, 1976; cited in Guilbert & Park Jr, 1985, p. 743).

Diamond placers are no exception and have a highly variable distribution of diamonds where ‘pools’ of higher concentrations, as a result of clustering, promote a nugget mineralisation pattern (see Sichel, 1973). In view of this, and when compared to other more homogenous mineral deposits (as illustrated in Figure 5.1), diamond placer resources (alluvial and marine) are amongst the most difficult to estimate. Another reason for this difficulty is the low grade of diamond concentration (Figure 5.1). For example, the average grade mined from the Witwatersrand gold placer (the entire Witwatersrand basin) prior to the 1990s was approximately, 7 ppm (parts per million, which equates to 7 grams of gold per ton; Guilbert & Park Jr, 1985). Comparatively, the total diamond production from the Namibian mega-placer, over a period of 73 years, totals 56 million carats from 407 million tons of ore processed (Schneider & Miller, 1992). Using parts per million for comparison, this translates to a grade of 0.03 ppm. Note that one part per million is equivalent to one gram per ton (Peters, 1987) and a metric carat equals 0.2 grams (Lynn *et al.*, 1998).

Comparing the study area to the above, and using parts per million for ease of comparison, the average grade for the entire ED Area is considerably lower at approximately 0.003 ppm. This is also lower than the bedrock-floored linear and pockets beaches that are developed farther down-drift, as discussed in Chapter 2. However, the deposits within close proximity to the Orange River mouth yield the largest average diamond size within the Namibian mega-placer. On average, it is approximately 1.3 carats per stone in the study area. The largest diamond recovered in the ED Area weighed 245 carats (Hallam, 1964) and 211 carats at Alexander Bay in South Africa, on the opposite (south bank) of the present Orange River (Keyser, 1972). This occurrence of larger than average diamonds at the terminal point of the fluvial delivery has been viewed as anomalous (for example Sutherland, 1982). Most

fluvial diamond placers, as demonstrated by Sutherland (1982), exhibit downstream fining in the diamond size due to fluvial sorting with increasing distance from the source rock. The degree of change in size is dependent on the distance travelled. As an example, Sutherland (1982) demonstrates that the average diamond size at the distal point of the Sewa River in Sierra Leone, West Africa, would be approximately 80% smaller than that found in the proximal reaches, if transported over a distance of 170 km from source.

Figure 5.2 illustrates the average diamond size for Meso-age terraces along the Orange River course over a distance of approximately 1,000 km. These results are from either mining or prospecting operations. It is clear from the figure that the change in average diamond size in the direction of transport is not significant. The size within the ED Area is approximately one-third of that occurring upstream at Silverstream. This is in marked contrast to the general principal that diamond sizes diminish significantly with distance as discussed by Sutherland (1982). Although viewed as anomalous, the large average diamond size at the Orange River mouth is in fact ascribed to the anomalous nature of the Orange River as described by Ward & Bluck (1997), Jacob & Bluck (2002) and Jacob (2005). They demonstrate that:

- 1) The steep gradient of the ancestral Orange River increased flow competence to transport boulder-size gravel. The latter was sourced from the escarpment comprising Precambrian country rocks (see Figure 2.2 for reference to escarpment and Chapter 2 for review of regional setting).
- 2) As the ancestral Orange River evolved, the gravel bed-load size coarsened, particularly so during the deposition of the Meso-fluvial terraces (Plio-Pleistocene times) where large boulders were delivered to the Atlantic Coast.
- 3) Coarse gravel input from tributaries into the main channel has played a critical role in increasing the gravel bed-load size at the most distal reaches of the Orange River. Similar to the diamonds, the gravel size distribution thus bears no resemblance of typical hydraulic sorting where a systematic downstream decrease in gravel size is expected.

Diamond size distribution in the Meso-Orange River deposits is, therefore, not an expression of typical fluvial sorting as shown by Sutherland (1982); a fact also realised by van Wyk & Pienaar (1986). This unusual distribution is possibly a reflection of the influence of flash-flooding rather than continuous flow. With hyper-arid conditions already in place

during the Plio-Pleistocene (Meso-times; Ward *et al.*, 1983; Ward & Corbett, 1990), inconsistent discharge rates – from peak floods to periods of no river flow, as it occurs today – would have not been unusual for the Orange River, even though it is regarded as a perennial system (Bluck, *et al.*, 2005). In contrast, the Central and West African drainage systems (modern and Cretaceous) that have been investigated by Sutherland (1982) are, and have been since these times, in perpetual flow. It would, therefore, be erroneous to apply Sutherland's (1982) statistical model to the Orange River, given the unusual character of the river as discussed above and in Chapter 4.

However, unlike the palaeo-Orange River deposits, a decrease in diamond size within the palaeo-littoral deposits of the Namibian mega-placer is strikingly evident in a down-drift direction with a 77% decrease in size over a distance of 110 km (see Sutherland, 1982; Schneider & Miller, 1992). This is attributed to longshore sorting (Hallam, 1964; Sutherland, 1982; Bluck *et al.*, 2005). As mentioned earlier, the largest average diamond size occurs within deposits close to the Orange River mouth. Hence, the decline in size only starts at the point where the outfall of fluvial sediment is reworked by marine processes. This is the ED Area, which represents the transitional boundary between the fluvial (Orange River) and the marine (Atlantic Ocean) 'conveyors'; more specifically it is the end of the fluvial sediment delivery and the start of the marine reworking. Here, coarse gravel and a range of diamond sizes are introduced at this boundary, which are in turn, reworked and dispersed in a down-drift direction by longshore processes. The result is a northward decrease in gravel and diamond size, down-drift of the ED Area (Hallam, 1964; Sutherland, 1982; Schneider & Miller, 1992). The larger diamonds are thus retained in the coarser gravel that is within and near to the palaeo-Orange River mouth. The smaller diamonds, however, are released into the littoral zone, due to poor retention by the coarse gravel fabric, to be deposited in linear and pocket beaches. The ED Area can therefore be viewed as a giant 'sieve', filtering out the fine-grained diamond population into the littoral zone.

This process of natural 'sieving' whereby diamonds are either retained or filtered out is controlled by sediment pore size, which in turn, is allied to gravel fabric. Worthy of mention is that the diamond concentration process within the Plio-Pleistocene littoral deposits was active only after the main influx of diamonds to the Atlantic Coast; approximately 20 million years later. Sea-level fluctuated considerably since the influx of diamonds and it is likely that diamonds were concentrated in various ways at each sea-level change. It is thus,

remarkable that a general down-drift (northward) decrease in diamond size was maintained throughout the evolution of the Atlantic coastline since the main introduction of diamonds.

Diamond delivery to the coast was shown to be one of diminishing trend with minimal input during the Plio-Pleistocene and very little thereafter. Diamond introduction was at its peak during the Late Oligocene and Miocene (see Chapter 2; Bluck *et al.*, 2005; Jacob, 2005). Notwithstanding, this decline in diamond input, the Plio-Pleistocene littoral deposits are highly diamondiferous, suggesting that the offshore sector was an alternative source whereby diamonds were scavenged from pre-existing beach deposits during sea-level fluctuations as described in Chapter 2. Therefore diamond concentrations within the host sediments are seen as products of recycling, but conditions for their entrapment had to be in place to ensure optimum mineralisation of the deposits. Diamond size, nonetheless, retained a longshore diminishing trend away from the Orange River mouth in part due to the inheritance of pre-sorted diamond populations, coupled with a high degree of hydraulic sorting.

When the diamond characteristics such as shape, colour and surface features are considered, some trends are apparent. Studies on a population of littoral diamonds (having average sizes of 0.07 carats, 0.25 carats and 0.9 carats) from palaeo-linear beaches north of the study area, showed that the diamonds, displayed the following features (D. Robinson, pers. comm., 2009):

- 1) Dodecahedral diamonds are the dominant crystal form followed by octahedral shapes;
- 2) Yellow is the dominant colour and is typical of 'Type 1' diamonds, which have a higher nitrogen content and are thus tougher (Seal, 1990);
- 3) Appreciable abrasion features are relatively scarce; and
- 4) Large percussion scars are common, as a result of impact with other transported particles such as diamonds and to a lesser degree, gravel clasts.

As noted by Sutherland (1982) diminishing size during transport can be attributed to either preferential downstream transport of finer-grained diamonds or breakage and attrition of large, inferior quality diamonds. Extreme rounding of a diamond due to transportation is rare, whilst abrasion features for transported diamonds are more typically manifested in a 'frosted' appearance at crystal points and edges (D. Robinson, pers. comm., 2009). Given that the littoral diamond population exhibit features suggesting that attrition and breakage is

negligible, the diamond distribution along the coast is thus an accurate measure of hydraulic sorting in the littoral zone as noted by Sutherland (1982). The breakage and attrition of lower quality diamonds, as well as percussion scarring, would have taken place mainly during fluvial transport.

Aside from the publications by the author (included as Appendix A), the mechanisms of diamond entrapment and retention in barrier beaches and barrier spits within river mouth settings have not been documented due to the scarcity of such diamond-bearing deposits. Although, the ED Area is considered a giant 'sieve' to the littoral zone, diamonds would have nonetheless accumulated in various degrees of concentration within certain parts of the deposits. Therefore, this chapter, being the first record of diamond distribution in such settings, will focus on correlating the diamond data to various facies as a means of highlighting specific mineralisation patterns. In addition, through an understanding of the physical conditions under which the different facies accumulated as discussed in Chapter 3, the mechanisms that controlled diamond mineralisation patterns can possibly be inferred at a facies level. In this context, diamonds are thus merely a component of the gravel. They are clasts with a specific density of 3.51 g/cm^3 (Cairncross, 2004) deposited with other gravel clasts of different compositions that may have similar (for example epidote at 3.4 g/cm^3 to 3.51 g/cm^3 ; Cairncross, 2004) or different densities (for example quartz at 2.7 g/cm^3 and banded ironstone at 5.18 g/cm^3 to 5.26 g/cm^3 ; Macintosh, 1983). Note that although the term 'mineralisation' is used almost exclusively for the introduction of ore and gangue minerals into a pre-existing host rock (Whitten & Brooks, 1987), it is at times used loosely to describe the accumulation of detrital diamonds in placer deposits (see Duggan *et al.*, 2007; SAMREC, 2007).

Owing to the low grade and limited sampling, a basic statistical analysis of diamond data for each depositional sub-environment has been undertaken. This chapter, documents the results and analysis of sample data obtained from three main exploration programmes undertaken during the 1950s, 1970s and early 1990s. Mention must be made that this analysis on barrier beach and barrier spit deposits is the first of its kind. The raw data used are included in Appendix B and on a compact disc (CD) accompanying the appendix volume. In this analysis, two parameters are considered important (see also Appendix B):

- 1) Average grade (diamond concentration); this is based on the stone density distribution in a given sample unit (recorded in tons) and is expressed as stones per hundred ton (spht). (Note that diamonds are also loosely referred to as stones in this study).
- 2) Average diamond (stone) size; this is the average weight of the diamonds for a given sample unit and is expressed as carats per stone (cts/stn). As mentioned previously, a metric carat (ct) is equivalent to 0.2 grams (Lynn *et al.*, 1998).

When the grade (diamond concentration) of a marine placer deposit is examined, it has been shown by Sichel (1973) that sampling of such a deposit will typically return a large number of barren samples due to the erratic distribution of diamonds as mentioned previously. The consequential lognormal plot of the grade distribution will generally display a strong deviation from lognormality with the histogram highly skewed (due to the higher frequencies of barren results) to resemble an inverted J-shape (Sichel, 1973; Oosterveld *et al.*, 1987; Rombouts, 1995). In contrast to grade, the diamond size distribution tends to follow lognormality as a result of continuous sorting by wave and longshore currents (Sichel, 1973, Oosterveld *et al.*, 1987; Rombouts, 1995). In fact, increased sorting will reduce the lognormal variance as in the case of littoral deposits (Rombouts, 1995). It thus follows that areas near the Orange River mouth will have larger average sizes associated with higher lognormal variability, whilst areas farther down-drift, will show smaller average sizes with lower variability (Sichel, 1973; see Appendix B for further discussion on grade and stone size sampling).

5.2 FACIES MINERALISATION

5.2.1 Facies A: Barrier spit

The type-section in the G25 sample trench represents the first recorded pattern of diamond mineralisation within a gravel barrier spit sequence (Figure 5.3). Discrete sampling of the individual sub-environments was undertaken at the G25 trench (from one trench excavation only) and besides the sample results from the Facies C gravel beaches, there is no other dataset from similar environments to compare with. Nonetheless, the sampling results show a cross-beach (north-east to south-west) pattern of mineralisation. The grade is significantly higher in the gravel beaches found on the landward side (Sub-facies A3) where the spit recurves into the lagoon, whilst comparatively lower grades are found in the intertidal gravel deposits that are in direct contact with the open ocean (seaward-facing; Sub-facies A1).

The area of poor grade is confined to the subtidal inlet deposits (Sub-facies A2) where sand and poorly-sorted gravel sheets dominate.

Noteworthy is the stone size distribution. The largest average size was recovered from the intertidal, seaward-facing gravel beaches (Sub-facies A1), but the spit-recurve (Sub-facies A3; landward-facing beaches) and subtidal inlet (Sub-facies A2) deposits yielded similar average stone sizes that are considerably smaller than those of the seaward-facing beaches (Sub-facies A1). The overall diamond data is tabulated in Table 5.1.

The paucity of samples (only seven) from the barrier spit environment does not allow for any reasonable descriptive statistical presentation. Consequently, basic statistics and associated graphical illustrations that are used in discussion for the other marine environments are not presented here. Given that the results are supported by only a few stones (in total 283 from seven samples), especially for the inlet environment (two stones only from one sample; see Appendix B), and although barren samples are absent, there is the possibility of a biased grade and stone size result. Nevertheless, the results provide a first approximation for future comparison.

Table 5.1: Overall diamond results for barrier spit from the G25 trench

Sub-facies	Sub-environment	Average grade (spht)	Average stone size (cts/stn)
A1	Seaward-facing beach face	>3.0 <4.0	>1.0 <1.3
A2	Tidal inlet	>0.9 <1.0	>0.4 <0.5
A3	Landward-facing recurve beaches	>12.0 <13.0	>0.4 <0.5

5.2.2 Facies B: Transgressive lag

Unlike the thick gravel accumulations of Facies A and C, the thin boulder lag of Facies B has been subjected to depositional processes that are different, producing a contrasting mineralisation pattern. Here the diamond distribution is influenced by current- and wave-induced raking, whereas kinetic sieving – a ‘jigging’ process that aids gravel size- and shape-sorting (see Chapter 3, Section 3.5.4) – is more typical in beach deposits (Facies A and C) within an intertidal setting (see Chapter 3).

Selective sampling of Facies B gravels has demonstrated that they have poor grades, but yield a large average stone size (Table 5.2). When grade and average stone size are examined, a clear mineralisation pattern emerges. The distribution of higher grade (Figure 5.4) and larger-than-average size (Figure 5.5) have similar trends in a south-west to north-east direction (perpendicular to the present coastline) – these larger grade and size values are confined to the most landward end of the transgressive sheet.

The only obvious average stone size trend in a south-east to north-west direction (parallel to the present coastline) is the sudden decrease at trench G45 to 1.1 cts/stn (Figure 5.5A). Also, the zone of exceptionally large diamonds occupies a broader area south-east of trench G19. This subtle ‘bulging’ of the zone is coincident with the schist bedrock island, but surprisingly does not extend southwards to trench G4 where bedrock is still present (Figure 5.5B).

Descriptive statistics for the transgressive lag are presented in Table 5.3. In addition, dispersion graphs illustrate the spread of data for grade (Figure 5.6A) and average stone size (Figure 5.6B). Frequency distribution graphs are also included in Figure 5.6 as insets and these have data classes equal to those used in Figures 5.4 & 5.5 for ease of comparison. It is clear from the dispersion graphs that both the average stone size and grade depict positively skewed data due to the influence of outliers, more particularly the average stone size which is skewed due to the recovery of a single large diamond (16.8 carats). This is also evidenced in the skewness values recorded in Table 5.3. In addition to the outliers, zero values also have an obvious influence and account for 20% of the dataset. When the frequency distribution graph for grade is viewed (Figure 5.6A), a tight concentration of values between zero and 1 spht is apparent, whilst the graph for stone size shows a large number of values greater than 1.0 cts/stn (Figure 5.6B).

Table 5.2: Overall diamond results for transgressive lag

Facies	Environment	Average grade (spht)	Average stone size (cts/stn)
B	Transgressive lag	<1.0	>1.4 <2.0

Table 5.3: Descriptive statistics for the transgressive lag diamond data

	No of samples	Min value	Max value	Mean	Geometric mean	σ	Var	CV	<i>sk</i>
spht	107	0.0	4.3	0.5	N/A	0.7	0.5	1.4	2.7
cts/stn	86	0.2	16.8	1.5	1.08	1.9	3.5	1.3	6.5

σ = standard deviation, Var = variance, CV = coefficient of variation, *sk* = skewness

5.2.3 Facies C: Barrier beach

By using the 1950s and 1970s sampling results (see Appendix B for sampling data) that were returned from a beach section where the entire spectrum of sub-facies (C1 to C2) was preserved, a representative appreciation of the Facies C mineralisation patterns was gained (Table 5.4).

The highest grade is confined to the upper beach face of Sub-facies C1 (Figure 5.7). On either side (landward and seaward) of this zone of high grade, the beach toe (outer frame of Sub-facies C1) and washovers (back-barrier of Sub-facies C2) in comparison have lower grades. Note, however, that the grade of the washover sub-environment is lower than that of the beach toe.

When the average stone size is considered (Figure 5.8), the beach toe (outer frame of Sub-facies C1) is the area where the largest diamonds accumulate, despite sporadic occurrences of larger than average diamonds elsewhere in the beach face and washover sub-environments. At the beach toe, the largest diamonds are confined to the more seaward regions. It has also been demonstrated that the outer frame is typified by an accumulation of the largest and most mobile clasts on a barrier beach. It thus implies there is an empirical relationship between diamond size and gravel size. Figure 5.9A broadly illustrates this relationship where the trend in average stone size closely mirrors the average boulder size, save for the outlier at the G39.5 trench.

When the entire foreshore (Sub-facies C1) is compared to that of the backshore (supratidal washover of Sub-facies C2) setting (Figure 5.9B & C), a clear pattern emerges, namely:

- 1) There is relative consistency in the grade and average stone size along strike (parallel to the present coastline) for both depositional sub-environments;
- 2) The grade is roughly, on average, three times greater in the foreshore compared to that of the washover (see also Spaggiari *et al.*, 2006); and
- 3) The average stone size in the foreshore (Sub-facies C1; 1.3 cts/stn) is slightly larger than that in the backshore setting (Sub-facies C2; 1.1 cts/stn). This is mainly due to the influence of the larger average stone size in the beach toe of the foreshore setting.

Descriptive statistics for the barrier beach is presented in Tables 5.5 (grade) and 5.6 (stone size), whilst dispersion graphs for grade and stone size in Figures 5.10 & 5.11, respectively, represent graphical summaries of diamond data for the outer frame (beach toe), beach face and washover settings. These figures include frequency distribution graphs as insets with data classes that are similar to those used in Figures 5.7 & 5.8 for ease of comparison.

Like the transgressive lag data, outliers skew the data so that the dispersion graphs are, to some degree, positively skewed. When grade is considered, the standard deviation for the beach face is significantly high (Table 5.5) due to a spread of higher values. These higher values correlate to the upper beach face where grades are highest as shown in Figure 5.7 and in the frequency distribution graph (Figure 5.10B). More significantly, in comparison with other sub-facies of equal sample size, only one zero value is recorded in the upper beach face dataset. Figure 5.12 illustrates the grade results of a barrier beach from equal-sized samples and clearly shows that the highest grade, which is confined to the upper beach face, is related to a geological influence and not a function of sample size (see also Appendix B, Section 1.3.2). In contrast, the washover deposits are largely influenced by the high number of zero values that represent as much as 64% of the washover results; the highest of the entire diamond dataset (see Figure 5.10C). Intriguingly, the frequency distribution trends of the washover and middle beach face are similar (Figure 5.10B & C), both are influenced by the large number of zero values.

As regards the average stone size, the outer frame (beach toe) contains the largest stones. However, when the entire barrier beach environment is considered (in Figure 5.9C), there is in fact little variability in stone size between sub-environments, save for the outliers influencing the outer frame and beach face results. In fact, both of these last two sub-

environments display similar trends in their frequency distribution graphs (see Figure 5.11A & B).

Table 5.4: Overall diamond results for barrier beach

Sub-facies	Sub-environment	Average grade (spht)	Average stone size (cts/stn)
C1	Beach toe	>3.0 <4.0	>1.3 <1.5
C1	Beach face	>12.0 <13.0	>1.0 <1.2
C2	Washover fan	>1.0 <2.0	>1.0 <1.2

Table 5.5: Descriptive statistics for barrier beach grade data (spht)

	No of samples	Min value	Max value	Mean	Geometric mean	σ	Var	CV	sk
Beach Toe	40	0	23.5	3.2	N/A	4.3	18.5	1.3	3.0
Beach face	50	0	65.0	12.0	N/A	14.6	213.6	1.2	2.2
Washover	33	0	6.3.0	1.1	N/A	1.8	3.4	1.6	1.8
Foreshore (BF + BT)	90	0	65.0	3.9	N/A	12.1	148.0	3.0	3.0

σ = standard deviation, Var = variance, CV = coefficient of variation, sk = skewness, BF = beach face, BT = beach toe

Table 5.6: Descriptive statistics for barrier beach stone size data (cts/stn)

	No of samples	Min value	Max value	Mean	Geometric mean	σ	Var	CV	sk
Beach Toe	31	0.3	5.4	1.4	1.1	0.9	0.8	0.6	2.9
Beach face	36	2.7	7.8	1.1	1.1	1.2	1.5	1.1	4.1
Washover	12	0.1	2.7	1.1	0.8	0.8	0.7	0.7	0.6
Foreshore (BF + BT)	67	0.3	7.8	1.3	1.1	1.0	1.1	0.8	3.8

σ = standard deviation, Var = variance, CV = coefficient of variation, sk = skewness, BF = beach face, BT = beach toe

5.2.4 Facies D: Storm gravel sheet

Consideration is given only to Sub-facies D3 as diamond accumulations are confined to the storm gravel sheets. Only the diamond data pertaining to the area north-west of, and including, the G19 sample trench were used; the gravel sheets of Sub-facies D3 are absent south of G19 where the Facies D succession thins abruptly (see Appendix E). Results show, as expected, that the storm gravel sheets of Sub-facies D3 are poorly mineralised and have the poorest grade of all the facies types investigated in the study area (Table 5.7). No trend was apparent in the average stone size or grade (Figure 5.13) when the results are examined, which could also be a function of the limited number of samples that are used in the analysis.

Descriptive statistics for the storm gravel sheet sub-environment is presented in Table 5.8, whilst dispersion graphs illustrates the amount of data dispersion around the mean for grade (Figure 5.14A) and average stone size (Figure 5.14B). Frequency distribution graphs are also included in the figure as insets and have similar data classes as those used in Figure 5.13 for ease of comparison. One striking feature when the grade results are viewed in the dispersion graph is that most values are significantly less than 1 spht with a clustering of results between zero and 0.2 spht (Figure 5.14A). Statistically, the storm gravel sheet setting has the lowest standard deviation of all sub-environments, followed by the transgressive lag. In addition to this, the grade frequency distribution graph is similar to that of the transgressive lag where grades are equally below 1 spht (compare Figures 5.6A & 5.14A) and they have equivalent skewness values of 2.7 (compare Tables 5.3 and 5.5). Noteworthy is that both the storm gravel sheet and transgressive lag are subtidal deposits.

The stone size dispersion graph illustrates a positively skewed representation due to outliers, but most of the data report to values less than 1 ct/stn with a clustering between zero and 0.5 cts/stn (Figure 5.14B). The storm gravel setting has one of the lowest average stone sizes within the entire marine sequence, third to that of the recurve and tidal inlet deposits within the barrier spit environment.

Table 5.7: Overall diamond results for storm gravel sheet

Sub-facies	Environment	Average grade (spht)	Average stone size (cts/stn)
D3	Storm gravel sheets	<1.0	>0.5 <0.7

Table 5.8: Descriptive statistics for the storm gravel sheet diamond data

	No of samples	Min value	Max value	Mean	Geometric mean	σ	Var	CV	<i>sk</i>
spht	31	0.0	1.1	0.1	N/A	0.2	0.1	1.6	2.7
cts/stn	24	0.2	2.9	0.6	0.5	0.6	0.3	1.0	2.3

σ = standard deviation, Var = variance, CV = coefficient of variation, *sk* = skewness.

5.3 ECONOMIC POTENTIAL OF FACIES

Although the ED Area deposits are considered to be of low economic potential as discussed in Section 5.1, the results presented in either geographical space or using basic descriptive statistics demonstrate two main areas favourable for higher diamond concentrations (grades) in these low-grade settings. These are foreshore deposits in barrier beach environments, more particularly the upper beach face area, and in spit recurves of barrier spit environments. Lower grades are confined to the tidal inlet, washover, transgressive lag and storm gravel sheet settings. Intriguingly, the offshore sheet-like deposits such as the transgressive lag and storm gravel sheet, having similar characteristics, return the lowest grades. Evidently, these two settings have statistical data that are relatively comparable.

Yielding the largest average stone size are the transgressive lag and foreshore deposits, more specifically the outer frame (beach toe). These settings are geologically contiguous as demonstrated in Chapter 3 where the transgressive lag boulders are an inherited component from the outer frame deposit. The diamond size of the latter also influences the entire foreshore sub-environment by raising the average size when the results are combined with the beach face. The smaller diamonds are to be found in the storm gravel sheets in the shoreface environments, as well as tidal inlet and spit recurve deposits of barrier spit environments.

Although, there are differences in diamond concentration (grade) and size, it does not necessarily imply that the deposits with highest grades have the greatest potential. In fact, the potential of a diamond deposit is amongst others, dependent on its ton value (or *in situ* value) expressed as U.S. dollar per ton (US\$/ton; Hanson WestHouse, undated) It is generally

considered that alluvial diamonds, unlike their primary source counterparts, are of exceptional quality; as in the case of the Namibian mega-placer where the yield is 95% gem quality (Hallam, 1964; Schneider & Miller, 1992; Jennings, 1995; Marshall & Baxter-Brown, 1995). Therefore, diamond value expressed as an average price per carat, traditionally in U.S. dollars per carat (US\$/ct; Rombouts, 1995; Chapman & Boxer, 2004), is expected to be high in alluvial diamonds. The value is dependent on a number of criteria (see Lynn *et al.*, 1998), of which diamond size (carat weight) is considered important. It therefore follows that larger, gem-quality diamonds command higher values. There are various statistical approaches to ascertain the average value of a diamond population (see Rombouts, 1995), but a critical requirement is that the size of a diamond population under valuation must be significantly large – in the order of several thousand stones given that a high variability of stone sizes and quality will be present (Rombouts, 1995; Chapman & Boxer, 2004; see also Appendix B). In addition to diamond size, another measure equally important in determining ton value is grade. Here grade is expressed differently (carats per ton; cts/ton) to what is applied in Section 5.2 so that it is aligned to the methods of establishing ton values. These methods are briefly discussed in Appendix B.

In view of the above, the potential of a deposit is ultimately reliant on the diamond value (including size) and grade. Using these two end members a hierarchy of facies potential can ostensibly be estimated in the ED Area. This approach is in its most simplistic form and does not conform to traditional statistical analyses for estimating diamond values per size distribution (see Rombouts, 1995), given that there is a scarcity of diamond value data in the public domain. Understandably, diamond values per specified stone sizes are not available considering the sensitivity of such information. The values used as a base-line in Figure 5.15 to rank the ED Area deposits have been sourced from limited internet-based reports pertaining only to average diamond sizes from mining and prospecting results (Venmyn, 2007; Martineau, 2008; Alexkor, 2009; Trans Hex, 2009). This may not be statistically valid and possibly a poor representation of the ED Area. Therefore, the values estimated and assigned to the ED Area facies (Table 5.9) must be used with caution, but they nevertheless provide a rough guide (considering the dearth of such data) to gain an appreciation of ton values. Mention must be made that the base-line values sourced from the public domain represent palaeo-Orange River diamonds and those from littoral deposits of Quaternary age along the Atlantic Coast south of the study area in South Africa and thus provide a fair comparison for estimating ton values in the study area.

With diamond values for each of the facies approximated using the regression equation in Figure 5.15 and their ton values estimated (see Table 5.9), two main hierarchical populations are clearly evident in the ED Area. One (designated as A in Figure 5.16) reports to a zone of low grade and low U.S. dollar per ton values irrespective of diamond size, whilst the opposite typifies the other (designated B in Figure 5.16). Population A comprises, unsurprisingly, storm gravel sheet, transgressive lag, tidal inlet and washover deposits. In this mix, the average stone sizes are considerably different with the largest belonging to the transgressive lag. While this deposit has the highest diamond value (US\$/ct), its low grade engenders an ineffectual ton value. Even if the average diamond value (US\$/ct) is doubled, the effect is insufficient to raise the ton value. However, by increasing both the grade and average diamond value by the same order of magnitude, it will invoke a more positive response. In addition to this, the deposit is viewed to be less attractive due to the shoreface sediments covering the boulder lag. Here, higher mining costs are required to remove the shoreface sediments (overburden cover) in order to access the transgressive lag.

By contrast, population B consists exclusively of the foreshore deposits with the spit recurves included. The latter is regarded as part of a foreshore setting as discussed in Chapter 3. These deposits have great potential in view of their higher US\$/ton values and the limited overburden cover. However, the concept of higher grade deposits having lower potential is best illustrated here. Although, the spit recurve deposits have the highest grade within the entire study area, (as much as four times than its seaward-facing foreshore equivalents), its US\$/ton value is less due to the smaller average diamond size. Notwithstanding its lower grade, the barrier beach foreshore deposits having a larger average stone size is in contrast the highest ranked deposit (Figure 5.16).

In summary, diamond mineralisation within the ED Area varies greatly, but a degree of hierarchy in facies potential is evident with respect to the various ton values. The results demonstrate that deposits with the highest potential belong to the foreshore, having larger average stone sizes and higher grades. Whereas, the lowest potential is typical of those deposits having the lowest grade and a small average stone size, such as the storm gravel sheet. Additional factors have to be considered to ultimately determine their true economic value and the application thereof is beyond the scope of this study. These factors include, amongst others, overburden (barren cover sediments) thickness, volume of mineralised

deposit, resource estimation using appropriate geostatistical methods, mining and processing costs (see Dominy *et al.*, 2002).

Table 5.9: General ranking of facies according to diamond potential

Rank	Average stone size (cts/stn)	Average grade (cts/ton)	Diamond value (US\$/ct)	Ton value (US\$/ton)	Facies and (environment)	Sub-environment
1	1.30	0.052	921.41	48	C (Barrier beach)	Foreshore
2	1.20	0.038	886.71	34	A (Barrier spit)	Foreshore
3	0.47	0.059	561.44	33	A (Barrier spit)	Spit recurve
4	1.10	0.012	834.67	10	C (Barrier beach)	Washover
5	1.50	0.008	1008.15	8	B (Transgressive lag)	
6	0.44	0.004	548.43	2	A (Barrier spit)	Tidal inlet
7	0.60	0.001	617.82	1	D (Shoreface)	Storm gravel sheet

5.4 MINERALISATION MODELS

One common feature that governs diamond concentration within the linear and pockets beaches down-drift of the ED Area is the bedrock character onto which these deposits were emplaced. There is now a general consensus that a competent bedrock footwall has greater propensity to yield fixed trapsites in the form of wave-cut gullies and potholes. These are favourable sites for higher concentrations of diamonds as demonstrated by Hallam (1964), Murray *et al.* (1970), Keyser (1972), Rogers *et al.* (1990), Apollus (1995), Corbett (1996) and Jacob (2006).

Save for the small bedrock island, the predominant footwall type in the ED Area comprises unconsolidated sediments of either fluvial or marine origin that do not promote the development of fixed trapsites. With the absence of a bedrock footwall influence, it is envisaged that, amongst others, specific conditions of littoral deposition, as discussed in Chapter 3, would have controlled diamond concentration and stone size distribution in the barrier deposits. This distribution and associated processes are graphically summarised in Figures 5.17 to 5.20, which includes a statistical summary of average grade against stone size in Figure 5.18.

Studies by Apollus (1995) and Jacob (2001) looked at the influence of wave-cut bedrock gullies in the highly mineralised pocket and linear beaches, respectively, and whilst it has been demonstrated that bedrock is a critical factor for increasing diamond concentration, the processes of diamond accumulation in these settings are more complicated. For example, Apollus (1995) demonstrates that, in places, higher concentrations of smaller diamonds have been found within shell-dominated, sand-rich sediment and not in gravel. This contrasts with the conventional assumption that gravel is the dominant host for diamond accumulation. In addition, millimetre thick layers comprising exclusively diamond have been reported within gully settings (I. Corbett, pers. comm., 2010). These mono-layers of diamond are exceptionally rare. It therefore suggests that in bedrock settings the trapsites exert the greater control, whereas sediment character is inconsequential. It also implies that for diamonds to accumulate in large quantities where sediment behaviour has little bearing on such concentrations, diamond availability plays an additional and important role.

Although, there is a large literature base on placer formation processes, which cover heavy minerals other than diamond in fluvial and marine settings, there is a considerable lack of data when diamond concentration in gravel beaches is considered; especially for gravel barrier forms within palaeo-river mouth settings. Studies have shown that hydraulic sorting of heavy minerals in placer deposits (alluvial and marine) is aided by a mechanism such as suspension, entrainment, transport or shear sorting or a combination of these (Reid & Frostick, 1985; Hughes *et al.*, 2000; Carling & Breakspear, 2006). In marine settings, the hydraulic sorting in beach deposits is related primarily to swash and backwash processes, but most heavy mineral studies have focused on sand-sized beaches where swash infiltration is limited due to low sediment permeability. Consequently, these studies do not provide a comparative framework to work from given that flow conditions in a highly reflective, steep-sloping gravel beach would be significantly different due to higher percolation rates that are allied to gravel porosity. In this context, the model of interstitial concentration discussed by Reid & Frostick (1985), Allan & Frostick (1999) and Carling & Breakspear (2006) has particular applicability, even though such studies were focused on fluvial placers. They demonstrate that interstice entrapment of heavy minerals plays a critical role. Here, the gravel pore spaces act as trapsites and thus the heavy minerals do not necessarily accumulate at the surface, but concentrate within the gravel body.

Such gravel beach processes have equally been identified as the main control on diamond distribution in pocket beach deposits that are in part (and uncommonly) floored by fluvial sediments. Millad (2004) demonstrates that gravel beach processes, coupled with wave hydrodynamics are fundamental in manipulating diamond size and concentration. The results, however, are not fully applicable to the study area given that the coastal configuration of pocket beaches and associated wave hydrodynamics, which are influenced by bedrock headlands, differ to the study area. Nonetheless, Millad (2004) provides evidence that the gravel fabric influences diamond distribution. For example, he notes that where the average diamond size increases, it correlates to an increase in gravel coarseness, which in turn is related to higher wave energy.

Obviously, beaches that receive appreciable amounts of diamonds are likely to develop into economic deposits. However, to create such an ideal placer deposit, the accumulated diamonds will have to be retained for a reasonable length of time within the sediment host; a prerequisite that is linked to gravel beach processes alone when bedrock trapping is absent. For example, diamond retention would be higher in barrier deposits that are in rapid progradation and to enhance their economic value, a large quantity of diamonds must be introduced, as would be the case where pulses of diamonds are delivered to the shoreline (see Bluck *et al.*, 2005; Spaggiari *et al.*, 2006).

With this backdrop, it is clear that sorting mechanisms in gravel beaches and their importance in generating a diamond placer within a swash- and backwash-dominated setting cannot be satisfactorily addressed until more data become available. More importantly, unlike other heavy minerals, diamonds are by nature hydrophobic and thus their behaviour in water during the concentration process is not adequately known given that a lowering of the frictional drag is expected (Yoder, 1993; Marshal & Baxter-Brown, 1995). Nonetheless, despite a lack of empirical data, conceptual models are inferred to provide a hypothetical appreciation of the processes that govern diamond emplacement and retention within barrier beach and barrier spit deposits. Here diamond accumulation is linked to barrier-forming processes; a study that has not been attempted before. Although conjectural, the models not only present a starting point in understanding diamond concentration within barrier types, but also provide a record for future comparative studies.

5.4.1 Seaward facing intertidal deposits

Within the palaeo-Orange River mouth, the seaward-facing intertidal deposits in the spit and barrier beach settings (Facies A and C) have some of the highest diamond concentrations of the littoral deposits, as well as a larger-than-average diamond size (Figure 5.17).

As discussed in Chapter 3, the intertidal setting is the most energetic part of the beach where it is subjected to vigorous wave energy. Here, the interplay between swash and backwash moves sediment continuously over a rough gravel surface generating turbulence. This promotes intense sorting as demonstrated by the extreme clast shape- and size-sorting observed in the present and palaeo-gravel beaches at Terrace Bay and within the study area, respectively. However, given that the beach gravels are highly porous, the strength and endurance of the backwash is short lived due to infiltration. It has been demonstrated that the effect of infiltration on swash uprush is limited, whilst it is more significant on the backwash (Masselink & Li, 2001). Percolation of the water mass on the return flow is consequently rapid through the open gravel framework. This would suggest that backwash has a limited influence on diamond sorting at surface, given that the infiltration clears the beach face effectively (Masselink & Li, 2001). Hence, it is plausible that diamonds percolate through the sediment pile in a similar fashion to that of gravel clasts. The gravel framework onto which the diamonds are emplaced would ultimately control the degree and depth of percolation, as well as diamond size.

A framework with a large open pore space would permit diamonds to descend into the sediment pile until they reach a level where the pore size is too small to allow them further passage. However, diamonds that are smaller than the pore space at any level within the sediment pile will be returned into the immediate offshore to be removed by longshore currents or recycled into the littoral to be thrown back onto the beach face. Moreover, diamonds that remain on the gravel carpet surface, being significantly larger than the pore space, are rejected to accumulate at the beach toe. It therefore suggests that diamond concentration is linked to extreme gravel sorting, which creates templates for diamond retention. More significantly, gravel size which governs pore space size, would then control diamond size. Reid & Frostick (1985), Allan & Frostick (1999), as well as Carling & Breakspear (2006), discuss such a mechanism (interstitial sorting) for concentrating heavy minerals in alluvial placers. They note that the coarser framework was deposited first, whilst

the heavy minerals, as part of the matrix, filtered into the pore space at a later stage. This infiltration is also aided by *in situ* ‘rocking’ (kinetic sieving or ‘jigging’) of the gravel clasts during swash incursions. This leads to expansion of pore throats (i.e. dilation of the gravel framework *sensu* Allan & Frostick, 1999) and, coupled with fluid suction, diamond particles are allowed to penetrate deeper into the sediment pile.

However, the beach environment is highly mobile where beach build-up and break-down occurs frequently. Sediment erosion can be significant in storm conditions, removing as much as a metre of gravel (Spaggiari *et al.*, 2006). This means that sediment exchange with the offshore, or with other sectors of the beach, is frequent. Consequently, there are few places where diamonds can accumulate, after repeated sorting events over a protracted period, to ultimately generate a rich placer. Of significance, is that the diamonds must remain in place (once trapped) for any meaningful accumulation. It, thus, raises the question how diamonds can be retained in a highly mobile setting.

It is envisaged that the middle sector of the beach is the diamond ‘sort-room’. Diamonds rejected from this sector of the beach are either added to the beach toe or upper beach face, or alternatively returned to the littoral zone. In comparison to the mobile middle sector, both the upper beach face and beach toe sub-environments are relatively stable and remain static for longer periods and are sites for better diamond concentration.

Large cobble to boulder clasts make up the beach toe (Sub-facies C1) and are thus trapsites for the larger diamonds, given the large pore space between the clasts. The beach toe is a gently inclined environment, which is the first to receive the more energetic part of the swash uprush and is subjected to backwash ex-filtration as it returns through the porous beach. This rakes the sediments repeatedly to winnow out the finer diamonds, whilst the larger population that is trapped within the gravel pore space remains relatively stationary. The local turbulence induced around the boulders is largely governed by gravel size. Also gravel infilling takes place during the winnowing process and with successive infilling of the pore space, the trapped diamonds are sealed off from further reworking. Noteworthy, is that the process of percolation in this environment is absent.

In contrast to the beach toe, the upper beach is reworked more effectively during storms only. During such periods, a rising water table would saturate the beach (Orford, 1977) filling

the pore-spaces. This fluidisation of the beach reduces backwash percolation and promotes beach erosion. Concomitant with the erosion is the removal of the diamond population, which is thrown back onto the beach face at successively higher levels. The accumulation of diamonds at the highest level, corresponding to the limit of swash uprush, would thus remain static for a period of time before being reworked by the next, more vigorous storm. Diamonds can therefore accumulate through a process of abandonment. If sediment supply to the beach face is sustained and is greater than sediment removal, beach progradation will occur, further increasing the retention potential of the abandoned diamonds. The mechanism associated with the deposition and preservation of diamonds within the upper beach face is thus storm beach sedimentation.

Observations on garnet (specific density of 3.4 g/cm^3 to 3.6 g/cm^3 ; Cairncross, 2004) accumulations in gravel beaches along both MA1 and the Skeleton Coast by Hallam (1964) correspond well to the diamond results discussed in the preceding chapter. He notes that significant garnet concentrations were confined to the upper beach face just below the beach ridge. Similarly, garnet concentrations have been observed in the modern beaches near the Orange River mouth in Oranjemund, Namibia by the author. Where the beach comprises very coarse sand to granules it has, as expected, a steep profile. Here garnet concentrations are also confined to the upper beach face. Conversely, where the beach is finer grained, a lower profile yields fewer garnets that are spread over a greater area.

5.4.2 Back-barrier and spit recurve deposits

Unlike the foreshore where the beach face is subjected to continuous wave attack and reworking, sediments in the back-barrier setting are protected from the energetic surf zone and are rarely reworked. These sub-environments, notably, beach ridges (Sub-facies C1), washover fans (Sub-facies C2) and to some degree, the landward regions of the spit recurves (Sub-facies A3) are storm produced and thus their emplacement is intermittent.

The diamond populations within washover fans represent a reasonable measure of the diamond size population within the beach face setting. Diamonds are scavenged from the beach face and transferred to the back-barrier during storms. This accounts for similar average diamond sizes. It has also been demonstrated that amongst other factors, breach points in a beach ridge direct sediment-charged swash incursions into the back-barrier (Carter & Orford, 1980, 1981). This would suggest that washovers have a tendency to be localised

and thus a small area of the foreshore is sampled for its diamond content. Also, more aggressive overwashing is capable of adding sand and clay rafts to the fan sediments, further diluting the gravel component. Once deposited, there is virtually no further exchange with the foreshore and no reworking of the washover fans to remove the fine sediments. Hence, the low diamond concentration in washover deposits can be ascribed to a combination of limited sampling of the beach face, infrequent exchange with the foreshore and an absence of reworking to remove the diluting sediments.

Unlike the washover fans, the landward regions of the spit recurves are subjected to reworking under a lower wave energy regime, in comparison to the more energetic foreshore setting. Regardless of the lower energy setting, the waves refracting around the spit head still have the competence to wash out finer sediments from the landward-facing beaches. During fair-weather, this reworking is relatively gentle under reduced wave height. However, the wave height is increased during storm periods, promoting more aggressive reworking. Consequently, these landward-facing beaches are subjected to continuous reworking, even though wave energy levels are inconsistent.

The diamond population in the landward-facing beaches (Sub-facies A3) is significantly smaller than the washover deposits (Sub-facies C2). This not only suggests a different mode of emplacement, but also indicates that once the diamonds have accumulated in the spit recurves, there has been no further interaction with the seaward-facing beaches through washover processes. As discussed, the seaward-facing beaches have a comparatively larger average diamond size, as much as three to five times more, than their landward-facing counterparts.

The smaller diamond size reflects a longshore-transported population that has been rejected, possibly several times, from the foreshore. This would imply that the coarse seaward-facing beaches are not effective in trapping the smaller diamond population. It further suggests that a portion of the longshore-transported diamonds do not bypass the spit head, but instead, is directed through the inlet to accumulate at the spit recurves. This is not unusual. Longshore transported particles do have the propensity to either cross the entrances of estuarine-lagoons or move into the inlet to be added either to the spit (see Chapter 3, Section 3.3.5) or inlet channel environments, as noted by Kidson *et al.* (1958) and Carr (1965). A portion of this 'deflected' diamond population is also retained in the subtidal

deposits of the inlet, which is discussed in Section 5.2. It is therefore conceivable that the diamonds in spit recurves do not represent the population contained within foreshore deposits, but instead are a good representation of the rejected littoral diamond population that is moving northward along the coast.

5.4.3 Subtidal deposits

In this section, consideration is given to all gravel-dominated subtidal environments and thus the spit inlet deposits (Sub-facies A2) is included in the discussion. Of all the depositional sub-environments, the subtidal regions have the poorest concentration of diamonds given the limited amount of reworking in these submerged settings.

As noted in Chapter 3, the most seaward part of the foreshore – the beach toe (Sub-facies C1) – is characterised by an accumulation of large spherical clasts. It has also been demonstrated that the boulder bed (Facies B), representing a transgressive lag, is the residual accumulation of beach toe material left behind on the shoreface during shoreline retreat. It thus, follows that the diamond mineralisation in the transgressive lag should exhibit some traits similar to that of the beach toe. The overall average diamond size reflects this similarity where the average size in the transgressive lag (1.5 cts/stn) is not too different to that of the beach toe (1.3 cts/stn).

During shoreline retreat, as sea-level rises, the boulders left behind on the shoreface would be subjected to limited reworking. It is envisaged that reworking would be initially effective at the leading edge of the transgression where winnowing is more conducive to rake the sediment pile. This accounts for the zone of better diamond concentration in the most-landward regions of the transgressive lag. However, as the shoreface advances landward, the winnowing decreases with increasing water depth and is replaced by sediment dilution where shoreface sands fill available pore space. More importantly, there is no further diamond replenishment from the shoreline.

Storms are conducive for emplacing foreshore sediment into the shoreface by powerful wave-induced rip currents. Associated with this sediment transfer is the movement of diamonds where they are scavenged from intertidal hosts. The larger diamonds occurring at the most landward end of the storm gravel sheets coincide with the larger gravels as discussed in Chapter 3. This is a function of gravel size entrapment that is also seen in the beach toe

environment. Once sediment is ripped from a small area of the beach, a pulse of diamond-bearing sediment is transferred to lower-energy, shoreface settings where they are rapidly deposited. Winnowing of the sediment melange is thus significantly limited. Longshore drift winnowing may take place, but it is likely to be short-lived due to the influx of entrained sediment. The result is extensive dilution of the gravel sheets. Post-storm recovery periods would see an introduction of additional fine sediment, such as sand, blanketing the gravel sheets. Similar to the transgressive lag, there is no further diamond replenishment from the foreshore setting.

Given the mobility and high deposition rates, as well as the fine-grained nature of the sand-dominated sediments associated with spit elongation, it is not surprising that the subtidal deposits at the spit head have poor diamond concentrations. The diamonds are retained in the gravel fraction, but the lack of clast sorting, the sandy nature of the gravel and, more significantly, the abundance of light zeolite pebbles (specific density of 2.0 g/cm^3 to 2.2 g/cm^3 ; Cairncross, 2004) is indicative that sediment reworking is lacking. However, the overall average diamond size within these sediments closely matches those that are retained in the landward-facing beaches of the spit recurves. This implies that a portion of the diamond population directed through the inlet to the spit recurves was trapped at the spit head.

CHAPTER 6 – DISCUSSION OF RESULTS

6.1 STRATIGRAPHIC MODEL

Diamondiferous onshore littoral deposits of varying age are developed sporadically over a distance of approximately 1,800 km along the Atlantic coastline from Namaqualand in South Africa through the study area and northwards to the Skeleton Coast in Namibia and beyond into southern Angola (Figure 6.1). However, this entire suite of variable age deposits that range from Eocene to Holocene age is not always preserved along the Atlantic coastline and thus the coastal stratigraphy is fragmented. The inconsistent preservation is promoted in part through the antecedent topography controlling deposition (see for example Pether, 1994) and post-depositional geomorphic processes. More importantly, sea-level fluctuations had a considerable impact where reoccupation of previous sea-level stands has completely or partially removed earlier depositional signatures. For example, Pickford & Senut (1999) show that in Namaqualand, South Africa, marine deposits between 40 m and 45 m above msl contain terrestrial and marine fossils of Early, Middle and Late Miocene age, suggesting that this particular altitude was occupied by sea-level at least three times during the Miocene. The resultant effect is reworking of older deposits into younger ones. In addition, elevation heights of comparable-age deposits are inconsistent along the Atlantic coastline at various localities and whilst tectonism is suspected for this disparity (for example Dingle *et al.*, 1983), more conclusive evidence is required given the difficulty in unravelling the contributions from tectonism and eustasy to palaeo-shoreline positions (see Roberts & Brink, 2002). Therefore, there is great difficulty in correlating palaeo-shorelines, particularly those of Palaeogene to Early Quaternary, along the entire Atlantic coastline of southern Africa due to elevation inconsistencies (for example see Figure 4.4), differences in stratigraphic preservation, re-occupation of previous shoreline levels and more significantly, as noted by Dingle *et al.* (1983) and Roberts & Brink (2002), imprecise age determination. Figure 6.2 illustrates broadly this fragmented stratigraphic setting and the preferential survival of various deposits. It also clearly shows a large gap in shoreline history between the Eocene and Early Miocene where onshore marine deposits of Oligocene age are not preserved along the Atlantic coastlines of South Africa and Namibia (Dingle *et al.*, 1983).

When the deposits of Plio-Pleistocene age (30 m Package equivalents) are considered, their stratigraphic make-up is equally fragmented and the sediment character is remarkably

variable. Figure 6.3 illustrates, broadly, the regional distribution of diamond-bearing Plio-Pleistocene shorelines and their preservation along the Atlantic Coast of South Africa and Namibia. Along the Namaqualand coast in South Africa, there is greater preservation of shoreface deposits, whereas gravel-bearing foreshore settings that fringe wave-cut cliffs are preserved to a lesser degree (Hallam, 1964; P. Gresse, pers. comm., 2010; W. Macdonald, pers. comm., 2010; J. Ward, pers. comm., 2010). In these foreshore settings, the deposits are typically beaches and barrier forms are absent (see Chapter 1, Section 1.4 on difference between barrier beach and beach deposit). In addition, there appears to be no down-drift change in deposit character such as that seen in Namibia where there is a ubiquitous change from barrier to linear beach types. This, however, does not necessarily imply that barrier beach deposits did not evolve along the Namaqualand coast. Their absence may be a reflection of post-depositional erosion or such deposits were not exposed by mining activities. For example, remnants of barrier deposits, notably lagoon and inlet sediments, have been recorded by Pether (1994) in the older 50 m package shoreline, suggesting that barrier deposits are not an unusual feature of the Namaqualand palaeo-coastline.

In Namibia, the greatest representation of diamondiferous Plio-Pleistocene littoral deposits is within southern Namibia, which is characterised by a progressive down-drift change in deposit character from the Orange River mouth. However, these onshore marine occurrences become more sporadic farther north where isolated deposits as far as southern Angola have been recorded (see Nunn, 1984). Although, the preservation of 30 m Package deposits is variable along the Namibian coast, there is a greater degree of foreshore preservation when compared to the Namaqualand coastline in South Africa. Therefore, the study area not only represents a small part of the greater Plio-Pleistocene shoreline along the Atlantic Coast from South Africa into Namibia, but also yields a more complete sedimentary record that reflects a comprehensive history of Plio-Pleistocene sea-levels. Noteworthy, is that this degree of sea-level resolution along the entire Namaqualand and Namibian coasts has, thus far, only been recorded from the study area.

The stratigraphic sequence within the study area comprises stacked sequences of barrier spits and barrier beaches within accommodation space provided by the palaeo-Orange River mouth. It is worth mentioning that the palaeo-Orange River mouth is the largest palaeo-mouth setting along the Namaqualand and Namibian Coasts (see Bluck *et al.*, 2005). More significantly, it is the terminal point of the largest westward draining palaeo-river in southern

Africa. This palaeo-river system is seen as a large transient placer that supplied coarse gravel together with diamonds to the Atlantic Coast (Bluck *et al.*, 2005; Jacob, 2005). Simply put, the palaeo-Orange River was a large gravel conveyor system carrying diamonds. Consequently, these attributes provided favourable conditions for the growth of barrier spits and barrier beaches, provided that sediment supply was sustained. Unlike the fluviially derived sand and mud fractions that were easily dispersed by wave and longshore drift energy, the gravel accumulated close to the outfall and was added to coastline features such as barrier or beach deposits. Sediment supply was, however, episodic during the Plio-Pleistocene as evidenced from the Meso-Orange River terraces of that age (Jacob, 2005) and from the study area where there is a large sediment size range. There were thus times when river competence was remarkably high to supply boulder-sized gravel, whilst at times it was only capable of delivering sand to the coast. This variability in supply was likely to have produced significant shifts in the coastline position with seaward growth during sediment surplus and landward retreat on a diminishing supply. Obviously the area nearest the outfall will have the greater accumulation of gravel, whereas those farthest down-drift will be gravel starved if there are no intermediary river inputs. Thus, the coastline maintained a down-drift thinning wedge of gravel-bearing features. Of these, the barrier deposits were confined to the palaeo-river mouth where the coastal accretion was at its widest. These were in turn replaced down-drift by bedrock-floored linear beaches and possibly pocket beaches; the last forming the most distal and narrow end of the coastal wedge. Pocket beaches are only preserved in the younger deposits and are thus assumed to have also evolved during 30 m Package times.

A further consequence of an episodic sediment supply is that there is a propensity to promote alternating phases of barrier spit and barrier beach growth as described by Orford *et al.* (2001). This would account for the different barrier forms within the palaeo-Orange River mouth even though the same depositional processes were operating at the same time. In this context, Orford *et al.* (2001) argue that the barrier forms may represent different end members of a continuum where, for example, barrier spits are predecessors to barrier beaches and the latter are precursors to linear beaches. Therefore, the gravel beach forms within the study area only represent part of their evolutionary paths. In view of this, the coastal wedge in southern Namibia can be seen as an evolutionary continuum of palaeo-gravel beach forms. This evolutionary path, controlled in part by the palaeo-Orange River outfall, extends over a distance of approximately 110 km. Thereafter and farther down-drift, this evolutionary path is not so evident where the coastline becomes gravel-starved and sand-dominated. It would,

therefore, follow that gravel size also declines in a down-drift direction. This is apparent in the beach forms immediately north of the present Orange River (Hallam, 1964; Bluck *et al.*, 2001). The decline in gravel size is thought to have been controlled by decreasing sediment supply and is not a function of diminishing longshore drift power (Bluck *et al.*, 2007). In fact, small agate pebbles of Orange River origin have been found in 30 m Package sediments at Walvis Bay approximately 700 km north of the study area (Spaggiari & Ward, 2004; Bluck *et al.*, 2005), whilst diamonds have been recovered from the Skeleton Coast gravel beaches that are approximately 1,000 km down-drift of the study area (Hallam, 1964). The diamonds are assumed to be Orange River derived (Spaggiari & Ward, 2004; Bluck *et al.*, 2005). These occurrences provide conclusive evidence that longshore drift transport was active for over a distance of more than 1,000 km along the Namibian coast during the Plio-Pleistocene.

6.2 SEA-LEVEL AND PRESERVATION MODEL

It has been demonstrated in Chapter 4 that high-frequency sea-level oscillations were responsible for building the barrier deposits within the study area. Sea-level amplitudes varied with predominantly smaller and fewer, but larger fluctuations driving the growth and stacking of barrier deposits into a 16 m marine package. The study area, therefore, comprises a multitude of transgressive and normal regressive accumulations with only small portions of their greater sequences being preserved. More specifically, only the highstand deposits have been preserved, whilst those generated by forced regression and lowstand cycles have been mostly removed, save for the relict submerged barrier-deposits of presumably Late Pleistocene age occurring 15 km offshore and 20 km to the north of the study area (Corbett & Burrell, 2001; Gray 2002). These are interpreted as remnants of a forced regression that have been drowned *in situ* during a subsequent rapid transgression (Corbett & Burrell, 2001).

It has been shown in Chapter 4, that the high-frequency sea-level oscillations are superimposed on a transgression. The latter correlates to the transgressive maxima at approximately 3.2 Ma (TB 3.6 third-order cycle of Haq *et al.*, 1987; Pether, 2000) and is thought to be responsible for the emplacement of the 30 m Package shoreline in the study area and elsewhere along the Namaqualand and Namibian coastline using Pickford & Senut's (1999) age of 3.5-2.5 Ma. Eustatic highstands with elevations ranging from 25-38 m above

msl have been proposed by Krantz (1991) between 3.2 and 3.5 Ma, which closely corresponds to the elevation heights of the 30 m Package.

Final abandonment of 30 m Package shoreline took place during a forced regression, and whilst the timing thereof is unknown, this event has, in part, promoted the preservation of a 16 m marine package within the palaeo-Orange River mouth. At this stage the shoreline was a great deal farther seaward – in today's offshore environment – but re-occupation of the westernmost part of the study area occurred during the next major transgression depositing a younger barrier beach (undated, but assumed to be 0.4 Ma; Rogers *et al.*, 1990) at a much lower elevation and eroding into the 30 m Package barrier deposits. Therefore, as discussed in Chapter 4, the sea-level history recorded in the study area represents a complex superimposition of three principal cycles. These are fourth order-cycles of high-frequency oscillations that are not recorded elsewhere along the Namaqualand and Namibian coasts. They are superimposed on a transgressive event correlating to Haq *et al.* (1987) third-order cycles (for example Pether, 1994) and are in turn, superimposed on an overall regression that correlates to Haq *et al.* (1987) second-order cycle, which led to the abandonment of the 30 m Package shoreline.

Although the fourth-order cycles are an expression of spasmodic sea-level changes over short time spans, the Orange River was capable of adjusting accordingly as shown by Jacob (2005) where Plio-Pleistocene (Meso-Orange) fluvial deposits reflect short phases of incision and aggradation. Inasmuch as these fluvial deposits reflect sea-level changes, there is difficulty in correlating incision and aggradation cycles to the sea-level record in the study area. River incision may have been a result of major forced regressions, whilst aggradation was a response to transgressions. It must also be noted that using river incised gradients to extrapolate Meso-Orange River profiles, Jacob (2005) demonstrates that the Orange River, at times, extended well offshore of the present Orange River mouth during the Plio-Pleistocene. In addition, and as mentioned earlier, remnants of submerged barrier beaches on a gravel delta, possibly of Late Pleistocene age, occur offshore of the study area at depths of 90-120 m (Corbett & Burrell, 2001; Gray, 2002). In spite of the correlating difficulties, these submerged deposits coupled with the extrapolated gradient provide convincing evidence that the shorelines shifted considerably seaward during forced regressions.

Whilst sea-level fluctuations were responsible for the evolution of the study area, the preservation of a 16 m thick marine package is unexpected given that the remaining age-equivalent deposits along the entire Namaqualand and Namibian coast, emplaced by the same transgressive event, rarely attain a thickness of six metres. Hence it raises the question of what mechanisms have encouraged the preservation of such a thick sedimentary record within the study area. A combination of four depositional mechanisms is invoked; these are:

- 1) A transgression (correlating to third order cycles of Haq *et al.*, 1987) created the accommodation space for the deposition of 30 m Package deposits along the entire Namaqualand and Namibian coast even though it was interrupted by a number of smaller sea-level fluctuations.
- 2) The large palaeo-river mouth setting allowed the barrier shoreline to migrate farther landward than any part of the coastline. Note that on a forced regression, the palaeo-Orange River mouth and its associated outfall maintained a large areal configuration, as it occurs offshore of the study area. Therefore, throughout its evolution during transgressions and regressions, sediment accumulation would have been greatest in these river mouth settings. The relict gravel barrier beach deposits submerged offshore of the study area as noted by Gray (2002) bears testament to such a setting where parts of their gross morphology have been drowned in place. Here barrier deposits, up to five meters thick and developed along strike for two kilometres (Gray, 2002), have been preserved.
- 3) A perpetual supply of sediment from the palaeo-Orange River, albeit episodic, promoted coastline construction during both regressions and transgressions. Fractionation of the fine outfall sediment such as sand and mud were dispersed by wave and longshore energy, ensuring that only the gravel fraction accumulated at the coastline. When forced regressions are considered, down-stepping terrace-like shorelines and their associated submerged shoals of river outfall, would have extended well offshore of the study area. Also, these were not necessarily constructed directly offshore of the present Orange River mouth given that the palaeo-Orange River had the propensity to migrate down-drift under a northward-directed longshore drift, cutting a large swath of horizontal ground.
- 4) Subsidence of the palaeo-river mouth area due to sediment compaction has been briefly discussed in Chapter 4 and is suspected as one of the mechanisms to encourage sediment preservation. The process of sediment compaction would have lowered barrier elevation relative to a stable sea-level (see Chapter 4). If sediment supply was sustained during subsidence, barrier aggradation would have continued so that beach ridge elevation was

maintained above mean sea-level, whilst a large part of the barrier feature remained below sea-level. Basically the process was comparable to that of a still stand. By contrast, shorelines that were deposited on bedrock would, obviously, not have subsided. Hence, the preservation of these deposits was greatly reduced, but not where deposition occurred within topographic hollows as noted by Pether (1994) for the coastal deposits in Namaqualand, South Africa. Consequently, the antecedent topography controlled both the depositional environment and preservation potential of sediments.

If subsidence due to compaction is considered to have played a role in the study area, the timing thereof would have been prior to the deposition of the barrier beach deposits. This line of evidence is based on the transgressive boulder lag leading to the barrier beach deposits. Here the lag sheet maintains a horizontal attitude along strike from the bedrock high that floors the lag deposit in the south-eastern part of the study area to the north-west where the boulders overlie unconsolidated sediments (see Figures 3.15A & 3.16A). Therefore, if subsidence were to have taken place during and after barrier beach deposition, the transgressive lag on either side of the bedrock high would have subsided to an elevation lower than that on the bedrock high. It thus brings into question whether local tectonism can be considered as an alternative mechanism to sediment compaction. Regional uplift of the western continental margin of southern Africa during the Late Pliocene/Early Pleistocene has been advocated by Partridge & Maud (1987), Partridge (1998) and Wigley (2004). While the effects of this event is not evidently appreciable along the Namibian coast, it is assumed that it was responsible for the northward tilting of the 'F' bedrock-cliff base and associated Plio-Pleistocene beach ridge elevations, as noted by Hallam (1964; see also Chapter 2, Section 2.2). Worthy of mention is that a geophysical lineament has been identified immediately north of the present Orange River mouth and has an offshore to onshore extension, directed towards the south-west and north-east, respectively (Corner, 2008).

Although, the lineament is based solely on a geophysical signature and has not been conclusively identified in the field, it may represent a fault zone along which crustal movement has taken place (B. Corner, pers. comm., 2010). If the land mass was tilted northwards as invoked by Hallam (1964), it is conceivable that re-activation of this fault with an associated uplift may have occurred, raising the wave-cut bedrock platforms onto which the linear beaches were deposited with a concomitant tilting to the north. Subsidence of the study area may have also accompanied the uplift, to provide appreciable accommodation

space for maximum preservation of barrier features. Dingle *et al.* (1983) have alluded to the effects of local tectonics along the Namaqualand and south Namibian coast where uplift or subsidence may have caused one area of the coast to either submerge or emerge relative to others. Mention must also be made that re-activation of faults during Plio-Pleistocene to Recent times is not an unusual phenomenon in Namibia. For example, Viola *et al.* (2005) note the occurrence of neotectonic faulting in central and southern Namibia along the Hebron and Dreyling-Platz faults during the Early Pleistocene and also in the Skorpion Mine pit that is 90 km north-north-east of the study area. While a tectonic model to explain subsidence in the study area is appealing, evidence thereof is scant, but should be investigated as an alternative mechanism to sediment compaction. This may also adequately explain differences in the elevation heights of shoreline features across the bedrock and fluvial sediment boundary as discussed in Chapter 4.

6.3 DIAMOND EMPLACEMENT MODEL

Underpinned by a vigorous wave climate, conditions for the development of the Namibian mega-placer were well-established during the Plio-Pleistocene (see de Decker, 1988). In fact, this wave climate was in place since the Eocene as discussed in Chapter 2, and may have intensified during the Plio-Pleistocene (Pickford & Senut, 1999). It is these vigorous coastal processes that fractionated the pulses of different sediment types delivered by the palaeo-Orange River. Here, large discrete bodies of sediment injected into the coastal system were dispersed with the finer sediments spread away from the outfall, whereas gravel accumulated near the shoreline to be added to coastal features. Within the river mouth setting, wave and longshore energy facilitated the construction of barrier deposits that had unrestricted landward space to migrate and grow. It is here where the coarsest gravel accumulated. However, immediately and farther down-drift, greater wave energy was expended in cutting bedrock platforms, gullies and potholes, as well as bedrock-cliffs. This was bolstered by the gravel clasts which were used as an abrasive medium to facilitate the cutting process as described by Jacob (2001). Linear and pocket beach forms developed on these bedrock wave-cut features. Therefore throughout its evolution, the coastal segment at the palaeo-Orange River outfall, since the Eocene, has developed in such a manner described above at every geographical position it held during either a transgression or regression.

Sourced from fertile kimberlites within the interior of southern Africa, diamonds and other fluvial sediments were delivered to the coastline since the Eocene (Bluck *et al.*, 2005; Jacob, 2005). It is envisaged that pulses of diamonds were transported to the Atlantic Coast, but not all of the diamonds reached the coastline; some would have been retained in trapsites along the palaeo-Orange River course (Jacob, 2005). However, a diminishing supply of diamonds to the Atlantic Ocean since the Eocene is apparent (Bluck *et al.*, 2005; Jacob, 2005) with an insignificant contribution from the palaeo-Orange River during the Plio-Pleistocene and thereafter. Paradoxically, the Plio-Pleistocene and younger gravel shorelines have the highest diamond concentrations in the Namibian mega-pacer, suggesting that diamond input was principally from another source – the offshore from pre-existing coastal deposits. Therefore, the role of the palaeo-Orange River as a diamond conduit was insignificant during the Plio-Pleistocene, but its contribution as a gravel conveyor was fundamental to coastal evolution. Noteworthy is that the diamonds introduced to the Atlantic Coast since the Eocene until Plio-Pleistocene times, must have resided in their gravel beach hosts for a considerable time before they were tapped and incorporated into younger Plio-Pleistocene shorelines. However, considering that sea-level fluctuated throughout these periods, it is conceivable that diamonds were recycled into progressively younger deposits since the Eocene.

Given that the offshore is seen as the principal diamond reservoir, a key aspect of diamond introduction into an evolving shoreline, such as the 30 m Package during the Plio-Pleistocene, would have been a process of ‘farming’ the diamonds from older submerged deposits. To achieve this, a sea-level fall (and concomitant lowering of the wave base) is firstly required to re-work previous shoreline deposits that are highly diamondiferous, such as those of Late Palaeogene and Early Neogene ages when diamond input to the coast from the palaeo-Orange River was at its peak (Bluck *et al.*, 2005; Jacob, 2005). Secondly, a subsequent transgression is required to drive the sediment and diamonds landward until sea-level reaches positional stability to allow shoreline growth. Therefore, the ‘farming’ process is seen as a retrieval of diamonds during a regression and shoreline mineralisation on a transgression. It thus follows that the diamond characteristics are inherited from the older deposits. These will include sorted populations in a down-drift direction. While it has been advocated that the overall diamond size decreases down-drift from the study area – a function of longshore sorting (Hallam, 1964; Sutherland, 1982; Schneider & Miller, 1992, Figure 6.4A) – the decrease is not entirely constant, but has an irregular distribution with anomalous large average sizes punctuating the overall trend (Figure 6.4B). Equally, the diamond concentration

along the coastline exhibits an irregular trend with an overall increase in a down-drift direction (Figure 6.4B).

Figure 6.4 illustrates these distributions, and although the irregularity could be a result of different trapping mechanism, the data used in the figure is a combination from all beach types of varying ages. Therefore, the anomalous peaks in the graph could also reflect the introduction of a diamond population having a larger average size or higher concentration during a specific time. Bluck *et al.* (2005) demonstrate that the longshore diamond size change has greater complexity. The longshore-transported population was, at different localities, contaminated by the introduction of diamonds from older higher-lying shorelines (such as Eocene to Miocene age). The erosion of these older terraces through sheetwash or stream action introduced a specific average size or quantity of diamonds to an evolving shoreline. Therefore the diamond population within Plio-Pleistocene beaches would comprise a mix of populations. Nonetheless, what is clearly apparent from Figure 6.4 is that the largest average diamond size and lower concentration occurs within the palaeo-Orange River mouth area.

Diamond size not only decreased in a longshore drift direction, but also through time since the Plio-Pleistocene as shorelines became younger. Hallam (1964) notes that 30 m Package deposits (*Donax rogersi*-bearing or 'Upper Terrace' deposits) have a larger average diamond size than the younger *Donax serra*-bearing 'Lower Terrace' deposits. Notwithstanding the larger average diamond size in the palaeo-river mouth, this trend is equally evident in the barrier deposits alone. Comparing the diamond size frequency distribution from the study area with that from Holocene barrier deposits, as shown in Figure 6.5A illustrates a greater percentage of smaller diamonds in the younger barriers with a concomitant lower percentage of larger diamonds. Mention must be made that the Holocene size frequency distribution comprises a mix of results from Holocene barrier deposits of varying age (approximately 5,000 BP to 7,000 BP). Thus, on a finer resolution looking at these Holocene deposits only, a declining trend in diamond size may not be clearly apparent. Nonetheless, when the diamond population from the Holocene barrier deposits in their totality are compared with that of the study area, a declining trend is evident. In addition to this size change through time, the gravel component of river sediments delivered to the coast also decreased in quantity and size since the Plio-Pleistocene as evidenced from the greater amount of sand and smaller gravel size in the Holocene barrier deposits (personal

observation; J. Ward, pers. comm., 2010). It is therefore conceivable that the average diamond size extracted from a diamond pool and trapped within a barrier beach during the recycling process became progressively smaller in concert with a decreasing gravel size through time (Figure 6.5B).

If the general perspective of an offshore source is held, then basically the large diamonds within the study area would have been sourced from an older shoreline that similarly hosted larger diamonds and, more importantly, it would be assumed that the diamond size and concentration throughout the older shoreline would have a down-drift distribution that was equally irregular. Diamond recycling is, however, seen as a more complex process and a particular diamond distribution trend along a coastline would in fact, represent several generations of recycling, making it difficult to predict diamond pathways. Figure 6.6 illustrates such a recycling process where, for example, diamondiferous shelf deposits exposed on a regression are reworked during sea-level fall (see Corbett, 1996) and the diamonds are recycled into regressive shorelines, each having a particular diamond distribution trend. Following the lowstand, the regressive shorelines are reworked on a transgression and each transgressive shoreline at a particular point in time and space would also have a diamond distribution trend. These, however, would be removed as the transgression proceeds landward and so the process is repeated until sea-level decelerates to a highstand and stabilises, allowing shoreline growth. It is at this point where diamond accumulation is best preserved, only if later transgressions reach their maximum at lower elevations.

However, diamond preservation within the host sediments is a function of trapping and retention, which also governs the degree of diamond concentration. Therefore, specific shoreline conditions are required to enhance diamond trapping and their retention; these being fixed trapsites such as gullies and potholes that are cut into bedrock platforms. Among others, Jacob (2001, 2006) and Apollus (1995, 2002) have demonstrated the importance of such trapsites to facilitate high levels of diamond concentration. By generating long-lived sites of turbulence, fixed trapsites have the capacity to accumulate and retain diamonds supplied through generations of recycling (Spaggiari *et al.*, 2006). Therefore, it is conceivable that such fixed trapsites exerted the primary control in shorelines that are bedrock-floored, whilst the coarse gravel adopted a secondary role as an abrasive medium to cut the platforms and associated trapsites as described in detail by Jacob (2006). Evidence for this is provided by

Apollus (1995). He notes that high diamond concentrations from a bedrock gulley where marine sediments of Eemain age contained abundant sand and shell with, surprisingly, minor gravel.

Unlike the bedrock-floored areas, diamond concentration was significantly poor within the palaeo-river mouth – as little as one-tenth and even as low as one hundredth of that in the bedrock-floored settings – given the paucity of fixed trapsites. In fact, the barrier deposits were ineffective in retaining diamonds. There was significant leakage into the longshore drift where the rejected population moved northwards to be later extracted from the passing bed-load into bedrock-floored beaches. These were predominately the smaller diamonds and although the process of leakage was significant, a small population was nevertheless retained. Here gravel exerted the primary role where clast sorting and gravel size, coupled with the preservation potential of depositional environments, controlled the trapping and retention process. A larger diamond population was retained in the barrier deposits, albeit at lower concentrations, by virtue of the large gravel size that accumulated in close proximity to the river mouth. Thus, the last is seen as a giant ‘diamond sieve’ to the littoral irrespective of whether diamond input was from the offshore or fed by the palaeo-Orange River. From the discussions above, several key issues are noteworthy. These are discussed below.

6.3.1 Diamond delivery to barrier deposits

Diamonds are delivered to the shoreline during a transgression, only if the preceding regression has ‘farmed’ older shorelines. It is envisaged that significant diamond input to mineralise the 30 m Package barrier deposits occurred subsequent to three main regressions (see Figure 6.7A & B). The first was during the emplacement of the barrier spits, whilst the second took place at the start of barrier beach construction, more specifically the start of the ‘E’ barrier beach complex. The third saw diamond input during the deposition of the ‘D’ barrier beach before the entire 30 m Package shoreline was abandoned on a forced regression (Figure 6.7A & B). By contrast, the minor regressions that built up the barrier deposits may have tapped diamondiferous sediments, but the contribution from these regressions was likely to be far less significant than the main regressive phases. Thus, it is expected that the highest diamond concentrations should be confined to the barrier spits, more so the lower sequence (BS1 in Figure 4.8), as well as the base of the ‘E’ barrier beach complex (BB1 in Figure 4.9) and the ‘D’ barrier beach (BB5 in Figure 4.9). Sampling results, to some degree, demonstrate

this as shown in Figure 6.7A. The overall highest diamond concentrations are found within the barrier spits – although the results represent the entire barrier spit complex – and also in the ‘D’ barrier beach. Conversely, the ‘E’ barrier beach complex has the lowest, as little as one sixth than their ‘D’ equivalent. Considering that the ‘E’ barrier beach diamond data comprises a mix of results, it is difficult to ‘tease out’ the contribution from the base of the barrier complex. It is likely that its high concentration is diluted by the poorly mineralised deposits forming the remainder of the barrier complex that represent the minor transgressive/regressive stacking cycles.

6.3.2 Preservation of diamond cache

In a setting where diamond input is from the offshore with a minor contribution from river outfall, maximum diamond accumulation and retention is confined to highstand deposits (normal regressive package). Here progradation ‘seals’ off the diamond pool that has been emplaced on the transgression, preventing any further leakage of diamonds to the littoral as the shoreline extends seaward abandoning previous positions (Figure 6.7C). As progradation continues, followed by a forced regression, there is no further diamond replenishment from the offshore with an insignificant supply from landward sources (Meso-Orange River and erosion of older, higher-lying shorelines) and through erosion of the underlying barrier sediments over which the seaward-moving shoreline extends (Figure 6.7C). The resultant pattern of diamond distribution is one of higher concentrations at the most landward end of the highstand sequence (normal regressive package), followed by lower concentrations to the seaward (Figure 6.7C). By contrast, high diamond concentrations are expected to be more persistent throughout the entire normal regressive package if diamond input was predominantly from the palaeo-Orange River, rather than from the offshore. Diamond replenishment would then persist throughout shoreline progradation.

6.3.3 Diamond retention

The largest diamonds within the study area, confined to the transgressive boulder lag (see Chapter 5), provides an approximate measure of the maximum diamond size contributed by the offshore. It also demonstrates how gravel size governs the retention and leakage of a particularly diamond size. Such a process is also seen in the Skeleton Coast, Namibia, where the average diamond size is significantly small; as little as one-seventh the size of those in the study area (Spaggiari & Ward, 2004; see also Figure 6.4A for diamond size distribution). The Skeleton Coast palaeo-shorelines consist predominantly of coarse sediment, up to large

cobble gravel (personal observation), and are ineffective in trapping the small diamonds by virtue of the coarse gravel fabric. A dichotomy of gravel and diamond size thus typifies these palaeo-beaches and given that the majority of the Skeleton Coast diamonds fall within the small-size range, these coarse gravel shorelines are poorly mineralised. It then follows that the smaller diamonds approximate the size that has ‘leaked’ out of a foreshore environment into the littoral, which can be transported as far as southern Angola, approximately 1,400 km from the study area. Consequently, gravel size governs diamond size retention so that if a population of mixed diamond sizes is transported alongshore with no introduction from landward – as in the case of a transgression – the coarsest gravel near the river outfall will trap the largest diamonds in transport, whilst the smaller will be rejected back into the littoral to be finally trapped by a smaller gravel size farther down-drift.

6.3.4 Diamond-rich sediment pulses

The anomalous diamond yields of exceptional concentration as described by Apollus (1995) for those in sand- and shell-dominated sediments within gullies may represent a pulse of diamond-enriched sediment that migrated landward during a relatively fast sea-level rise. In fact, an extraordinary and rare occurrence of a mono-layer of diamonds preserved in a bedrock gully feature within the 1 Plant Area (see Figure 1.2 locality), some 95 km north of the study area, provides more convincing evidence of such diamond-enriched sediment pulses (pers. comm., I. Corbett, 2010). Therefore diamond recycling and their landward translocation may have been in the form of sediment-hosted pulses. Although their pathways are difficult to map out, it is evident that they originated from a pre-existing coastal segment yielding equally high diamond concentrations. These pre-existing localities of high diamond concentrations would have been positioned to the south-west (offshore) of the newly evolved shoreline given that sediment movement was to the north, driven by north-easterly directed waves and a northward directed longshore drift.

Divers, working in the present offshore extracting diamond-bearing gravel with suction hoses at depths of 10-20 m, have reported that mined out potholes and gullies are replenished with diamond-bearing gravel within several months (M. Botha, pers. comm., 2010). This replenishing gravel, referred to as ‘travel gravel’ by the divers, is moved shoreward by coastal currents and probably derived from a pre-existing submerged palaeo-shoreline. The moving ‘travel gravel’ therefore represents a pulse of diamondiferous sediment

and is a possible modern example of how diamonds are recycled and moved along the coast since the Eocene (see Bluck *et al.*, 2007).

6.3.5 Sediment dispersal related to diamond concentration

The segregation process, of removing finer sediments into the sediment bypass system and adding gravel to the shoreline, allied with a buoyant shelf, was fundamental to the diamond concentration process. Removal of unwanted, diluting sediments such as sand and mud, enhanced diamond concentrations. Simply and hypothetically put, if a sediment body of 1,000 m³, yielding diamonds to the weight of 500 carats (note a carat is equivalent to 0.2 grams; Lynn *et al.*, 1998) comprises 80% sand and 20% gravel, its diamond concentration would be 0.5 cts/m³ (500 carats/1,000 m³). Total removal of the sand would see an enrichment of 80% in the diamond concentration to 2.5 cts/m³ (500 cts/200 m³). Thus, the more condensed a gravel sequence is, the greater the enrichment. Inasmuch as longshore drift and wave energy are the major role players in segregating the sediments, the importance of a buoyant shelf cannot be ignored. The stability of the shelf ensured sediments were continuously within wave base to facilitate the segregating process. The combination of these attributes was key to developing the Namibian marine mega-placer. It, however, does not necessarily imply that shelf subsidence was absent during the Plio-Pleistocene. In fact, Dingle *et al.* (1983) note that the limited Neogene terrigenous sedimentation on the shelf off the Orange River is partly due to slight subsidence of the shelf since the Mid-Tertiary, coupled with an overriding effect of the dispersion process as discussed above. This implies that shelf subsidence was inadequate to disrupt sediment dispersion and the development of a highly economic diamond placer.

CHAPTER 7– CONCLUSIONS AND FUTURE RESEARCH

7.1 CONCLUSIONS

7.1.1 Palaeo-Orange River mouth setting

- 1) Diamondiferous gravel barrier spits and barrier beaches of Plio-Pleistocene age (30 m Package), occupy a small segment of the larger palaeo-shoreline in southern Namibia. Confined to a river mouth setting of an ancestral Orange River, these deposits form part of the Namibian mega-placer. However, immediately down-drift of these barrier features, the character of the palaeo-shoreline changes where it is dominated by bedrock-floored linear and pocket beaches. This change from barrier spits through barrier beaches to linear and pocket beach features is thought to be a result of diminishing gravel supply in a down-drift direction.
- 2) Aside from their geomorphological features, the recognition of these barrier types is based exclusively on their internal structures, which in turn, differentiate them from the underlying delta sediments and other shoreline features. Although, the mega-placer palaeo-shorelines have evolved under the same coastal conditions, the barrier deposits differ to their linear and pocket beach counterparts. This is due to local variations in the coastline and sediment supply. Consequently, shoreline features evolving in river mouth settings have barrier morphologies and their mobility is unhindered due to the availability of space. Here, washover fans producing landward dipping cross-strata are a distinguishing feature. Away from the river mouth where linear beaches are backed by a bedrock-cliff, there is no landward space for movement, thus the fringing beaches are 'fixed' in place and lack a barrier shape and washover deposits.
- 3) Landward migration rates of barrier features within a river mouth will consequently be more rapid under a rising sea-level and migrate farther landward. Their maximum transgressive position will be offset from linear beaches of corresponding age, making it difficult to correlate beach sequences along strike.
- 4) Of the entire 30 m Package shoreline that is developed over 1,800 km of coastline in South Africa (Namaqualand) and Namibia, the highest preservation is within the palaeo-Orange River mouth. Here a comprehensive sea-level history is recorded in a 16 m sequence of

barrier sediments. This sequence also represents the thickest accumulation of 30 m Package deposits. Six evolutionary stages of barrier building have been identified, beginning with the development of barrier spits that occupy the lowest part of the stratigraphic record and culminating in a barrier beach. The emplacement of these barriers was controlled by a combination of sediment supply, sea-level fluctuations, a large river mouth setting and coastal subsidence.

- 5) Sediment supply to the Atlantic Ocean was spasmodic and shoreline growth was in concert episodic. Under these conditions coastal features in close proximity to the outfall changed from barrier spits to barrier beaches, depending on the variability of sediment supply. The vertical stacking of these barrier types is a consequence of sea-level rise, aided in part by coastal subsidence. However, the barrier stratigraphy developed under a more complex sea-level history. Whilst an overall regression saw the progressive abandonment of older shorelines along the Atlantic Coast through time, a superimposed transgression was responsible for the emplacement of 30 m Package deposits along the entire west coast of southern Africa. It also provided the accommodation space. Within this sea-level rise, numerous transgressive and regressive cycles of short duration encouraged the growth and vertical stacking of different barrier types. These barrier deposits therefore provide evidence that the sea-level rise responsible for emplacing the 30 m Package was not regular during the Plio-Pleistocene as previously anticipated, but was interrupted by high frequency sea-level oscillations.
- 6) Only highstand deposits (normal regressive packages) have been preserved, which are a small representation of the greater shoreline configuration. Thus, these barrier remnants are only part of the entire evolutionary path of the 30 m Package in Namibia that has evolved under a wave climate that is not significantly different to that of today.
- 7) The coarsest gravel accumulated at the river mouth and by virtue of their size, these clasts were not suitably mobile under longshore transport, but were instead added to barrier deposits that evolved in close proximity to the outfall. Farther down-drift, longshore sorting of the more mobile gravel saw a northward decline in size and sediment supply. Hence, the river mouth setting is a favourable area for thick accumulations of coarse gravel. It is this accumulation that governed diamond concentration within the palaeo-Orange River mouth.

7.1.2 Diamond potential of barrier deposits

- 1) Within the Namibian mega-placer, the palaeo-river mouth yields lower concentrations of diamonds due to the incompetent footwall and consequent paucity of fixed trapsites. By contrast, the bedrock-floored beaches have higher concentrations where a large percentage of the diamonds is trapped within gullies and potholes. Diamond concentration within barrier sediments are thus controlled exclusively by a process of interstitial trapping that is governed by the gravel fabric. The larger pore space not only allows a greater depth of diamond percolation into the barrier sediments, but also traps the larger size. Thus, diamond concentration is allied to kinetic sieving; a process that is also fundamental for gravel size sorting. It is for this reason that the palaeo-river mouth setting has the largest average diamond size within the entire mega-placer. Varying degrees of diamond concentrations are evident in different depositional facies. These are linked to depositional processes.
- 2) Diamond concentrations in a barrier beach are highest in the foreshore (more specifically the beach face), whilst the backshore (washover) and shoreface (transgressive lag and storm gravel sheets) settings are uneconomical. Conversely, average diamond size is largest within the shoreface (in the transgressive lag), followed by the foreshore (beach toe) and backshore (washover).
- 3) As regards the barrier spit, the foreshore environment of spit recurves (landward facing intertidal zone) has the highest diamond concentrations, whilst the tidal inlet has the lowest. Average diamond size is largest in the foreshore (seaward facing intertidal zone), but considerably smaller in both the spit recurves and tidal inlet.
- 4) When the economic potential of each depositional facies is considered based on their ton value (US\$/ton), the foreshore setting is the most promising, particularly in the barrier beach, followed by the barrier spit (which includes the spit recurves).
- 5) Although an appreciable quantity of diamonds was introduced to the palaeo-river mouth setting, diamond retention in the barrier deposits was poor, resulting in leakage of the smaller fraction back into the littoral where they are transported alongshore.

7.1.3 Diamond emplacement model

- 1) Diamond introduction to the shoreline during Plio-Pleistocene and younger times was mainly from the offshore and not from the Orange River. The shelf setting is thus seen as the diamond reservoir. Shorelines are only mineralised through a process of ‘farming’ whereby sea-level fluctuations rework pre-existing diamond-bearing deposits. The ‘farming’ process is complex, but the main requirements are a forced regression to source the diamonds from pre-existing deposits and a subsequent transgression to drive the diamonds landward. Throughout the ‘farming’ process, diamonds are size-sorted and concentrated into pulses of sediment by longshore currents and wave energy. It is only at the point of maximum transgression that there is greater accumulation of diamonds in the barrier deposits. A subsequent normal regression on a highstand will isolate the diamond cache from wave energy as the shoreline builds seaward, effectively preventing further diamond leakage. Thus, maximum preservation of diamonds takes place during progradation on a highstand, whilst forced regressions are mainly seen as gravel conveyors. During the vertical build up of barrier types, diamond introduction was greatest where forced regressions of significant amplitude exposed large areas of the shelf for the subsequent transgression to ‘farm’, whereas the contribution from minor regressions were less significant.

- 2) The gravel component of river sediment delivered to the palaeo-river mouth not only declined in quantity with time, but also in particle size. Diamond size equally declined in concert with the gravel. Here larger diamonds were progressively extracted from the diamond pool and retained by the coarser gravel during sediment recycling when the shelf was ‘farmed’. Consequently, the 30 m Package barriers (*Donax rogersi*-bearing) have a larger average diamond size than the younger *Donax serra*-bearing barriers.

- 3) The palaeo-Orange River mouth has played a fundamental role in the mineralisation process of the entire mega-placer shoreline. Being at the interface of river sediment input and marine dispersion, the river mouth was an intermediary reservoir of sediment to the marine realm. Coastal processes dispersed the sediment to different parts of the Atlantic Coast, with the coarsest gravel accumulating at the river mouth. The latter dictates the position of barrier deposits and, in turn, the accumulation of coarse gravel. The presence of considerably coarse Orange River gravel, as in the case of the offshore sector, thus

provides a clue of an ancestral outfall. In addition to this, the river mouth acted as a giant ‘diamond sieve’ to the littoral environment, retaining a population of the larger diamonds.

- 4) By understanding sedimentary facies architecture (which is the spatial distribution of the different sedimentary facies – the latter is characterised by the grain sizes, lithology, geometry, sedimentary structures, fossil content and palaeo-currents) of river mouth settings, barrier deposits of low economic value can be more effectively targeted during sampling, evaluation and mining campaigns.

7.2 FUTURE RESEARCH

- 1) Barrier sediment preservation within the palaeo-river mouth setting is, in part, linked to coastal subsidence. Although, local tectonism is thought to be responsible for the northward tilting of the coastal area, it may have also induced tectonic subsidence. Detailed studies on Plio-Pleistocene tectonism should be considered. This will substantiate tectonic effects along the Namaqualand and Namibian coastline that may have also promoted differential movement of the coastal tract in a ‘piano-key’ style, thereby augmenting sediment preservation.
- 2) The sea-level history recorded within the palaeo-Orange river mouth is based primarily on facies relationships, but the timing of depositional events cannot be ascertained due to the lack of absolute age indicators. Thus, the integration of onshore marine settings with the offshore geology and the Orange River terraces of corresponding time frames should be explored to constrain better the sea-level history of the study area. It will also improve the understanding of diamond pathways under fluctuating sea-levels.
- 3) The variation in diamond size and concentration along the coast (offshore and onshore settings) should be investigated in greater detail as a means of establishing a link between erratic diamond distribution trends and diamond-rich sediment pulses. Given that diamond movement in the offshore is perceived to be in the form of such pulses, the erratic diamond distribution – also encouraged by trapping mechanisms – may correlate to diamond pulses introduced at various positions along the coastline. This will aid in the mapping of diamond pathways from both the offshore (older, submerged shorelines) and onshore (older, higher-lying shorelines).

- 4) A detailed study of the palaeo-river mouth diamonds for comparison with the down-drift populations to determine changes in diamond characteristics that will aid the identification of diamond-rich sediment pulses. For example, populations that have a high degree of percussion scarring may be a reflection of diamond abundance where collision of diamond particles is prevalent.
- 5) Test the notion that wave climate variability through Plio-Pleistocene to Present times was insignificant through detailed comparisons of gravel beach macro-morphology within the study area with that from present gravel beaches along the Skeleton Coast.

REFERENCES

- Abreu, V.S., Hardenbol, J., Haddad, G.A., Baum, G.R., Droxler, A.W. and Vail, P.R. (1988). Oxygen isotope synthesis: a Cretaceous ice-house? In: de Graciansky, P.C., Hardenbol, J., Jacquin, T. and Vail, P.R. (Eds). Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, *Society of Economic Palaeontologists and Mineralogists*, special publication no. 60, 75-80.
- Aizawa, M., Bluck, B., Cartwright, J., Milner, S., Swart, R. and Ward, J. (2000). Constraints on the geomorphological evolution of Namibia from the offshore stratigraphic record. *Communications of the Geological Survey of Namibia*, vol. 12, 337-346.
- Alexkor. (2009). Alexkor Limited 2009 Annual Report, p.52. Website, <http://www.alexkor.co.za>
- Allan, A.F. and Frostick, L. (1999). Framework dilation, winnowing, and matrix particle size: the behaviour of some sand-gravel mixtures in a laboratory flume. *Journal of Sedimentary Research*, vol. 69, no.1, 21-26.
- Andrews, P.B. (1970). Facies and genesis of a hurricane washover fan, St. Joseph Island, central Texas coast. Report of Investigations, no. 67. *Bureau of Economic Geology*, University of Texas, Austin, U.S.A., p. 147.
- Anthony, E.J. and Dolique, F. (2001). Natural and human influences on the contemporary evolution of gravel shorelines in northern France between the Seine estuary and Belgium. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 132-148. Westbury, Otley, West Yorks, U.K.
- Apollus, L.A. (1993). Sedimentary logging of megatrenches in the 'G' area. *Internal report*, Consolidated Diamond Mines (Pty.) Ltd.
- Apollus, L.A. (1995). The distribution of diamonds on a Late Cainozoic gravel beach, southwestern Namibia. *Unpublished M.Sc. thesis*, Department of Geology and Applied Geology, University of Glasgow, Scotland, p. 170.

- Austin, M.J. and Masselink, G. (2006). Observations of morphological change and sediment transport on a steep gravel beach. *Marine Geology*, vol. 229, 59-77.
- Bailey, A.C., Law, J.D.M., Cadle, A.B. and Phillips, G.N. (1990). The Zandfontein Quartzite Formation, a marine deposit in the Central Rand Group, Witwatersrand Supergroup. *South African Journal of Geology*, vol. 93, no. 1, 135-146.
- Barnes, R.S.K. (2001). The geomorphology and ecology of the shingle-impounded coastal lagoon systems of Britain. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 77-106. Westbury, Otley, West Yorks, U.K.
- Barwis, J.H. and Hayes, M.O. (1984). Antidunes on modern and ancient washover fans. *Journal of Sedimentary Petrology*, vol. 55, no. 6, 907-916.
- Barwis, J.H. and Makurath, J.H. (1978). Recognition of ancient tidal inlet sequences: an example from the Upper Silurian Keyser Limestone in Virginia. *Sedimentology*, vol. 25, 61-82.
- Bascom, W. (1964). *Waves and beaches: the dynamics of the ocean surface*. Anchor Books, Doubleday & Company, Inc., New York, p. 267.
- Benn, D.J. and Ballantyne, C.R. (1992). Pebble shape (and size!) – discussion. *Journal of Sedimentary Petrology*, vol. 62, no. 6, 1147-1150.
- Besler, H. (1996). The Tsondab Sandstone Formation in Namibia and its significance for the Namib erg. *South African Journal of Geology*, vol. 99, no. 1, 77-88.
- Bhattacharya, J.P. and Giosan, L. (2003). Wave-influenced deltas: geomorphological implications for facies reconstruction. *Sedimentology*, vol. 50, 187-210.
- Birch, G.F., Day, R.W. and du Plessis, A. (1991). Nearshore Quaternary sediments on the West Coast of southern Africa. *Bulletin of the Geological Survey of South Africa*, bulletin 101, p. 14.

- Bird, E.C.F. (1972). *Coasts. An introduction to systematic geomorphology*. Australian National University Press, p. 246.
- Blair, T.C. (1999). Sedimentology of gravelly Lake Lahontan highstand shoreline deposits, Churchill Butte, Nevada, U.S.A. *Sedimentary Geology*, vol. 123, 199-218.
- Blott, S.J. and Pye, K. (2008). Particle shape: a review and new methods of characterisation and classification. *Sedimentology*, vol. 55, 31-63.
- Bluck, B.J. (1967). Sedimentation of beach gravels: examples from South Wales. *Journal of Sedimentary Petrology*, vol. 37, 128-156.
- Bluck, B.J. (1999). Clast assembling, bed forms and structure in gravel beaches. *Transactions of the Royal Society of Edinburgh Earth Sciences*, vol. 89, 291-323.
- Bluck, B.J. (In press). Structure of gravel beaches and their relationship to tidal range. *Sedimentology*.
- Bluck, B.J. and Ward, J.D. (2000). The Orange River – Namib Desert link: a long-lived sediment dispersal system in southern Africa. Abstract Volume, *Geoluanda 2000 International Conference* (14th African Colloquium on micropaleontology, 4th Colloquium on the stratigraphy and the palaeogeography, on the South Atlantic, Regional Meeting on South Atlantic Mesozoic correlations (ICGP381), 4th Annual Meeting on the Kibaran Orogeny (ICGP418), pg. 30. University Agostinho Neto, Department of Geology and Angolan Association of Geologists, Luanda, Angola.
- Bluck, B.J., Ward, J.D., Cartwright, J. and Swart, R. (2007). The Orange River, southern Africa: an extreme example of a wave-dominated sediment dispersal system in the South Atlantic Ocean. *Journal of the Geological Society*, vol. 164, 341-351.
- Bluck, B.J., Ward, J.D. and de Wit, M.J.C. (2005). Diamond mega-placers: southern Africa and the Kaapvaal Craton in a global context. In: McDonald, L., Boyce, A.J., Butler, I.B., Herrington, R.J. and Polya, D.A. (Eds). *Mineral deposits and earth evolution. Geological Society, London, Special Publications*, vol. 248, 231-245.

- Bluck, B.J., Ward, J.D. and Spaggiari, R.I. (2001). Gravel beaches of southern Namibia. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 56-76. Westbury, Otley, West Yorks, U.K.
- Blum, M.D. and Törnqvist, T.E. (2000). Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology*, vol. 47, 2-48.
- Boothroyd, J.C. (1985). Tidal inlets and tidal deltas. In: Davis, R.A. Jr. (Ed.). *Coastal sedimentary environments*, second revised, expanded edition, 445-525, Springer Verlag.
- Boggs, S. Jr. (2001). *Principles of sedimentology and stratigraphy*. Pearson Prentice Hall, Upper Saddle River, p. 726.
- Bose, P.K. and Das, N.G. (1986). A transgressive storm- and fair-weather wave-dominated shelf sequence: Cretaceous Nimar Formation, Chakrud, Madhya Pradesh, India. *Sedimentary Geology*, vol. 46, 147-167.
- Brown, J., Colling, A., Park, D., Phillips, J., Rothery, D. and Wright, J (1989). *Waves, tides and shallow-water process*. Pergamon Press, Oxford, p. 187.
- Brown, R.W., Gallagher, K., Griffin, W.L., Ryan, C.G., de Wit, M.C.J., Belton, D.X., and Harman, R. (1998). Kimberlites, accelerated erosion and evolution of the lithospheric mantle beneath the Kaapvaal Craton during the mid-Cretaceous. *7th International Kimberlite Conference, Cape Town. Abstract volume*, 105-107. University of Cape Town, South Africa.
- Brown, R.W., Rust, D.J., Summerfield, M.A., Gleadow A.J.W. and de Wit, M.J.C. (1990). An early Cretaceous phase of accelerated erosion on the south-western margin of Africa: Evidence from apatite fission-track analysis and the offshore sedimentary record. *International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements*, vol. 17, 339-350.

- Brown, R.W., Summerfield, M.A. and Gleadow, J.W. (2002). Denudation history along a transect across the Drakensberg Escarpment of southern Africa derived from apatite fission track thermochronology. *Journal of Geophysical Research*, vol. 107, 1-18.
- Brundrit, G.B. and Shannon, L.V. (1989). Cape storms and the Agulhas Current: a glimpse of the future? *South African Journal of Science*, vol. 85, 619-620.
- Buscombe, D. and Masselink, G. (2006). Concepts in gravel beach dynamics. *Earth-Science Reviews*, vol. 79, 33-52.
- Butt, T. and Russell, P. (2000). Hydrodynamics and cross-shore sediment transport in the swash-zone of natural beaches: a review. *Journal of Coastal Research*, vol. 16, no. 2, 255-268.
- Cairncross, B. (2004). *Field guide to rocks and minerals of Southern Africa*, p. 292, Struik Publishers, South Africa.
- Caldwell, N.E. and Williams, A.T. (1985). The role of beach profile configuration in the discrimination between differing depositional environments affecting coarse clastic beaches. *Journal of Coastal Research*, vol. 1, no. 2, 129-139.
- Carling, P.A. and Breakspear, R.M.D. (2006). Placer formation in gravel-bedded rivers: a review. In: Els, B.G. and Eriksson, P.G. (Eds). Special issue: Placer Formation and Placer Minerals, *Ore Geology Reviews*, vol. 28, no 4, 377-401.
- Carr, A.P. (1965). Shingle spit and river mouth: short-term dynamics. *Transactions of the Institute of British Geographers*, no. 36, 117-129.
- Carr, A.P. (1969). The growth of Orford Spit: cartographic and historical evidence from the Sixteenth Century. *Geographical Journal*, vol. 135, 28-29.
- Carr, A.P. (1983). Shingle beaches: aspects of their structure and stability. In: Anon (Ed.) *Shoreline protection*. London, Thomas Telford, 69-76.

- Carrington, A.J. and Kingsley, B.F. (1969). *Pleistocene molluscs from the Namaqualand coast. Annals of the South African Museum*, vol. 52 (9), 189-223.
- Carter, R.W.G. (2002). *Coastal environments. An introduction to the physical, ecological and cultural systems of coastlines*. St Edmundsbury Press Limited, Suffolk, p. 611.
- Carter, R.W.G. and Orford, J.D. (1980). Gravel barrier genesis and management: a contrast. *Coastal Zone 80, Proceedings of the 2nd Symposium on Ocean Management*, American Society of Civil Engineers, 2, 1304-1320.
- Carter, R.W.G. and Orford, J.D. (1981). Overwash process along a gravel beach in south-east Ireland. *Earth Surface Processes and Landforms*, vol. 6, 413-426.
- Carter, R.W.G. and Orford, J.D. (1984). Coarse clastic barrier beaches: a discussion of the distinctive dynamic and morphosedimentary characteristics. *Marine Geology*, vol. 60, 375-388.
- Carter, R.W.G. and Orford, J.D. (1988). Conceptual Model of Coarse Clastic Barrier Formation from Multiple Sediment Sources. *Geographical Reviews*, vol. 78, no. 2, 221-239.
- Carter, R.W.G., Forbes, D.L., Jennings, S.C., Orford, J.D., Shaw, J. and Taylor, R.B. (1989). Barrier and lagoon coast evolution under differing relative sea-level regimes: examples from Ireland and Nova Scotia. *Marine geology*, vol. 88, 221-242.
- Carter, R.W.G., Orford, J.D., Forbes, D.L. and Taylor, R.B. (1990). Morphosedimentary development of drumlin-flank barriers with rapidly rising sea level, Story Head, Nova Scotia. *Sedimentary Geology*, vol. 69, 117-138.
- Cartwright, J., Swart, R. and Corner, B. (2008). The Namibian coastal margin. In: Miller, R.McG. (author). *The Geology of Namibia. Palaeozoic to Cenozoic, volume 3*. Ministry of Mines and Energy, Geological Survey of Namibia, 28-1 to 28-13.

- Casshyap, S.M. and Aslam, M. (1992). Deltaic and shoreline sedimentation in Saurashtra Basin, Western India: an example of infilling in an Early Cretaceous failed rift. *Journal of Sedimentary Petrology*, vol. 62, no. 6, 972-991.
- Cattaneo, A. and Steel, R.J. (2003). Transgressive deposits: a review of their variability. *Earth Science Reviews*, vol. 62, 187-228.
- Catuneanu, O. (2002). Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. *Journal of African Earth Sciences*, vol. 35, 1-43.
- Catuneanu, O. (2006). *Principles of sequence stratigraphy*. Elsevier, p. 375.
- Catuneanu, O., Martins-Netob, M.A., and Eriksson, P.G. (2005). Precambrian sequence stratigraphy. *Sedimentary Geology*, vol. 176, 67-95.
- Chapman, J.G. and Boxer, G.L. (2004). Size distribution analyses for estimating diamond grade and value. *Lithos*, vol. 76, 369-375.
- Chaston, I.R.M. and Napier-Munn, T.J. (1974). Design and operation of dense-medium cyclone plants for the recovery of diamonds in Africa. *Journal of the South African Institute of Mining and Metallurgy*, December 1974, 120-133.
- Cheel, R.J. and Leckie, D.A. (1992). Coarse-grained storm beds of the upper Cretaceous Chungo Member (Wapiabi Formation), Southern Alberta, Canada. *Journal of Sedimentary Petrology*, vol. 62, no. 6, 933-945.
- Cheng, K.L. (1982). Sedimentology of nearshore marine bar sequences from a Paleozoic depositional regressive shoreline deposit of the central coast of Ghana, West Africa. *Journal of Sedimentary Petrology*, vol. 52, no. 1, 199-208.
- Clifton, H.E. (1969). Beach lamination: nature and origin. *Marine Geology*, vol. 7, 553-559.

- Clifton, H.E. (1976). Wave-formed sedimentary structures: a conceptual model. In: Davis, R.A. Jr and Ethington, E.L. (Eds). Beach and nearshore sedimentation. *Society of Economic Palaeontologists and Mineralogists*, special publication no. 24, 126-148.
- Clifton, H.E. (1981). Progradational sequences in the Miocene shoreline deposits, southeastern Caliente Range, California. *Journal of Sedimentary Petrology*, vol. 51, no. 1, 165-184.
- Clifton, H.E. (1988). Sedimentologic approaches to paleobathymetry, with applications to the Merced Formation of central California. *PALAIOS*, determining paleobathymetry, vol. 3, no. 5, 507-522.
- Clifton, H.E. and Dingler, J.R. (1984). Wave-formed structures and paleoenvironmental Reconstruction. *Marine Geology*, vol. 60, 165-198.
- Coco, G., Burnet, T.K. and Werner, B.T. (2003). Test and self-organisation in beach cusp formation. *Journal of Geophysical Research*, vol. 108, no. C3, 46-1 to 46-11.
- Coleman, J.M. and Huh, O.K. (2004). Senegal channel, WDD contributions. Website, <http://www.geol.lsu.edu/WDD>
- Collinson, J.D. and Thomson, D.B. (1989). *Sedimentary structures*. 2nd edition, Unwin Hyman, London, p. 207.
- Compton, J.S. (2006). The mid-Holocene sea-level highstand at Bogenfels Pan on the southwest coast of Namibia. *Quaternary Research*, vol. 66, 303-310.
- Cook, D.O. (1970). The occurrence and geologic work of rip currents off southern California. *Marine Geology*, vol. 9, 173-186.
- Cooper, J.A.G. (2001). Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Sedimentary Geology*, vol. 40, 99-122.

- Cooper, J.A.G. (2002). The role of extreme floods in estuary-coastal behaviour: contrasts between river- and tide-dominated microtidal estuaries. *Sedimentary Geology*, vol. 150, 123-137.
- Cooper, J.A.G. and Pilkey, O.H. (2004). Sea level rise and shoreline retreat: time to abandon the Brunn Rule. *Global and Planetary Change*, vol. 43, 157-171.
- Corbett, A. (2002). *Diamond beaches; a history of Oranjemund*. Namdeb Diamond Corporation (Pty.) Ltd, p. 144.
- Corbett, I.B. (1989). The sedimentology of diamondiferous deflation deposits within the Sperrgebiet, Namibia. *Unpublished Ph.D. thesis*, University of Cape Town, Cape Town, South Africa, p. 430.
- Corbett, I.B. (1996). A review of diamondiferous marine deposits of western southern Africa. *Africa GeoScience Review*, vol. 3, no. 2, 1-18.
- Corbett, I.B. and Burrell, R. (2001). The earliest Pleistocene(?) Orange River fan-delta: an example of successful exploration delivery aided by applied Quaternary research in diamond placer sedimentology and palaeontology. *Quaternary International*, vol. 82, 63-73.
- Corner, B. (2008). Crustal framework of Namibia derived from an integrated interpretation of geophysical and geological data. In: Miller, R.McG. (author). *The Geology of Namibia. Archean to Mesoproterozoic, volume 1*. Ministry of Mines and Energy, Geological Survey of Namibia, 2-1 to 2-19.
- Corvinus, G. (1983). *The raised beaches of the west coast of South West Africa/Namibia: an interpretation of their archaeological and palaeontological data*. München, Verlag C.H. Beck, p. 109.
- Corvinus, G. and Hendey, Q.B. (1978). New Miocene vertebrate locality and Arrisdrift in South West Africa. *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie*, vol. 4, 193-205.

- Dale, D.C. and McMillan, I.K. (1996). Report on 1995/1996 onshore Namdeb samples given to the Geological Laboratory by John Ward. *Internal report*, Geolaboratory, Mineral Resources Unit, De Beers Marine, Cape Town, South Africa.
- Dale, D.C. and McMillan, I.K. (2003). Foraminifera from the basal conglomerates below the E-beach, megatrench G29, Mining Area 1, near Oranjemund. *Internal report*, Geolaboratory, Mineral Resources Unit, De Beers Marine, Cape Town, South Africa.
- Dardis, G.F. and Grindley, J.R. (1988). Coastal Geomorphology. In: Moon, B.P. and Dardis, G.F. (Eds). *The geomorphology of southern Africa*, 141-174. Southern Book Publishers, Johannesburg, South Africa.
- Dasgupta, P. (1995). A new model of inclinometer and its application in determination of attitude of foreset planes. *Journal of Sedimentary Research*, vol. 65, no. 3, 562-563.
- Davies, D.K., Ethridge, F.G. and Berg, R.R. (1971). Recognition of barrier environments. *The American Association of Petroleum Geologists Bulletin*, vol. 55, 550-565.
- Davies, J.L. (1964). A morphogenic approach to world shorelines. *Zeitschrift für Geomorphologie*, vol. 8, 127-142.
- Davies, J.L. (1972). *Geographical variation in coastal development*. Edinburgh, Oliver & Boyd, Edinburgh, p. 204.
- Davis, R.A. Jr. (1985). Beach and nearshore zone. In: Davis, R.A. Jr. (Ed.). *Coastal sedimentary environments*, second revised, expanded edition. Springer-Verlag, 379-438.
- Davis R.A. Jr. and Clifton H.E. (1987). Sea level change and the preservation potential of wave dominated and tide dominated coastal sequences. In: Nummedal, D., Pilkey, O.H. and Howard, J.D. (Eds). Sea level fluctuation and coastal evolution, *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 41, 167-178.
- Davis, R.A. Jr. and Fitzgerald, D.M. (2004). *Beaches and coasts*. Blackwell Publishing Company, p. 419.

- Davis, R.A. Jr. and Hayes, M.O. (1984). What is a wave dominated coast? *Marine Geology*, vol. 60, 313-329.
- DeCelles, P.G. (1987). Variable preservation of Middle Tertiary, coarse-grained nearshore and outer-shelf storm deposits in southern California. *Journal of Sedimentary Petrology*, vol. 57, no. 2, 250-264.
- DeCelles, P.G., Langford, R.P. and Schwartz, R.K. (1983). Two new methods of palaeocurrent determination from trough cross-stratification. *Journal of Sedimentary Petrology*, vol. 53, no. 2, 629-642.
- De Decker, R.H. (1987). The geological setting of diamondiferous deposits on the inner shelf between the Orange River and Wreck Point, Namaqualand. *Bulletin of the Geological Survey of South Africa*, bulletin 86, p. 99.
- De Decker, R.H. (1988). The wave regime on the inner shelf south of the Orange River and its implications for sediment transport. *South African Journal of Geology*, vol. 91, no. 3, 358-372.
- Demarest, J.M. II. and Kraft, J.C. (1987). Stratigraphic record of Quaternary sea levels: implications for more ancient strata. In: Nummedal, D., Pilkey, O.H. and Howard, J.D. (Eds). Sea level fluctuation and coastal evolution, *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 41, 223-239.
- De Wit, M. (2007). The Kalahari epeirogeny and climate change: differentiating cause and effect from core to space. *South African Journal of Geology*, vol. 110, 367-392.
- De Wit, M.C.J. (1993). Cainozoic evolution of drainage systems in the North-Western Cape. *Unpublished Ph.D. thesis*, University of Cape Town, Cape Town, South Africa, p. 371.
- De Wit, M.C.J. (1996). The distribution and stratigraphy of inland alluvial diamond deposits in South Africa. *Africa Geoscience Review, special edition*, 19-33.

- De Wit, M.C.J. (1999). Post-Gondwana drainage and the development of diamond placers in west South Africa. *Economic Geology*, vol. 94, 358-371.
- De Wit, M.C.J., Ward, J.D., Bramford, M.K. and Roberts, M.J. (2009). The significance of the Cretaceous diamondiferous gravel deposit at Mahura Muthla, Northern Cape Province, South Africa. *South African Journal of Geology*, vol. 112, 89-108.
- De Wit, M.C.J., Ward, J.D. and Spaggiari, R.I. (1992). A reappraisal of the Kangnas dinosaur site, Bushmanland, South Africa. *South African Journal of Science*, vol. 88 (9/10), 504-507.
- Dias, J.M.A., Pilkey, O.H. and Heilweil, V.M. (1984). Detrital mica: environmental significance in north Portugal continental shelf sediments. *Comunicações dos Serviços Geológicos de Portugal*, t. 70, fase, 1, 93-101.
- Dickinson, W.W. and Woolfe, K.J. (1997). An *in situ* transgressive barrier model for the Nelson Boulder Bank, New Zealand. *Journal of Coastal Research*, vol. 13, no. 3, 937-952.
- Didenkulova, I.I., Slunyaev, A.V., Pelinovsky, E.N. and Kharif, C. (2006). Freak waves in 2005. *Natural Hazards and Earth System Sciences*, vol. 6, 1007-1015.
- Dingle, R.V. (1993). Structural and sedimentary development of the continental margin off southwestern Africa. *Communications of the Geological Survey of Namibia*, vol. 8, 35-43.
- Dingle, R.V. and Hendey, Q.B. (1984). Late Mesozoic and Tertiary sediment supply to the eastern Cape basin (SE Atlantic) and palaeo-drainage systems in southwestern Africa. *Marine Geology*, vol. 56, 13-26.
- Dingle, R.V., Siesser, W.G. and Newton, A.R. (1983). *Mesozoic and Tertiary Geology of Southern Africa*. A.A. Balkema, Rotterdam, p. 375.
- Dingler, J.R. (1974). Wave-formed ripples in nearshore sands. *Unpublished Ph.D. thesis*, University of California, Saint Diego, U.S.A., p. 136.

- Domínguez, J.M.L., Martín, L. and Bittencourt, A.C.S.P. (1987). Sea level history and Quaternary evolution of river mouth-associated beach-ridge plains along the east-southeast Brazilian coast; a summary. In: Nummedal, D., Pilkey, O.H. and Howard, J.D. (Eds). Sea level fluctuation and coastal evolution, *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 41, 115-127.
- Dominy, S.C., Noppé, M.A. and Annels, A.E. (2002). Errors and uncertainty in mineral resource and ore reserve estimation: the importance of getting it right. *Exploration and Mining Geology*, vol. 11, no. 1-4, 77-98.
- Donselaar, M.E. (1989). The Cliff House Sandstone, San Juan Basin, New Mexico: model for the stacking of 'transgressive' barrier complexes. *Journal of Sedimentary Research*, vol. 59, no. 1, 13-27.
- Doyle, L.J., Carder, K.L. and Steward, R.G. (1983). The hydraulic equivalence of mica. *Journal of Sedimentary Petrology*, vol. 53, no. 2, 643-648.
- Droser, M.L. and Bottjer, D.J. (1989). Ichnofabric of sandstones deposited in high-energy nearshore environments: measurement and utilization. *PALAIOS*, Vol. 4, no. 6, 598-604.
- Duggan, S., Lantuéjoul, C. and Prins, C. (2007). Towards an optimal sample support. In: Costa, J.F.C.L. and Koppe, J.C. (Eds). Abstract Volume. Sampling of Particulate Materials, *Third World Conference on Sampling and Blending*, WCSB3, 23-25 October, 2007, Porto Alegre: Brazil. Workshop text (Short course), 126-137.
- Dupré, W.R. (1984). Reconstruction of paleo-wave conditions during the Late Pleistocene from marine terrace deposits, Monterey Bay, California. *Marine Geology*, vol. 60, 435-454.
- Eddison, J., Carr, A.P. and Jolliffe, I.P. (1983). The evolution of the barrier beaches between Fairlight and Hythe. *The Geographical Journal*, vol. 149, no. 1, 39-53.
- Elliott, T. (1978). Clastic shorelines. In: Reading, H.G. (Ed.). *Sedimentary environments and facies*, Blackwell Scientific Publications, London, 143-177.

- Elliott, T. (1986). Siliciclastic shorelines. In: Reading, H.G. (Ed.). *Sedimentary environments and facies*. 2nd Edition, Blackwell Scientific Publications, London, 155-188.
- Els, B.G. and Mayer, J.J. (1992). Transgressive and progradational beach and nearshore facies in the late Archean Turfontein Subgroup of the Witwatersrand Supergroup, Vredefort area, South Africa. *South African Journal of Geology*, vol. 95, no. 1/2, 60-73.
- Evans, A.M. (1987). *An introduction to ore geology*. Blackwell Scientific Publications, Oxford, p. 358.
- Everts, C.H., Eldon, C.D. and Moore, J. (2002). Performance of cobble berms, southern California. *Shore and Beach*, vol. 70, 5-14.
- Firth, C.R., Smith, D.E., Hansom, J.D. and Pearson, S.G. (1995). Holocene spit development on a regressive shoreline, Dornoch Firth, Scotland. *Marine Geology*, vol. 124, 203-214.
- Forbes, D.L. and Boyd, R. (1987). Gravel ripples on the inner Scotian Shelf. *Journal of Sedimentary Petrology*, vol. 57, no.1, 46-54.
- Forbes, D.L., Orford, J.D., Carter, R.W.G., Shaw, J. and Jennings, S.C. (1995). Morphodynamic evolution, self-organisation and instability of coarse-clastic barriers on paraglacial coasts. *Marine Geology*, vol. 126, 63-85.
- Forbes, D.L., Taylor, R.B., Orford, J.D., Carter, R.W.G. and Shaw, J. (1991). Gravel barrier migration and overstepping. *Marine Geology*, vol. 97, 305-313.
- Fowler, J.A. (1976). The alluvial geology of the Lower Orange River and adjacent coastal deposits, South West Africa. *Unpublished M.Sc. thesis*, Faculty of Science, University of London, U.K., p. 285.
- Fowler, J.A. (1982). Sedimentology and distribution of heavy minerals in the Lower Orange River valley. *Unpublished Ph.D. thesis*, Faculty of Science, University of London, U.K., p. 317.

- Franceschini, G. and Compton, J.S. (2004). Aeolian and marine deposits of the Tabakbaai Quarry area, western Cape, South Africa. *South African Journal of Geology*, vol. 107, 619-632.
- Friedman, G.M. and Sanders, J.E. (1978). *Principles of Sedimentology*. New York: John Wiley, p. 769.
- Frimmel, H.E. (1995). Metamorphic evolution of the Gariep Belt. *South African Journal of Geology*, vol. 98, 176-190.
- Frimmel, H.E. (2008). Neoproterozoic Gariep Orogen. In: Miller, R.McG. (author). *The Geology of Namibia. Neoproterozoic to Lower Palaeozoic, volume 2*. Ministry of Mines and Energy, Geological Survey of Namibia, 14-1 to 14-39.
- Graham, D. and Midgley, N. (2000). Triangular diagram plotting spreadsheet (tri-plot). Website, <http://www.davidgraham.org.uk>
- Graham, J. (1988). Grain collection and analysis of field data. In: Tucker, M. (Ed.). *Techniques in sedimentology*, 5-62. Blackwell Scientific Publications, London.
- Gray, R. (2002). Proximal and distal relationship between coarse gravel beach remnants of the Plio-Pleistocene Orange River delta. *Abstract Volume. 11th IAGOD, Quadrennial Symposium and Geocongress*, unpaginated, Geological Survey of Namibia, Windhoek, Namibia.
- Gresse, P.G. (1988). Washover boulder fans and reworked phosphorite in the Alexander Bay Formation. *South African Journal of Geology*, vol. 91, no. 3, 391-398.
- Gruszynski, M., Rudowski, S., Semil, J., Slominski, J. and Zrobek, J. (1993). Rip currents as a geological tool. *Sedimentology*, vol. 40, 217-236.
- Guilbert, J.M. and Park C.F. Jr. (1985). *The geology of ore deposits*. W.H. Freeman and Company, New York, p. 985.

- Guilcher, A. (1969). Pleistocene and Holocene sea level changes. *Earth-Science Reviews*, vol. 5, 69-97.
- Gupta, S. and Allen, P.A. (1999). Fossil shore platforms and drowned gravel beaches: evidence for high-frequency sea-level fluctuations in the distal Alpine Foreland basin. *Journal of Sedimentary Research*, vol. 69, no. 2, 394-413.
- Gurney, J.J., Levinson, A.A. and Smith, H. (1991). Marine mining of diamonds off the west coast of southern Africa. *Gems and Gemology*, vol. 27, no. 4, 206-219.
- Gurney, J.J., Walker, C.S.H., Prinsloo, K., Borchers, R. and Flemming, B.W. (1982). Diamond recoveries from the surf zone of the Namaqualand coast near the Olifants River. *Sedimentology 82, Sedimentology applied to Exploration Mining, Engineering and Environmental Studies*, Johannesburg (13-14 September, 1982), Abstract volume, 84-87.
- Hails, J.R. (1976). Placer deposits. In: Wolf, H.K. (Ed.). *Hand book of stratabound and stratiform deposits*, vol. 3, 213-244, Elsevier, New York.
- Hallam, C.D. (1964). The geology of the coastal diamond deposits of southern Africa. In: Haughton, S.H. (Ed.). *The geology of some ore deposits in southern Africa. Geological Society of South Africa*, vol. 2, 671-729.
- Hanson, E.K., Moore, J.M., Bordy, E.M., Marsh, J.S., Howarth, G. and Robey, J.V.A. (2009). Cretaceous erosion in central South Africa: evidence from upper-crustal xenoliths in kimberlite diatremes. *South African Journal of Geology*, vol. 112, no. 2, 125-140.
- Hanson WestHouse (undated). The diamond industry. *Sector Review, Metals and Mining*. Website, <http://www.hansonwesthouse.com>
- Haq, B.U., Hardenbol, J. and Vail, P.R. (1987). Chronology of fluctuating sea levels since the Triassic. *Science*, vol. 235, 1156-1167.

- Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G. (1975). Depositional environments as interpreted from primary sedimentary structures and stratification sequences. *Society of Economic Paleontologists and Mineralogists, short course no. 2, Lecture notes*, Dallas, p. 161. Society for Sedimentary Geology.
- Harms, J.C., Southard, J.B. and Walker, R.G. (1982). Structures and sequences in clastic rocks. *Society of Economic Paleontologists and Mineralogists, short course no. 9, Lecture notes*, p. 249. Calgary, Society for Sedimentary Geology.
- Hart, C. (2003). Overview of diamond recovery techniques. *South African Institute of Mining and Metallurgy, Colloquium: Diamonds-Source to use*. Abstract volume, 29-30 October 2003, SA National Museum of Military History, Saxonwold, p. 10. South African Institute of Mining and Metallurgy.
- Hartley, A.J. and Jolley, E.J. (1999). Unusual coarse, clastic, wave-dominated shoreface deposits, Pliocene to Middle Pleistocene, northern Chile: implications for coastal facies analysis. *Journal of Sedimentary Petrology*, vol. 69, no. 1, 105-114.
- Hartstein, N.D. and Dickinson, W.W. (2006). Wave energy and clast transport in eastern Tasman Bay, New Zealand. *Earth Surface Processes and Landforms*, vol. 31, issue 6, 703-714.
- Haslett, S.K. and Curr, R.H.F. (2001). Stratigraphy and palaeoenvironmental development of Quaternary coarse clastic beach deposits at Plage de Mezpeurleuch, Brittany (France). *Geological Journal*, vol. 36, 171-182.
- Hay, W.W. and Brock, J.C. (1992). Temporal variation in intensity of upwelling off southwest Africa. In Summerhays, C.P., Prell, W.L. and Emeis, K.C. (Eds). *Upwelling systems: Evolution since the Early Miocene*. *Geological Society of London, Special Publication 63*, 463-497.
- Hayes, M.O., Michel, J. and Betenbaugh, D.V. (2010). The intermittently exposed, coarse-grained gravel beaches of Prince William Sound, Alaska: comparison with open-ocean gravel beaches. *Journal of Coastal Research*, vol. 26, no. 1, 4-30.

- Helland-Hansen, W. and Martinsen, O.J. (1996). Shoreline trajectories and sequences: description of variable depositional-dip scenarios. *Journal of Sedimentary Research*, vol. 66, no. 4, 670-688.
- Hendey, Q.B. and Volman, T.P. (1986). Last interglacial sea levels and coastal caves in the Cape Province, South Africa. *Quaternary Research*, vol. 25, 189-198.
- Héquette, A., Desrosiers, M., Hill, P.R. and Forbes, D. (2001). The influence of coastal morphology on shoreface sediment transport under storm-combined flows, Canadian Beaufort Sea. *Journal of Coastal Research*, vol. 17, no. 3, 507-516.
- Hesp, P.A. (2006). Sand beach ridges: definitions and re-definitions. *Journal of Coastal Research*, special issue 39, 72-79.
- Hesp, P.A., Dillenburg, S.R., Barboza, E.G., Tomazelli, L.J., Ayup-Zouain, R.N., Esteves, L.S., Gruber, N.L.S., Toldo Jr, E.E., Tabajara, L.L.C. and Clerot, L.C.P. (2005). Beach ridges, foredunes or transgressive dunefields? Definitions and an examination of the Torres to Tramandaí barrier system, Southern Brazil. *Anais da Academia Brasileira de Ciências*, vol. 77(3), 493-508.
- Hine, A.C. (1979). Mechanisms of berm development and resulting beach growth along a barrier spit complex. *Sedimentology*, vol. 26, 333-351.
- Hiroki, Y. and Masuda, F. (2000). Gravelly spit deposits in a transgressive systems tract: the Pleistocene Higashikanbe Gravel, central Japan. *Sedimentology*, vol. 47, 135-149.
- Hobday, D.K. and Banks, N.L. (1971). A coarse-grained pocket beach complex, Tanafjord (Norway). *Sedimentology*, vol. 16, no. 2, 129-135.
- Holcombe, R. (2009). GEORient © 2009 (version 9.4.4) stereographic projections and rose diagram plots. Website, <http://www.holcombe.net.au/software>

- Hughes, M.G., Keene, J.B. and Joseph, R.G. (2000). Hydraulic sorting of heavy mineral grains on a medium sand beach. *Journal of Sedimentary Research*, vol. 70, no. 5, 994-1004.
- Hughes, P. and Brundrit, G.B. (1995). Sea-level rise and coastal planning: a call for stricter control in river mouths. *Journal of Coastal Research*, vol. 11, no. 3, 887-898.
- Hughes, P., Brundrit, G.B. and Shillington, F.A. (1991). South African sea-level measurements in the global context of sea-level rise. *South African Journal of Science*, vol. 87, no. 9, 447-453.
- Illenberger, W.R. (1991). Pebble shape (and size!). *Journal of Sedimentary Petrology*, vol. 61, no. 5, 756-767.
- Illenberger, W.R. (1992). Pebble shape (and size!) – reply. *Journal of Sedimentary Petrology*, vol. 62, no. 6, 1151-1155.
- Ilman, D.L. and Guza, R.T. (1982). The origin of swash cusps on a beach. *Marine Geology*, vol. 49, 133-148.
- Immenhauser, A. (2009). Estimating palaeo-water depth from the physical rock record. *Earth-Science Reviews*, vol. 96, 107-139.
- Isla, F.I. (1993). Overpassing and armouring phenomena on gravel beaches. *Marine Geology*, vol. 110, 369-376.
- Isla, F.I. and Bujalesky, G.G. (1993) Saltation on gravel beaches, Tierra del Fuego, Argentina. *Marine Geology*, vol. 115, 263-270.
- IUGS (2009). International Union of Geological Sciences. International Commission on Stratigraphy. Website, <http://www.stratigraphy.org>

- Jacob, J. (2001). Late Proterozoic bedrock geology and its influence on Neogene littoral marine diamondiferous trapsites, MA1 – Sperrgebiet, Namibia. *Unpublished M.Sc. thesis*, University of Cape Town, Cape Town, South Africa, p. 140.
- Jacob, J., Ward, J.D., Bluck, B.J., Scholtz, R.A. and Frimmel, H.E. (2006). Some observations on diamondiferous bedrock gulley trapsites on Late Cainozoic, marine cut platforms of the Sperrgebiet, Namibia. In: Els, B.G. and Eriksson, P.G. (Eds). Special issue: Placer Formation and Placer Minerals, *Ore Geology Reviews*, vol. 28, no 4, 493-506.
- Jacob, R.J. (1999). Inshore *JAGO*, '99 dive 592 log. *Internal report*, Namdeb Diamond Corporation (Pty.) Ltd.
- Jacob, R.J. (2005). The erosional and Cainozoic depositional history of the lower Orange River, southwestern Africa. *Unpublished Ph.D. thesis*, University of Glasgow, Glasgow, Scotland, vols 1 & 2, p. 432.
- Jacob, R.J. and Bluck, B.J. (2002). Downstream clast size change, rates of clast size change and the influence of local tributary input, lower Orange River, Southwestern Africa, *Abstract volume, IAS 16th International Sedimentological Congress*, Rand Afrikaans University, Johannesburg, South Africa, July 2002, 173.
- Jacob, R.J., Bluck, B.J. and Ward, J.D. (1999). Tertiary-age diamondiferous fluvial deposits of the Lower Orange River valley, southwestern Africa. *Economic Geology*, vol. 94, 749-758.
- Jennings, C.M.H. (1995). The exploration context for diamonds. *Journal of Geochemical Exploration*, vol. 53, 113-124.
- Jennings, R. and Shulmeister, J. (2002). A field based classification scheme for gravel beaches. *Marine geology*, vol. 186, 211-228.
- Johnson, H.D. and Baldwin, C.T. (1986). Shallow siliciclastic seas. In: Reading, H.G. (Ed.). *Sedimentary environments and facies*. 2nd Edition, Blackwell Scientific Publications, London, 289-298.

- Johnson, M.R. (1992). A proposed format for general-purpose comprehensive graphic logs. *Sedimentary Geology*, vol. 81, 749-758.
- Jol, H.M., Lawton, D.C and Smith, D.G. (2002). Ground penetrating radar 2-D and 3-D subsurface imaging of a coastal barrier spit, Long Beach, WA, U.S.A. *Geomorphology*, vol. 53, 165-181.
- Jury, M.R., Shillington, F.A., Prestidge, G. and Maxwell, C.D. (1986). Meteorological and oceanographic aspects of a winter storm over the south-western Cape Province, South Africa. *South African Journal of Science*, vol. 82, 315-319.
- Kaiser, E. (1926). *Die Diamantenwüste Südwestafrikas*. Dietrich (Ernst Vohsen), Berlin, vols 1 & 2.
- Kendall, C.G.St.C. and Lerche, I. (1988). The rise and fall of eustasy. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and van Wagoner, J.C. (Eds). Sea-level changes: an integrated approach. *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 42, 3-18.
- Keyser, U. (1972). The occurrence of diamonds along the coast between the Orange River estuary and the Port Nolloth Reserve. *Bulletin of the Geological Survey of South Africa*, bulletin 54, p. 24.
- Kidson, C., Carr, A.P. and Smith, D.B. (1958). Further experiments using radioactive methods to detect the movement of shingle over the sea bed and alongshore. *Geographical Journal*, vol. 124, 210-218.
- King, C.A.M. and Mc Cullagh, M.J. (1971). A simulation model of a complex recurved spit. *Journal of Geology*, vol. 79, 22-37.
- King, H.F., McMahon, D.W. and Butjor, G.J. (1982). A guide to the understanding of ore reserve estimation. *Supplement to the AusIMM Proceedings, no. 281*. Australasian Institute of Mining and Metallurgy.

- Kirk, R.M. (1975). Aspects of surf and run up processes on mixed sand and gravel beaches. *Geografiska Annaler, Series A, Physical Geography*, 117-133.
- Kirk, R.M. (1980). Mixed sand and gravel beaches: morphology, processes and sediments. *Progress in Physical Geography*, vol. 4, 189-210.
- Kirk, R.M. and Lauder, G.A. (2000). Significant coastal lagoon systems in the South Island, New Zealand: Coastal processes and lagoon mouth closure. *Science for conservation*, no. 146, Department of Conservation, Wellington, New Zealand, 1-46.
- Kokot, R.R., Monti, A.A.J. and Codignotto, J.O. (2005). Morphology and short-term changes of the Caleta Valdés barrier spit, Argentina. *Journal of Coastal Research*, vol. 21, no. 5, 1021-1030.
- Komar, P.D. and Miller, M.C. (1974). Sediment threshold under oscillatory waves. *American Society of Civil Engineers. Proceedings of the fourteenth coastal engineering conference*, June 24-28, 756-775.
- Komar, P.D. and Miller, M.C. (1975). On the comparison between the threshold of sediment motion under waves and unidirectional currents with a discussion of the practical evaluation of the threshold. *Journal of Sedimentary Petrology*, vol. 45, 362-367.
- Krantz, D. (1991). A chronology of Pliocene sea-level fluctuations: the U.S. middle Atlantic coastal plain record. *Quaternary Science Reviews*, vol. 10, 163-174.
- Krapf, C. (2003). Ephemeral river systems at the Skeleton Coast, NW Namibia. *Unpublished Ph.D. thesis*, Bayerischen Julius-Maximilians, University of Würzburg, Germany, p. 200.
- Krumbein, W.C. (1941). Measurement and geologic significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Petrology*, vol. 11, 64-72.
- Lambeck, K., Esat, T.M. and Potter, E. (2002). Links between climate and sea levels for the past three million years. *Nature*, vol. 419, 199-206.

- Leckie, D. (1988). Wave-formed, coarse-grained ripples and their relationship to hummocky cross-stratification. *Journal of Sedimentary Petrology*, vol. 58, no. 4, 607-622.
- Leeder, M.R. (1988). *Sedimentology: Process and product*. Unwin Hyman, London, p. 344.
- Leithold, E.L and Bourgeois, J. (1984). Characteristics of coarse-grained sequences deposited in nearshore, wave-dominated environments – examples from the Miocene of south-west Oregon. *Sedimentology*, vol. 31, 749-775.
- Le Mehaute, B., Divoky, D. and Lin, A. (1969). Shallow water waves: a comparison of theories and experiments. *American Society of Civil Engineers*, vol. 1, part 1, chapter 7, 86-107.
- Leatherman, S.P. (1983). Barrier dynamics and landward migration with Holocene sea level rise. *Nature*, vol. 301, no. 3, 415-417.
- Lindholm, R.C. (1987). *A practical approach to sedimentology*. Allen and Unwin, London, p. 276.
- Long, A.J., Waller, M.P. and Stupples, P. (2006). Driving mechanisms of coastal change: peat compaction and the destruction of late Holocene coastal wetlands. *Marine Geology*, vol. 225, 63- 84.
- López-Blanco, M., Marzo, M. and Piña, J. (2000). Transgressive-regressive sequence hierarchy of foreland, fan-delta clastic wedges (Montserrat and Sant Llorenç del Munt, Middle Eocene, Ebro basin, NE Spain. *Sedimentary Geology*, vol. 138, 41-69.
- Lorang, M.S. (2000). Predicting threshold mass for a boulder beach. *Journal of Coastal Research*, vol. 16, no. 2, 432-445.
- Lorang, M.S. (2002). Predicting the crest height of a beach. *Geomorphology*, vol. 48, 87-107.

- Loureiro, E. and Granja, H.M. (2001). Short-term morphodynamics of a shingle beach (Esposende, N.W. Portugal). In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 148-159. Westbury, Otley, West Yorks, U.K.
- Lynn, M.D., Wipplinger, P.E. and Wilson, M.G.C. (1998). Diamonds. In: Wilson, M.G.C. and Anhaeusser, C.R. (Eds.). *The Mineral Resources of South Africa*, sixth edition, handbook 16, 232-258, Council for Geoscience, South Africa.
- Macdonald, L., Jacob, R.J. and Ward, J.D. (1999). Further aspects of the diamondiferous gravel terraces of the lower Orange River. In: Lee-Thorp, J. and Clift, H. (Eds.). *The Environmental Background to Hominid Evolution, XV International Congress. International Union for Quaternary Research*, 3–11 August 1999, Durban, South Africa, Abstract Volume, 113-114.
- Macintosh, E.K. (1983). *Rocks, minerals and gemstones of Southern Africa: a collector's guide*. Struik Publishers, Cape Town, p. 120.
- Mäkinen, J. and Räsänen, M. (2003). Early Holocene regressive spit-platform and nearshore sedimentation on a glaciofluvial complex during the Yoldia Sea and the Ancylus Lake phases of the Baltic Basin, SW Finland. *Sedimentary Geology*, vol. 158, 25-56.
- Marshall, T.R. and Baxter-Brown, R. (1995). Basic principles of alluvial diamond exploration. *Journal of Geochemical Exploration*, vol. 53, 277-292.
- Martineau (2008). BRC DiamondCore fourth open tender of 1,325.60 carats realises US\$668,845. *Resource Investor*. Website, <http://www.resourceinvestor.com>
- Martini, L.P. (1975). Sedimentology of a lacustrine barrier system at Wasaga Beach, Ontario, Canada. *Sedimentary Geology*, vol. 14, 169-190.
- Massari, F. and Parea, G.C. (1988). Progradational gravel beach sequences in moderate- to high-energy, microtidal marine environment. *Sedimentology*, vol. 35, 881-913.

- Masselink, G. and Li, L. (2001). The role of swash infiltration in determining the beachface gradient: a numerical study. *Marine Geology*, vol. 176, 139-156.
- Masselink, G. and Pattiaratchi, C.B. (1998). Morphological evolution of beach cusps and associated circulation patterns. *Marine Geology*, vol. 146, 93-113.
- Mathers, S. and Zalasiewicz, J. (1996). A gravel beach-rip channel system: the Westleton Beds (Pleistocene) of Suffolk, England. *Proceedings of the Geologist's Association*, vol. 107, 57-67.
- McLean, R.F. and Kirk, R.M. (1969). Relationships between grain size, size-sorting, and foreshore slope on mixed sand-shingle beaches. *New Zealand Journal of Geology and Geophysics*, vol. 12, 138-155.
- McKay, P.J. and Terich, T.A. (1992). Gravel barrier morphology: Olympic National Park, Washington State, U.S.A. *Journal of Coastal Research*, vol. 8, no. 4, 813-829.
- Meldahl, K.H. (1995). Pleistocene shoreline ridges from tide-dominated and wave-dominated coasts: northern Gulf of California and western Baja California, Mexico. *Marine Geology*, vol. 123, 61-72.
- Midtgaard, H.H. (1996). Inner-shelf to lower-shoreface hummocky sandstone bodies with evidence for geostrophic influenced combined flow, Lower Cretaceous, West Greenland. *Journal of Sedimentary Petrology*, vol. 66, no. 2, 343-353.
- Millad, M. (2004). The depositional history of two late Quaternary diamondiferous pocket beaches, south-western Namibia. *Unpublished M.Sc. thesis*, Rhodes University, Grahamstown, South Africa, p. 137.
- Miller, R.McG. (2008). *The Geology of Namibia. Palaeozoic to Cenozoic, volume 3*. Ministry of Mines and Energy, Geological Survey of Namibia, 23-1 to 23-11.
- Miller, R.McG. and Seely, M.K. (1976). Fluvio-marine deposits south-east of Swakopmund, South West Africa. *Madoqua*, vol. 9 (3), 23-25.

- Moore, A.E. and Verwoerd, W.J. (1985). The olivine melilitite – ‘kimberlite’ – carbonatite suite of Namaqualand and Bushmanland, South Africa. *Transactions of the Geological Society of South Africa*, vol. 88, 281-294.
- Morales, J.A., Borrego, J., Jiménez, I., Monterde, J. and Gil, N. (2001). Morphostratigraphy of an ebb-tidal delta system associated with a large spit in the Piedras Estuary mouth (Huelva Coast, Southwestern Spain). *Marine Geology*, vol. 177, 225-241.
- Murray, L.G., Joynt, R.H., O’Shea, D.O.C., Forster, R.W. and Kleinjan, L. (1970). The geological environment of some diamond deposits off the coast of South West Africa. In: Delany, F.M. (Ed.). *The geology of the East Atlantic continental margin. Institute of Geological Sciences, Report 70/13*, 123-141. ICSU/SCOR Working Party, 31 Symposium, Cambridge.
- Muto, T. and Steel, R.J. (1997). Principles of regression and transgression: the nature of the interplay between accommodation and sediment supply. *Journal of Sedimentary Research*, vol. 67, no. 6, 994-1000.
- Myrow, P.M. and Southard, J.B. (1991). Combined-flow model for vertical stratification sequences in shallow marine storm-dominated deposits. *Journal of Sedimentary Petrology*, vol. 61, no. 2, 202-210.
- Neal, A., Dackombe, R.V. and Roberts, C.L. (2001). Applications of ground-penetrating radar (GPR) to the study of coarse clastic (shingle) coastal structures. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 77-106. Westbury, Otley, West Yorks, U.K.
- Nemec, W. and Steel, R.J. (1984). Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits, In: Koster, E.H. and Steel R.J. (Eds). *Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists Memoir 10*, 1-31.
- Nichols, G. (1999). *Sedimentology and Stratigraphy*. Blackwell Science, London, p. 355.

- Nichols, M.M. and Biggs, R.B. (1985). Estuaries. In: Davis, R.A. Jr. (Ed.). *Coastal sedimentary environments*, second revised, expanded edition, 77-173. Springer-Verlag.
- Niedoroda, A.W., Swift, D.J.P., Hopkins, T.S. (1985). The shoreface. In: Davis, R.A. Jr. (Ed.). *Coastal sedimentary environments*, second revised, expanded edition, 533-615. Springer-Verlag.
- Niedoroda, A.W., Swift, D.J.P., Hopkins, T.S. and Ma, C. (1984). Shoreface morphodynamics on wave-dominated coasts. *Marine Geology*, vol. 60, 331-354.
- Nielsen, L.H., Johannessen, P.N. and Surlyk, F. (1988). A Late Pleistocene coarse grained spit-platform sequence in northern Jylland, Denmark. *Sedimentology*, vol. 35, 915-937.
- Nishikawa, T. and Ito, M. (2000). Late Pleistocene barrier-island development reconstructed from genetic classification and timing of erosional surfaces, paleo-Toyko Bay, Japan. *Sedimentary Geology*, vol. 137, 25-42.
- Nummedal, D. and Swift, D.J.P. (1987). Transgressive stratigraphy at sequence bounding unconformities: some principles derived from Holocene and Cretaceous examples. In: Nummedal, D., Pilkey, O.H. and Howard, J.D. (Eds). Sea-level fluctuations and coastal evolution. *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 41, 241-260.
- Nunn, P.D. (1984). Review of evidence for Late Tertiary shorelines. *Earth-Science Reviews*, vol. 20, 185-210.
- Oak, H.L. (1984). The boulder beach: a fundamentally distinct sedimentary assemblage. *Annals of the Association of American Geographers*, vol. 74, no. 1, 71-82.
- Ollerhead, J. and Davidson-Arnott, R.G.D. (1995). The evolution of Buctouche Spit, New Brunswick, Canada. *Marine Geology*, vol. 124, 215-236.

- Oosterveld, M.M. (2003). Evaluation of alluvial diamond deposits. Workshop: Alluvial diamonds in South Africa, 2 April 2003, Johannesburg. Directorate of Professional Programmes of the Geological Society of South Africa. *Geological Society of South Africa*, p. 17.
- Oosterveld, M.M., Campbell, D. and Hazell, K.R. (1987). Geology related to statistical evaluation parameters for a diamondiferous beach deposit. In: Lemmer, I.C., Schaum, H. and Camisani-Calzolari, F.A.G.M. (Eds). Proceedings of the Twentieth International Symposium on the Application of Computers and Mathematics in the Mineral Industries, 129-136, *The South African Institute of Mining and Metallurgy*, symposium series S9, APCOM 87, vol. 3, Geostatistics.
- Orford, J.D. (1975). Discrimination of particle zonation on a pebble beach. *Sedimentology*, vol. 22, 441-463.
- Orford, J.D. (1977). A proposed mechanism for storm beach sedimentation. *Earth Surface Processes and Landforms*, vol. 2, 381-400.
- Orford, J.D. (1986). Gravel beach profile characterisation and discrimination. *Journal of Coastal Research*, vol. 1, no. 2, 129-139.
- Orford, J.D. and Carter, R.W.G. (1982). Crestal overtop and washover sedimentation on a fringing sandy gravel barrier coast, Carnsore Point, southeast Ireland. *Journal of Sedimentary Petrology*, vol. 52, no. 1, 265-278.
- Orford, J.D., Carter, R.W.G. and Jennings, S.G. (1991). Coarse clastic barrier environments: evolution and implications for Quaternary sea-level interpretation. *Quaternary International*, vol. 9, 87-104.
- Orford, J.D., Forbes D.L. and Jennings S.C. (2002). Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. *Geomorphology*, vol. 48, 51-85.

- Orford, J.D., Jennings, S.C. and Forbes, D.L. (2001). Origin, development, reworking and breakdown of gravel- dominated coastal barriers in Atlantic Canada: future scenarios for the British coast. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology & geomorphology of coastal shingle*, 23-55. Westbury, Otley, West Yorks, U.K.
- Otvos, E.R. (2000). Beach ridges – definitions and significance. *Geomorphology*, vol. 32, 83-108.
- Packham, J.R. and Neal, A. (2001). Methods and terminology. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology & geomorphology of coastal shingle*, XV11–XX11, Westbury, Otley, West Yorks, U.K.
- Pallett, J. (Ed.). (1995). *The Sperrgebiet: Namibia's least known wilderness. An environmental profile of the Sperrgebiet or Diamond Area 1 in south-western Namibia*. DRFN and Namdeb, Windhoek, Namibia, p. 84.
- Partridge, T.C. (1998). Of diamonds, dinosaurs and diastrophism: 150 million years of landscape evolution in southern Africa. Alex L. du Toit memorial lecture no. 25. *South African Journal of Geology*, vol. 101, no. 3, 165-184.
- Partridge, T.C. and Maud, R.R. (1987). Geomorphic evolution of southern Africa since the Mesozoic. *South African Journal of Geology*, vol. 90, no. 2, 179-208.
- Pascucci, V., Martini, I.P. and Endres, A.L. (2009). Facies and ground-penetrating radar characteristics of coarse-grained beach deposits of the uppermost Pleistocene glacial Lake Algonquin, Ontario, Canada. *Sedimentology*, vol. 56, 529–545.
- Pedrozo-Acuña, A., Simmonds, D.J. and Reeve, D.E. (2008). Wave-impact characteristics of plunging breakers acting on gravel beaches. *Marine Geology*, vol. 253, 26–35.
- Peters, W.C. (1987). *Exploration and mining geology*. John Wiley & Sons, New York, p. 685.
- Pether, J. (1986). Late Tertiary and early Quaternary marine deposits of the Namaqualand coast, Cape Province: new perspectives. *South African Journal Science*, vol. 82, 464-470.

- Pether, J. (1994). The sedimentology, palaeontology and stratigraphy of the coastal plain deposits at Hondeklip Bay, Namaqualand, South Africa. *Unpublished M.Sc. thesis*, University of Cape Town, Cape Town, South Africa, p. 313.
- Pether, J. (2000). Deposits of the Namibian Coast. Chapter 3, Deposits of the West Coast, Pether, J., Roberts, D.L. and Ward, J.D. In: Partridge, T.C. and Maud, R.R. (Eds). *The Cenozoic of Southern Africa*, Oxford University Press, 41-46.
- Pether, J. (2003). Preliminary note on the intraformational conglomerates. *Internal report*, Geolaboratory, Mineral Resources Unit, De Beers Marine, Cape Town, South Africa.
- Pettijohn, E.J. (1975). *Sedimentary rocks* (3rd edition). Harper & Row Publishers, New York, p. 625.
- Phillips, J.D. and Slattery, M.C. (2006). Sediment storage, sea level, and sediment delivery to the ocean by coastal plain rivers. *Progress in Physical Geography*, vol. 30, no. 4, 513–530.
- Pickford, M. (1998). Onland Tertiary marine strata in southwestern Africa: eustasy, local tectonics and epeirogenesis in a passive continental margin setting. *South African Journal of Science*, vol. 94, 5-8.
- Pickford, M. and Senut, B. (1999). *Geology and Palaeobiology of the Namib Desert, southwestern Africa. Memoir 18*, Ministry of Mines and Energy, Geological Survey of Namibia, p. 155.
- Pickford, M. and Senut, B. (2003). *Geology and Palaeobiology of the central and southern Namib Desert. Volume 2: palaeontology of the Orange River valley, Namibia. Memoir 19*, Ministry of Mines and Energy, Geological Survey of Namibia, p. 398.
- Pillans, B. and Naish, T. (2004). Defining the Quaternary. *Quaternary Science Reviews*, vol. 23, 2271–2282.

- Pisces Environmental Services (Pty.) Ltd. (2008). Data gathering and gap analysis for assessment of cumulative effects of marine diamond mining activities on the BCLME Region. *Benguela Current Large Marine Ecosystem (BCLME) programme, Final report, Chapter 3*, Project: BEHP/CEA/03/02, 47-130.
- Posamentier, H.W., Jervey, M.T. and Vail, P.R. (1988). Eustatic controls on clastic deposition I – conceptual framework. In: Wilgus, C.K., Hastings, B.S., Posamentier, H., van Wagoner, J., Ross, C.A. and Kendall, C.G.St.C. (Eds). *Sea-level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication, no. 42*, 3-18.
- Posamentier, H.W. and Morris, W.R. (2000). Aspects of the stratal architecture of forced regressive deposits. In: Hunt, D. and Gawthorpe, R.L. (Eds). *Sedimentary responses to forced regressions, Geological Society of London, Special Publication, no. 172*, 19-46.
- Postma, G. (1995). Sea-level architectural trends in coarse-grained delta complexes. *Sedimentary Geology*, vol. 98, 3-12.
- Postma, G. and Nemeç, W. (1990). Regressive and transgressive sequences in a raised Holocene gravelly beach, southwestern Crete. *Sedimentology*, vol. 37, 907-920.
- Powers, M.C. (1982). Comparison chart for estimating roundness and sphericity. *AGI Data Sheet 18*. American Geological Institution.
- Prins, C.F. (2000). A workbook with geostatistical and some other techniques in mineral resource management. *De Beers in-house workshop notes*, p. 167.
- Pye, K. (2001). The nature and geomorphology of coastal shingle. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 2- 22. Westbury, Otley, West Yorks, U.K.

- Randall, E.R. and Fuller, R.M. (2001). The Orford Shingles, Suffolk, U.K.: evolving solutions in coastline management. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 242-260. Westbury, Otley, West Yorks, U.K.
- Rasmussen, H. (2000). Nearshore and alluvial facies in the Sant Llorenç del Munt depositional system: recognition and development. *Sedimentary Geology*, vol. 138, issues 1-4, 71-98.
- Reading, H.G. (1978). Facies. In: Reading, H.G. (Ed.). *Sedimentary environments and facies*. Blackwell Scientific Publications, London, 4-14.
- Reading, H.G. and Collinson, J.D. (1996). Clastic coasts. In: Reading, R.G. (Ed.). *Sedimentary environments, processes, facies and stratigraphy*, 3rd Edition, 154-231, Blackwell Scientific, Oxford.
- Reading, H.G. and Levell, B.K. (1996). Controls on the sedimentary rock record. In: Reading, R.G. (Ed.). *Sedimentary environments, processes, facies and stratigraphy*, 3rd Edition, 5-36, Blackwell Scientific, Oxford.
- Reddering, J.S.V. (1993). Sedimentary facies, sequences and depositional environments of the Mesozoic Robberg Formation in its type area, South Africa. *Unpublished Ph.D. thesis*, University of Port Elizabeth, Port Elizabeth, South Africa, p. 313.
- Reid, I. and Frostick, L.E. (1985). Role of settling, entrainment and dispersive equivalence and of interstice trapping in placer formation. *Journal of Geological Society*, vol. 142, 739-746.
- Reineck, H.E. and Singh, I.B. (1975). *Depositional sedimentary environments*. Springer Verlag, p. 439.
- Reinson, G.E. (1984). Barrier Island and associated strand-plain systems. In: Walker, R.G. (Ed.), *Facies Models*, 2nd Edition, Geoscience Canada, Reprint Series 1, 119-140.

- Rey, T., Lefevre, D. and Vella, C. (2009). Deltaic plain development and environmental changes in the Petite Camargue, Rhone Delta, France, in the past 2000 years. *Quaternary Research*, vol. 71, 284-294
- Roberts, D.L. and Brink, J.S. (2002). Dating and correlation of Neogene coastal deposits in the western Cape (South Africa): implications for neotectonism. *South African Journal of Geology*, vol. 105, no. 4, 337-352.
- Rodriguez, A.B., Hamilton, M.D. and Anderson, J.B. (2000). Facies and evolution of the modern Brazos Delta, Texas: wave versus flood influence. *Journal of Sedimentary Research*, vol. 70, no. 2, 283-295.
- Rogers, J. (1977). Sedimentation on the continental margin off the Orange River and the Namib Desert. *Bulletin of the Geological Survey of South Africa/University of Cape Town, Marine Geoscience Unit*, vol. 7, p. 210.
- Rogers, J., Pether, J., Molyneux, R., Genis, G., Kilham, J.L.V., Cooper, G. and Corbett, I.B. (1990). Cenozoic geology and mineral deposits along the west coast South Africa and the Sperrgebiet. *Guidebook Geocongress '90*, Geological Society of South Africa, PR1, p. 111.
- Rombouts, L. (1995). Sampling and statistical evaluation of diamond deposits. *Journal of geochemical exploration*, vol. 53, 351-367.
- Rosati, J.D., Dean, R.G. and Stone, G.W. (2010). A cross-shore model of barrier island migration over a compressible substrate. *Marine Geology*, vol. 271, 1-16.
- SACS (1980). *Stratigraphy of South Africa. Part 1: lithostratigraphy of the Republic of South Africa, South West Africa/Namibia and the Republics of Bophuthatswana, Transkei and Venda. Handbook 8*. Geological Survey of South Africa, p. 690.
- SAMREC (2007). The South African code for the reporting of exploration results, mineral resources and mineral reserves (the SAMREC code). Website, <http://www.Transhex.co.za>

- Schneider, G.I.C. and Miller, R.McG. (1992). Diamonds. *The Mineral Resources of Namibia*, 1st edition. Ministry of Mines and Energy, Windhoek, Namibia, 5.1-1 to 5.1-32.
- Scholtz, A. (1985). The palynology of the upper lacustrine sediments of the Arnot Pipe, Banke, Namaqualand - a summary. *Annals of the Geological Survey of South Africa.*, vol. 19, 85-87.
- Schumm, S.A. (1993). River response to base level change: implications for sequence stratigraphy. *Journal of Geology*, vol. 101, 279-294.
- Seal, M. (1990). The choice of diamonds for some scientific application. In: Saito, S., Fukunaga, O. and Yoshikawa, M. (Eds), *Science and technology of diamond*, 311-317.
- Sedgwick, P.E. and Davis R.A. Jr. (2003). Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. *Marine Geology*, vol. 200, 31-48.
- Seetharamaia, J., Farooqui, A., Suryabhadgavan, K.V. and Rao, K.N. (2005). Evolution of Iskapalli lagoon in Penner delta region, east coast of India - a sedimentological and palynological approach. *Indian Journal of Marine Sciences*, vol. 34, no. 3, 267-273.
- Siesser, W.G. (1977). Upper Eocene age of marine sediments at Bogenfels, based on calcareous nannofossils. In: Papers on biostratigraphic research. *Bulletin of the Geological Survey of South Africa*, bulletin 60, 72-74.
- Siesser, W.G. and Dingle, R.V. (1981). Tertiary sea-level movements around southern Africa. *Journal of Geology*, vol. 89, 83-96.
- Siesser, W.G. and Salmon, D. (1979). Eocene marine sediments in the Sperrgebiet, South West Africa. *Annals of the South African Museum*, vol. 79, no. 2, 9-34.
- Sherman, D.J. (1991). Gravel beaches. *Natural Geographic Research Exploration*, vol. 7, 442-452.

- Sherman, D.J., Orford, J.D. and Carter, R.W.G. (1993). Development of cusp-related, gravel size and shape facies at Malin Head, Ireland. *Sedimentology*, vol. 40, 1139-1152.
- Short, A.D. (1979). Three dimensional beach-stage model. *Journal of Geology*, vol. 87, 553-571.
- Sichel, H.S. (1973). Statistical valuation of diamondiferous deposits. *Journal of the South African Institute of Mining and Metallurgy*, vol. 73, no. 7, 235-240.
- Simpson, E.L. and Eriksson, K.A. (1990). Early Cambrian Progradational and transgressive sedimentation patterns in Virginia: an example of the early history of a passive margin. *Journal of Sedimentary Petrology*, vol. 60, no. 1, 250-264.
- Single, M. and Hemmingsen, M. (2001). Mixed sand and gravel barrier beaches of South Canterbury, New Zealand. In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Eds). *Ecology and geomorphology of coastal shingle*, 261-276. Westbury, Otley, West Yorks, U.K.
- Smith, C.B., Allsopp, H.L., Kramers, J.D., Hutchinson, G and Roddick, J.C. (1985). Emplacement ages of Jurassic-Cretaceous South African kimberlites by the Rb-Sr method on phlogopite and whole-rock samples. *Transactions of the Geological Society of South Africa*, vol. 88, 249-266.
- Smith, G.G. (2002). Coastal modelling study for the southern Mining Area 1: accretion, safety, environment. *CSIR report.*, ENV-S-C 2002-113, Stellenbosch, p. 57.
- Smith, G.G. (2006). Assessment of the cumulative effects of sediment discharges from onshore and nearshore diamond mining activities on the BLME. *CSIR report*, CSIR/NRE/ECO/ER/2006/0093/C, Benguela Current Large Marine Ecosystem Programme, BEHP/CEA/03/03, p. 181.
- Smith, R.M.H. (1986). Sedimentation and paleoenvironments of Late Cretaceous crater lake deposits in Bushmanland, South Africa. *Sedimentology*, vol. 33, 369-386.

- Sneed, E.D. and Folk, R.L. (1958). Pebbles in the lower Colorado River. Texas: a study in particle morphogenesis. *Journal of Geology*, vol. 66, 114-150.
- Soons, J.M., Shulmeister, J. and Holt, S. (1997). The Holocene evolution of a well nourished gravelly barrier and lagoon complex, Kaitorete 'Spit', Canterbury, New Zealand. *Marine Geology*, vol. 138, 69-90.
- Southard, J.B., Lambie, J.M., Federico, D.C., Pile, T.H. and Weidman, C.R. (1990). Experiments on bed configurations in fine sand under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification. *Journal of Sedimentary Petrology*, vol. 60, no. 1, 1-17.
- Spaggiari, R.I., Bluck, B.J. and Ward, J.D. (1999). Beaches, barriers and bars: sedimentary facies of Early Pleistocene diamondiferous deposits within the Orange River mouth, Namibia. In: Lee-Thorp, J. and Clift, H. (Eds). Abstract Volume. The environmental background to hominid evolution, XV International Congress, *International Union for Quaternary Research*, 3-11 August 1999, Durban, South Africa, 169-170.
- Spaggiari, R.I., Bluck, B.J. and Ward, J.D. (2006). Characteristics of Plio-Pleistocene littoral deposits within the palaeo-Orange River mouth. In: Els. B.G. and Eriksson, P.G. (Eds). Special issue: Placer Formation and Placer Minerals, *Ore Geology Reviews*, vol. 28, no. 4, 475-492.
- Spaggiari, R.I. and Ward, J.D. (2004). Re-appraisal of the Skeleton Coast diamondiferous onshore marine deposits: a perspective in 2004. *Internal Report*, Namdeb Diamond Corporation (Pty.) Ltd., file: GG-GG-03, ref. 65082, p. 43.
- Spaggiari, R.I., Ward, J.D. and Bluck, B.J. (2002). Quaternary diamond bearing beaches of southern Namibia. *Abstract volume, IAS 16th International Sedimentological Congress*, RAU Johannesburg, July 2002, 341.
- Stocken, C.G. (1962). The diamond deposits of the Sperrgebiet, South West Africa. Field trip, *4th Annual Congress of the Geological Society of South Africa*, p. 15.

- Stocken, C.G. (1977). CDM mine sampling and evaluation – an historical review. *Internal report*, Consolidated Diamond Mines of South West Africa (Pty.), p. 8.
- Stocken, C.G. (1978). A review of the later Mesozoic and Cainozoic deposits of the Sperrgebiet. *Internal report*, Consolidated Diamond Mines of South West Africa (Pty.), p. 38.
- Sutherland, D.G. (1982). The transport and sorting of diamonds by fluvial and marine processes. *Economic Geology*, vol. 77, 1613–1620.
- Swart, D.H. (1984). Inshore sediment movement along the west coast of South Africa. In: Martin, C.G.C. (Ed.). Proceedings of a Symposium Surveying Offshore Mining Concessions. *S. Afr. Waters. Surv. Dept. Publ.*, Univ. Cape Town, 1-8.
- Swift, D.J.P. and Niedoroda, A.W. (1985). Fluid and sediment dynamics on continental shelves. In: Tillman, R.W., Swift, D.J.P. and Walker, R.G. (Eds). Shelf sands and sandstone reservoirs, *Society of Economic Paleontologists and Mineralogists, short course No. 13, Lecture notes*, 47-53. Society for Sedimentary Geology.
- Tankard, A.J.T. (1975). The Late Cenozoic history and paleoenvironments of the coastal margin of the south-western Cape Province, South Africa. *Unpublished Ph.D. thesis*, Rhodes University, Grahamstown, South Africa, vols 1&2, p. 365.
- Tankard, A.T., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R. and Minter, W.E.L. (1982). *Crustal evolution of southern Africa: 3.8 billion years of earth history*. Springer-Verlag, New York, p. 523.
- Tchernia, P. (1980). Descriptive regional oceanography. In: Swallow, J.C (Ed.). *Pergamon Marine Series*, vol. 3. Pergamon Press, Oxford, p. 251.
- Törnqvist, T.E., Wallace, D.J., Storms, J.E.A., Wallinga, J., van Dam, R.L., Blauw, M., Derksen, M.S., Klerks, C.J.W., Meijneken, C. and Snijders, E.M.A. (2008). Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience*, vol. 1, 173-176.

- Trans Hex. (2009). Trans Hex 2009 annual report, p. 92. Website, <http://www.Transhex.co.za>
- Tyson, P.D. and Preston-Whyte, R.A. (2000). *The weather and climate of Southern Africa*. Oxford University Press, p. 396.
- Udden, J.A. (1914). Mechanical composition of clastic sediments. *Bulletin of the Geological Society of America*, vol. 25, 655–744.
- Vail, P.R. and Hardenbol, I. (1979). Sea-level changes during the Tertiary. *Oceans*, vol. 22, no. 3, 71-79.
- Van Heerden, I.L. (1986). Fluvial sedimentation in the ebb-dominated Orange Estuary. *South African Journal of Science*, vol. 82, 141-147.
- Van Heteren, S. and van de Plassche, O. (1997). Influence of relative sea-level change and tidal-inlet development on barrier-spit stratigraphy, Sandy Neck, Massachusetts. *Journal of Sedimentary Research*, vol. 67, no. 2, 350-363.
- Van Sickel, W.A., Kominz, M.A., Miller, K.G. and Browning, J.V. (2004). Late Cretaceous and Cenozoic sea-level estimates: backstripping analysis of borehole data, onshore New Jersey. *Basin Research*, vol. 16, 451–465.
- Van Wyk, J.P. and Pienaar, L.F. (1986). Diamondiferous gravels of the lower Orange River, Namaqualand. In: Anhaeusser, C.R. and Maske, S. (Eds). *Mineral deposits of Southern Africa*, vol. 2, Geological Society of South Africa, 2309-2321.
- Van Zyl, J.A. and Scheepers, A.C.T. (1992). Quaternary sediments and the depositional environment of the lower Uniab River area, Skeleton Coast, Namibia. *South African Journal of Geology*, vol. 95 (3/4), 108-115.
- Venmyn Rand (Pty.) Ltd. (2007). BRC Diamondcore National Instrument 43-101, technical report, pg 16-41. Website, <http://www.kigmining.com>.

- Viola, G., Andreoli, M., Ben-Avraham, Z., Stengel, I. and Reshef, M. (2005). Offshore mud volcanoes and onland faulting in southwestern Africa; neotectonic implications and constraints on the regional stress field. *Earth and Planetary Science Letters*, vol. 231, 147-160.
- Vos, R.G. and Hobday, D.K. (1977). Storm beach deposits in Late Palaeozoic Ecca Group, South Africa. *Sedimentary Geology*, vol. 19, 217-232.
- Walker, R.G. (1984). General introduction: facies, facies sequences and facies models. In: Walker, R.G. (Ed.), *Facies Models*, 2nd Edition, Geoscience Canada, Reprint Series 1, 1-10.
- Walker, R.G. (1985). Geological evidence for storm transportation and deposition on ancient shelves. In: Tillman, R.W., Swift, D.J.P. and Walker, R.G. (Eds). Shelf sands and sandstone reservoirs. *Society of Economic Paleontologists and Mineralogists, short course No. 13, Lecture notes*, 243-302. Society for Sedimentary Geology.
- Walker, R.G. and Bergman, K.M. (1993). Shannon sandstone in Wyoming: A shelf-ridge complex reinterpreted as lowstand shoreface deposits. *Journal of Sedimentary Petrology*, vol. 63, no. 5, 250-264.
- Ward, J.D. (1984). Aspects of the Cenozoic geology in the Kuiseb Valley, central Namib Desert. *Unpublished Ph.D. thesis*, University of Natal, Pietermaritzburg, South Africa, p. 310.
- Ward, J.D. (1988). Eolian, fluvial and pan (playa) facies of the Tertiary Tsondab Sandstone Formation in the central Namib Desert, Namibia. *Sedimentary Geology*, vol. 55, 143-162.
- Ward, J.D. (2000). Deposits of the Namibian Coast. Chapter 3, Deposits of the West Coast. Pether, J., Roberts, D.L. and Ward, J.D. In: Partridge, T.C. and Maud, R.R. (Eds). *The Cenozoic of Southern Africa*, Oxford University Press, 46-54.

- Ward, J.D. and Bluck, B.J. (1997). The Orange River: 100 million years of fluvial evolution in southern Africa. *6th International Conference of Fluvial Sedimentology*. University of Cape Town, South Africa. Abstract volume, 222.
- Ward, J.D. and Corbett, I. (1990). Towards an age for the Namib. In: Seely, M.K. (Ed.). Namib ecology: 25 years of Namib research. *Transvaal Museum, monograph 7*, Pretoria, 17-26.
- Ward, J.D., Jacob, R.J., de Wit, M.C.J., Spaggiari, R.I. and Bluck, B.J. (2002). Post Gondwana evolution of the Vaal-Orange River drainage system: economic implications. *Excursion guide, 16th International Sedimentological conference*. Rand Afrikaans University, Johannesburg, South Africa, p. 75.
- Ward, J.D., Seely, M.K. and Lancaster, N. (1983). On the antiquity of the Namib. *South African Journal of Science*, vol. 19, 175-183.
- Ward, J.D., van der Westhuizen, A., Jacob, R.J., Apollus, L. and Spaggiari, R.I. (1998). *7th International kimberlite conference. Excursion guide: West Coast field excursion*, University of Cape Town, Cape Town, South Africa, p. 23.
- Wavescape. (2004). Surfing in South Africa, surf report. Website, <http://www.wavescape.co.za>
- Wells, L.E. (1996). The Santa Beach ridge complex: sea level and progradational history of an open gravel coast in central Peru. *Journal of Coastal Research*, vol. 12, no. 1, 1-17.
- Wentworth, C.K. (1922). A scale of grade and class terms for clastic sediments. *Journal of Geology*, vol. 30, 377-392.
- Wiberg, P. (2000). A perfect storm: formation and potential for preservation of storm beds on the continental shelf. *Oceanography*, vol. 13, 93-99.

- Wickens, H. de V., McLachlan, I.R., (1990). The stratigraphy and sedimentology of the reservoir interval of the Kudu 9A-2 and 9A-3 boreholes. In: Hoal, B.G. (Ed.). The Kudu offshore drilling project. *Communications of the Geological Survey of Namibia*, vol. 6, 9–22.
- Wigley, R.A. (2004). Sedimentary facies from the head of the Cape Canyon: insights into the Cenozoic evolution of the western margin of South Africa. *Unpublished Ph.D. thesis*, University of Cape Town, Cape Town, South Africa, p. 247.
- Williams, A.T. and Caldwell, N. (1988). Particle size and shape in pebble beach sedimentation. *Marine Geology*, vol. 82, 199-215.
- Williams, R. (1996). *King of sea diamonds: the saga of Sam Collins*. Cape Town, W.J. Flesch and Partners, p. 176.
- Winn, R.D. (1991). Storm deposition in marine sand sheets: Wall Creek Member, Frontier Formation, Powder River basin, Wyoming. *Journal of Sedimentary Petrology*, vol. 61, no. 1, 86-101.
- Whitten, D.G.A and Brooks, J.R.V. (1987). *The Penguin dictionary of geology*. Penguin Books, Middlesex, England, p.520
- Woodborne, M.W. (1991). The geology of the diamondiferous inner shelf off Namaqualand between Stompneus Bay and White Point, just north of the Buffels River. *Bulletin of the Geological Survey of South Africa*, 99, p. 68.
- Wright, L.D. and Short, A.D. (1984). Morpho-dynamic variability of surf zones and beaches: a synthesis. *Marine Geology*, vol. 56, 93-118.
- Yagishita, K. (1994). Planar cross-bedding associated with rip currents of Upper Cretaceous formations, northeast Japan. *Sedimentary Geology*, vol. 93, 155-163.
- Yoder, M.N. (1993). Diamond properties and applications. In: Davies, R.F. (Ed.). *Diamonds and film coatings*, New Jersey, U.S.A., Noyes Publications, 1-30.

Zingg, T. (1935). Beitrag zur Scholtteranalyse. *Schweizer Mineralogische und Petrographische Mitteilungen*, vol. 15, 39-140.

**SEDIMENTOLOGY OF PLIO-PLEISTOCENE
GRAVEL BARRIER DEPOSITS
IN THE PALAEO-ORANGE RIVER MOUTH, NAMIBIA:
DEPOSITIONAL HISTORY AND DIAMOND MINERALISATION**

VOLUME 2

A thesis submitted in fulfilment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

of

RHODES UNIVERSITY

by

RENATO IGINO SPAGGIARI

March 2011

VOLUME 1

Chapters 1 to 7

References

VOLUME 2

All figures

Appendices A to E

**Make your own notes.
NEVER underline or
write in a book.**

LIST OF FIGURES

Chapter 1

1.1	Locality map showing position of study area within MA1 and in relation to different gravel beach types.....	1
1.2	Regional geological map of MA1 illustrating main geological features.....	2
1.3	Schematic meteorological map for the South Atlantic Ocean.....	3
1.4	Schematic representation of terminology used in this study for gravel barrier beaches.....	4
1.5	Generalised compilation of predominant sedimentary structures and sediment types for barrier beach sub-environments	5
1.6	Position of palaeo-Orange River mouth in study area.....	6
1.7	Schematic diagram illustrating use of poles to create a plane for measuring the attitude of gravel foresets	7

Chapter 2

2.1	Stratigraphic framework for the Cainozoic deposits discussed in Chapter 2.....	8
2.2	Map illustrating sediment dispersal pathways for gravel, sand and finer sediment	9
2.3	Schematic block model summarising regional setting	10
2.4	Schematic cross-section through the palaeo-marine beach deposits ('raised beaches') of the Namibian mega-placer	11
2.5	Schematic diagram illustrating general differences between the study area barrier beach sequences and age-equivalent beaches developed down-drift	12

Chapter 3

3.1	Block diagram illustrating the vertical and lateral stratigraphic relationship of the main sedimentary facies and sub-facies.	13
3.2	General distribution of Facies A.....	14

3.3	Schematic diagram illustrating stratigraphic relationship of Facies A and B, and footwall types.....	15
3.4	Cross-section of G25 trench illustrating lateral relationship of sub-facies with palaeo-current directions	16
3.5	Gravel deposits of Sub-facies A1	17
3.6	Cross-laminated sand and granule of Sub-facies A2.....	18
3.7	Gravel deposits of Sub-facies A3	19
3.8	Soft sediment folding in Sub-facies A3 gravels due to slumping	20
3.9	Deposits of Sub-facies A4	21
3.10	Cross-section of G25 trench depicting main characteristics of the coarser-grained units of Facies A	22
3.11	Modern analogue of Facies A setting	23
3.12	Schematic section looking down-drift through the gravel barrier spit at G25 illustrating depositional environments	24
3.13	Hypothetical depositional model for Facies A	25
3.14	Summary of Facies A stratigraphic and palaeo-environmental framework based on lateral relationship	26
3.15	General distribution of Facies B	27
3.16	Boulder bed of Facies B	28
3.17	General stratigraphic correlation of Facies B with other facies based on fossil assemblages	29
3.18	Hypothetical emplacement model of Facies B	30
3.19	Palaeo-environmental summary of Facies B	31
3.20	General distribution of Facies C	32
3.21	Cross-section of G29 trench illustrating vertical and lateral arrangement of sub-facies with palaeo-current directions	33
3.22	Geometry of Sub-facies C1 sedimentary units	34
3.23	Sphere-rich gravel sheet of Sub-facies C1	35

3.24	Cross-stratified gravel of Sub-facies C1	36
3.25	Disc-rich gravel sheet deposits of Sub-facies C1	37
3.26	Cross-stratified gravel of Sub-facies C2 with foresets dipping landward	38
3.27	Load structure in Sub-facies C2 clay deposits.....	39
3.28	Schematic diagram of a gravel barrier beach illustrating the different settings, their sub-facies and modern analogues thereof	40
3.29	Sorting fabrics in modern and ancient sediments with schematic model to illustrate normal grading.....	41
3.30	Clay clasts within beach sediments	42
3.31	A modern analogue of the Sub-facies C2 clay and silt depositional setting in Oranjemund, Namibia	43
3.32	Cross-section of G29 trench depicting main characteristics of the sub-facies	44
3.33	Summary of Facies C stratigraphic and palaeo-environmental framework based on a vertical succession where there is maximum preservation of sub-facies	45
3.34	General distribution of Facies D.....	46
3.35	Correlation of sub-facies in columnar cross-sections measured from the G39.5 mine face.....	47
3.36	Sub-facies D1 sand	48
3.37	Sub-facies D2 sediments	49
3.38	Sub-facies D2 gravel beds	50
3.39	Sand units of Sub-facies D3	51
3.40	Modern comparative of Sub-facies D1 subaqueous dunes.....	52
3.41	Orbital velocity vs. grain diameter for threshold of sediment movement	53
3.42	Threshold velocity for initiation of grain movement and bedform zonation for modern subaqueous dunes	53
3.43	Threshold velocity for initiation of grain movement and bedform zonation for Sub-facies D1	54
3.44	Schematic diagrams illustrating depositional setting of Facies D.....	55

3.45	Summary of Facies D stratigraphic and palaeo-environmental framework based on vertical relationship	56
------	---	----

Chapter 4

4.1	Fence diagram showing stratigraphy of ED area barrier deposits	57
4.2	Fence diagram and conceptual models illustrating relationship of beach forms to bedrock 'F' cliff.....	58
4.3	Uniab Delta, Skeleton Coast, Namibia	59
4.4	General stratigraphic setting of Neogene and Quaternary age coastal deposits from some localities along the Atlantic coastline of South Africa and Namibia	60
4.5	Beach-ridge plain.....	61
4.6	Conceptual models for river mouth deposition in a wave-dominated setting	62
4.7	Modern example of a deactivated barrier in Oranjemund, Namibia	63
4.8	Hypothetical model for the genesis of the barrier spit stratigraphy	64
4.9	Hypothetical model for the genesis of the barrier beach stratigraphy	65
4.10	Schematic illustration explaining the genesis of barrier spit deposits as discussed in Section 4.4.....	66

Chapter 5

5.1	Comparison of grade with geological continuity to illustrate estimation difficulty of ore deposits.....	67
5.2	Diamond size comparison of Meso-Orange River proximal deposits with marine deposits of similar age at the Orange River mouth	67
5.3	Schematic representation of a gravel barrier spit (Facies A) showing distribution of average grade and stone size	68
5.4	Average grade size distribution in Facies B (transgressive lag).....	69
5.5	Average stone size distribution in Facies B (transgressive lag)	70
5.6	Dispersion graphs for Facies B (transgressive lag) grade and stone size data	71

5.7	Average grade distribution in Facies C (gravel barrier beach).....	72
5.8	Average stone size distribution in Facies C (gravel barrier beach).....	73
5.9	Comparison of diamond results from foreshore and backshore settings in Facies C (barrier beach).....	74
5.10	Dispersion graphs for Facies C (barrier beach) grade data	75
5.11	Dispersion graphs for Facies C (barrier beach) stone size data.....	76
5.12	Grade versus sample size for barrier beach settings.....	77
5.13	Average stone size and grade distribution in Sub-facies D3 (storm gravel sheets)	78
5.14	Dispersion graphs for Sub-facies D3 (storm gravel sheet) grade and stone size data.....	79
5.15	Diamond value (US\$/ct) baseline data for estimating ED Area diamond values	80
5.16	Bubble chart illustrating ED Area deposits ton value (U\$/ton) against grade (cts/ton).....	81
5.17	Composite mineralisation diagram illustrating overall average grade and stone size for different depositional sub-environments in barrier spit and barrier beach deposits	82
5.18	Composite mineralisation diagram illustrating statistical summary of average grade against average stone size.....	83
5.19	Summary of hypothetical diamond mineralisation processes in a barrier beach	84
5.20	Summary of hypothetical diamond mineralisation processes in a barrier spit.....	85

Chapter 6

6.1	Regional distribution of onshore diamondiferous palaeo-littoral deposits.....	86
6.2	Stratigraphic representation of diamondiferous palaeo-shorelines along the Atlantic Coast of South Africa and Namibia	87
6.3	Regional distribution of 30 m Package (Plio-Pleistocene) onshore palaeo-littoral deposits	88

6.4	Average diamond size and average grade distribution within Plio-Pleistocene and younger littoral deposits along the Namibian coast.	89
6.5	Diamond size decline since the Plio-Pleistocene	90
6.6	Hypothetical model for diamond recycling process during sea-level fluctuations	91
6.7	Hypothetical model for diamond emplacement in barrier deposits confined to river mouth settings where fixed trapsites are absent	92

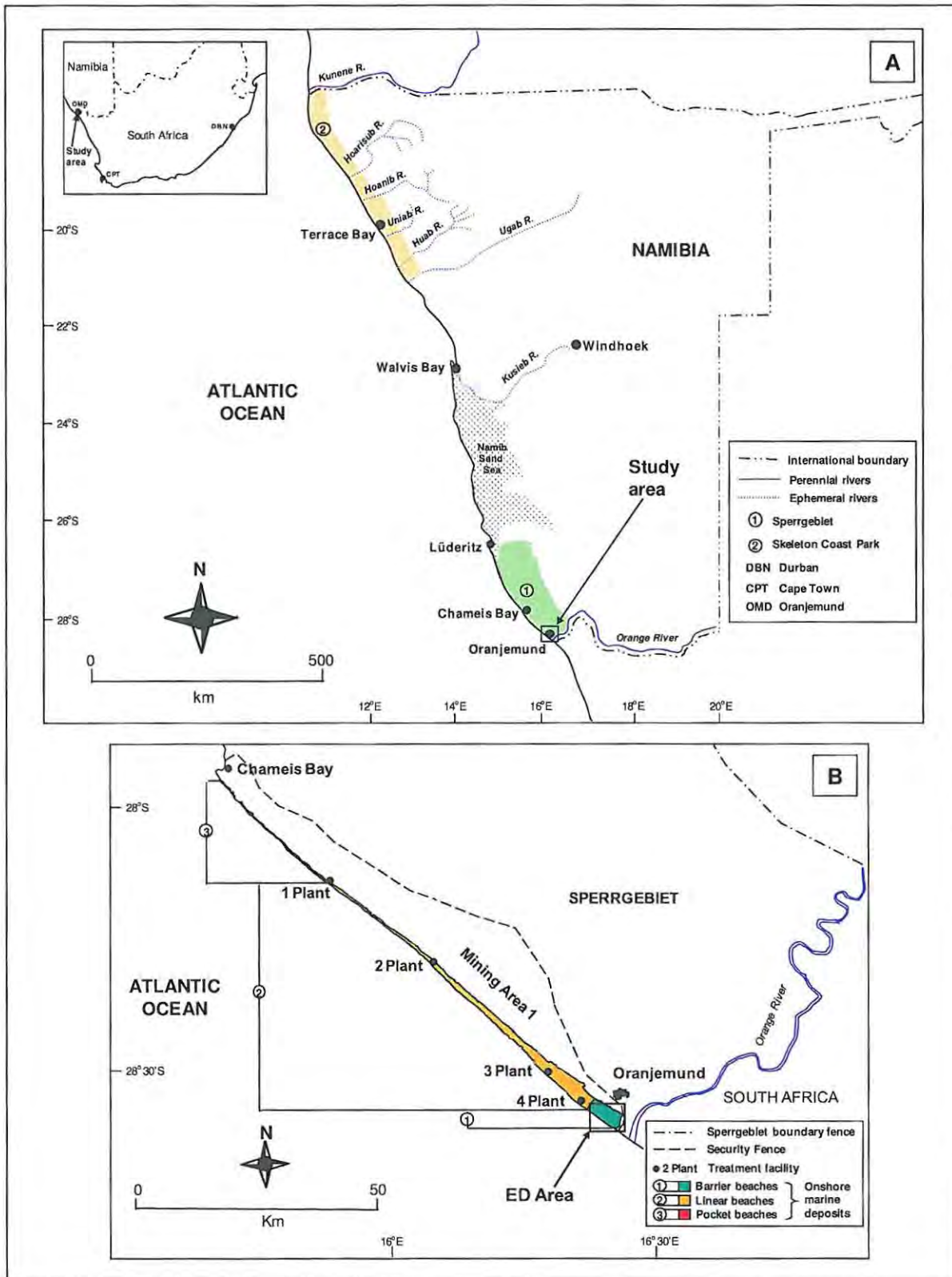
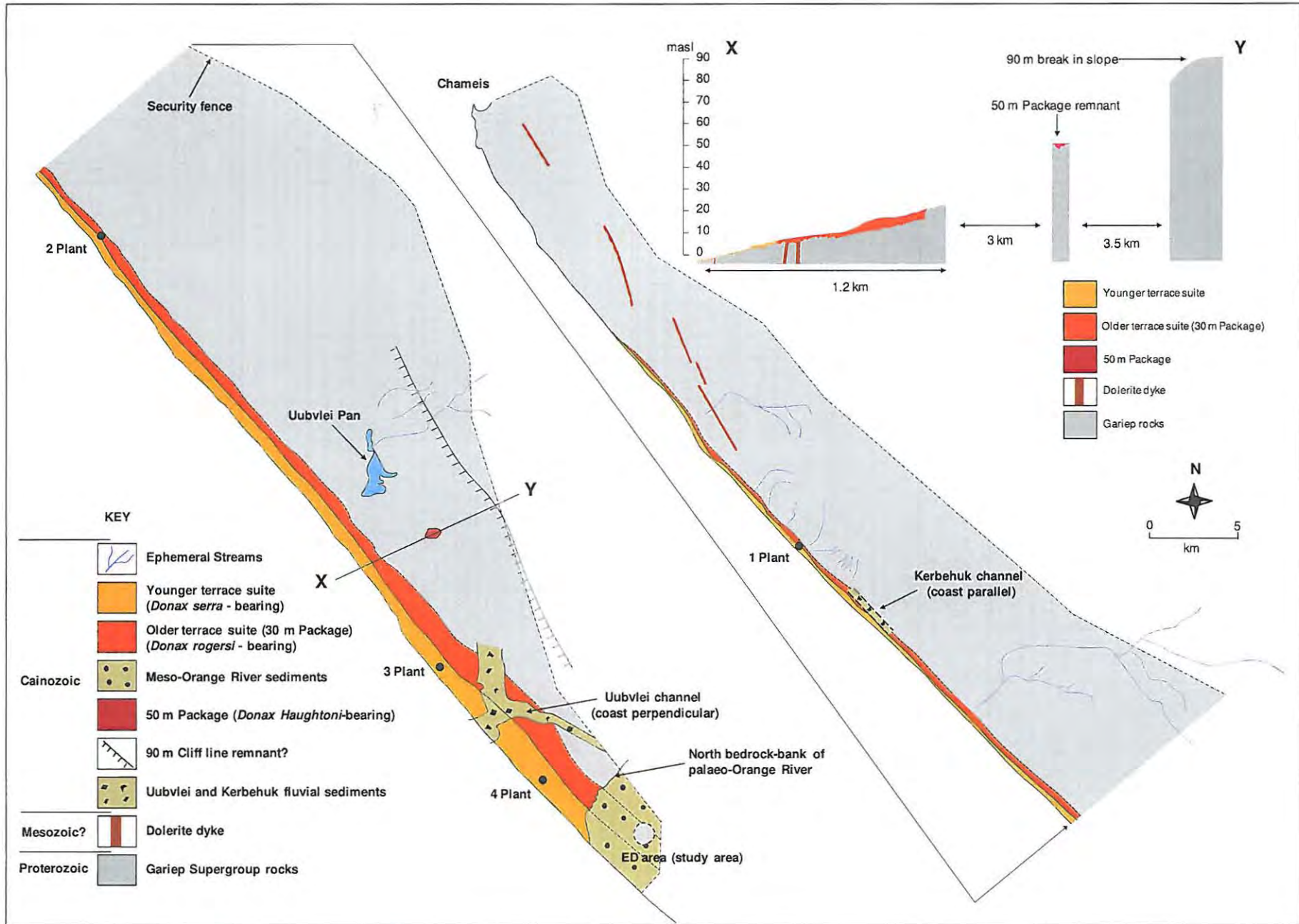


Figure 1.1: Locality map showing position of study area (A) within MA1 and in relation to different gravel beach types (B; source Spaggiari *et al.*, 2006).

Figure 1.2: Regional geological map of MA1 illustrating main geological features. Cross-section depicts palaeo-shoreline stratigraphy. See Chapter 2, Section 2.2 for detailed discussion on geological framework.



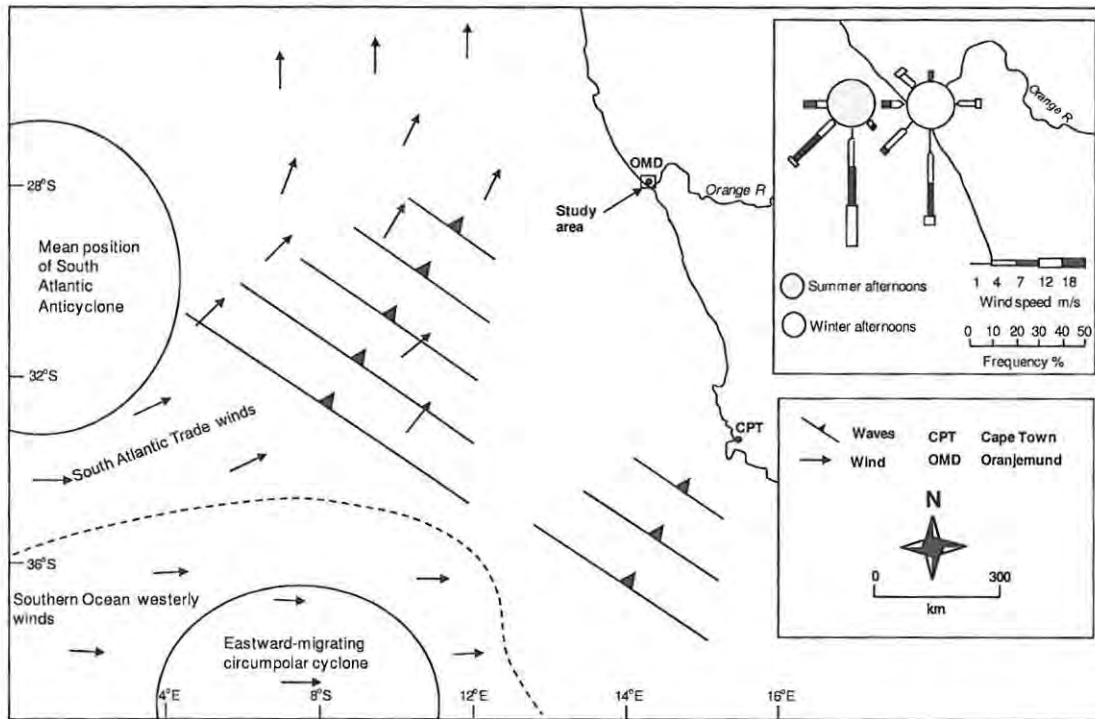


Figure 1.3: Schematic meteorological map for the South Atlantic Ocean (after Woodborne, 1991). Wind roses depict wind regime for winter and summer afternoons (after Rogers, 1977).

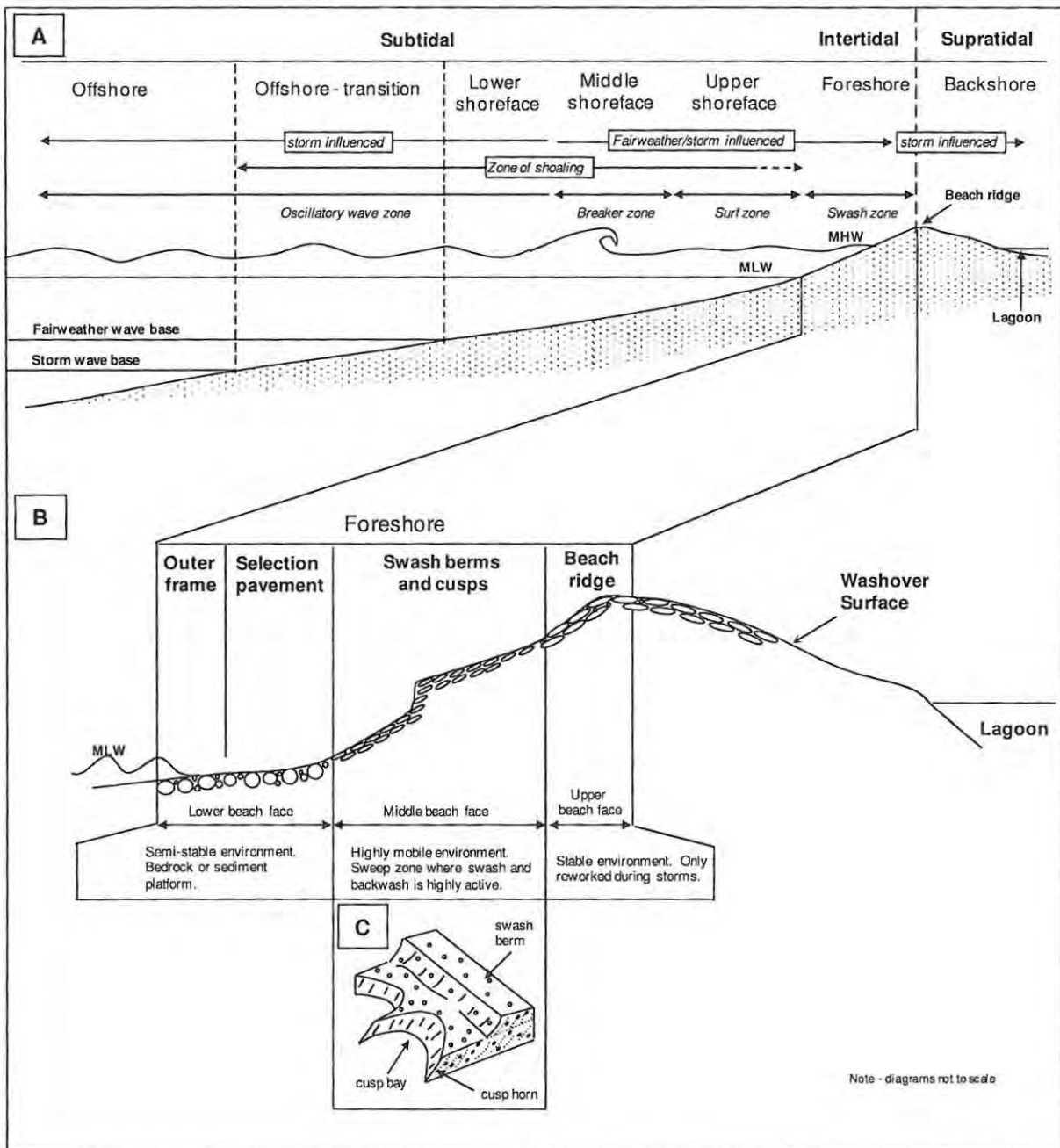
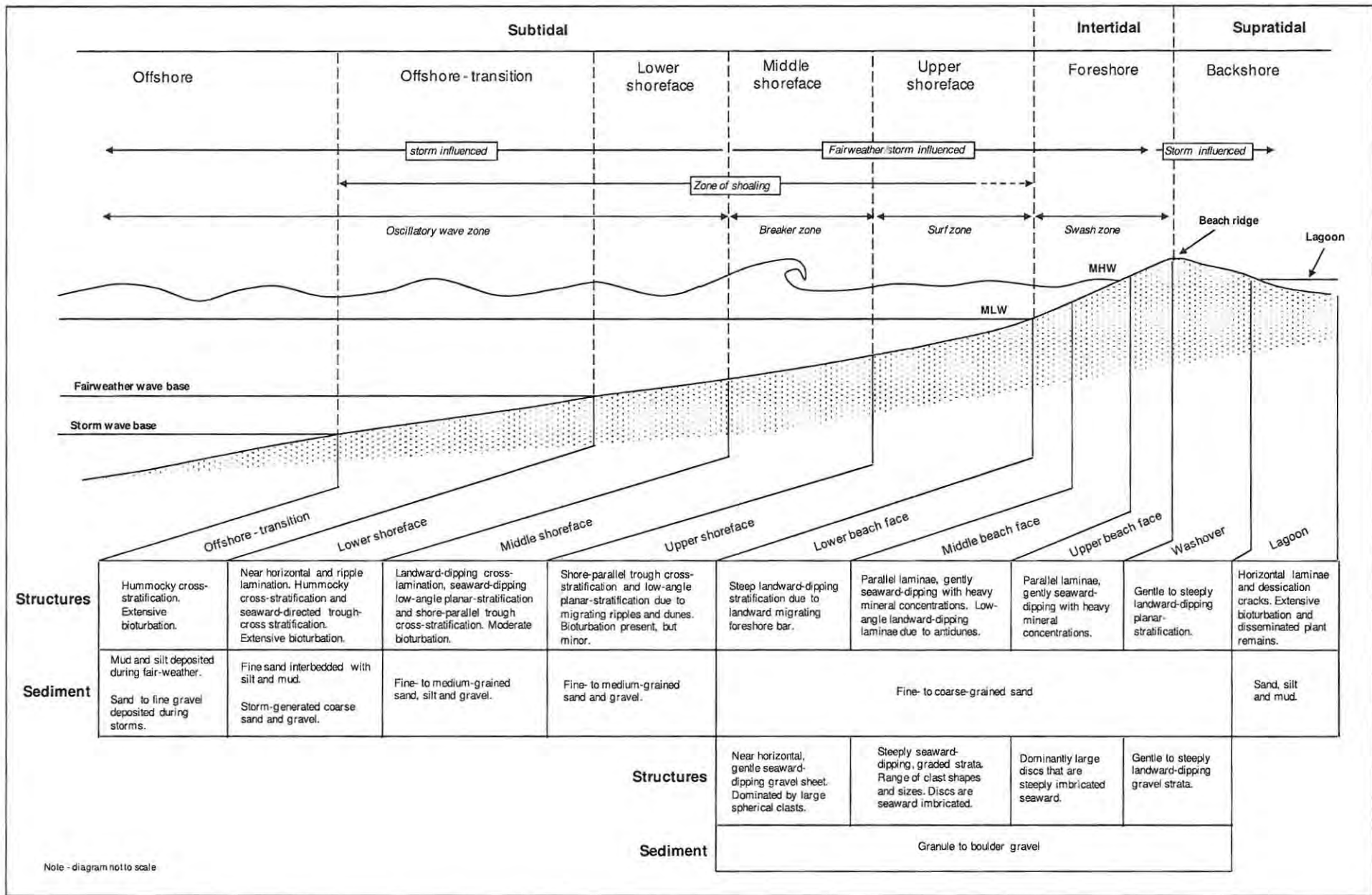


Figure 1.4: Schematic representation of terminology used in this study for gravel barrier beaches. The various depositional sub-environments (A), general gravel beach morphology of the foreshore (B) and an overall three-dimensional perspective of swash berm and cusp features (C) are illustrated. See text for explanation and sources. Note MHW = mean high water, MLW = mean low water.

Figure 1.5: Generalised compilation of predominant sedimentary structures and sediment types for barrier beach sub-environments. Source of information - Bluck (1967, 1999), Reineck & Singh (1975), Elliott (1978, 1986), Harms *et al.* (1982), Reinson (1984), Davis Jr (1985), Leeder (1988), Carter (1993), Reading & Collinson (1996), Nichols (1999), Boggs Jr (2001). Note MHW = mean high water, MLW = mean low water.



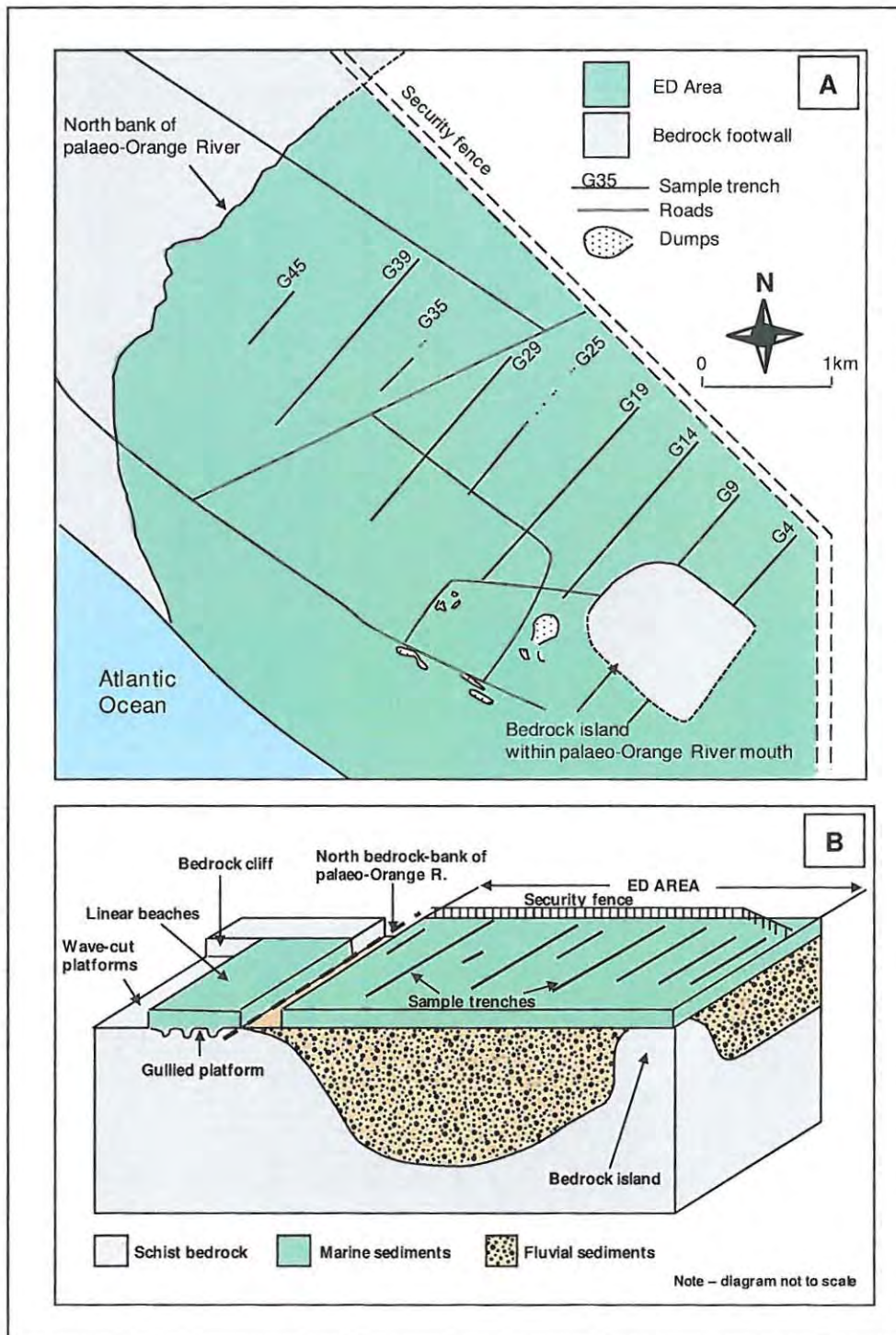


Figure 1.6: Position of palaeo-Orange River mouth in study area. (A) Plan view illustrating ED Area within palaeo-Orange River mouth. (B) Schematic block diagram illustrating broadly the marine and fluvial setting.

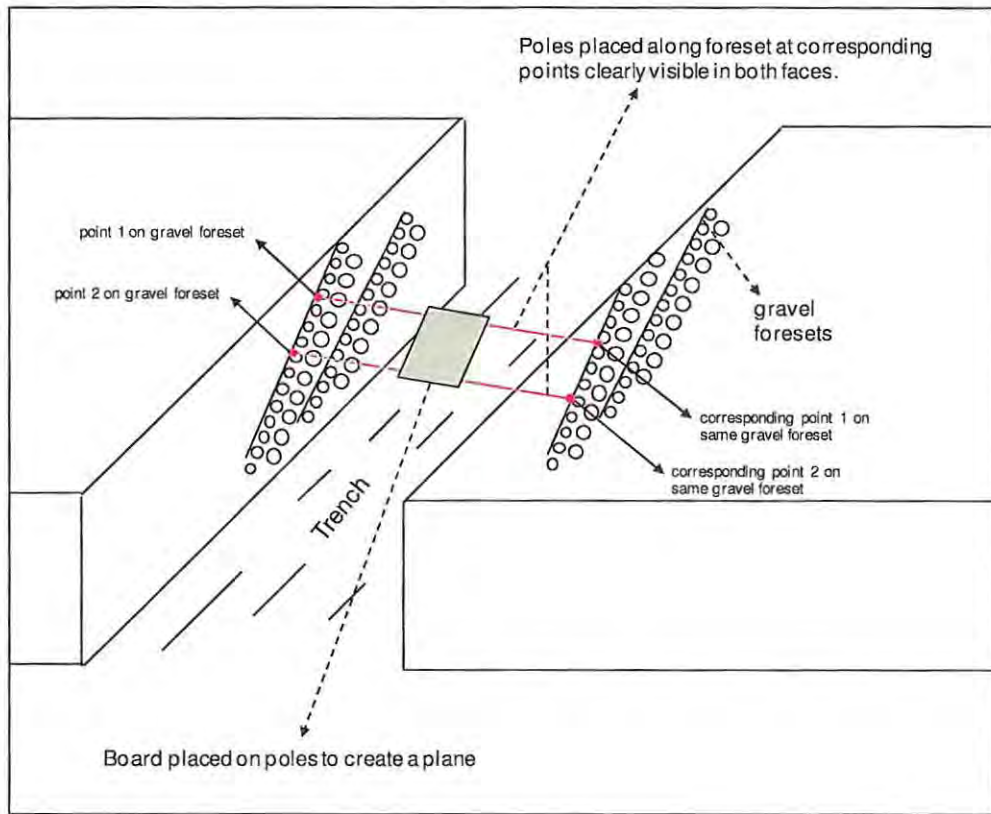


Figure 1.7: Schematic diagram illustrating use of poles to create a plane for measuring the attitude of gravel foresets.

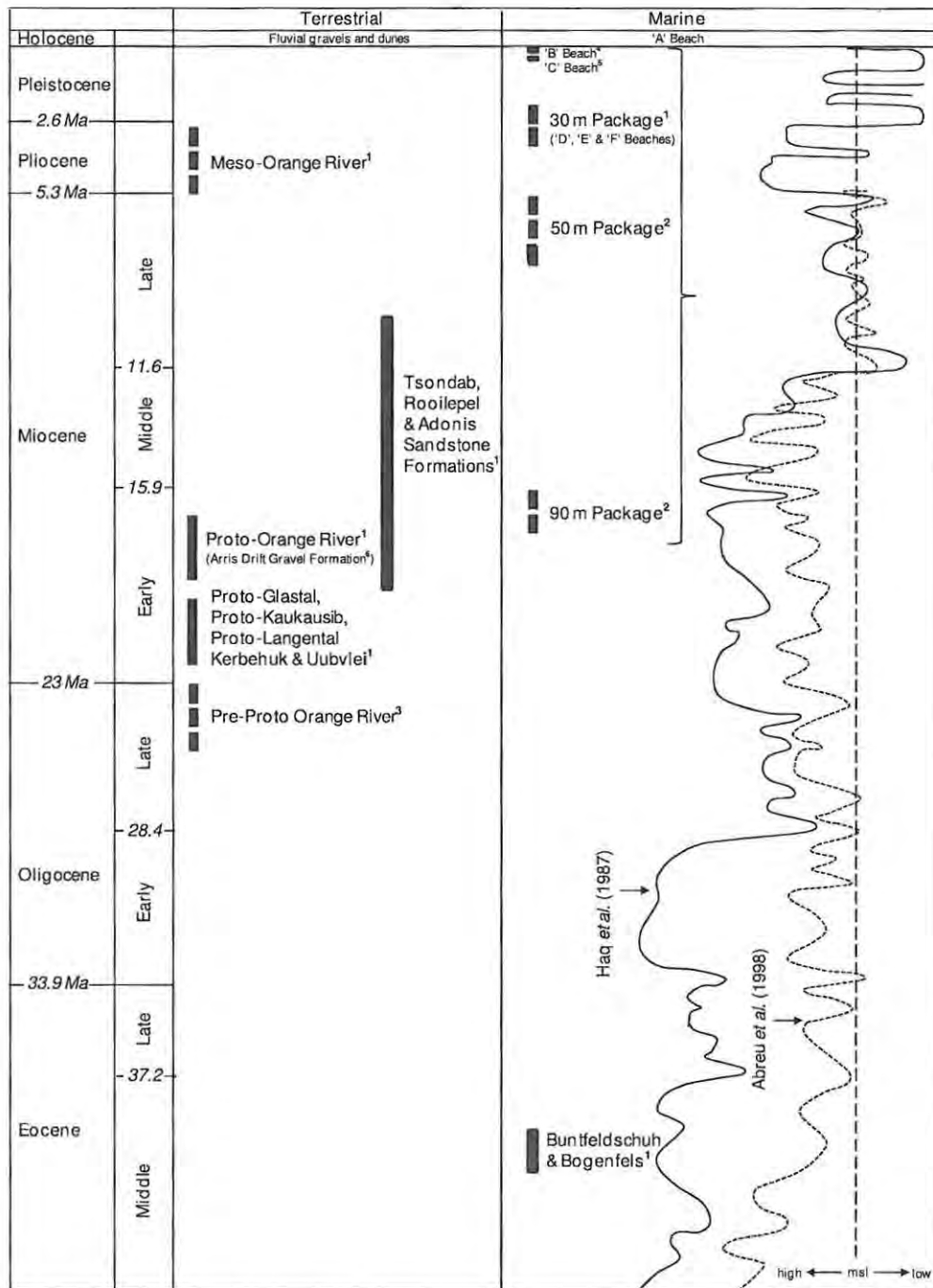


Figure 2.1: Stratigraphic framework for the Cainozoic deposits discussed in Chapter 2. Deposits are correlated to the eustatic curve of Abreu *et al.* (1998; in van Sickle *et al.*, 2004) and Haq *et al.* (1987). Information sourced from ¹Pickford & Senut (1999), ²Pether (2000), ³Bluck *et al.* (2005), ⁴Millad (2004), ⁵Rogers *et al.* (1990), ⁶SACS (1980). Stratigraphic time scale based on the International Stratigraphic chart (IUGS, 2009). Note that msl = mean sea-level.

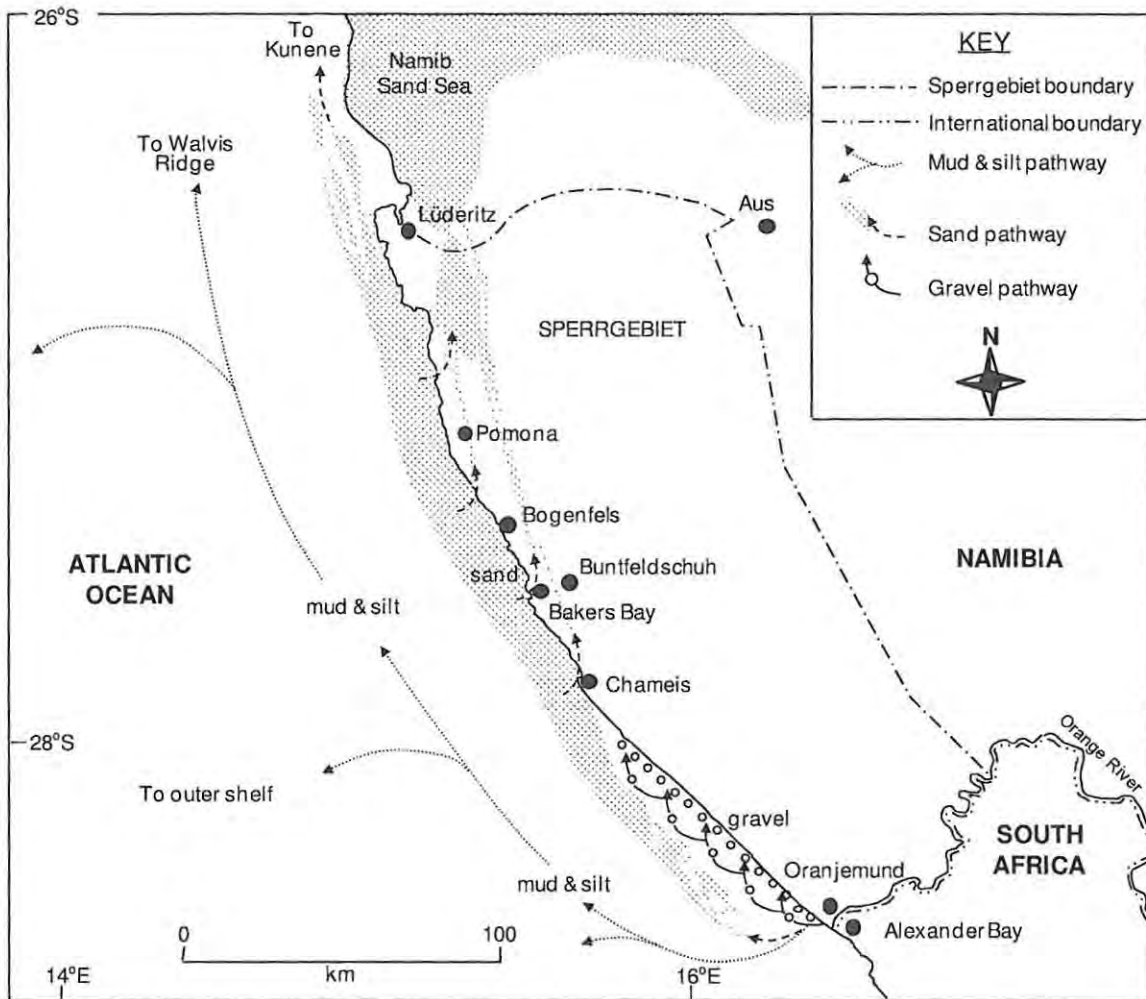
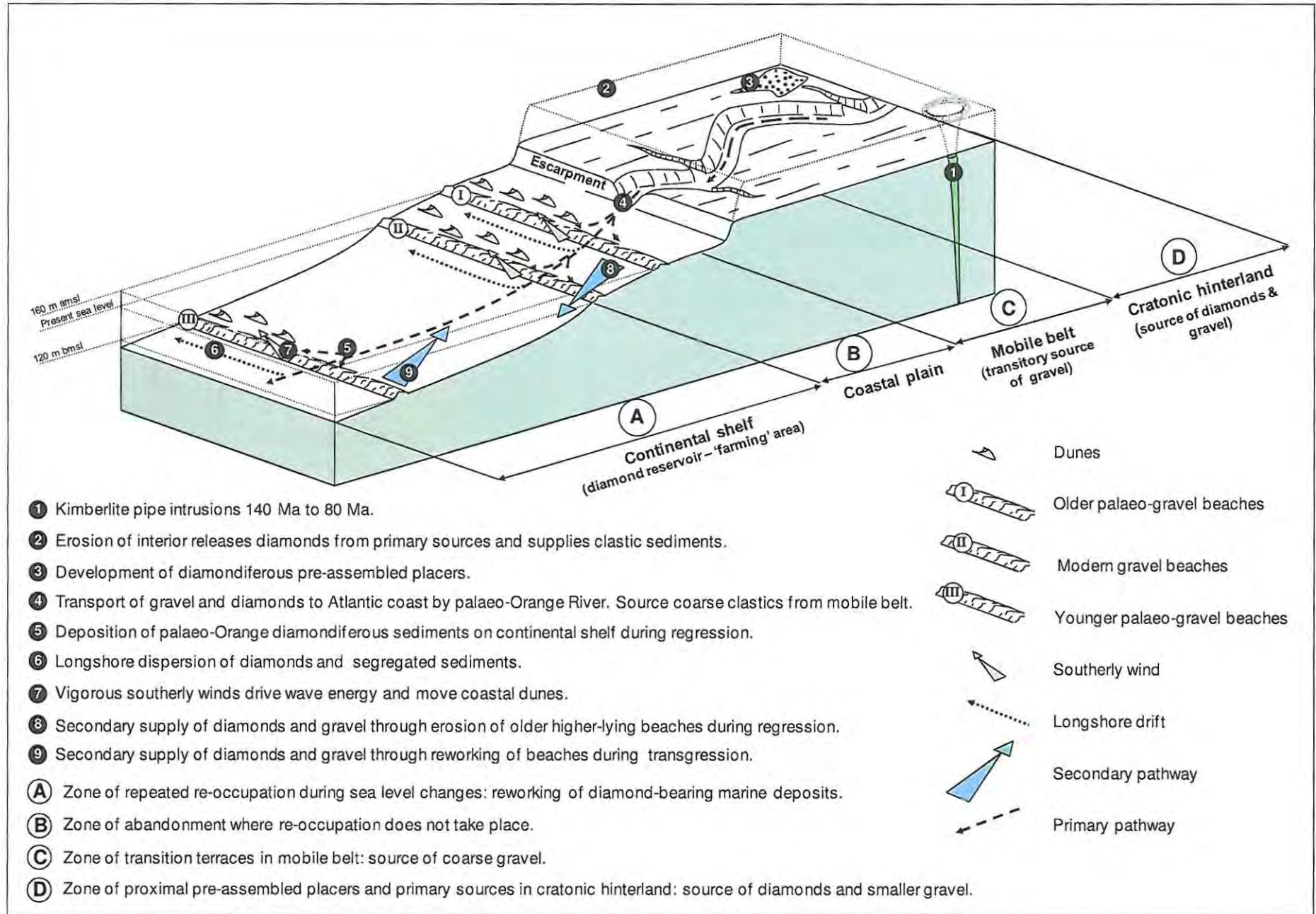


Figure 2.2: Map illustrating sediment dispersal pathways for gravel, sand and finer sediment (source Spaggiari *et al.*, 2006).

Figure 2.3: Schematic block model summarising regional setting (modified after Corbett, 2002).



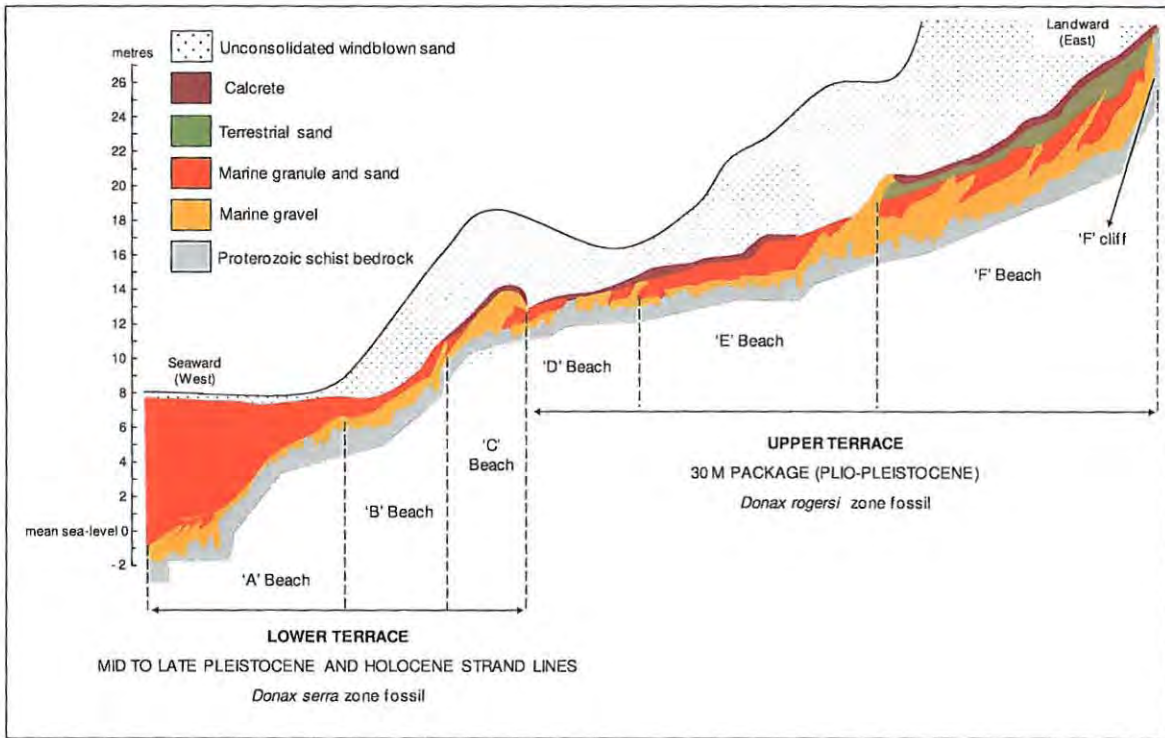


Figure 2.4: Schematic cross-section through the palaeo-marine beach deposits ('raised beaches') of the Namibian mega-placer illustrating the 'Upper Terrace' and 'Lower Terrace' suites (from Ward *et al.*, 1998).

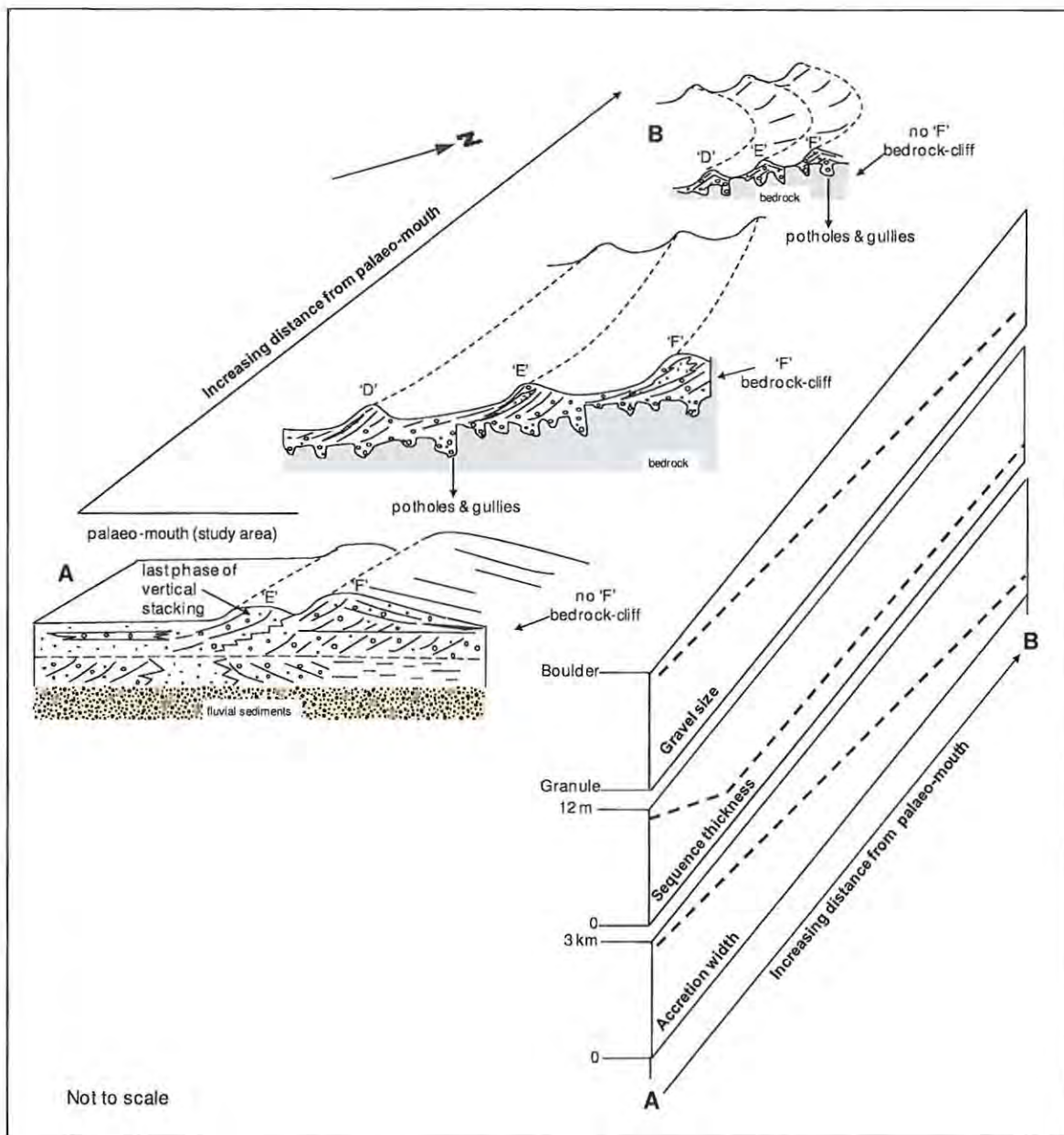


Figure 2.5: Schematic diagram illustrating general differences between the study area barrier beach sequences and age-equivalent beaches developed immediately down-drift. Note, these deposits represent the older 'Upper Terrace' suite (30 m Package of Pether, 1986) and are designated by their alphabetical code 'D', 'E' and 'F' as discussed in the text. **A** and **B** in block diagrams correspond to down-drift distance shown in graphs.

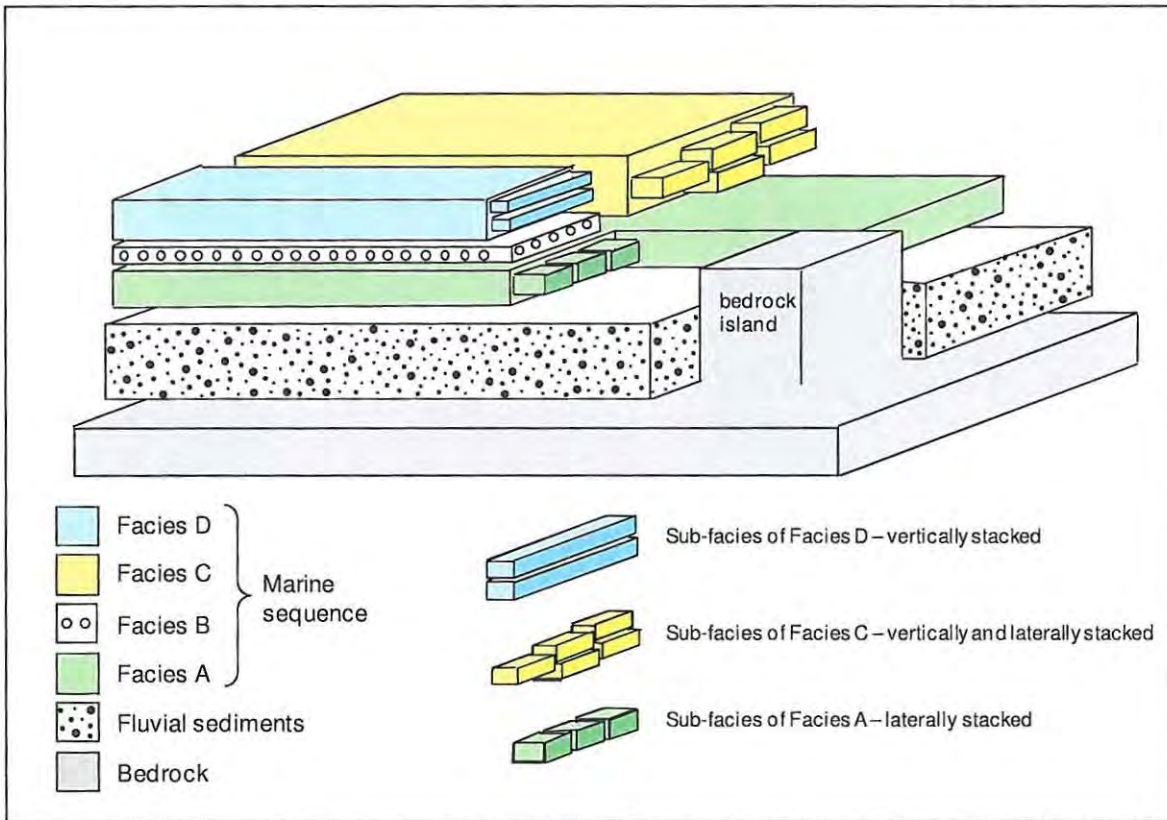
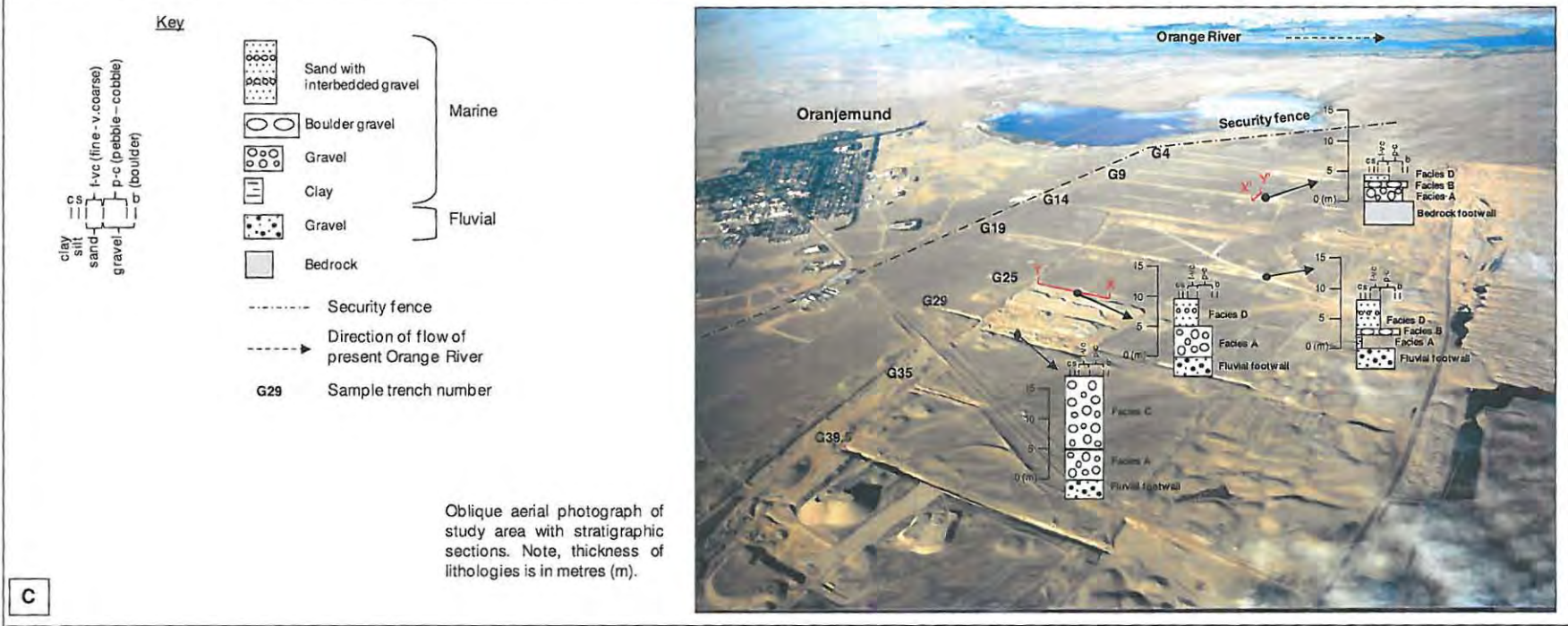
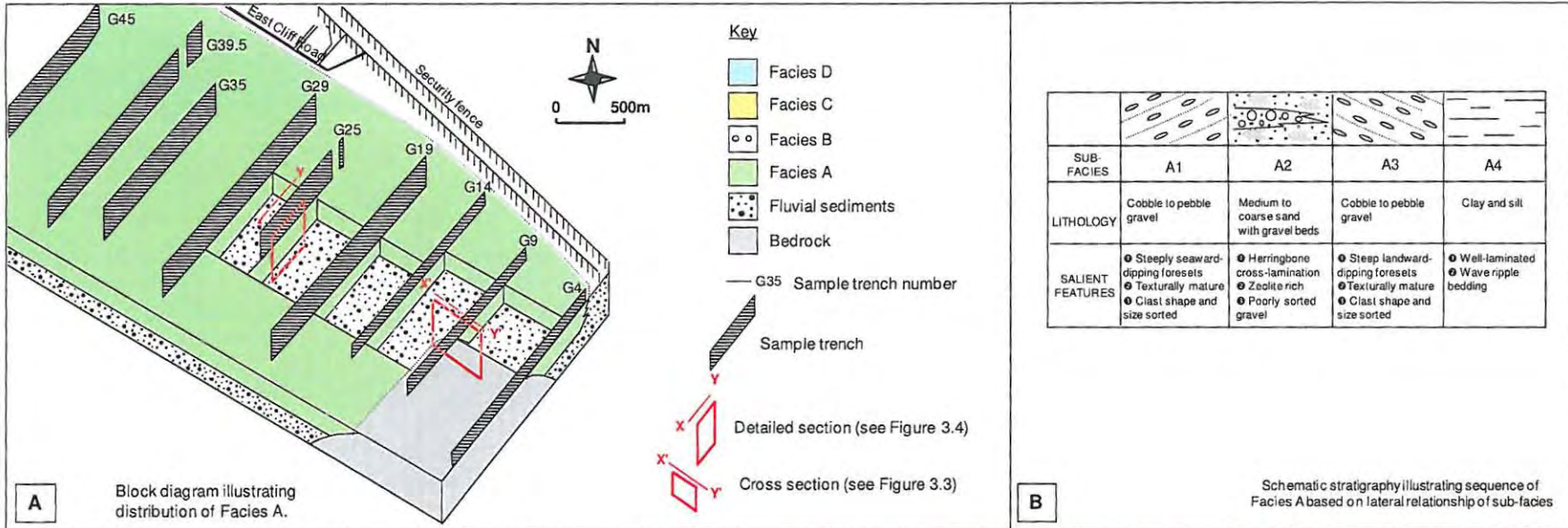


Figure 3.1: Block diagram illustrating the vertical and lateral stratigraphic relationship of the main sedimentary facies and sub-facies.

Figure 3.2: General distribution of Facies A. Block diagram (A) illustrating distribution with localities of cross-sections mapped. Stratigraphy of the sub-facies based on lateral relationship is depicted in (B). Oblique aerial photograph (C) illustrating distribution in the field and stratigraphic relationships superimposed (photograph by courtesy of J. Ward).



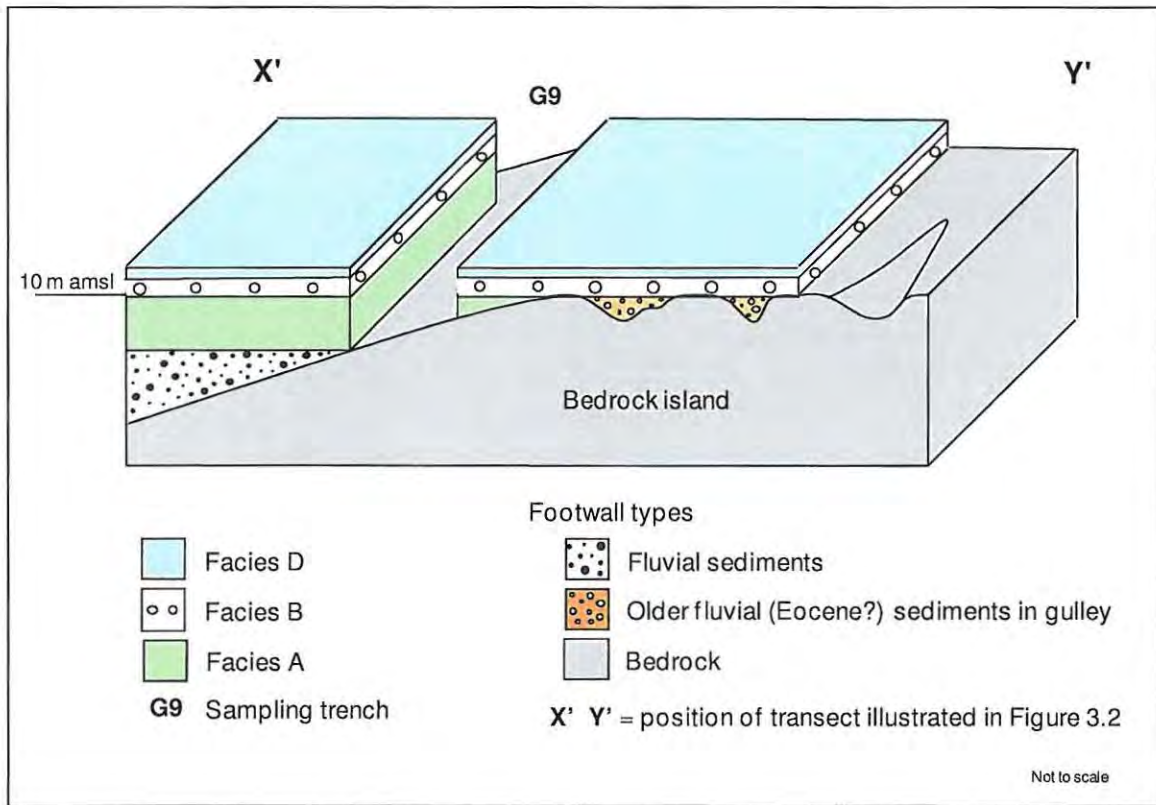
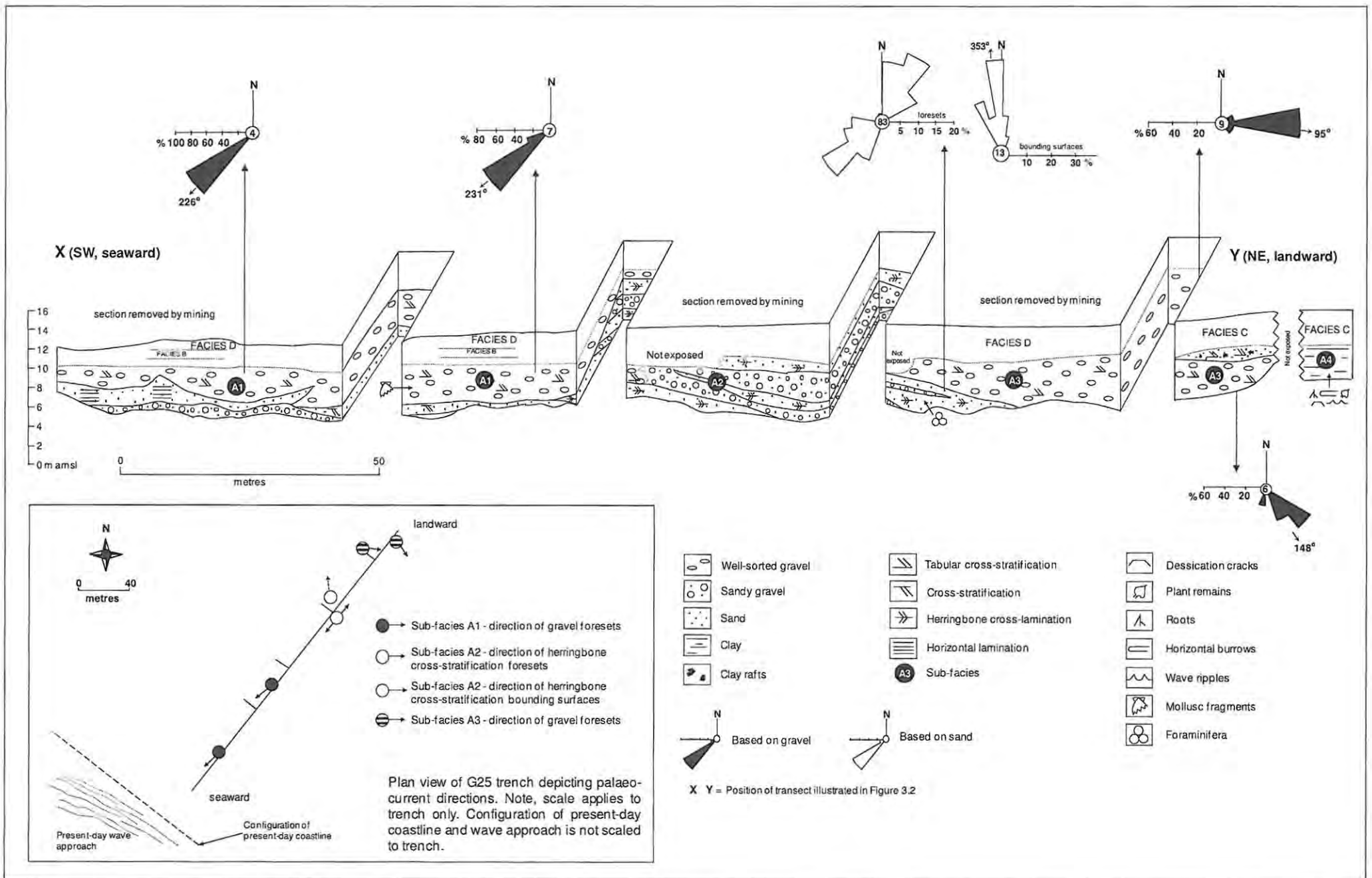
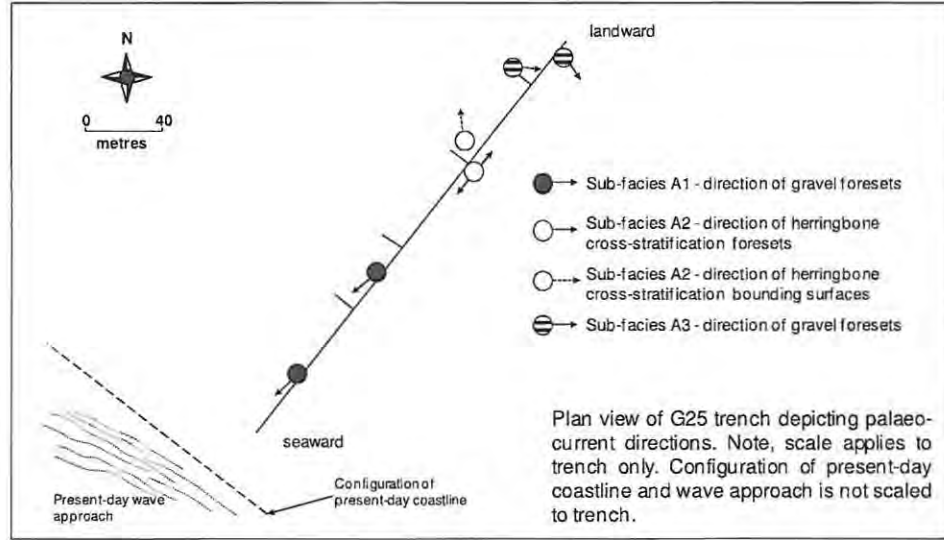
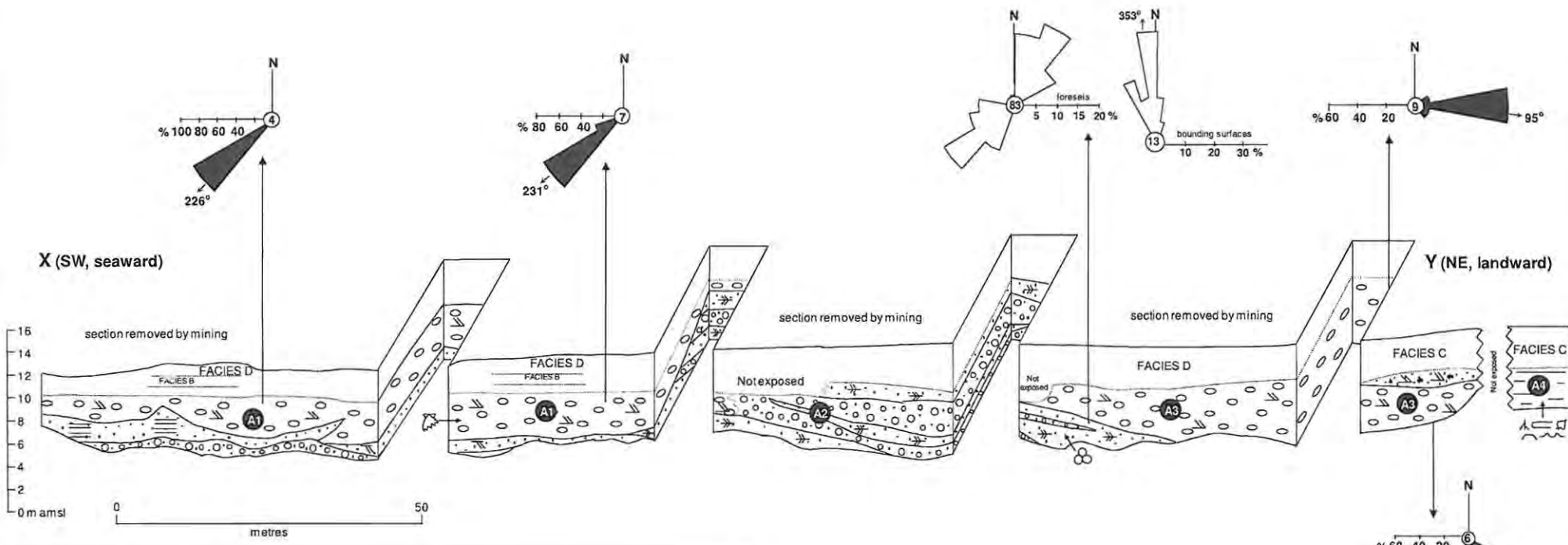


Figure 3.3: Schematic diagram illustrating stratigraphic relationship of Facies A and B, and footwall types

Figure 3.4: Cross-section of G25 trench illustrating lateral relationship of sub-facies with palaeo-current directions. Section is perpendicular to the present coastline, whilst T-sections are parallel.





- | | | |
|--------------------|------------------------------|--------------------|
| Well-sorted gravel | Tabular cross-stratification | Dessication cracks |
| Sandy gravel | Cross-stratification | Plant remains |
| Sand | Herringbone cross-lamination | Roots |
| Clay | Horizontal lamination | Horizontal burrows |
| Clay rafts | Sub-facies | Wave ripples |
| Based on gravel | Based on sand | Mollusc fragments |
| | | Foraminifera |
- X Y = Position of transect illustrated in Figure 3.2

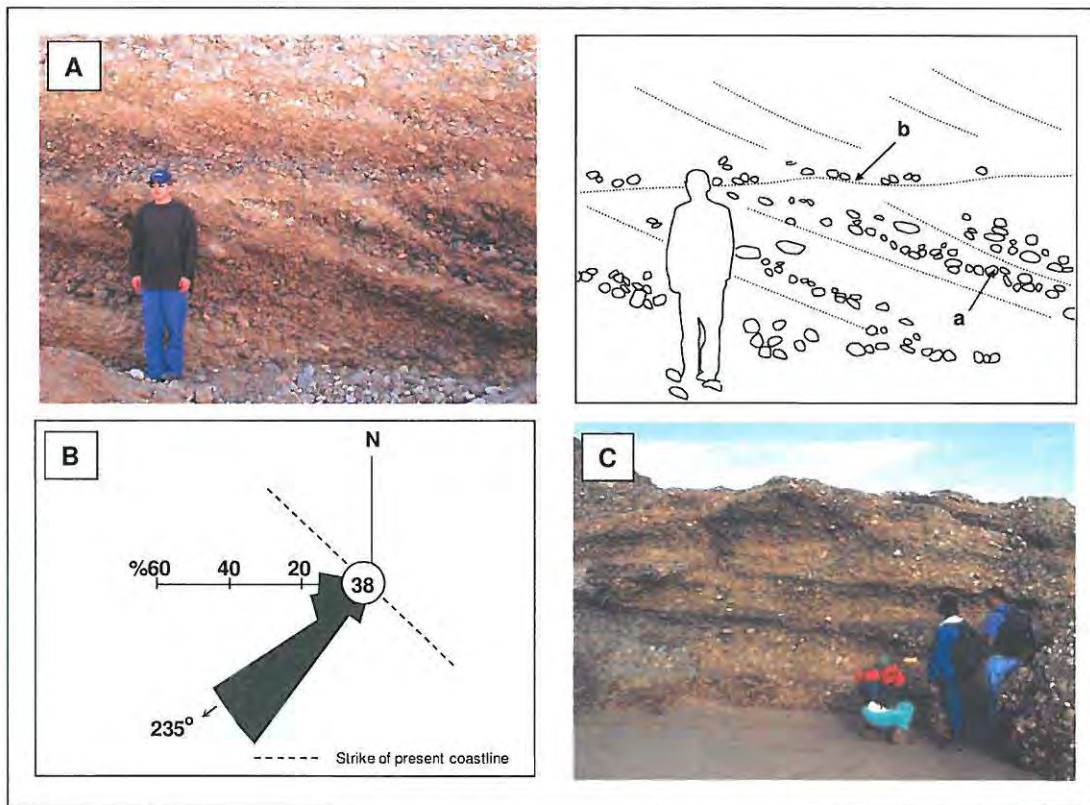


Figure 3.5: Gravel deposits of Sub-facies A1. Locality G25: (A) Gravel exhibiting tabular cross-stratification with steep seaward-dipping (SW) foreset strata (a). Note normal grading of foreset strata. Horizontal sheet of predominantly blade-shaped clasts (b) marks the boundary between cross-stratified sets. Person for scale = 1.9 m. Section measured is perpendicular to present coastline. (B) Rose diagram for palaeo-current directions of all gravel foresets shown in Table 3.2. (C) Similar gravel deposits of Cretaceous age in the Robberg Formation, Plettenberg Bay, South Africa, as described by Reddering (1993).

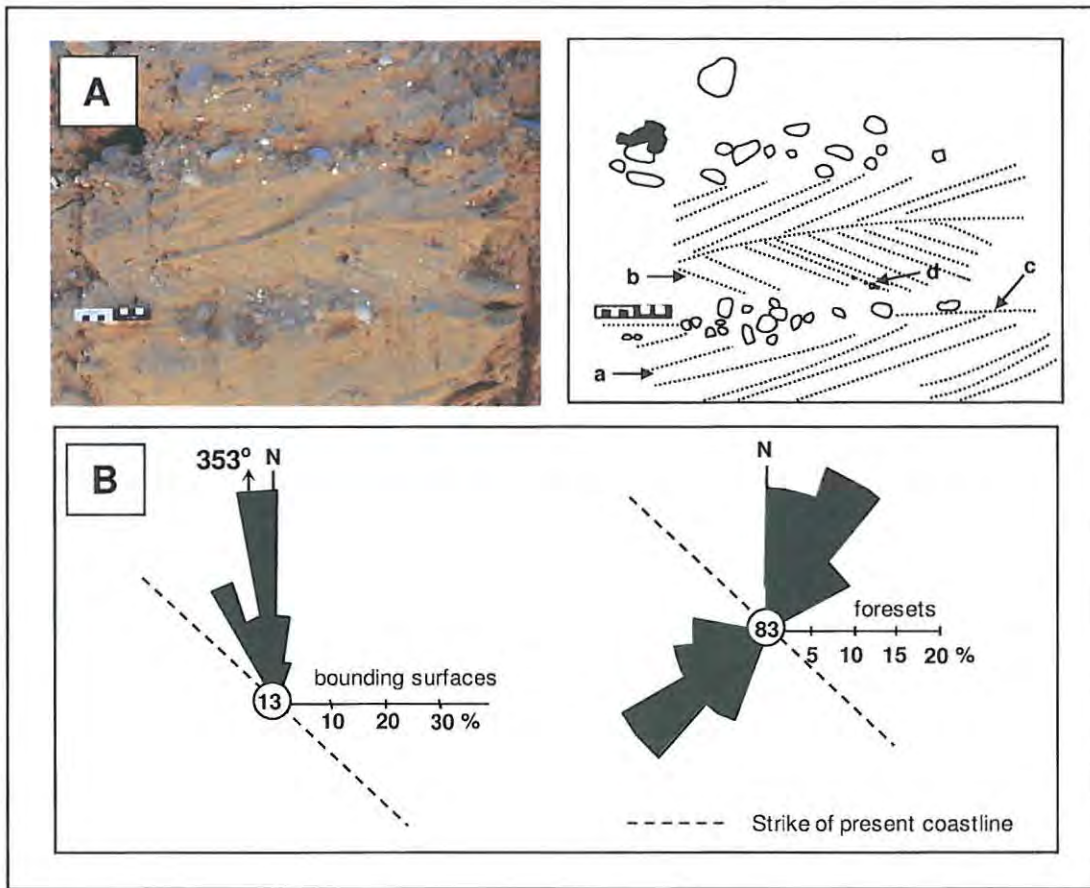


Figure 3.6: Cross-laminated sand and granule of Sub-facies A2. Locality G25: (A) Opposing cross-laminated sets (a & b) separated by bounding surfaces lined with small pebble lags (c). Foreset aligned pebbles (d) consist predominantly of zeolite clasts. Scale = 10 cm. Section measured is perpendicular to present coastline. (B) Rose diagrams illustrating palaeo-current directions of bounding surfaces and bipolar cross-stratification at G25 trench.

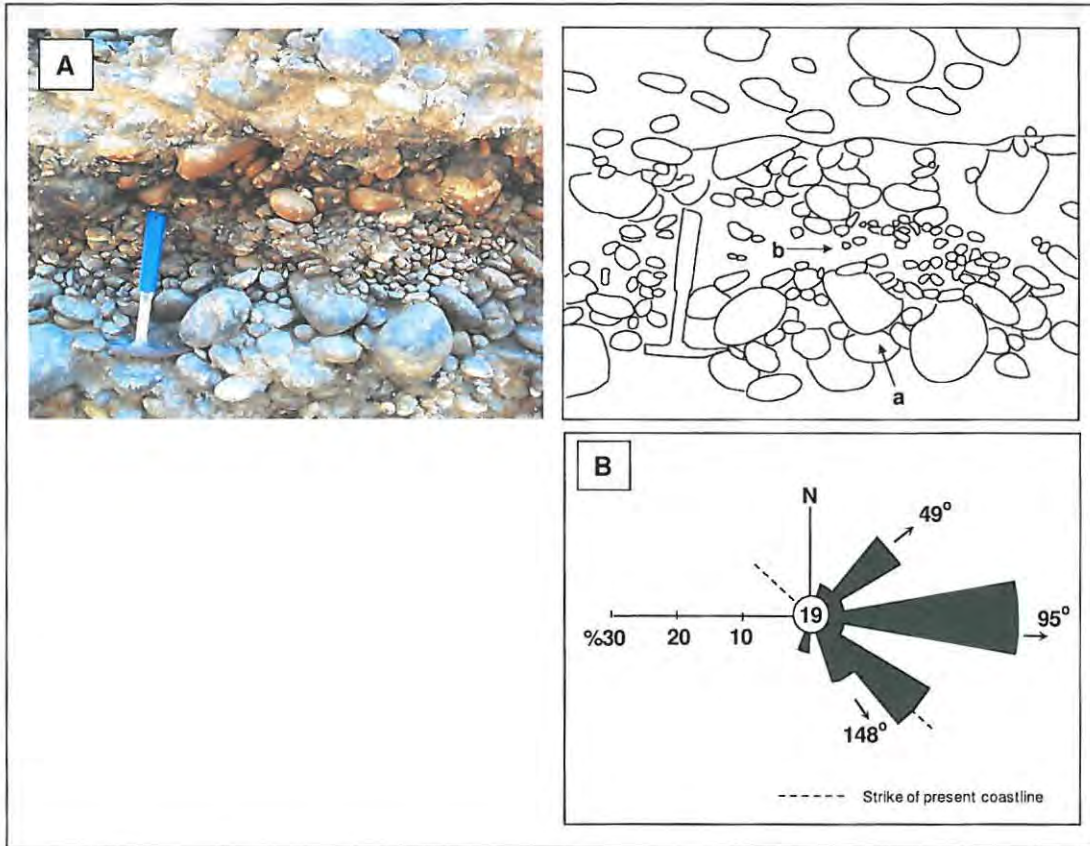


Figure 3.7: Gravel deposits of Sub-facies A3. Locality G25: (A) Normal grading from a large cobble base (a) through to small-pebble gravel (b). Note clast-supported openwork framework and high degree of sorting similar to Sub-facies A1. Hammer for scale = 29 cm in length. Section measured is perpendicular to present coastline. (B) Rose diagram illustrating palaeo-current directions of all gravel foresets shown in Table 3.4.

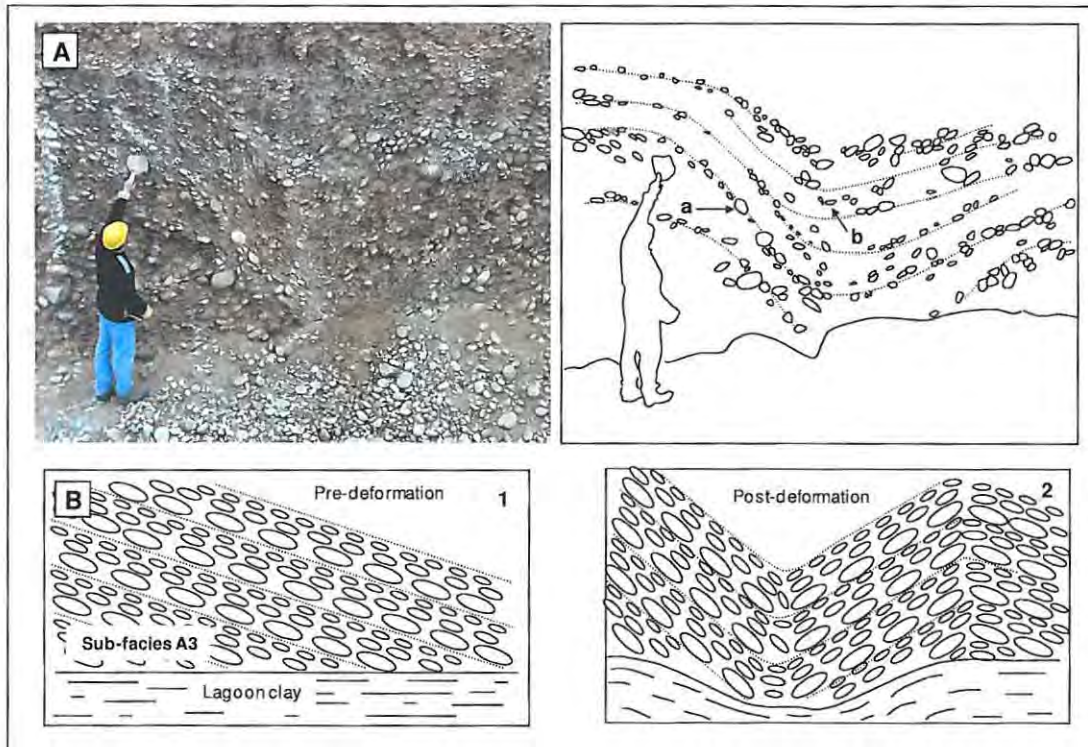


Figure 3.8: Soft sediment folding in Sub-facies A3 gravels due to slumping. Person for scale = 1.8 m. Section measured is perpendicular to present coastline. (A) Note the vertical position of clasts (a) and opposing imbricate dips (b). (B) Schematic cartoon illustrating mode of slumping. (1) Emplacement of gravel sequence onto clay. (2) Displacement of clay due to loading of overlying gravel followed by slumping into the accommodation space created by the displacement.

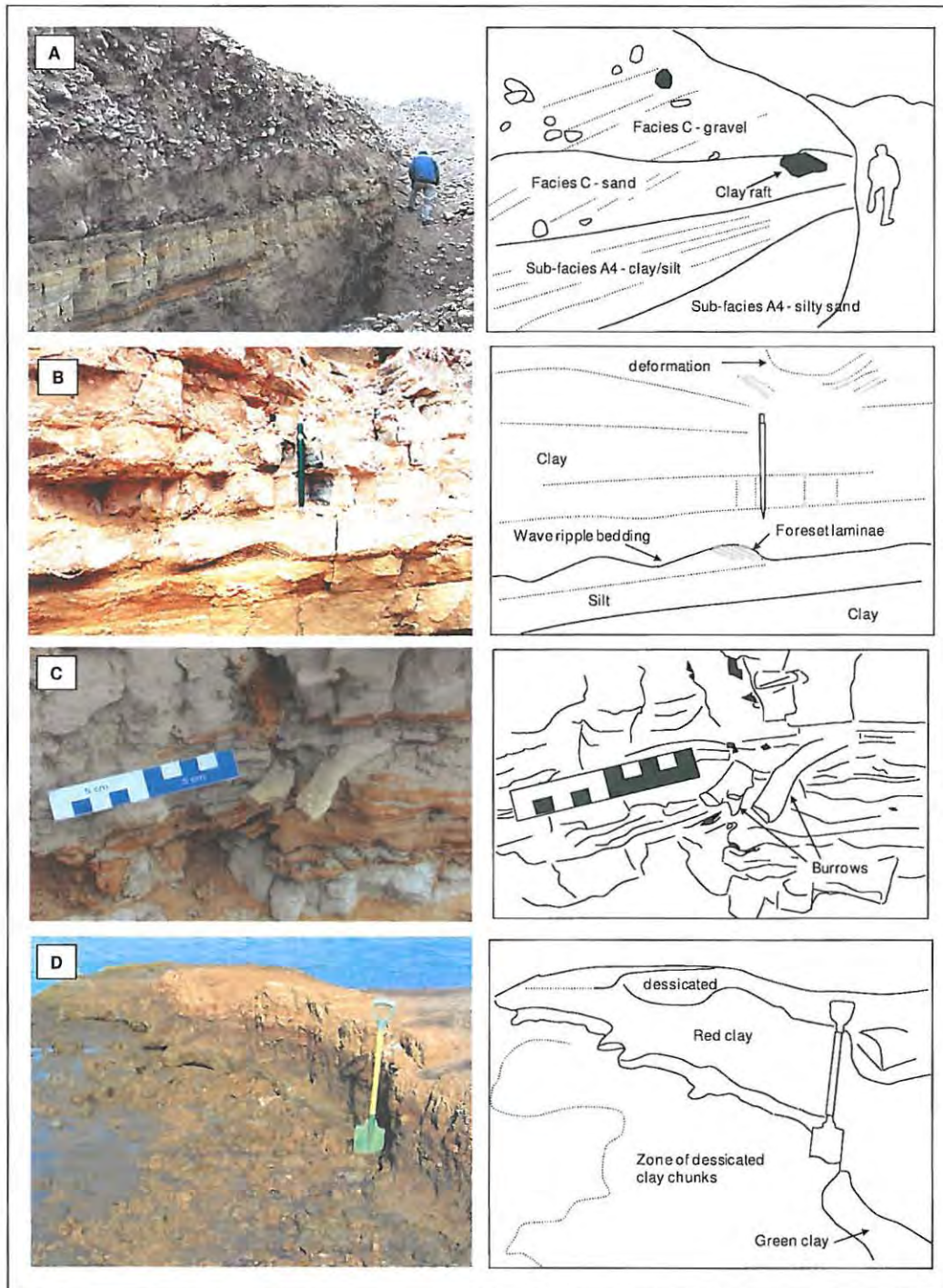


Figure 3.9: Deposits of Sub-facies A4. Locality G19: (A) Horizontal interbedded clay and silt. Section measured is perpendicular to present coastline. Person for scale = 1.7 m. (B) Locality G29: Close up of wave ripples illustrating seaward dipping foreset. Section measured is perpendicular to coastline. Pencil for scale = 15 cm. (C) Locality G19: Burrows in clayey silt. Scale = 10 cm. (D) Modern example of Sub-facies A4 along the banks of the Orange River immediately landward of a sand barrier beach. Spade for scale = 0.9 m.

Figure 3.10: Cross-section of G25 trench depicting main characteristics of the coarser-grained units of Facies A. Section is perpendicular to the present coastline, whilst T-sections are parallel.

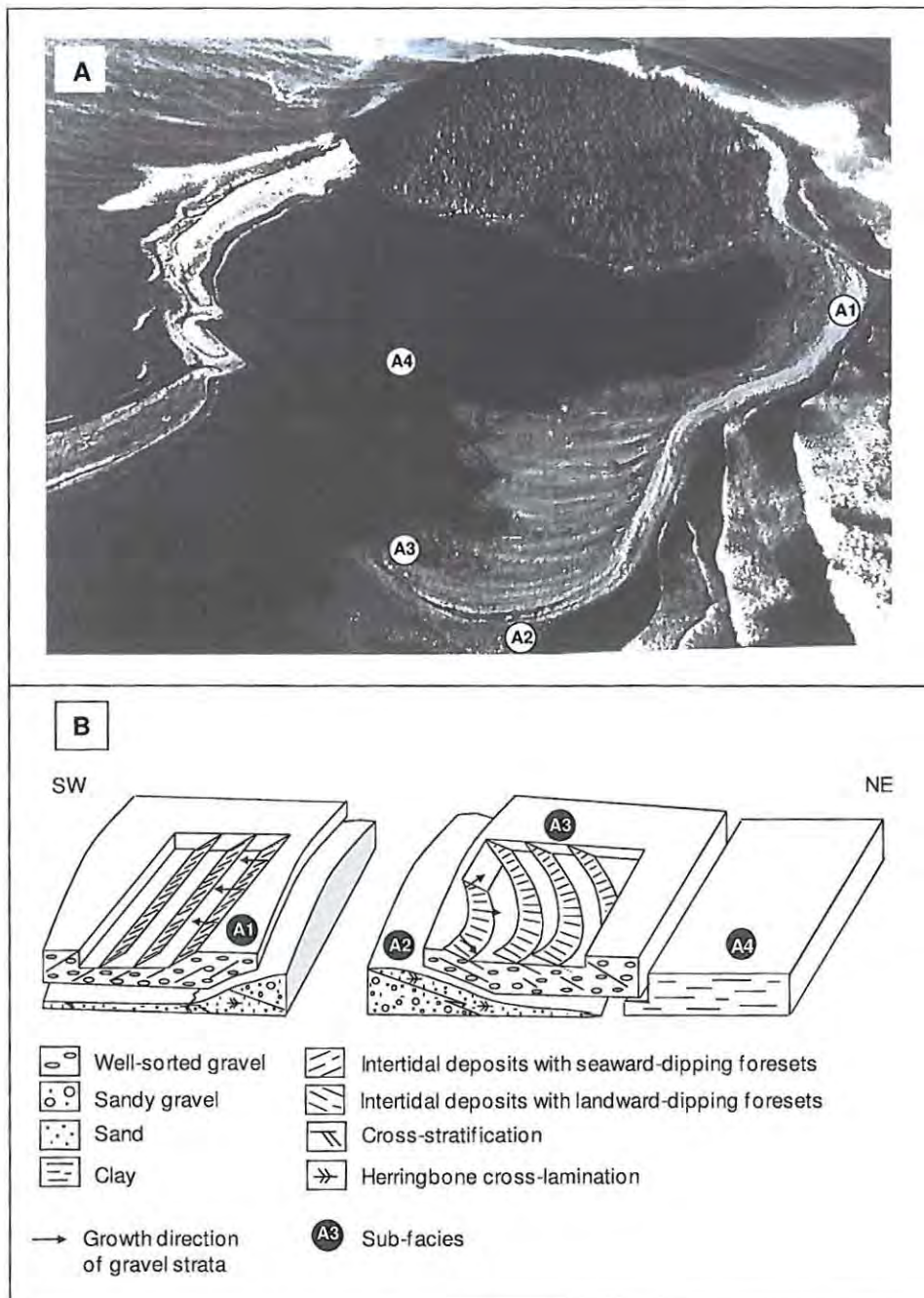


Figure 3.11: Modern analogue of Facies A setting. (A) Aerial photograph of modern gravel barrier spit at Fisherman's Beach, Nova Scotia, Canada (source Carter *et al.*, 1989). Note the wave refraction towards the spit head. Sub-facies A1 represents the seaward-facing intertidal zone; Sub-facies A2 represents the subtidal gravel armoured inlet platform as described by Carter *et al.* (1989); Sub-facies A3 is the intertidal gravels at the spit-recurve and Sub-facies A4 is the lagoonal environment. (B) Schematic block diagram illustrating geometry of the Facies A gravel barrier spit at G25. Note the radial growth of Sub-facies A3 in comparison to the more consistent linear growth of Sub-facies A1.

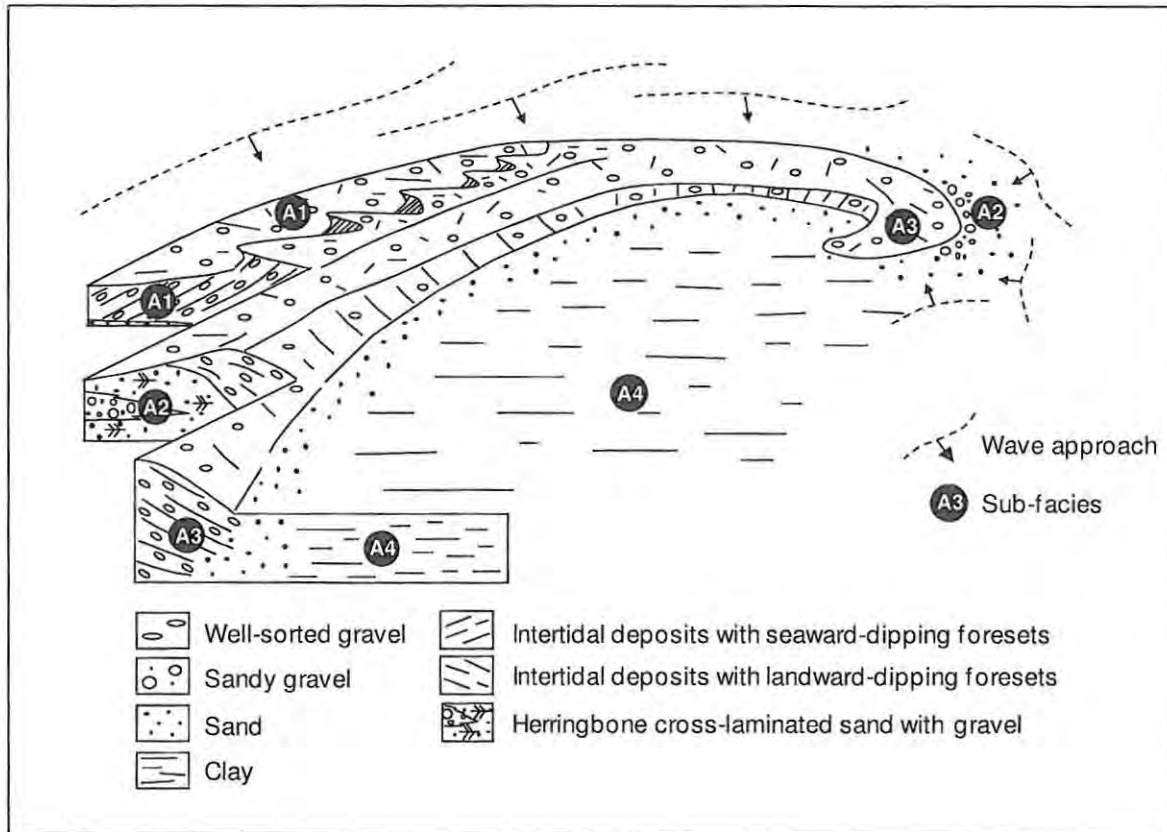


Figure 3.12: Schematic section looking down-drift through the gravel barrier spit at G25 illustrating depositional environments. Sub-facies A1 and A3 are intertidal deposits; A2 represents subtidal inlet deposits and A4 lagoon deposits (source Spaggiari *et al.*, 2006).

Figure 3.13: Hypothetical depositional model for Facies A. **(A)** Sand and gravel is moved alongshore by longshore drift. The sand fraction is entrained more easily and deposited at the spit head as a broad shallow subtidal platform where the sediment is moulded into 3-D megaripples. The trailing gravel fraction is transported in the form of swash bars (gravel nesses of Orford *et al.*, 1991) welding onto the beach face (1) and at the spit head (2) where wave refraction periodically occurs. During fair-weather the dominant south-westerly wave approach has a greater effect on the growth and modification of the inlet platform with minor reworking of the spit recurves. Storm periods would, in contrast, promote higher energy levels and increase spit head reworking, subjecting the recurve gravels to swash and backwash processes. **(B)** Storm-driven waves approaching from the north-west quadrant would induce greater reworking. Here the angle of wave entry into the inlet would allow refracted waves to maintain higher energy levels and wave heights than those from the south-west quadrant. This will, firstly, transport coarse sediment from the shoreface, as well as from the spit platform into the back-barrier and secondly, induce more aggressive reworking of the recurve sediments. Sub-facies A1 and A3 are intertidal gravel beaches; A2 represents shallow subtidal sediments and A4 represents estuarine-lagoon sediments. **(C)** Modern example of complete wave refraction around a northerly orientated headland at Hottentots Bay along the Namibian coast, located approximately 320 km north of the study area. Google Earth satellite image, May 2009 – Data SIO, NOAA, U.S.A Navy, NGA GEBCO.

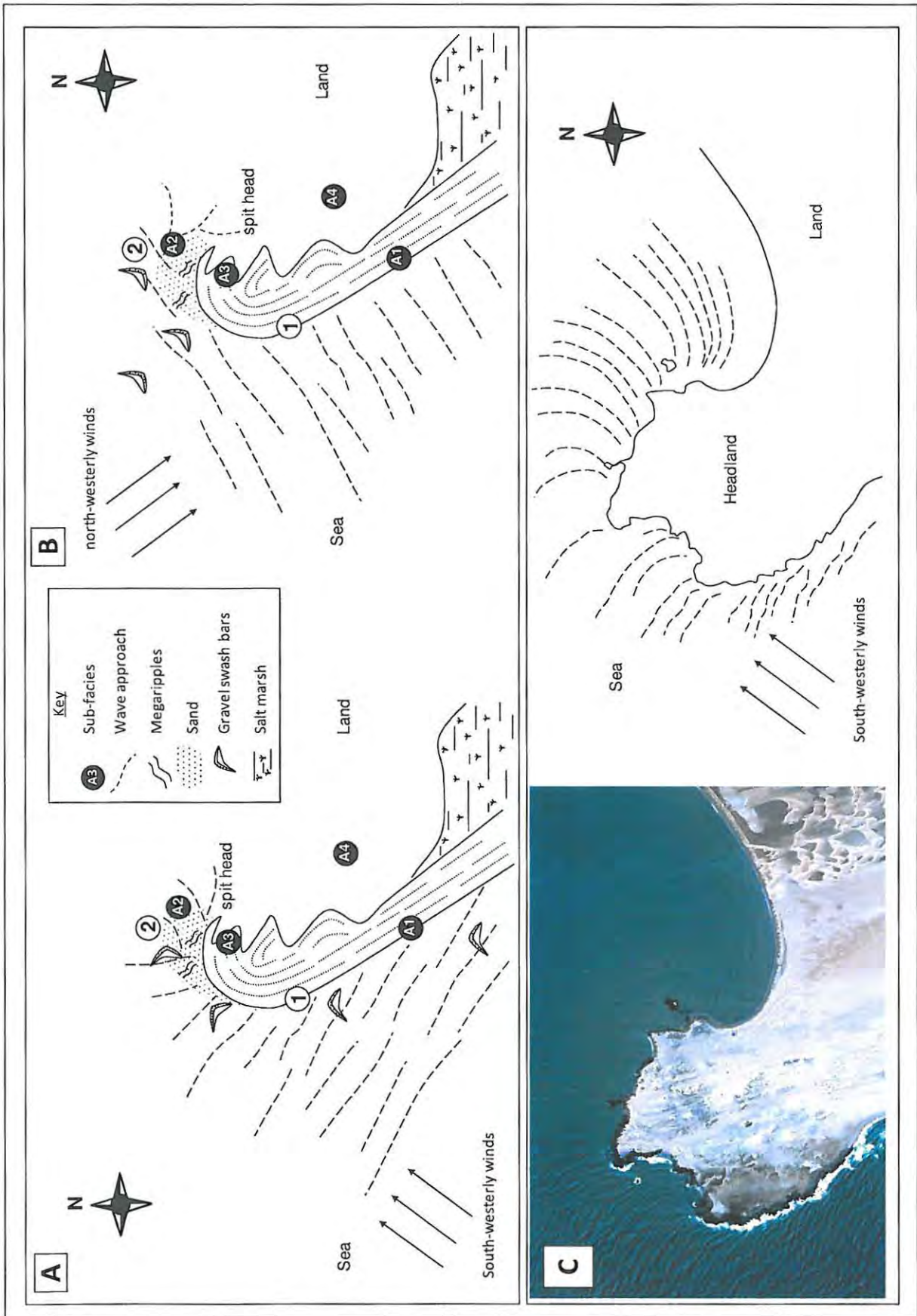


Figure 3.14: Summary of Facies A stratigraphic and palaeo-environmental framework based on lateral relationship.


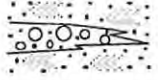

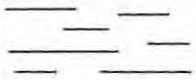
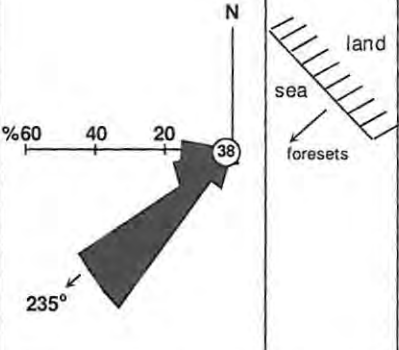
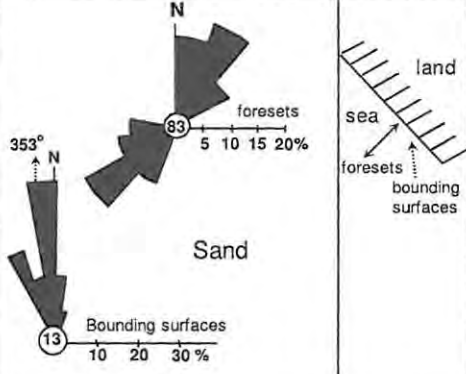
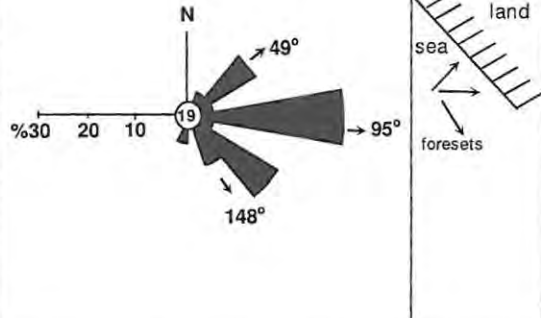
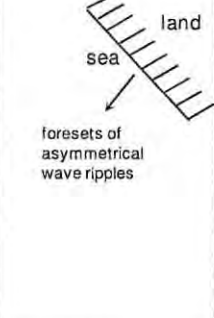
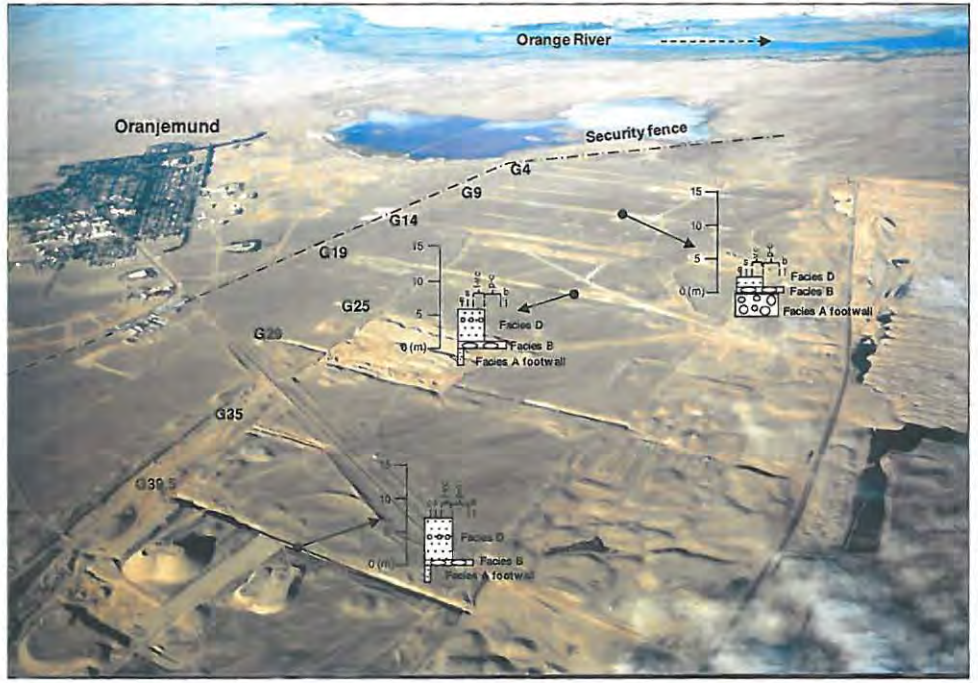
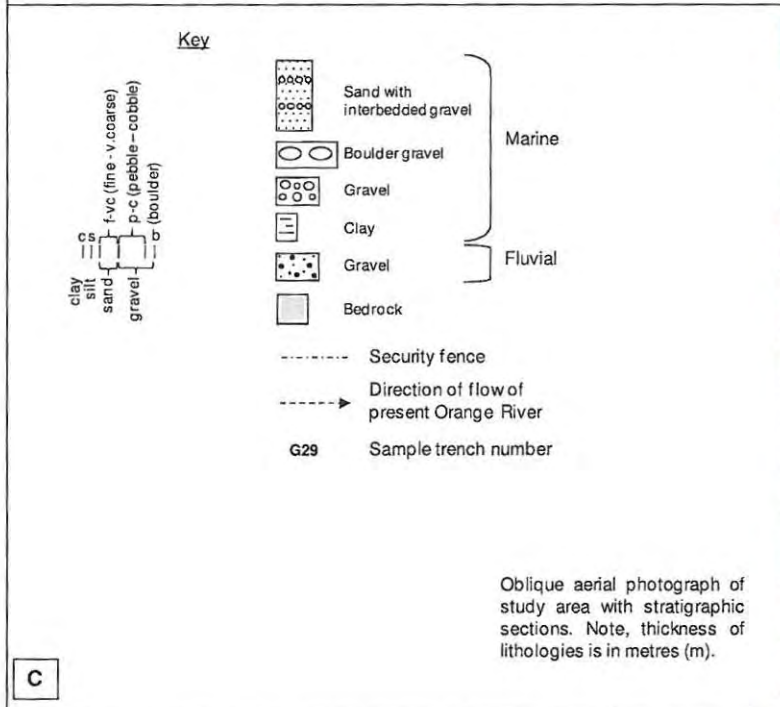
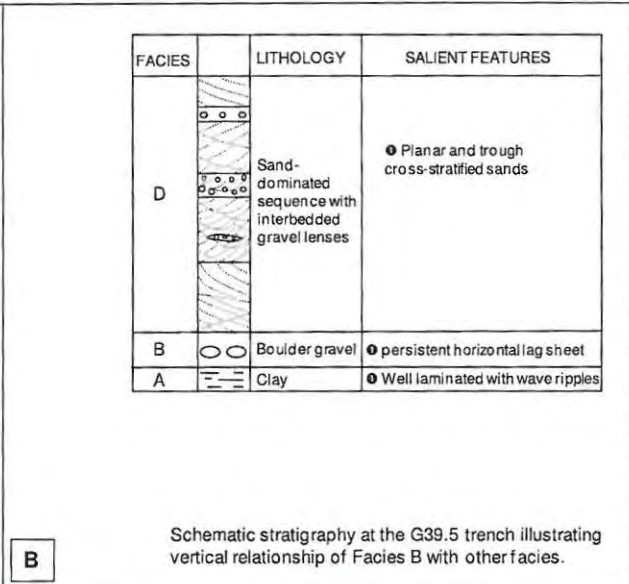
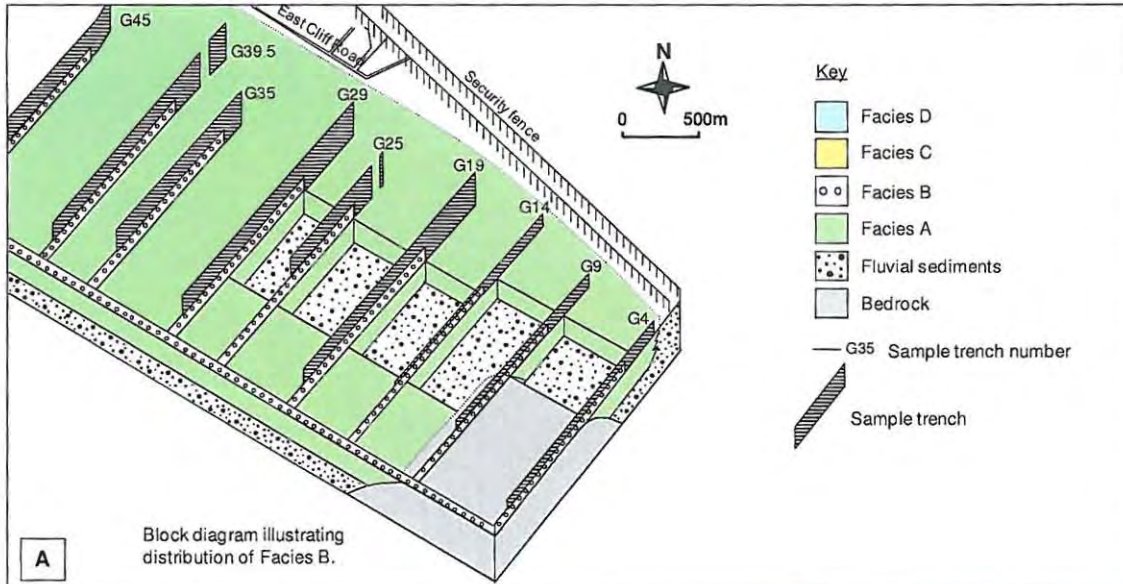
SUB-FACIES	A1	A2	A3	A4
				
SEDIMENTARY FEATURES	Cross-stratified gravel with steep Seaward-dipping foreset strata display normal grading. Texturally mature with high degree of clast size sorting and moderate shape sorting.	Medium to coarse sand and granule with bipolar cross-stratification. Interbedded gravel stringers and sheets with poorly sorted fabric. No clast shape and size sorting.	Cross-stratified gravel with normal graded foreset strata that dip landward and exhibit radial growth. Texturally mature with moderate degree of clast size and shape sorting.	Horizontal laminated clay and silty-clay. In places, wave ripples, desiccation cracks and root casts.
PALAEO - CURRENT DIRECTION				
INTERPRETATION	Upper beach face with swash berm and cusp bedforms. Seaward progradation of gravel beaches maintained by high sediment supply.	Tidal inlet sediments. Bipolar cross-stratification formed by 3-D megaripples. Gravel clasts derived from collapse of beach face at spit head.	Beach face at spit head where it curves away from open ocean into lagoon. Landward progradation of these gravel beaches occur during growth of spit recurve under considerable wave refraction.	Back barrier sediments cut off from sea by growth of spit.
	Open coast Intertidal setting	Subtidal setting	Subdued/protected Intertidal setting	Lagoon

Figure 3.15: General distribution of Facies B. Block diagram (A) illustrating distribution with localities of cross-sections mapped. Stratigraphy of Facies B in relation to other facies at G39.5 trench is shown in (B). Oblique aerial photograph (C) illustrating distribution in the field and stratigraphic relationships superimposed (photograph by courtesy of J. Ward).



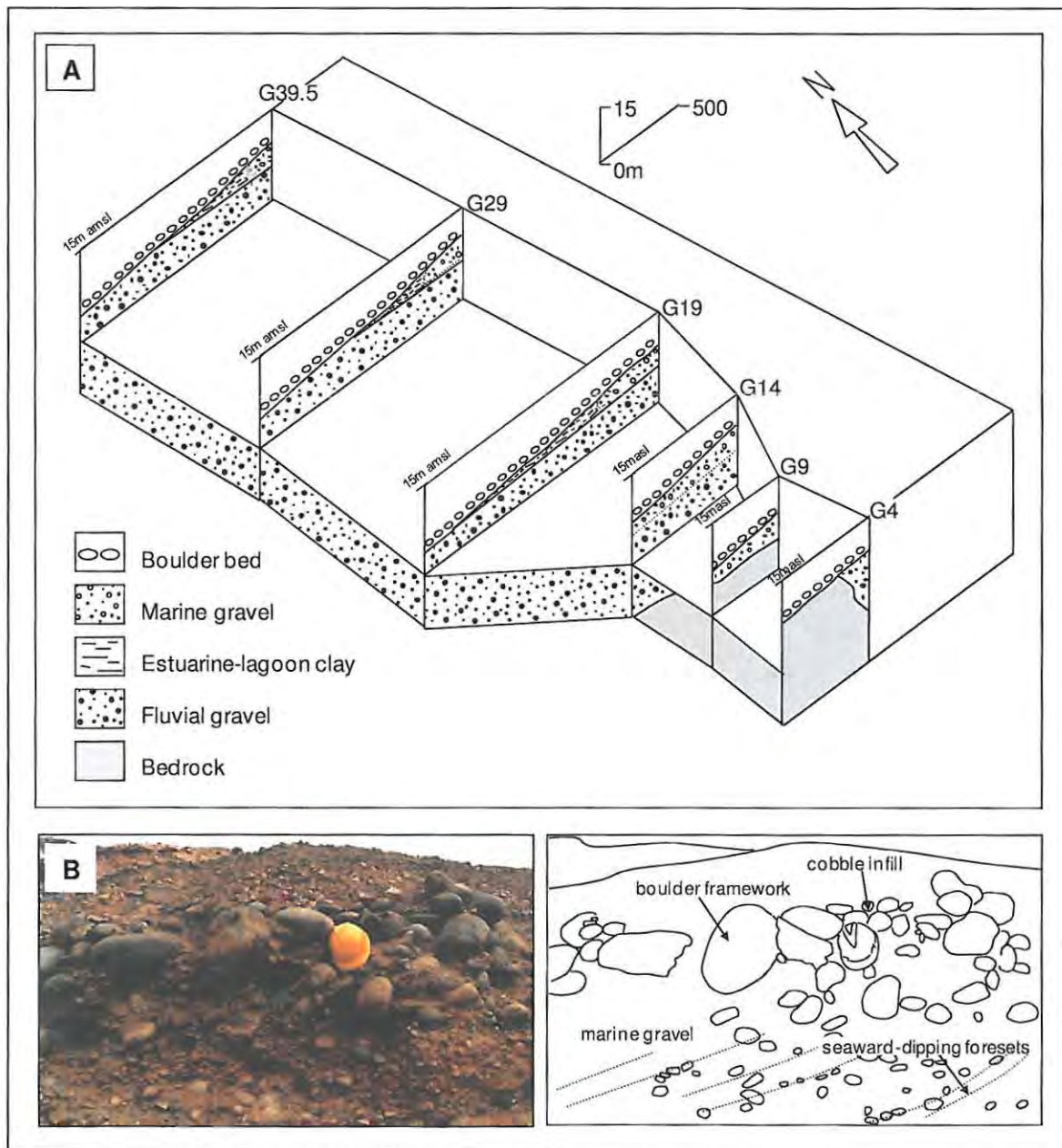


Figure 3.16: Boulder bed of Facies B. **(A)** Schematic block diagram illustrating distribution of boulder bed. Note the truncation of variable footwall types. **(B)** Localities G19: Close-up of Facies B showing boulder framework with infilling cobble to pebble gravel. Yellow safety hat for scale = 28 cm in length. Section measured is perpendicular to present coastline.

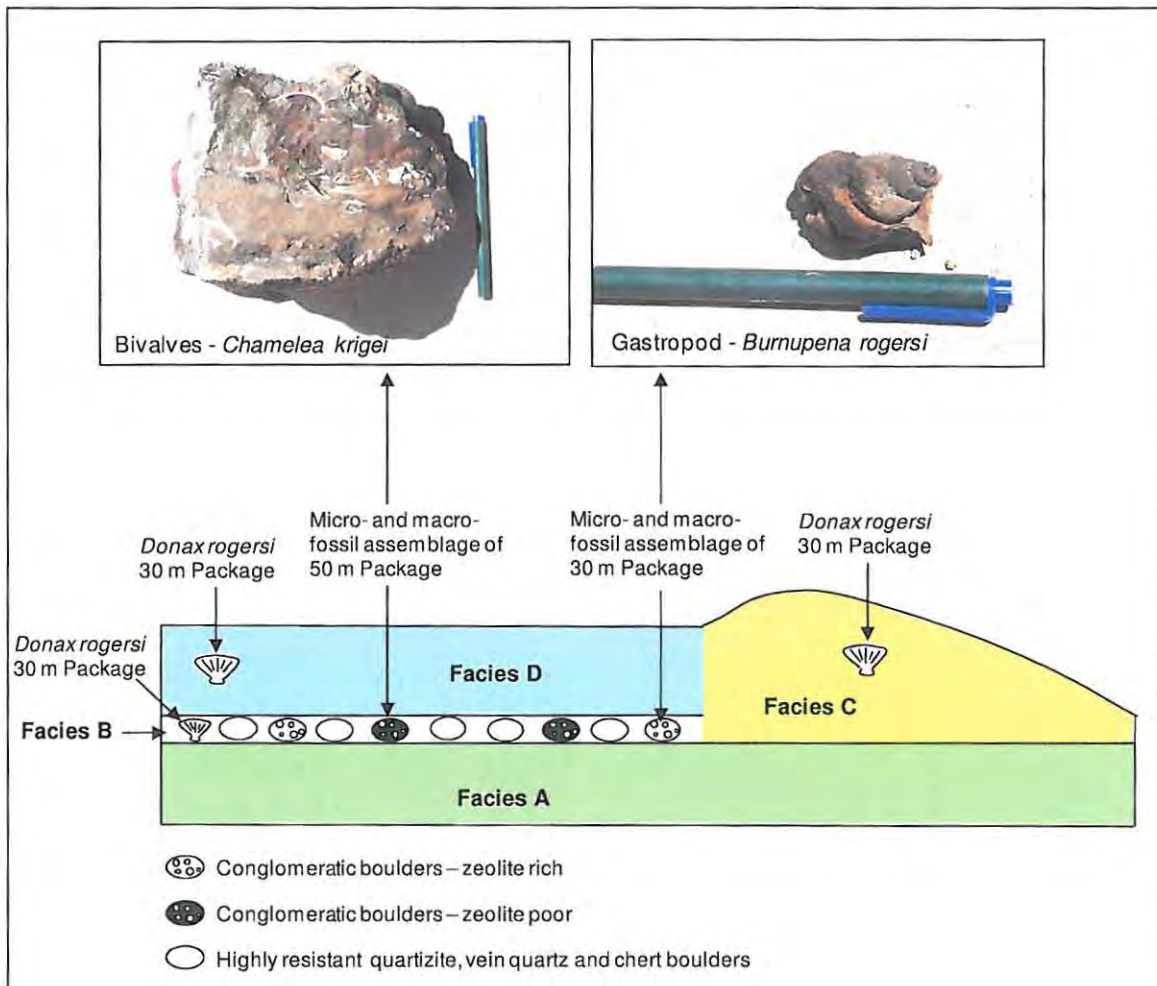


Figure 3.17: General stratigraphic correlation of Facies B with other facies based on fossil assemblages. Marker pen for scale = 14 cm.

Figure 3.18: Hypothetical emplacement model of Facies B. **(A)** Schematic diagrams illustrating deposition of the transgressive lag. (a) Boulder component added to a shoreline where it forms the most seaward margin of a gravel foreshore setting (Bluck's, 1967 outer frame). Increased longshore drift energy levels due to storms would promote size sorting. (b) Trail of boulders left behind in shoreface setting as shoreline migrates landward under a rising sea-level. Clast lithologies reflect different sediment types over which the shoreline migrated. T1 to T3 represent different depositional time frames. **(B)** Modern example of outer frame boulders (a) emergent during low tide along the Uniab coastline, Skeleton Coast, Namibia. Person for scale = 1.6 m. **(C)** Alongshore boulder sorting with large to medium boulders in foreground grading to small boulder to cobble-size gravel in background. Modern gravel beach along coastal road between Gordons Bay and Rooiels Bay, Western Cape, South Africa. Person for scale = 1.8 m.

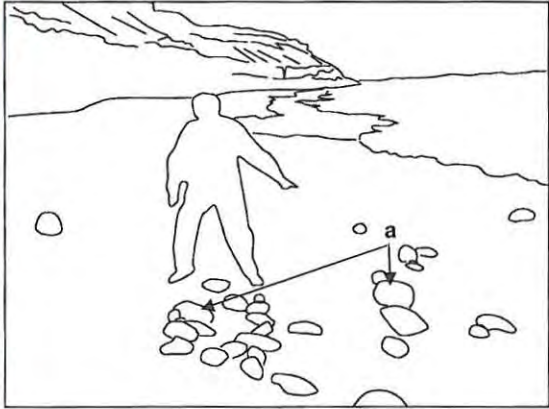
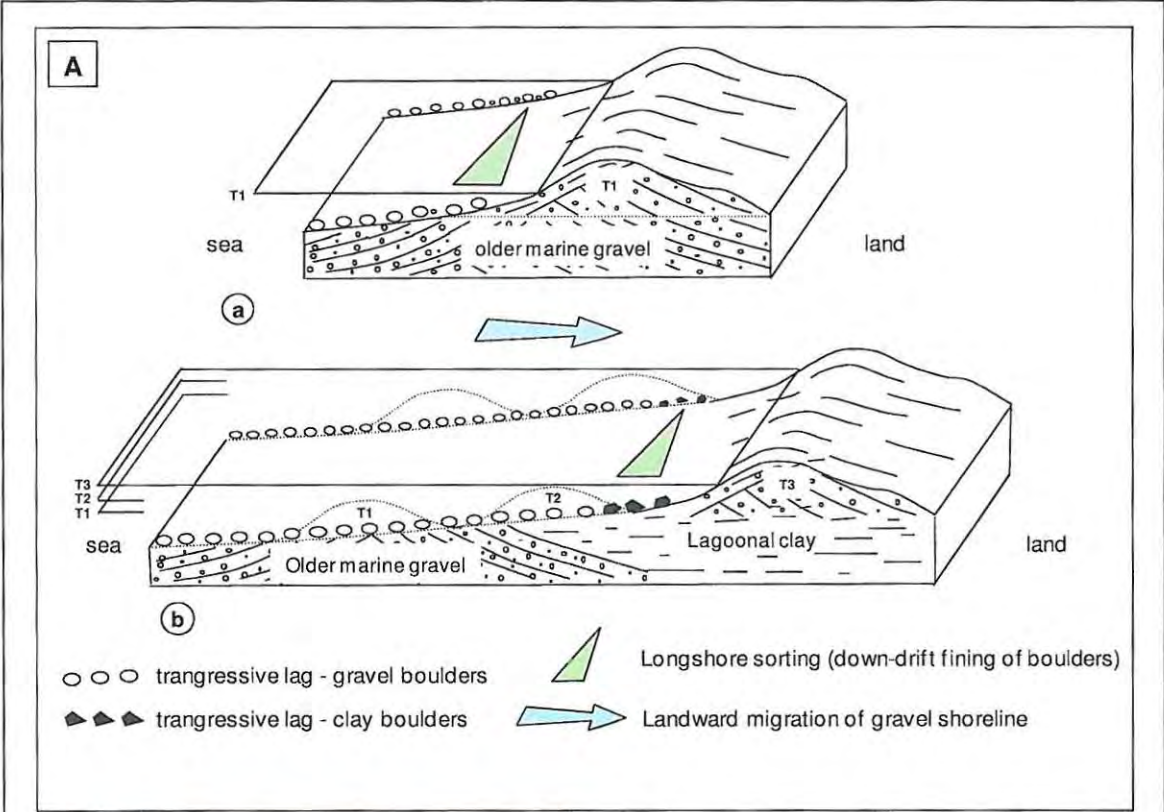


Figure 3.19: Palaeo-environmental summary of Facies B. Note the absence of palaeo-current data due to the lack of sedimentary structures.

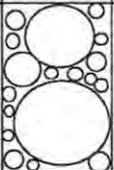
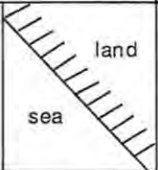
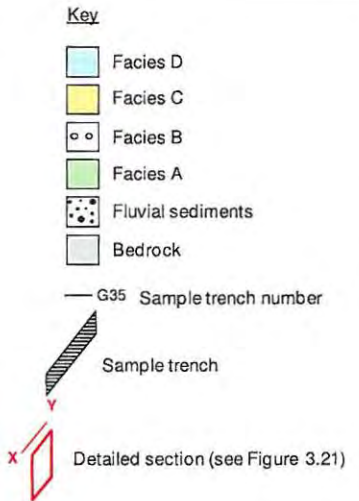
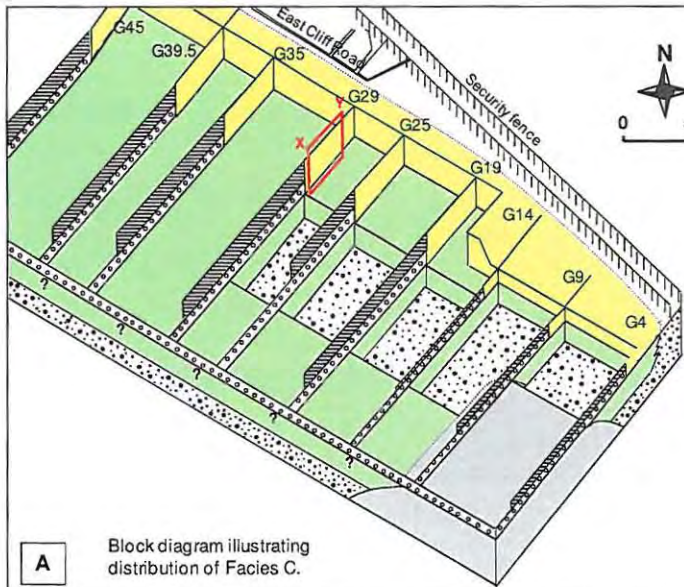
FACIES		SEDIMENTARY FEATURES	PALAEO-CURRENT DIRECTION	INTERPRETATION	
B		Thin gravel sheet dominated by spherical, well-rounded boulders. Gravel sheet armours erosive surface that separates underlying lagoon and foreshore deposits, as well as bedrock from overlying shoreface deposits	Structureless, lacking clast orientation. Gravel sheet laterally persistent, dipping slightly seaward.		Transgressive lag deposited in highly energetic wave-dominated setting.

Figure 3.20: General distribution of Facies C. Block diagram (A) illustrating distribution with localities of cross-sections mapped. Stratigraphy of the sub-facies based on vertical relationship is depicted in (B). Oblique aerial photograph (C) illustrating distribution in the field and stratigraphic relationships superimposed (photograph by courtesy of J. Ward).



A Block diagram illustrating distribution of Facies C.

SUB-FACIES	LITHOLOGY	SALIENT FEATURES
C2	Sandy gravel	<ul style="list-style-type: none"> ● Land ward-dipping foresets ● Rip-up clayrafts
	Clay and silt	<ul style="list-style-type: none"> ● Well-laminated ● Red, green or brown in colour ● Wave ripple bedding
C1	Cobble to pebble gravel	<ul style="list-style-type: none"> ● Predominantly discs and blades ● Rarely preserved
	Cobble to pebble gravel	<ul style="list-style-type: none"> ● Steep seaward-dipping foresets ● Mixture of clast shapes ● Seaward-imbriate discs
	Cobble to pebble gravel	<ul style="list-style-type: none"> ● Predominantly spheres ● Structureless

B Schematic stratigraphy illustrating sequence of Facies C based on vertical relationship of sub-facies.

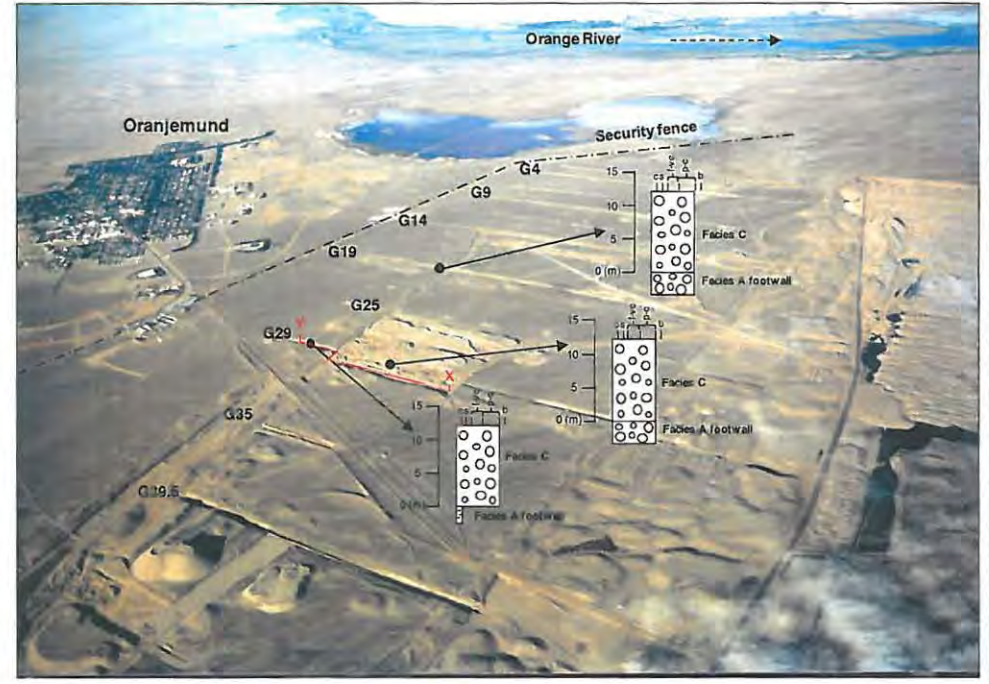
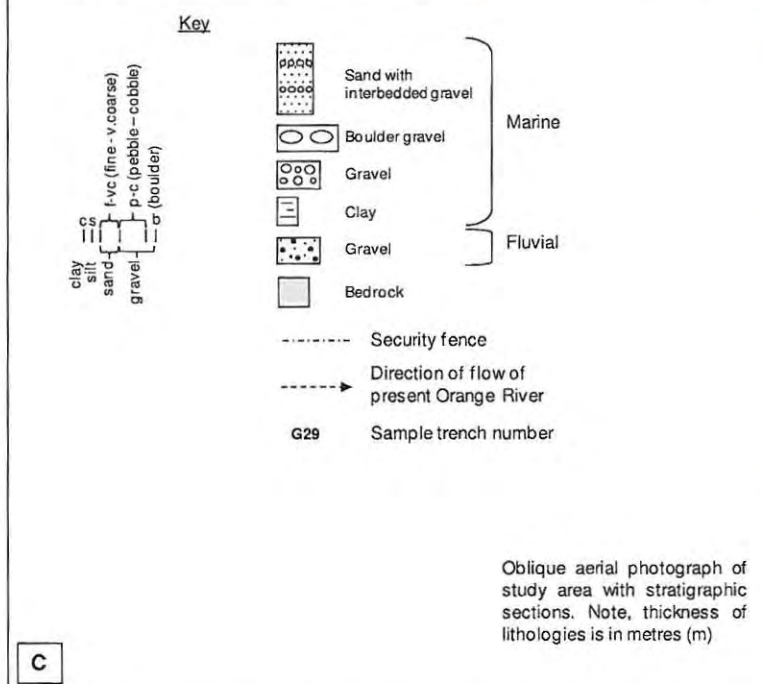
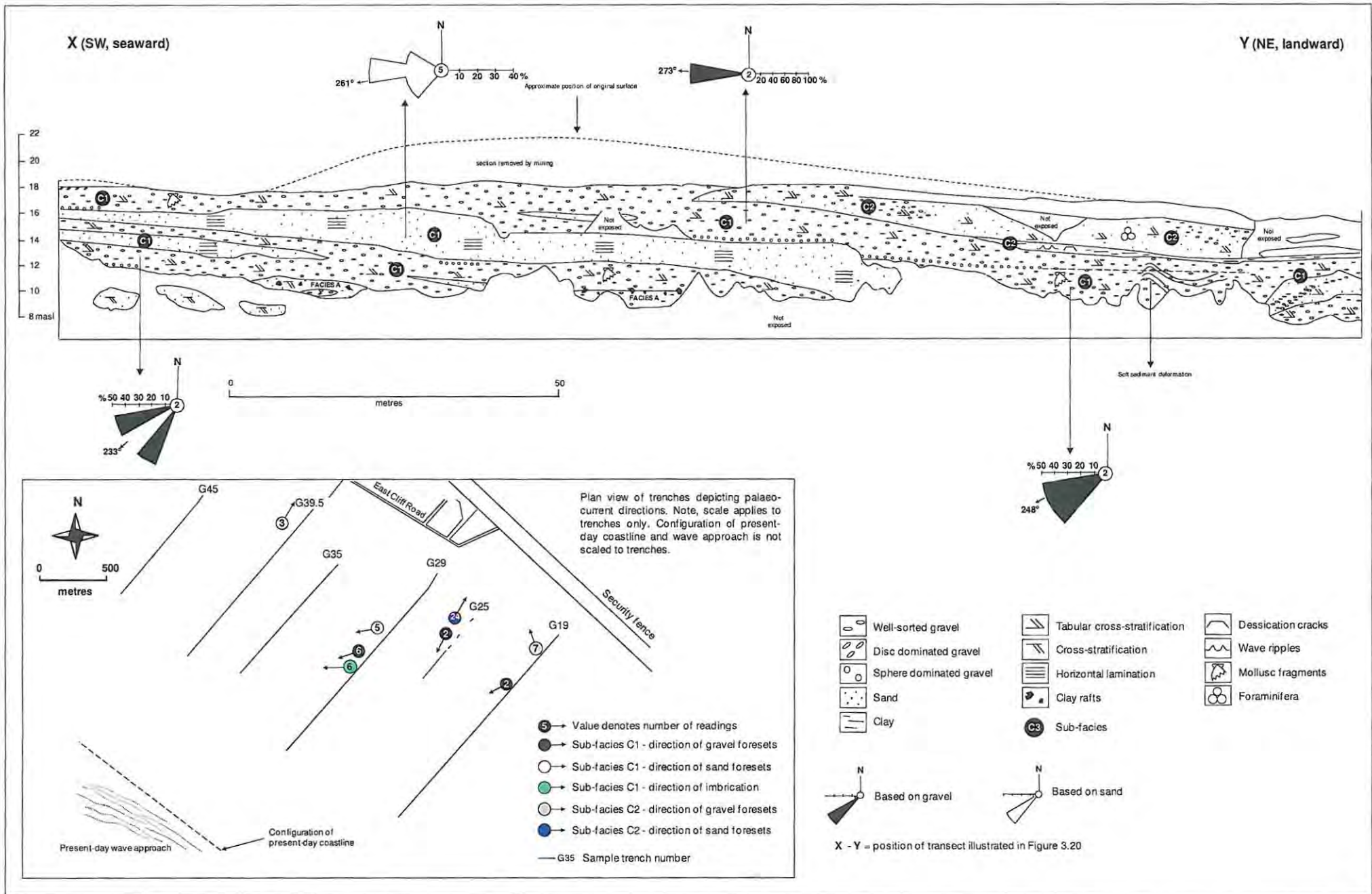
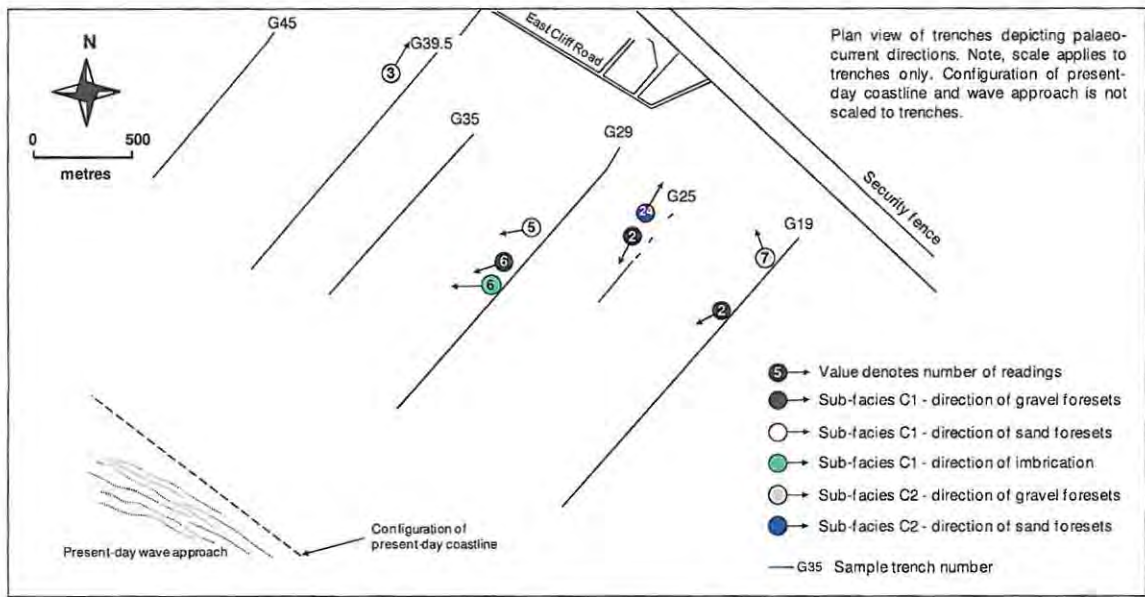
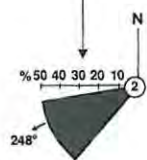
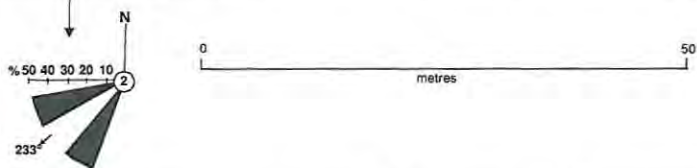
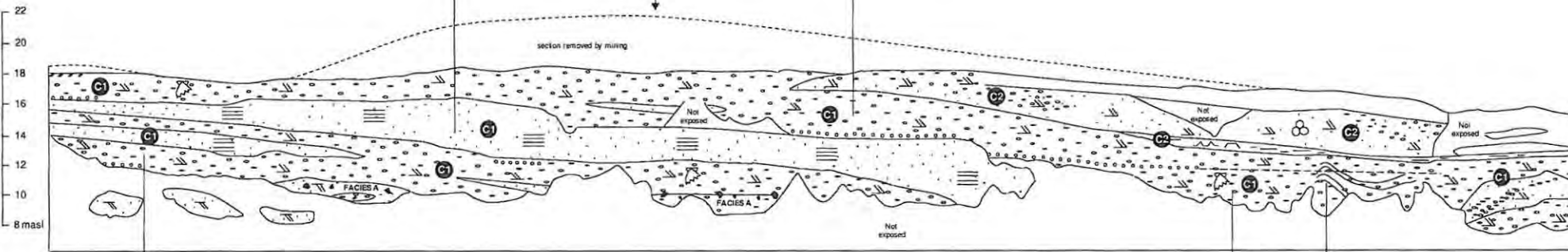


Figure 3.21: Cross-section of G29 trench illustrating vertical and lateral arrangement of sub-facies with palaeo-current directions. Section is perpendicular to present coastline.



X (SW, seaward)

Y (NE, landward)



- | | | | | | |
|--|-------------------------|--|------------------------------|--|--------------------|
| | Well-sorted gravel | | Tabular cross-stratification | | Desiccation cracks |
| | Disc dominated gravel | | Cross-stratification | | Wave ripples |
| | Sphere dominated gravel | | Horizontal lamination | | Mollusc fragments |
| | Sand | | Clay rafts | | Foraminifera |
| | Clay | | Sub-facies | | |
-
- | | | | |
|--|-----------------|--|---------------|
| | Based on gravel | | Based on sand |
|--|-----------------|--|---------------|

X - Y = position of transect illustrated in Figure 3.20

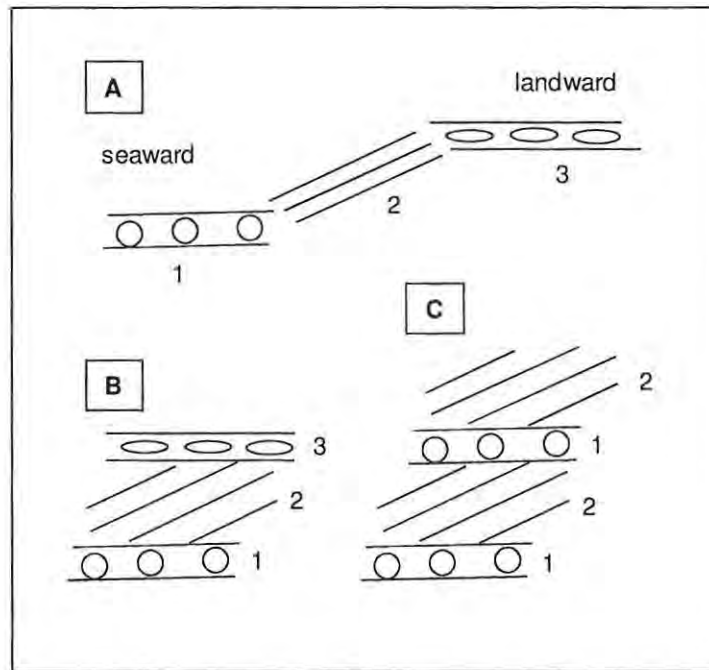


Figure 3.22: Geometry of Sub-facies C1 sedimentary units. Laterally arranged (A) and vertically stacked (B) units where the coarse disc- and blade-rich gravel sheet has been preserved. (C) Vertically stacked units where the coarse disc- and blade-rich gravel sheet is absent. Note the repetitive arrangement, which is the more common geometry seen in section. 1 = coarse gravel sheet dominated by spheres, 2 = cross-stratified gravel, 3 = coarse gravel sheet dominated by discs and blades.

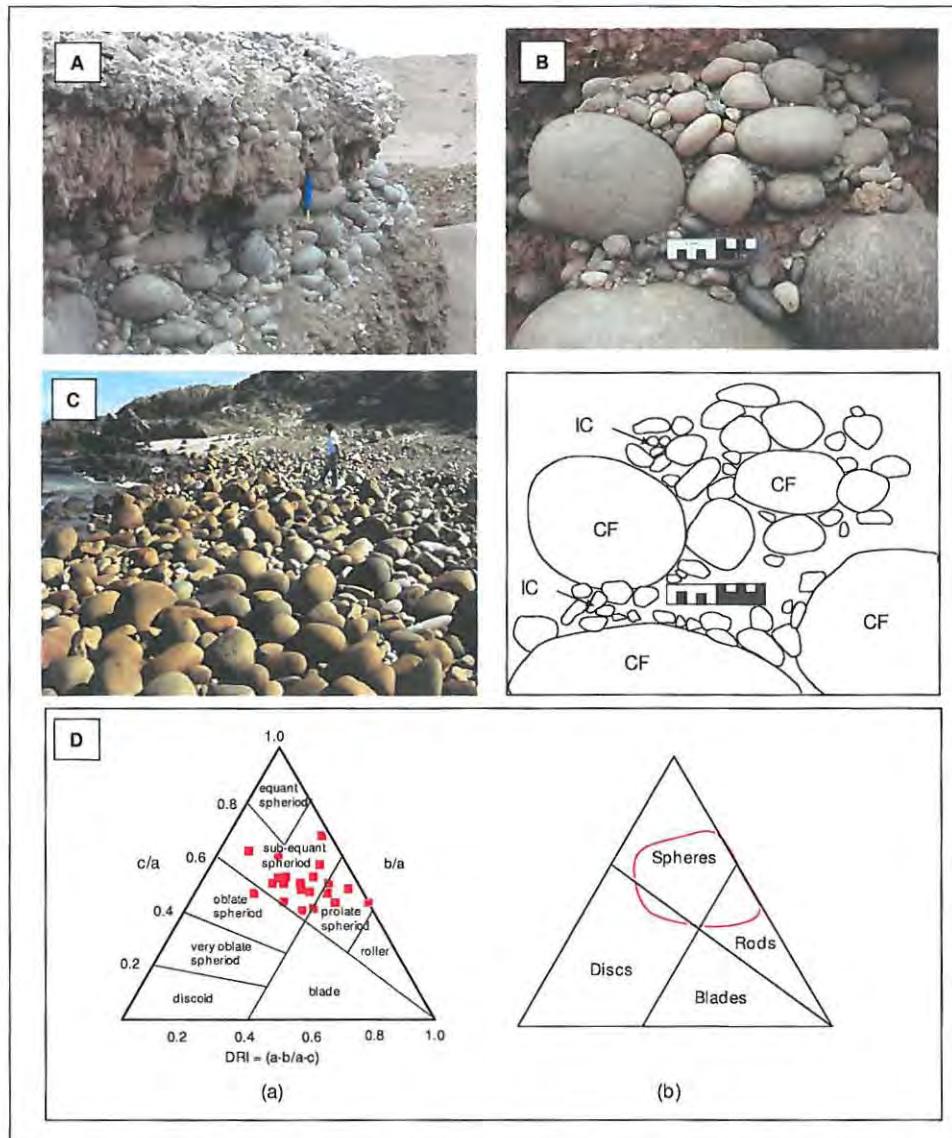


Figure 3.23: Sphere-rich gravel sheet of Sub-facies C1. Locality G29: (A) Sub-horizontal stratum comprising coarse gravel up to boulder size. Note predominance of spherical clasts. Hammer for scale = 29 cm. Section measured is parallel to present coastline. (B) Closer view of the gravel texture illustrating the infill (IC = infill clasts) of a cobble to boulder framework (CF = coarse framework). Scale = 10 cm. (C) Modern example along the coastal stretch between Gordons Bay and Rooiels Bay in the Western Cape, South Africa. Note the boulder-sized spheres and infilling fabric. Person for scale = 1.8 m. (D) Distribution of gravel shapes at G29 using a Folk form diagram (a) (Sneed & Folk, 1958; modified after Blott & Pye, 2008). Red squares represent individual clast measurements ($n = 22$). Simplified version of Blott & Pye's (2008) ternary diagram (b) illustrating position of grouping against basic clast shapes using Zingg's (1935) terminology. See Appendix B, Section 1.2.5 for explanation of ternary diagrams.

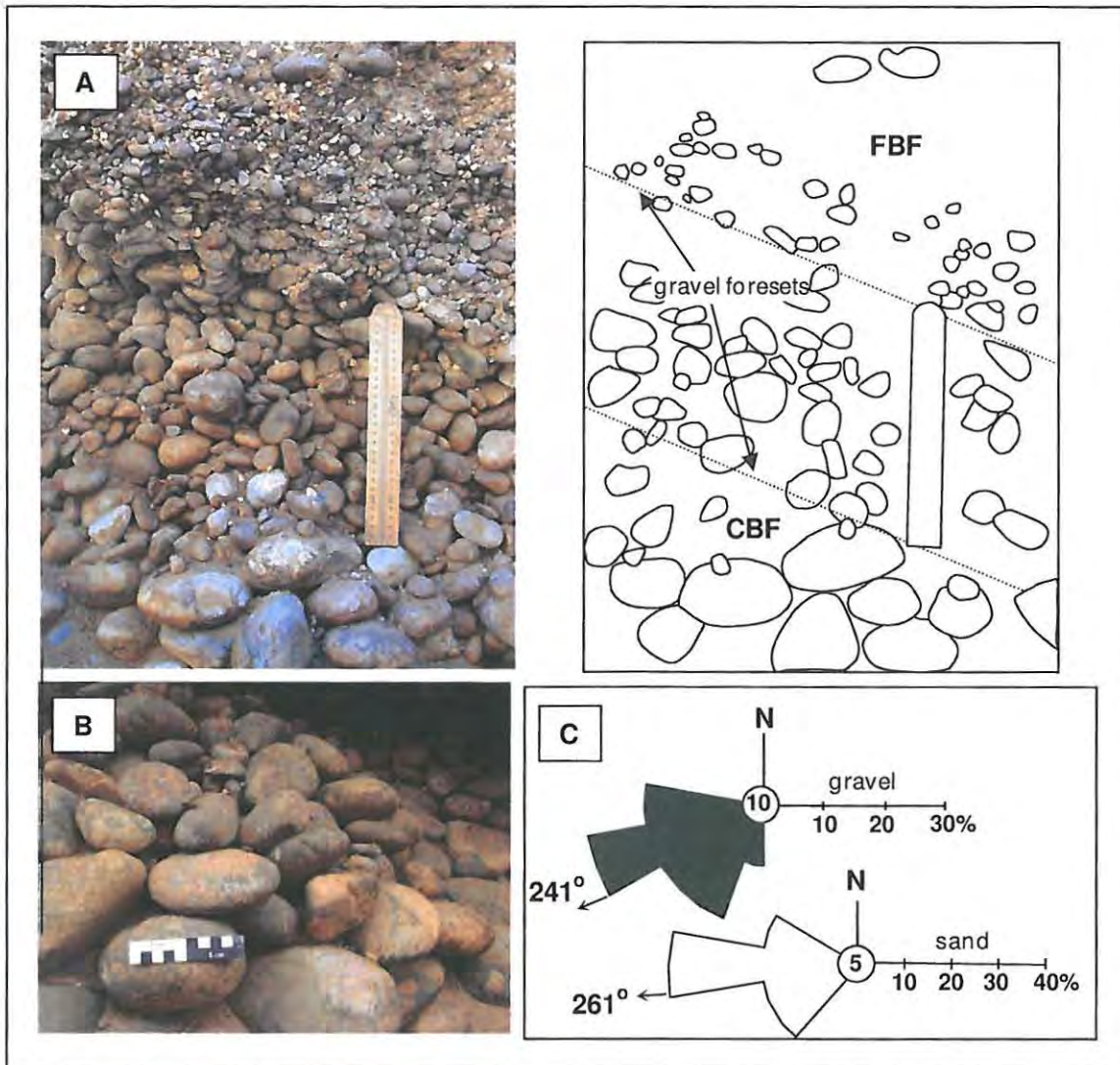


Figure 3.24: Cross-stratified gravel of Sub-facies C1. Locality G29: (A) Normal grading culminating in a blinding fabric. CBF = coarse basal fabric, FBF = fine blinding fabric. Section measured is perpendicular to present coast line. Ruler for scale = 25 cm. (B) Close-up of CBF illustrating open framework and lack of matrix. Scale = 10 cm. (C) Rose diagram for palaeo-current direction of all Sub-facies C1 cross-stratified gravel and laminated sand at trench G29 as recorded in Table 3.5.

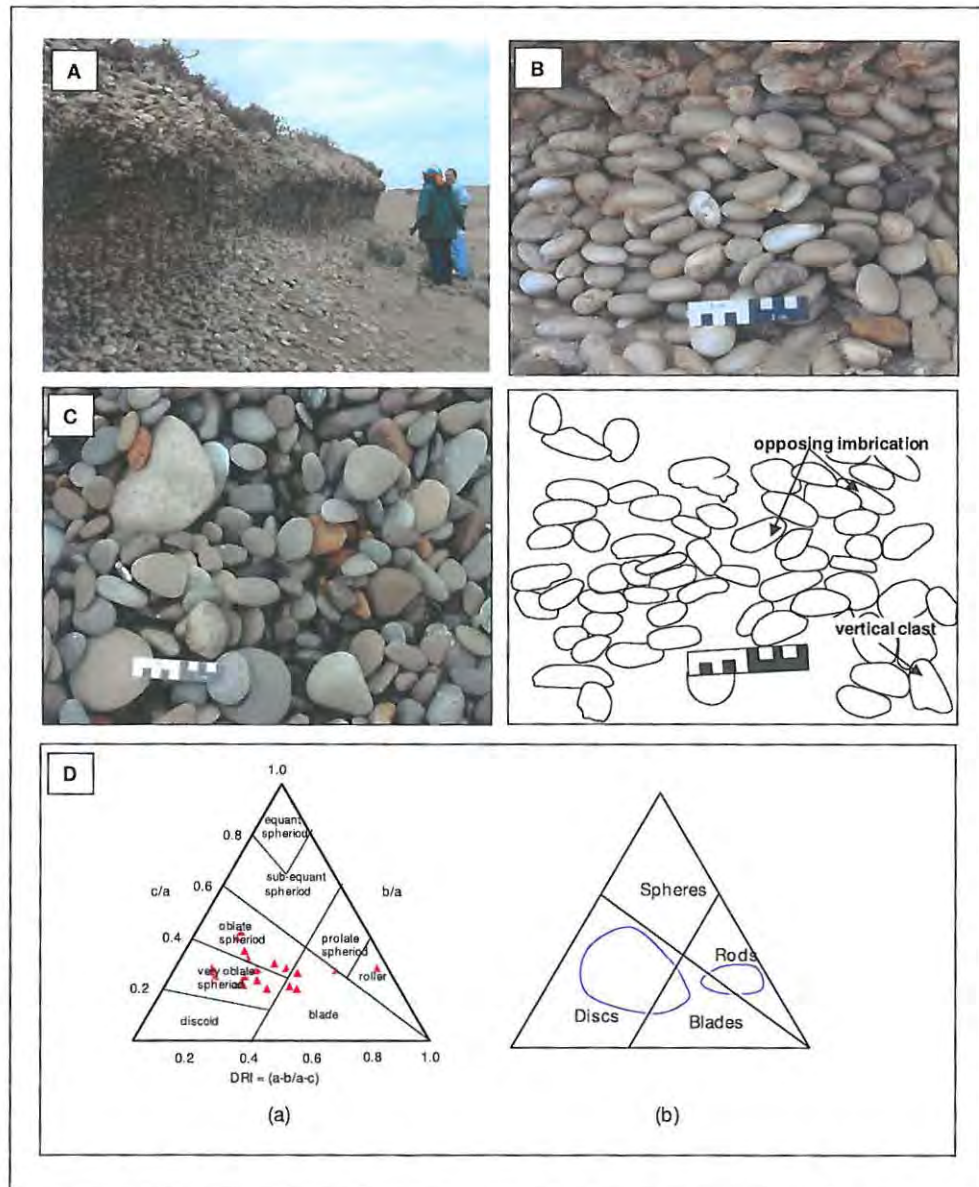


Figure 3.25: Disc-rich gravel sheet deposits of Sub-facies C1. Locality G39.5: (A) Horizontal stratum comprising disc- and blade-shaped clasts. Section measured is perpendicular to present coastline. People for Scale = 1.7 m. (B) Closer view of gravel fabric in section. Scale = 10 cm. (C) Modern example on surface at Terrace Bay along the Skeleton Coast, Namibia. Note similar fabric to that observed in study area. Scale = 10 cm. (D) Distribution of gravel shapes at G29 using a Folk form diagram (a) (Sneed & Folk, 1958; modified after Blott & Pye, 2008). Red triangles represent individual clast measurements ($n = 22$). Simplified version of Blott & Pye's (2008) ternary diagram (b) illustrating position of grouping against basic clast shapes using Zingg's (1935) terminology. See Appendix B, Section 1.2.5 for explanation of ternary diagrams.

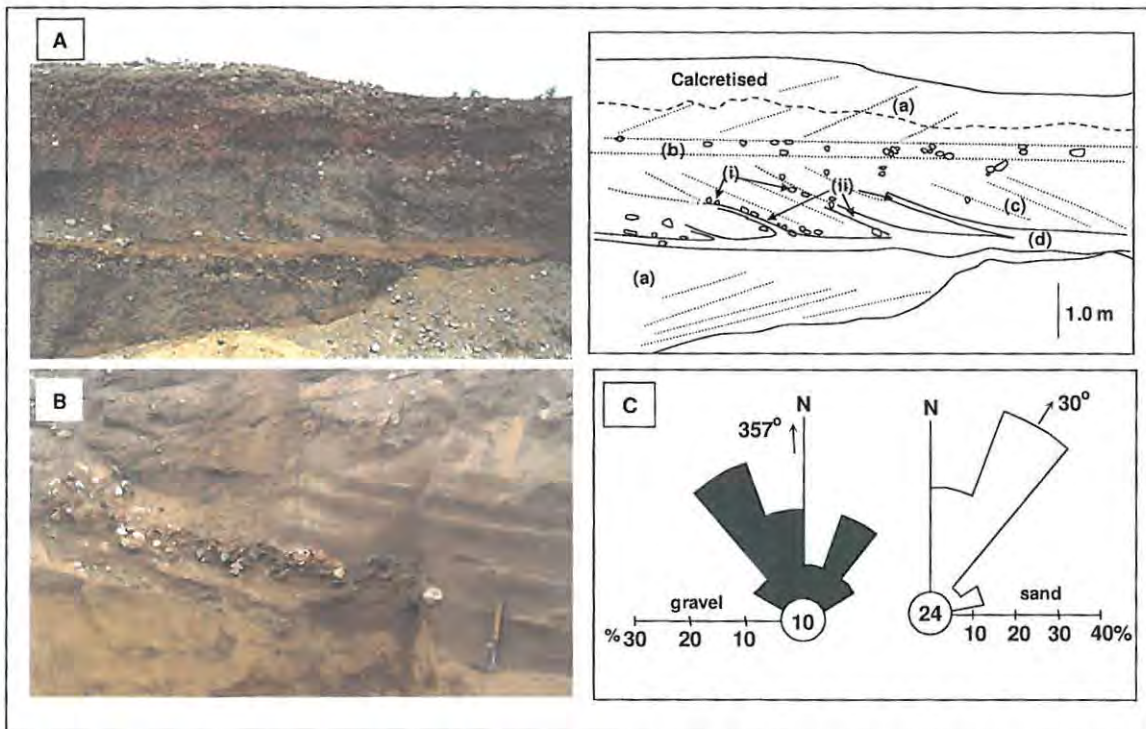


Figure 3.26: Cross-stratified gravel of Sub-facies C2 with foresets dipping landward. (A) Locality G29: Note the normal grading where coarser gravel forms the base of foreset strata (i) and distal interfingering with clay and silt (ii). Section measured is perpendicular to coastline. (a) = cross-stratified gravel of Sub-facies C1, (b) = coarse sphere-rich gravel of Sub-facies C1, (c) = cross-stratified gravel of Sub-facies C2, (d) = clay and silt deposits of Sub-facies C2. (B) Locality Chameis: Younger gravel sequence of Eemain age displaying similar landward dipping sediments (see also Millad, 2004). Hammer for scale = 29 cm. Section measured is perpendicular to present coastline. (C) Rose diagram for palaeo-current direction of all gravel foresets of Sub-facies C4 shown in Table 3.6 and of sand at trench G25.

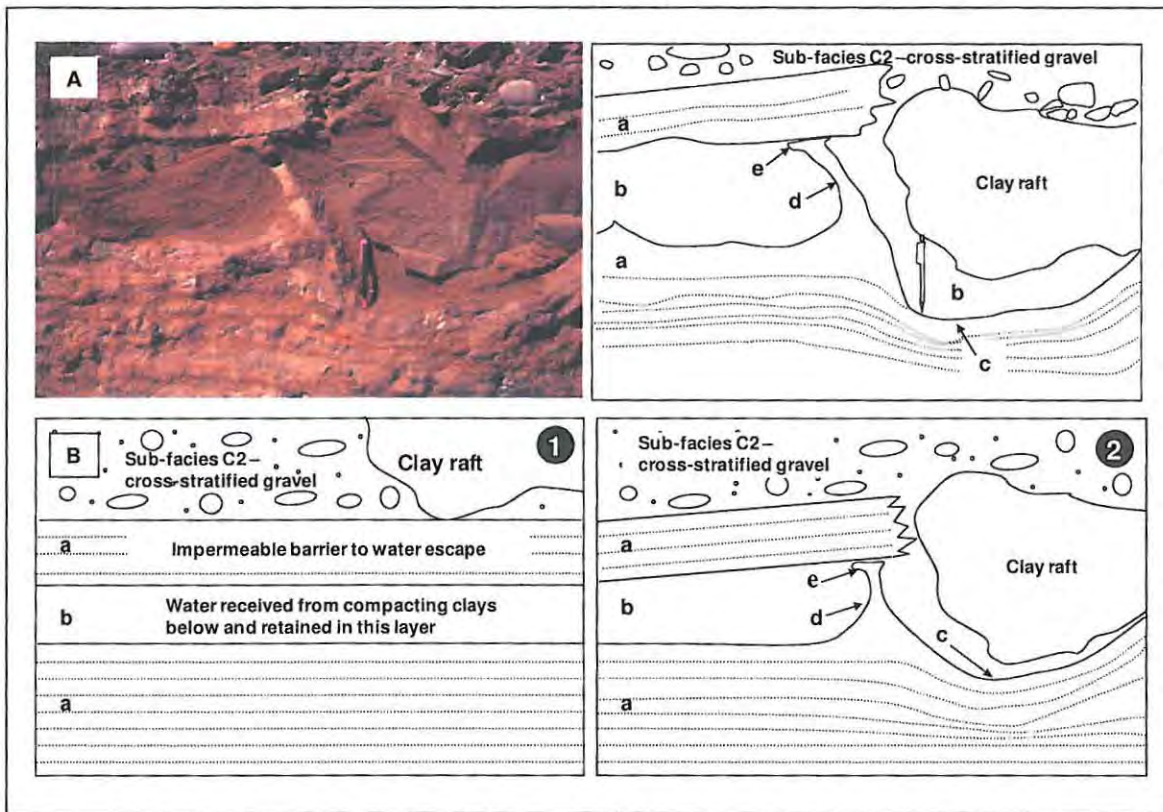
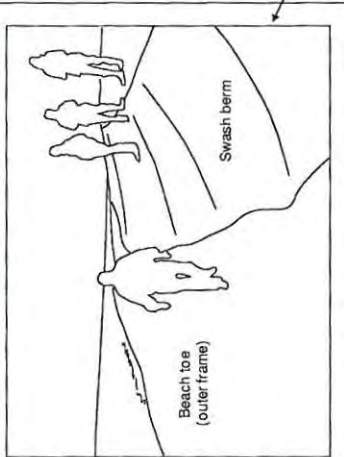


Figure 3.27: Load structure in Sub-facies C2 clay deposits. (A) Large clay raft distorting underlying clay (a) interbedded with silt layer (b). Note deformation of clay laminae (c) and flame structure (d) ‘mushrooming’ below upper clay layer (e). Pencil for scale = 15 cm. (B) Schematic cartoon illustrating mode of deformation. (1) Emplacement of clay raft with Sub-facies C2 cross-stratified gravel onto clay. (2) Disarticulation of clay due to loading of oversized clay raft, distorting underlying laminae and forming flame structure.

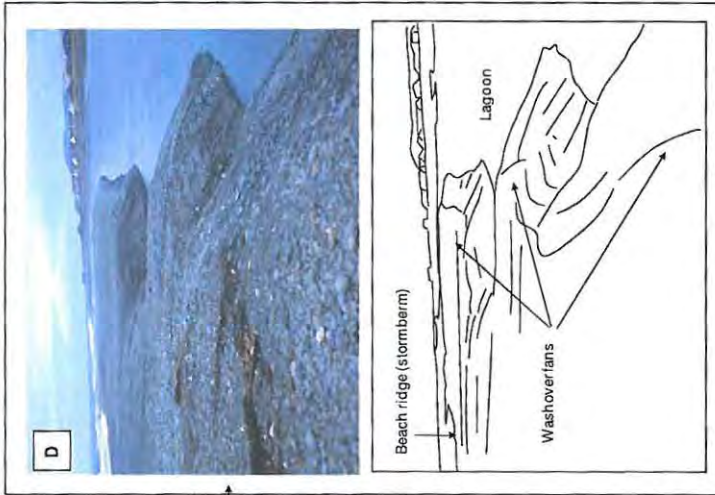
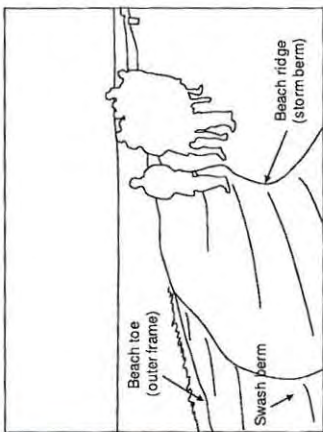
Figure 3.28: Schematic diagram of a gravel barrier beach illustrating the different settings, their sub-facies and modern analogues thereof. **(A)** Locality: Terrace Bay, Skeleton Coast, Namibia. An evolving outer frame (coarse spherical gravel sheet of Sub-facies C1) recognised by the accumulation of coarse spherical-shaped clasts. Person on outer frame deposit for scale = 1.6 m. Note the sorting process through 'overpassing' where the large spherical clasts are being rejected to finally accumulate at the beach toe. **(B)** Locality: Terrace Bay, Skeleton Coast, Namibia. A modern gravel swash berm (cross-stratified gravel of Sub-facies C1) in the middle sector of the beach, dipping steeply seaward. In section, this part of the face will be represented by cross-stratification with steeply seaward-dipping foresets. Person for scale = 1.9 m. **(C)** Locality: Terrace Bay, Skeleton Coast, Namibia. Modern analogue of a coarse disc- and blade-rich gravel sheet of Sub-facies C1. Note the predominance of blade- and disc-shaped clasts. Person standing most seaward for scale = 1.9 m. **(D)** Locality: Ballantrae, Scotland (photograph by courtesy of B. Bluck). Modern gravel washover fans (cross-stratified gravel of Sub-facies C2) extending landward into a back-barrier lagoon (clay and silt deposits of Sub-facies C2). Note the fan shape of the deposits.



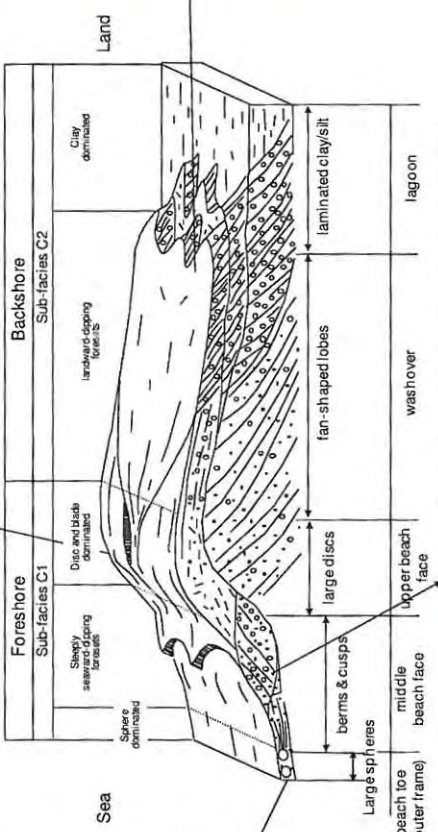
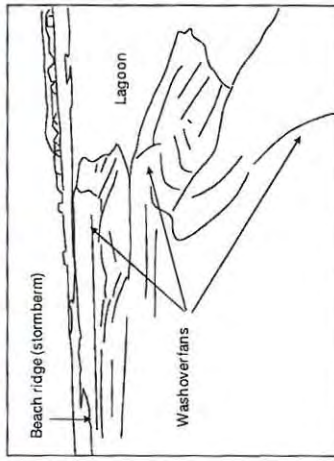
A



B



C



D

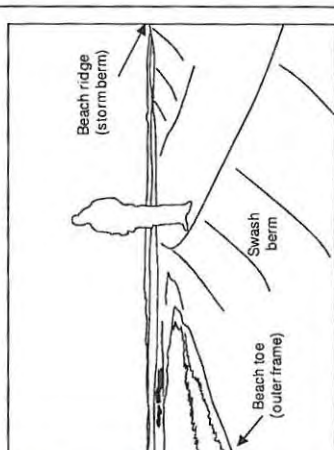
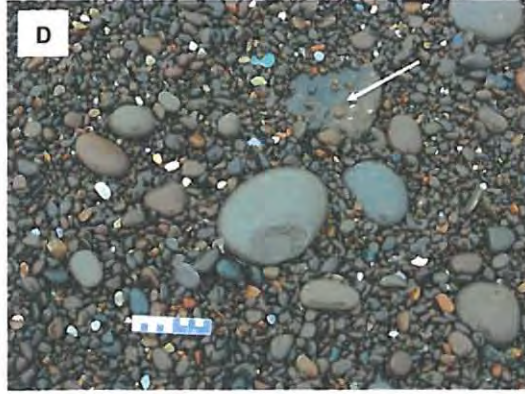
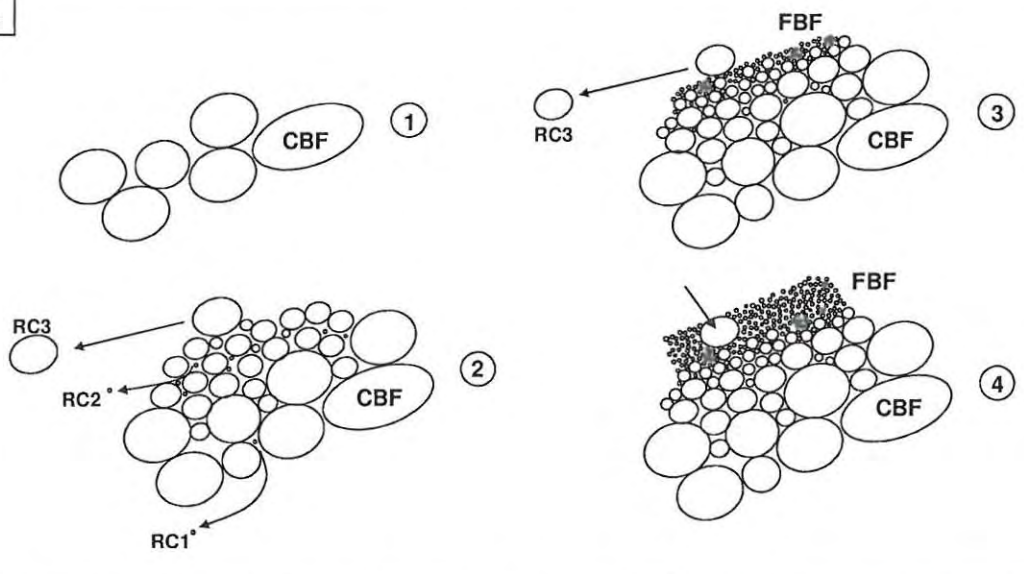


Figure 3.29: Sorting fabrics in modern and ancient sediments with schematic model to illustrate normal grading. Note that RC = rejected clast. (A) Diagram illustrating normal grading sorting process. (1) Coarse basal fabric (CBF) creates template for clasts to lock into existing fabric. (2) Clasts considerably smaller than CBF are rejected (RC1) by filtering through openwork framework. The next generation of clasts, once locked into CBF, creates a smaller template than the CBF fabric. Similarly, clasts significantly smaller than the newly created fabric, filter through as reject clasts (RC2). In contrast, clasts much larger than the fabric are also rejected where they roll off the gravel carpet (RC3). (3) Growth of the fine blinding fabric (FBF) continues once the smaller clasts have locked into the available fabric. Misfit clasts much larger than the modal size of the blinding fabric will be rejected (RC3). (4) If supply of modal gravel is consistently abundant, the larger misfit clasts (arrowed) can be buried by the finer gravel carpet. (B) Locality: Terrace Bay, Skeleton Coast, Namibia. Modern example of normal grading process seen at surface. Fine particles are locked into a coarser fabric to generate a template for the growth of a gravel carpet comprising uniform sized clasts, leading to normal grading. Notebook for scale = 19 cm in length. (C) Similar process recorded in Sub-facies C1 cross-stratified gravel where gravel size decreases upward into a blinding fabric. Section measured is perpendicular to present coastline. Ruler for scale = 25 cm. (D) Locality: Terrace Bay, Skeleton Coast, Namibia. Rejection and burial of misfit clasts at surface on modern beach. Note the partially buried cobble (arrowed). Scale = 10 cm. (E) Buried misfit clast in finer gravel carpet of Sub-facies C1 cross-stratified gravel as seen in section. Section measured is perpendicular to present coastline. Scale = 10 cm.

A



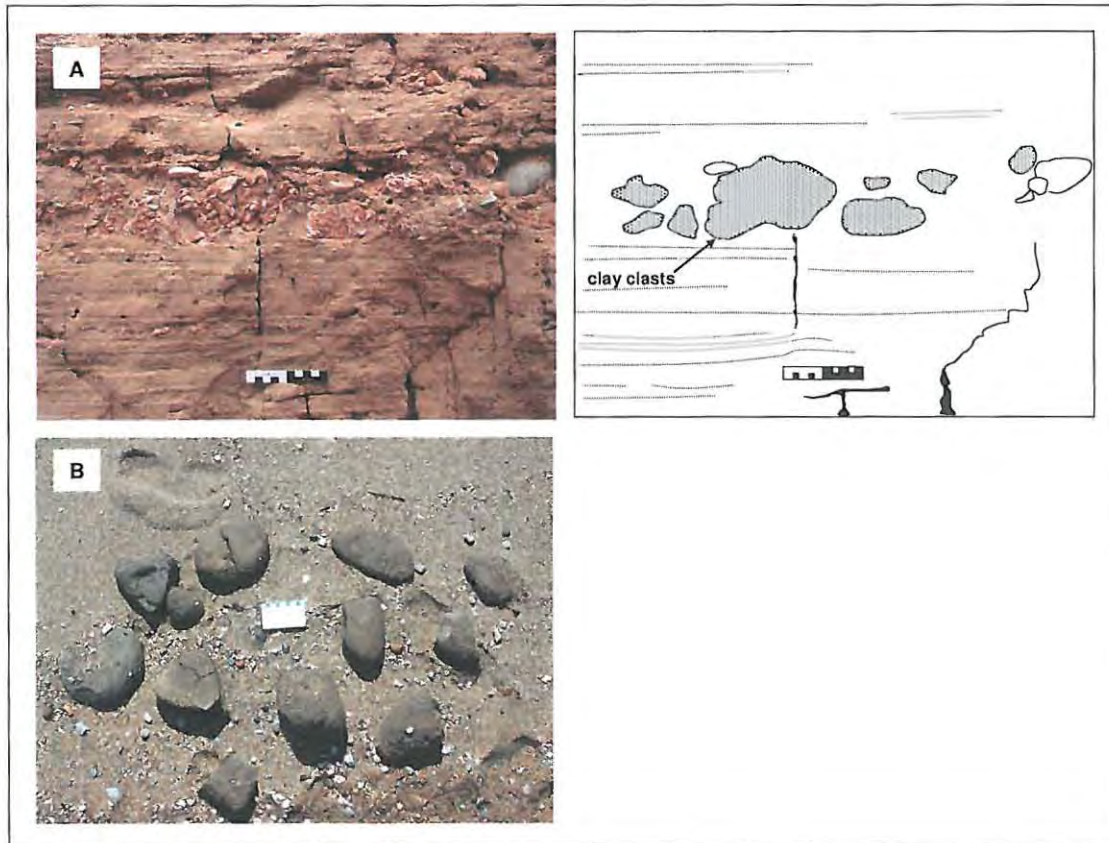


Figure 3.30: Clay clasts within beach sediments. (A) Locality G19: Clay clasts within sand beaches of Sub-facies C1. Scale = 10 cm. Section measured is perpendicular to the present coastline. (B) A selection of armoured clay clasts on the modern sand beach at Oranjemund near to the Orange River mouth, Namibia. Scale = 10 cm.

Figure 3.31: A modern analogue of the Sub-facies C2 clay and silt depositional setting in Oranjemund, Namibia. **(A)** An aerial view (looking south) of the present Orange River mouth illustrating (a) present barrier beach, (b) Holocene barrier beach and (c) Estuarine-lagoon, (d) back-barrier pond. **(B)** A close view of back-barrier pond illustrating the distribution of finer sediments. Vehicle for scale (circled).

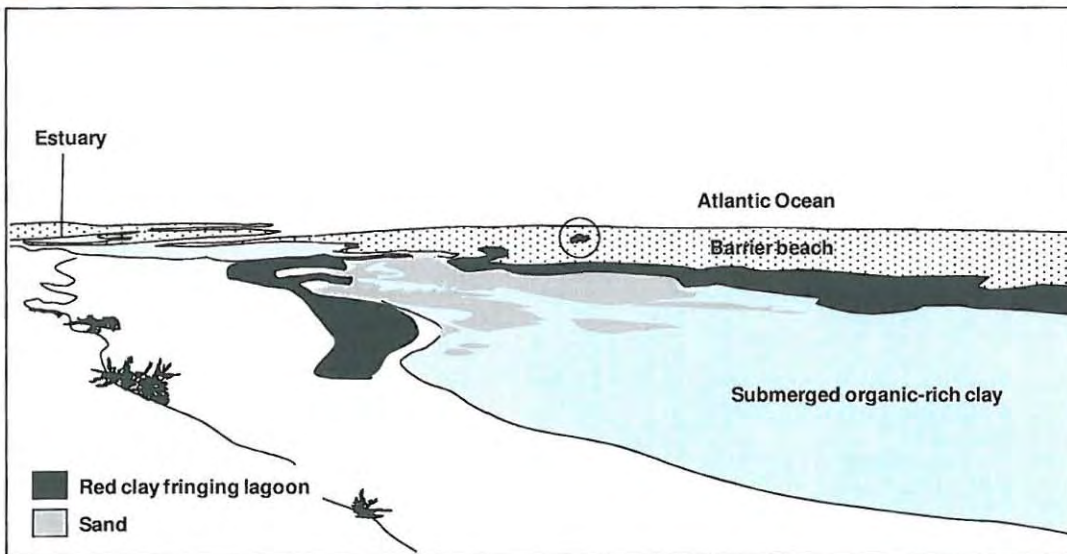
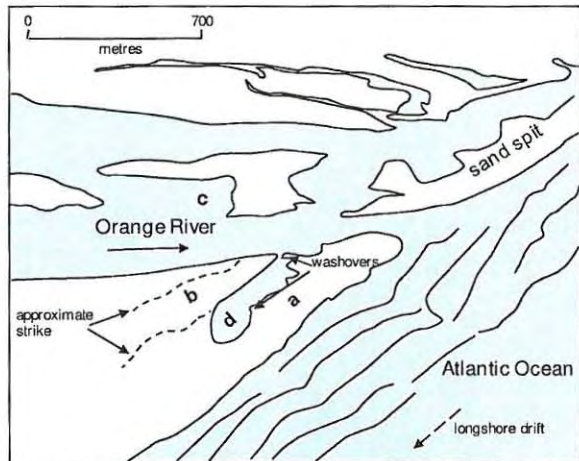
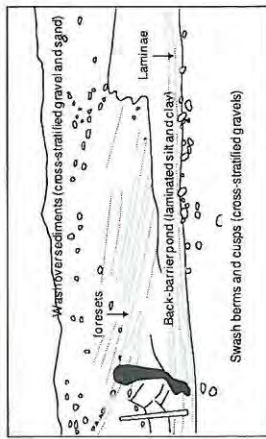
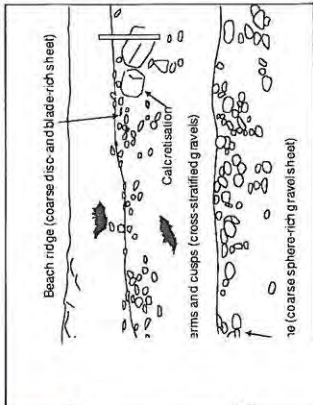


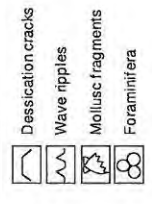
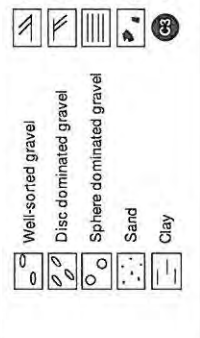
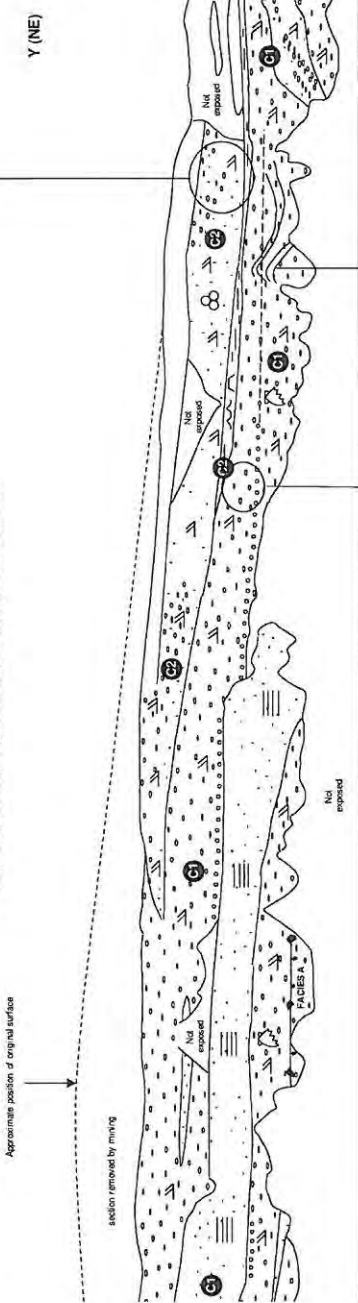
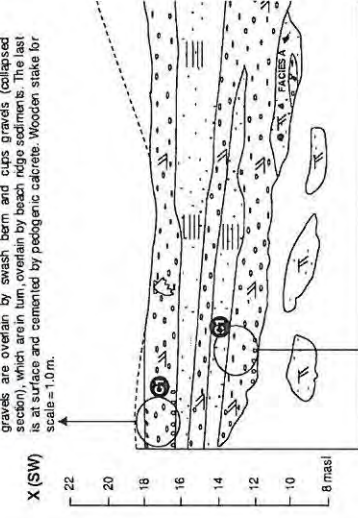
Figure 3.32: Cross-section of G29 trench depicting main characteristics of the sub-facies.
Section is perpendicular to present coastline.



Vertical stacking of Sub-facies C1 foreshore deposits. Outer frame gravels are overlain by swash berm and cusps gravels (collapsed section), which are in turn overlain by beach ridge sediments. The last is at surface and cemented by pebbly calcareous. Wooden stake for scale = 1.0m.



Vertical stacking of Sub-facies C2 back-barrier sediments. Washover fan deposits with landward-dipping foresets overlie clay/silt. These, in turn, overlie foreshore gravels of Sub-facies C1 with seaward-dipping foresets. Note the deformation features in the foreshore gravels. Survey staff for scale = 1.2 m.



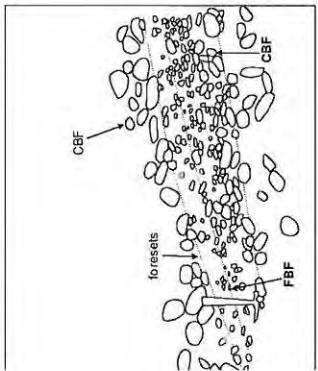
X - Y = position of transect illustrated in Figure 3.20

metres

50



Normal grading in seaward-dipping foreset strata of Sub-facies C1: cross-stratified gravels. Extreme clast size and shape sorting. Hammer for scale = 29 cm. CBF = coarse basal fabric, FBF = fine binding fabric.



Outer frame gravel of Sub-facies 1 comprising coarse cobble, sphere- to blade-shaped clasts. Hammer for scale = 29 cm.

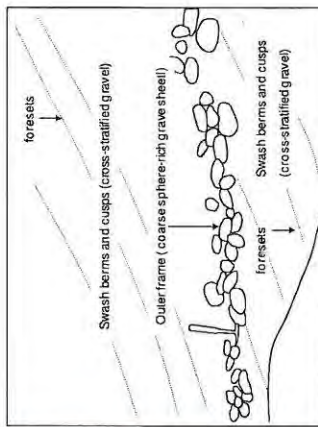


Figure 3.33: Summary of Facies C stratigraphic and palaeo-environmental framework based on a vertical succession where there is maximum preservation of sub-facies.


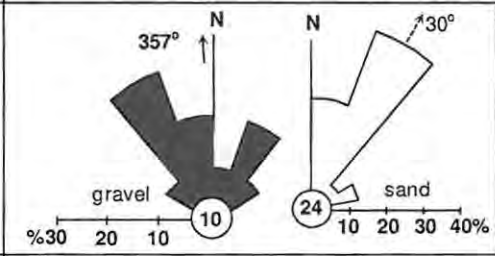

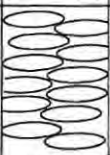

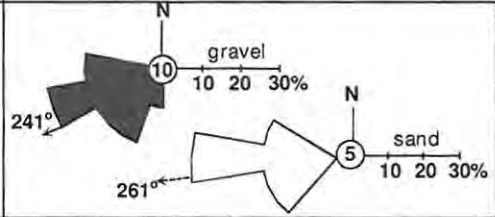
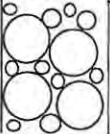
SUB-FACIES		SEDIMENTARY FEATURES	PALAEO-CURRENT DIRECTION	INTERPRETATION
C2		<p>Poorly shape- and size-sorted cross-stratified gravel with landward-dipping foresets. Foreset strata display normal grading. Variable clast shapes, but mostly disc and blades, which are imbricated landward. Clay rafts of back-barrier origin are present.</p>		<p>Backshore setting. Storm-generated wash over fan deposits prograding into and interfingering with back-barrier sediments. Source of gravel is the beach ridge and in part, the beach face.</p>
		<p>Fine laminated interbedded red clay and silt with fine sand. Wave rippled sediments with dessication cracks in places.</p>		<p>Backshore setting. Shallow body of water in back-barrier that is nourished by either wash over events or tidal exchange.</p>
C1		<p>Horizontal gravel sheet with predominantly cobble to large pebble discs and blades. Clasts display no preferred orientation, usually flat lying. Reverse grading is notable.</p>		<p>Foreshore setting. Large disc zone forming beach ridge, representing most landward part of foreshore. Storm deposition by overtopping where swash run-up reaches its maximum.</p>
		<p>Openwork framework and matrix-supported cross-stratified gravel with steeply seaward-inclined foresets. Foreset strata display normal grading. Variable clast shapes, but gravels are well shape- and size-sorted. Disc and blades are imbricated seaward. Clay clasts are not an uncommon component.</p>		<p>Foreshore setting. Zone of swash berms and cusps. Dominant sub-facies in the foreshore confined to middle sector of foreshore where size and shape sorting through clast selection and rejection is active.</p>
		<p>Near horizontal, structureless, sphere-rich strata. Primary openwork framework of large spheres filled in by smaller clasts.</p>		<p>Foreshore setting. Accumulation of most mobile clasts at beach toe forming the outer frame.</p>

Figure 3.34: General distribution of Facies D. Block diagram (A) illustrating distribution with localities of cross-sections mapped. Stratigraphy of the sub-facies based on vertical relationship is depicted in (B). Oblique aerial photograph (C) illustrating distribution in the field and stratigraphic relationships superimposed (photograph by courtesy of J. Ward).

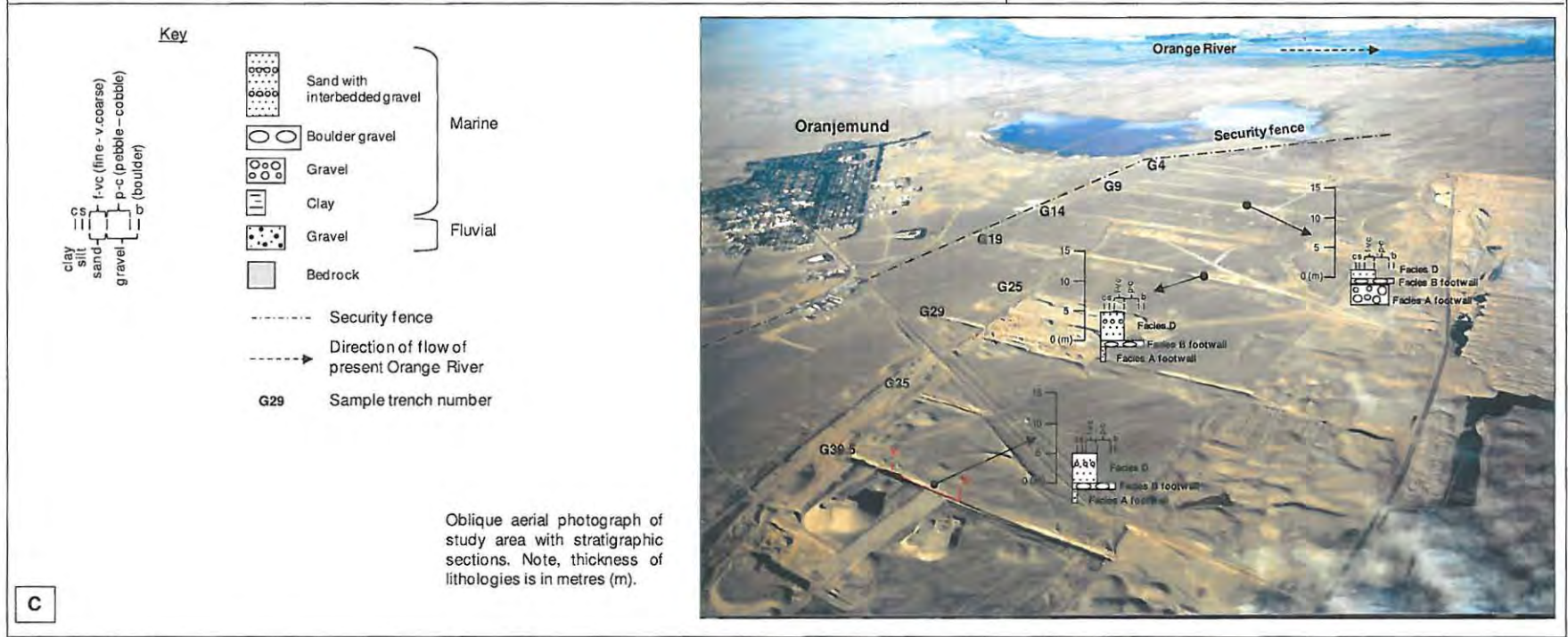
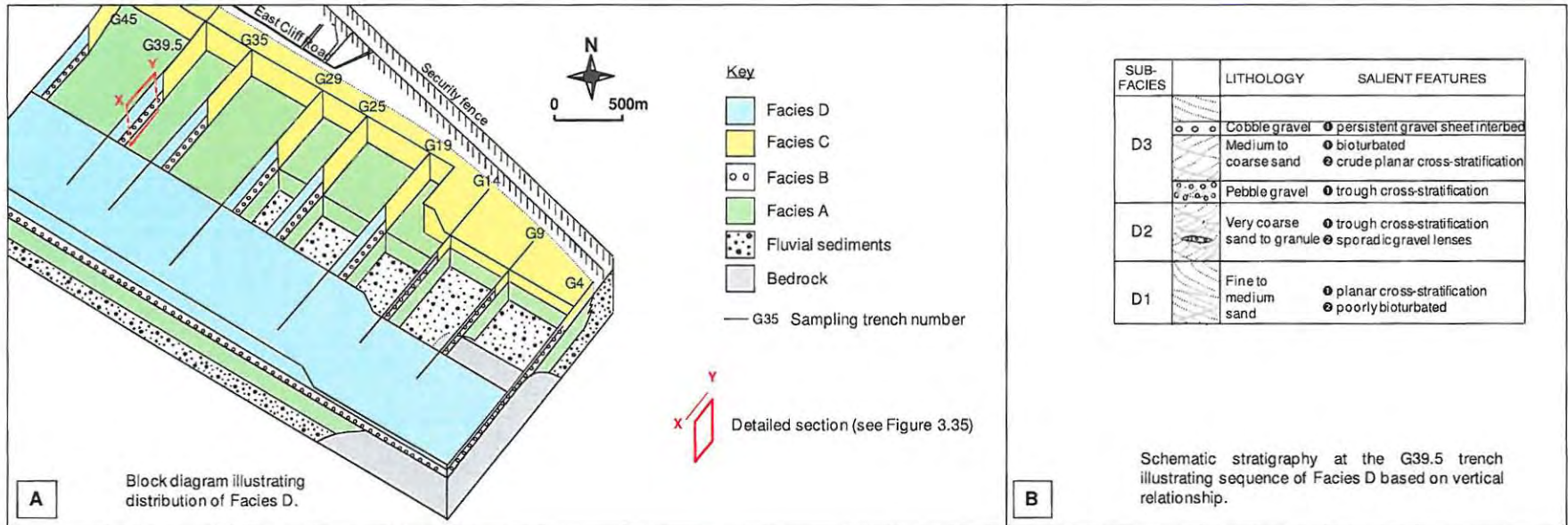
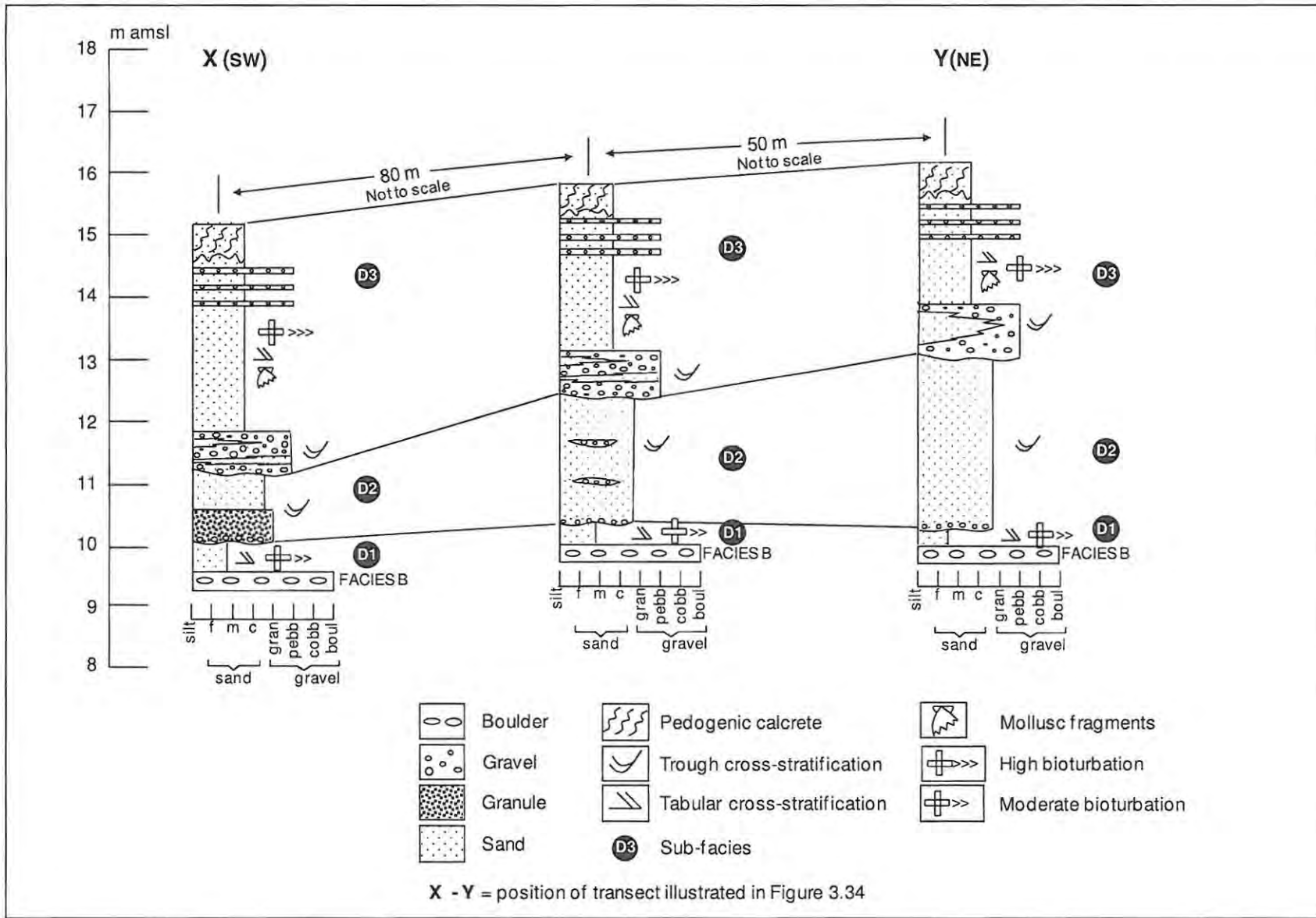


Figure 3.35: Correlation of sub-facies in columnar cross-sections measured from the G39.5 excavation. Sections are perpendicular to present coastline.



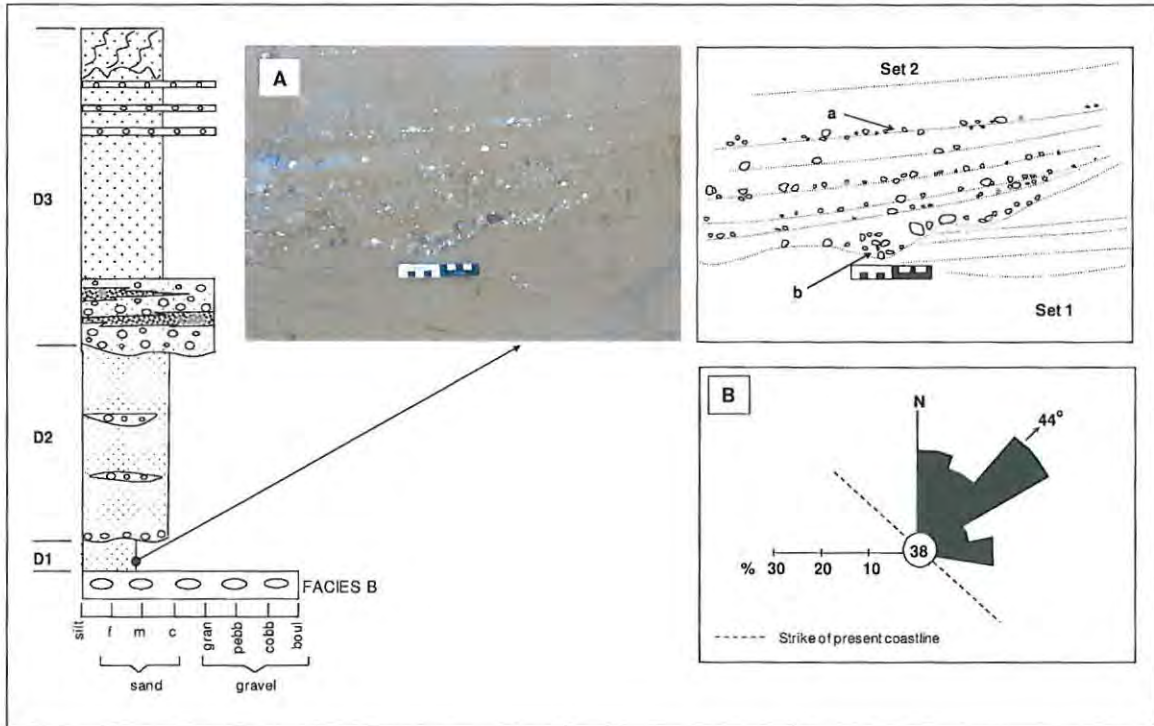


Figure 3.36: Sub-facies D1 sand. Locality G39.5: (A) Tabular cross-stratification with foreset-aligned pebbles (a) and pebble-lined scours (b). Scale bar =10 cm. (B) Rose diagram illustrating palaeo-current directions of the sub-facies at G39.5 trench. Columnar cross-section illustrates stratigraphic position of Sub-facies D1 (see also Figure 3.35). Section measured is perpendicular to present coastline.

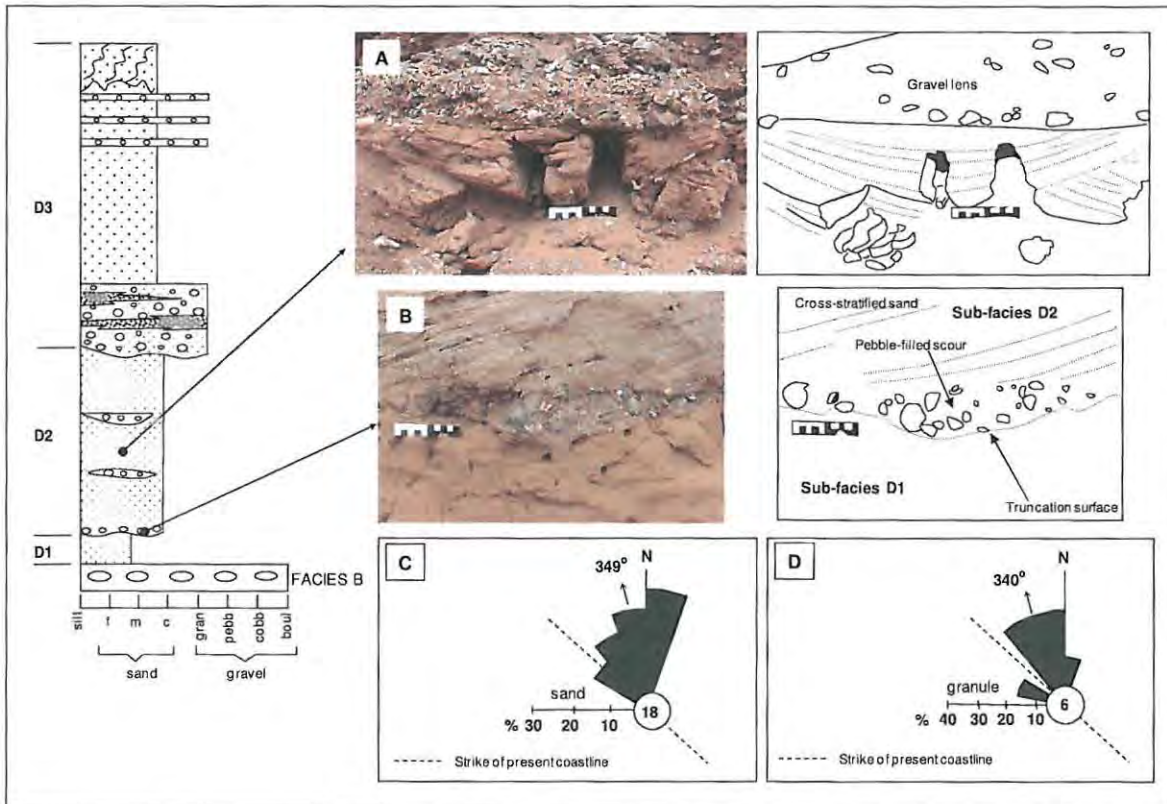


Figure 3.37: Sub-facies D2 sediments. Locality G39.5: (A) Trough cross-stratification in granule beds and (B) erosion of underlying Sub-facies D1 sediments by trough cross-stratified sand. Pebble-filled scours characterise the truncation surface. Rose diagrams illustrate palaeo-current directions for coarse to very coarse sand (C) and granule fraction (D) of Sub-facies at G39.5 trench. Scale bar = 10 cm. Section measured is perpendicular to present coastline. Columnar cross-section illustrates stratigraphic position of Sub-facies D2.

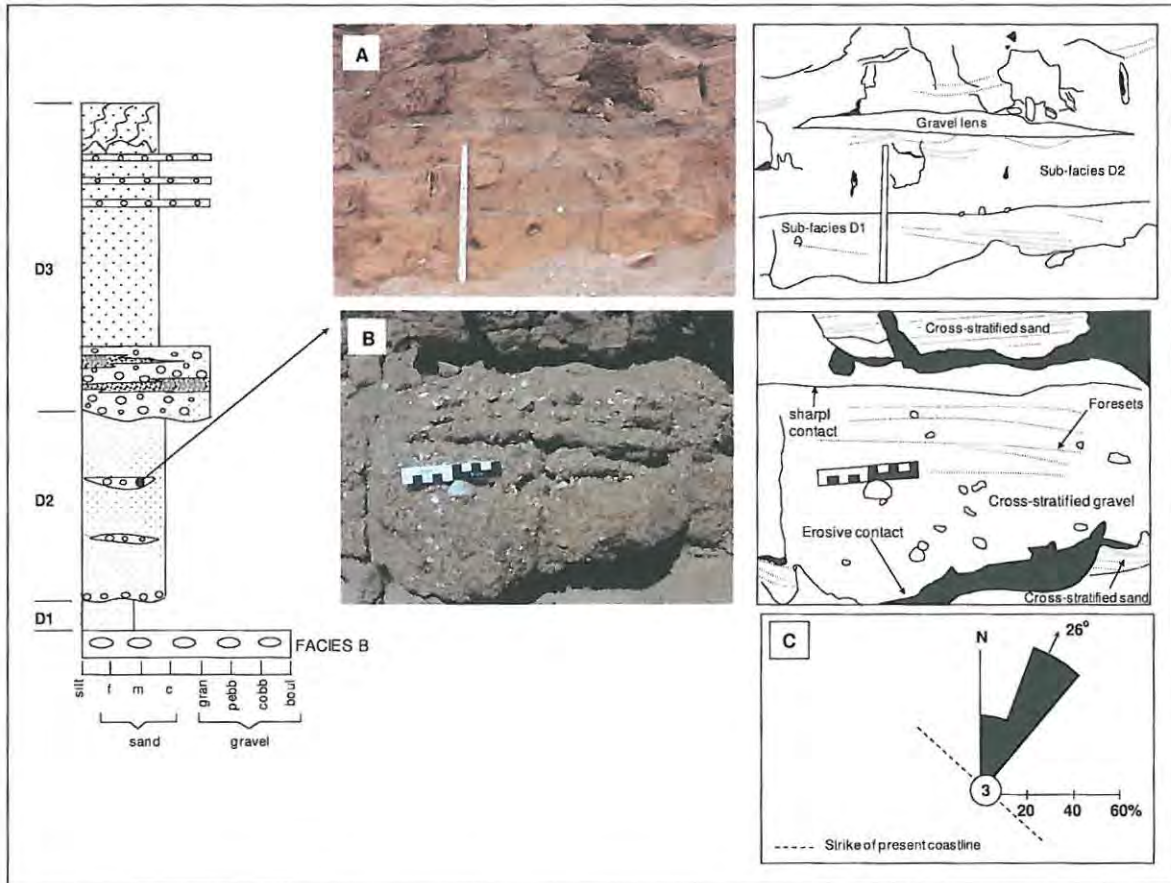
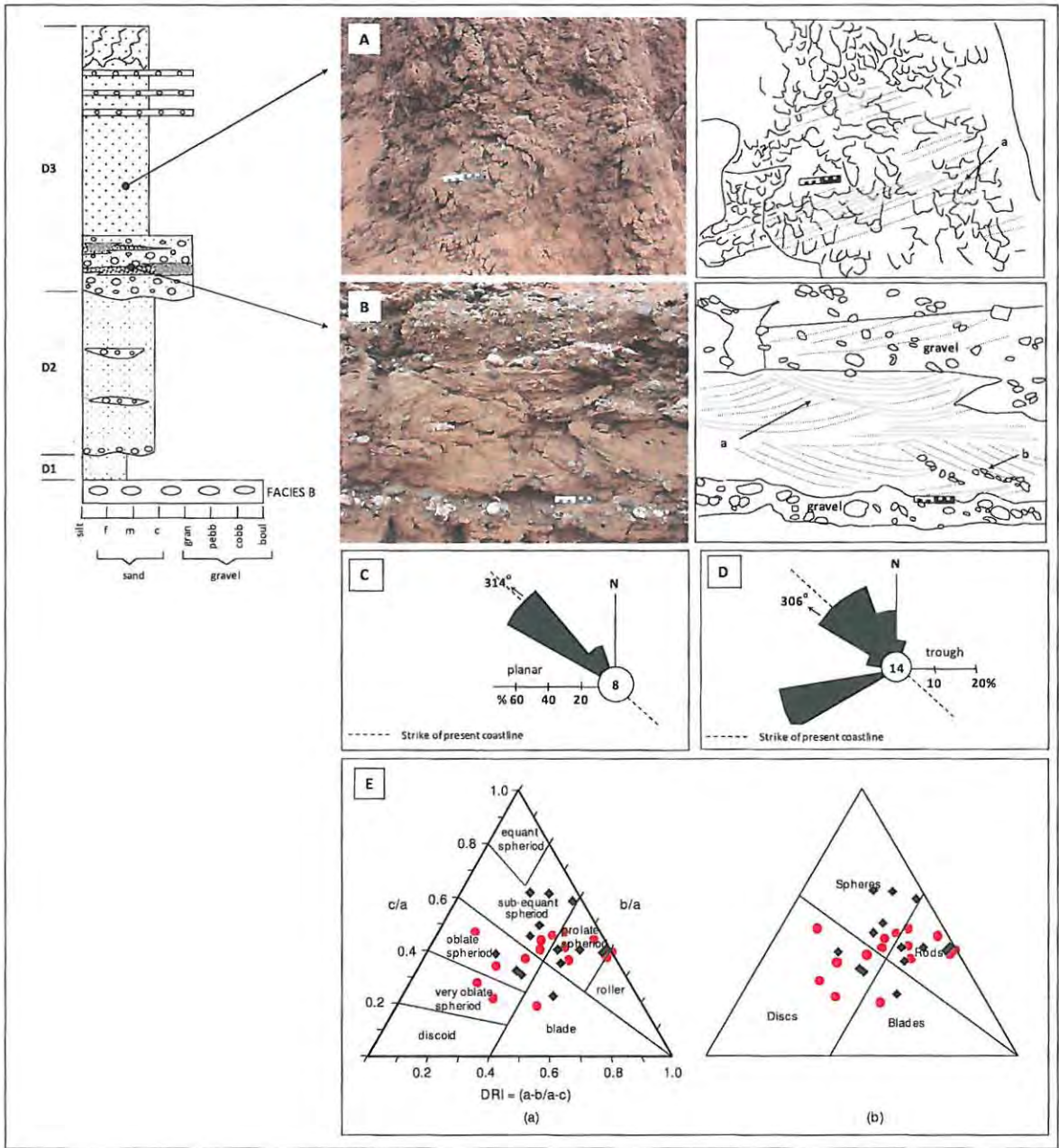


Figure 3.38: Sub-facies D2 gravel beds. Locality G39.5: (A) Lensoidal geometry of gravel sheet. Survey staff for scale = 1.2 m. (B) Close-up of gravel exhibiting crude cross-stratification. Note truncation of underlying sediment. Scale bar = 10 cm. (C) Rose diagram illustrating palaeo-current directions of gravel at G39.5 trench. Columnar cross-section illustrates stratigraphic position of Sub-facies D2. Section measured is perpendicular to present coastline.

Figure 3.39: Sand units of Sub-facies D3. Locality G39.5: (A) Bioturbated sand exhibiting crude planar cross-stratification (a). (B) Trough cross-stratified sand lenses in basal gravel sheet (a) with foreset aligned pebbles (b). Scale bar = 10 cm. Rose diagrams illustrate palaeo-current directions for (C) planar and (D) trough cross-stratification at G39.5 trench. Columnar cross-section illustrates stratigraphic position of Sub-facies D3. Sections measured are perpendicular to present coastline. (E) Representation of clast shapes in the Sub-facies D3 gravel sheets using a Folk form diagram (a) (Sneed & Folk, 1958; modified after Blott & Pye, 2008). Simplified version of Blott & Pye's (2008) ternary diagram (b) illustrating position of grouping against basic clast shapes using Zingg's (1935) terminology. See Appendix B, Section 1.2.5 for explanation of ternary diagrams. Red circles (n = 15) represent clasts from the north-eastern (landward) part of trench whilst black diamonds (n = 14) represent the south-western (seaward) part.



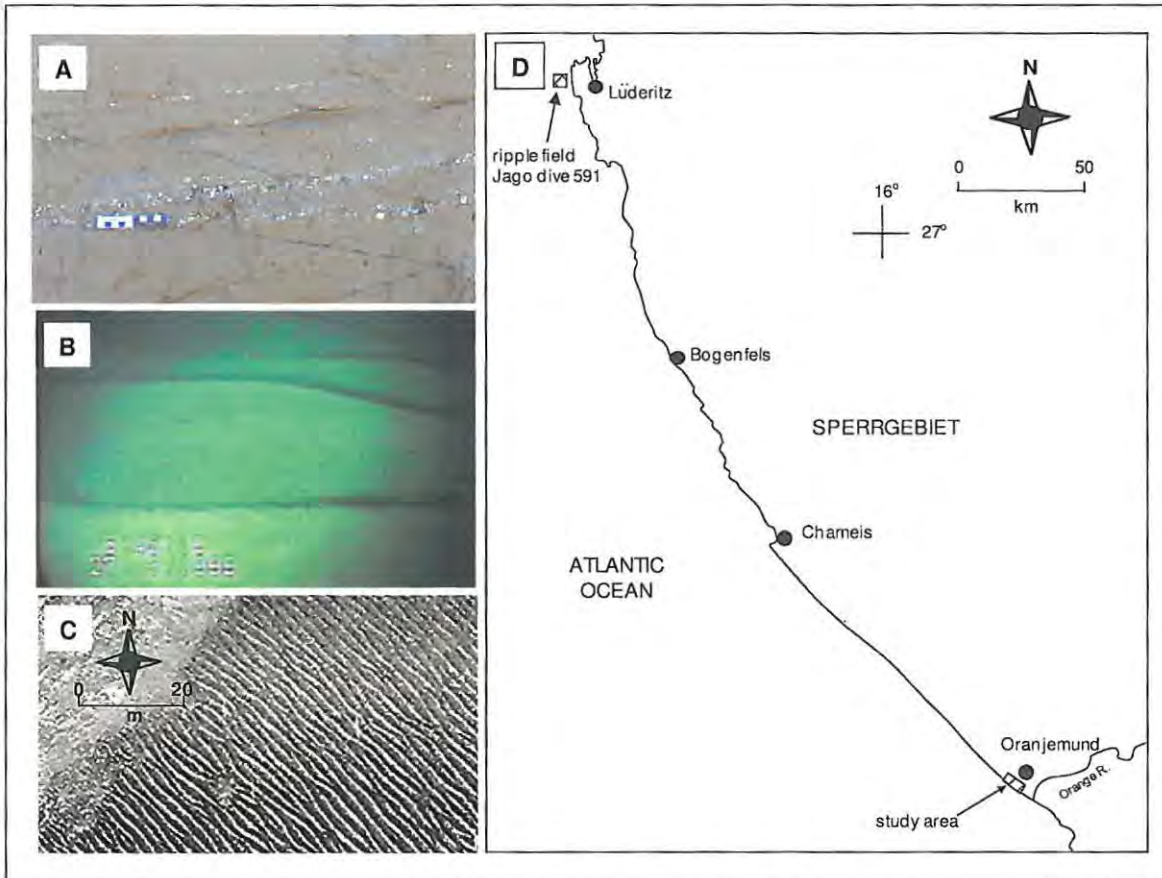


Figure 3.40: Modern comparative of Sub-facies D1 subaqueous dunes. (A) Planar cross-stratified beds of Sub-facies D1 at G39.5. Scale bar = 10 cm. Section measured is perpendicular to present coastline. (B) Modern 2-D subaqueous dunes at a depth of 60 m below msl photographed during *JAGO* dive nr. 591 (1999), Halifax dive site (photograph by courtesy of L. Apollus). Ripple height as per recordings is approximately 0.5 m (Jacob, 1999). (C) Side scan sonar image of rippled bed observed during *JAGO* dive nr. 591 (1999); image by courtesy of L. Apollus). Wave length of ripples is roughly one metre at a depth of 60 m below msl. (D) Locality map illustrating position of Halifax dive site in relation to study area.

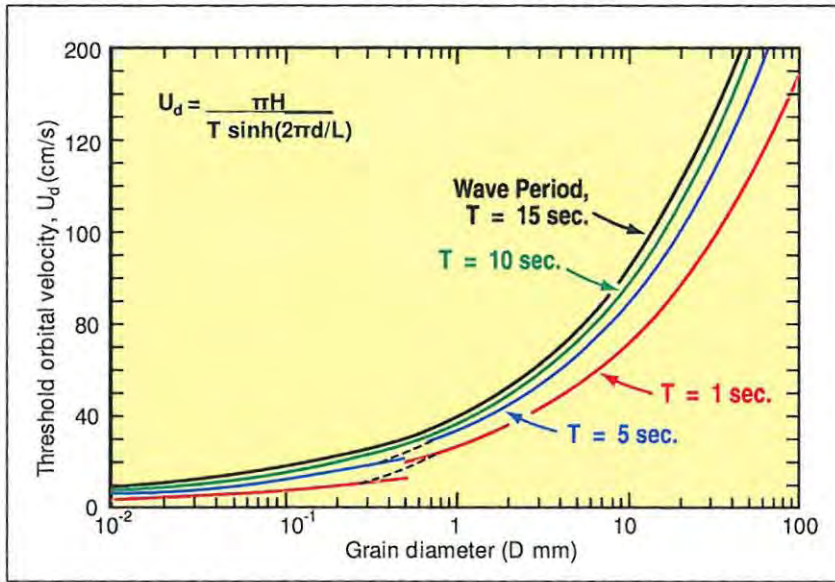


Figure 3.41: Orbital velocity (U_d) in cm/s vs. grain diameter (D) for threshold of sediment movement from Komar & Miller (1975).

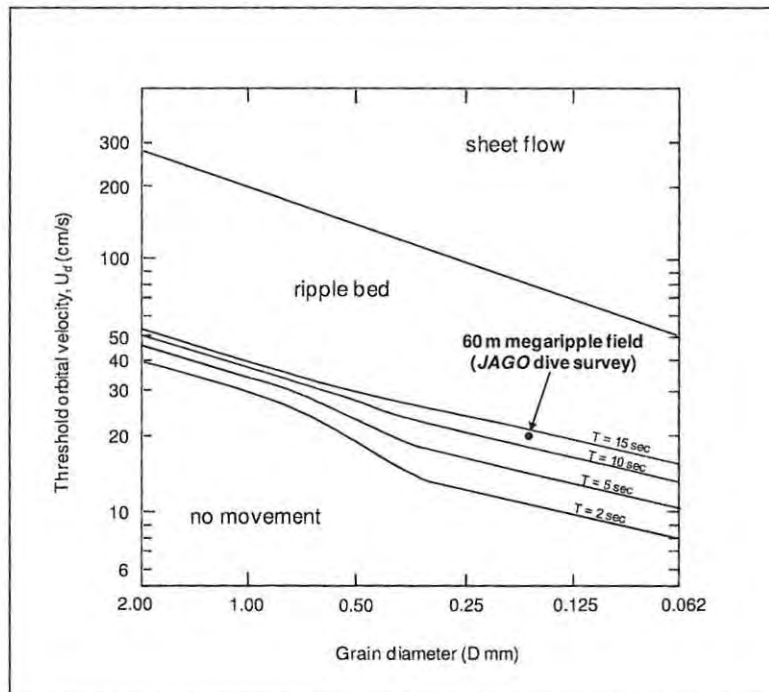


Figure 3.42: Threshold velocity for initiation of grain movement (after Komar & Miller, 1974) and bedform (rippled and flat) zonation (after Dingler, 1974). The diagram was sourced from Clifton (1976) to illustrate bedform initiation of modern subaqueous dunes in fine-grained sediment of 0.17 mm for an orbital velocity (U_d) of 20 cm/s (0.2 m/s) and average wave period of 12.5 seconds as shown in Table 3.10.

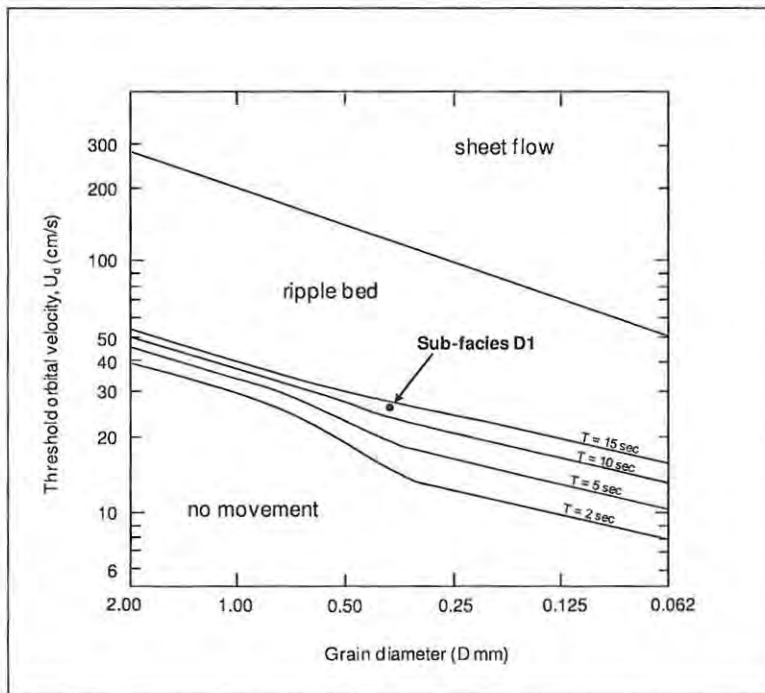


Figure 3.43: Threshold velocity for initiation of grain movement (after Komar & Miller, 1974) and bedform (rippled and flat) zonation (after Dingler, 1974). The diagram was sourced from Clifton (1976) to illustrate bedform initiation of Sub-facies D1 in medium-grained sediment of 0.35 mm for an orbital velocity (U_d) of 26 cm/s (0.26 m/s) and average wave period of 12.5 seconds as shown in Table 3.10.

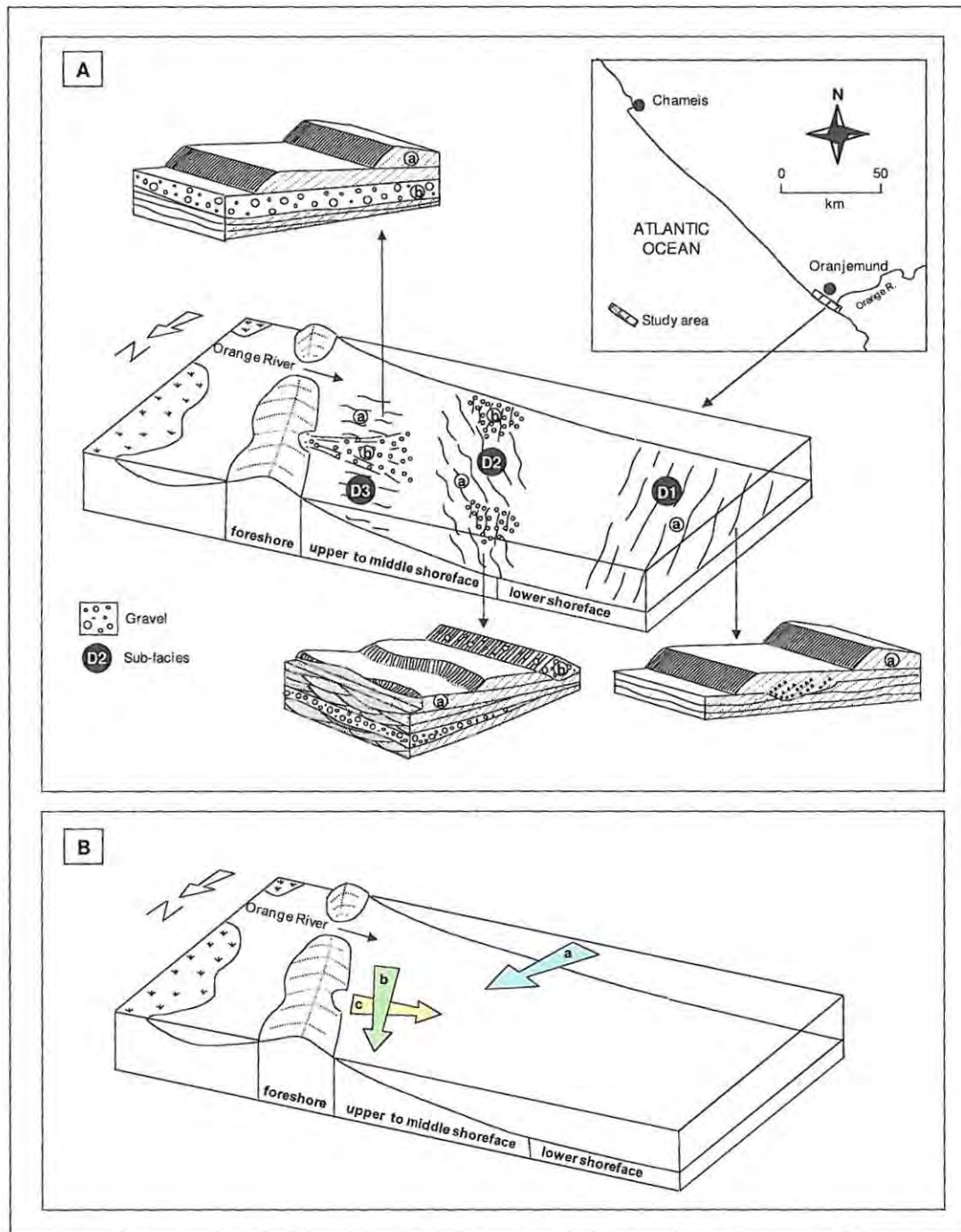


Figure 3.44: Schematic diagrams (not to scale) illustrating depositional setting of Facies D. (A) Inferred bedforms for Sub-facies D1, D2 and D3 (source, Harms *et al.*, 1975). Lower-case letters in bedforms correspond to those in the foreshore to shoreface block diagram. (B) Inferred direction of depositional currents of (a) southerly wave approach, (b) northerly-directed longshore drift and (c) offshore-directed rip currents.

Figure 3.45: Summary of Facies D stratigraphic and palaeo-environmental framework based on vertical relationship.

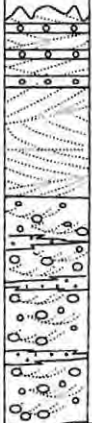
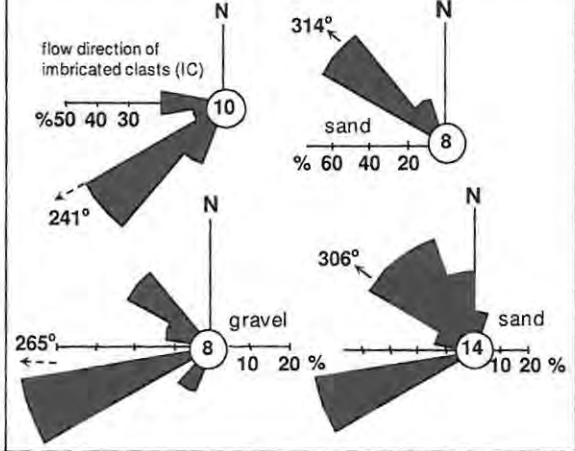
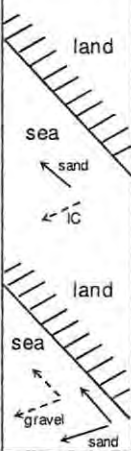

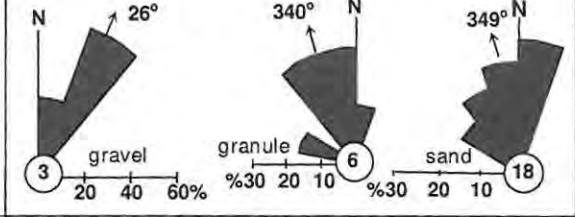
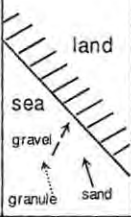

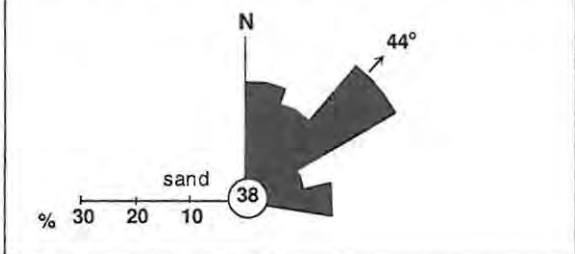
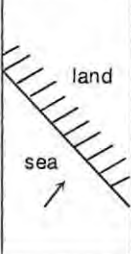
SUB-FACIES		SEDIMENTARY FEATURES	PALAEO-CURRENT DIRECTION		INTERPRETATION	
D3		<p>Medium to coarse sand interbedded with gravel sheets. Sand is highly bioturbated and displays crude tabular cross-stratification.</p> <p>Lenticular beds of interbedded pebble gravel and coarse to very coarse sand exhibiting trough cross-stratification.</p>			<p>Storm-dominated Deposition of gravel. Coarse material sourced from gravel shoreline and moved offshore by rip currents during peak events. Post-storm recovery is reflected by migrating sand ripples moving sub-parallel to shoreline under longshore drift.</p>	UPPER TO MIDDLE SHOREFACE
D2		<p>Coarse sand to granule trough cross-stratified beds with isolated lenticoid gravel beds.</p>			<p>Gravel storm deposition. Possible migration of gravel-sized ripples after storm peak, but remain static as lag deposits during normal conditions. Migrating sand bars and 3-D dunes occur during waning and post-storm stages.</p>	
D1		<p>Tabular cross-stratified fine- to medium-grained micaceous rich sand.</p>			<p>Deposition under storm conditions where subaqueous dunes migrate shoreward immediately after storm peak. High-energy conditions favour granule transport, while sand is entrained during waning stages.</p>	LOWER SHOREFACE

Figure 4.1: Fence diagram showing stratigraphy of ED area barrier deposits. The vertical and horizontal stratigraphic setting is illustrated in (A). Their planform distribution is shown on a Google Earth satellite image (B; May 2009 image – Data SIO, NOAA, U.S.A. Navy, NGA GEBCO. Note that the shoreface sediments are not shown in (B).

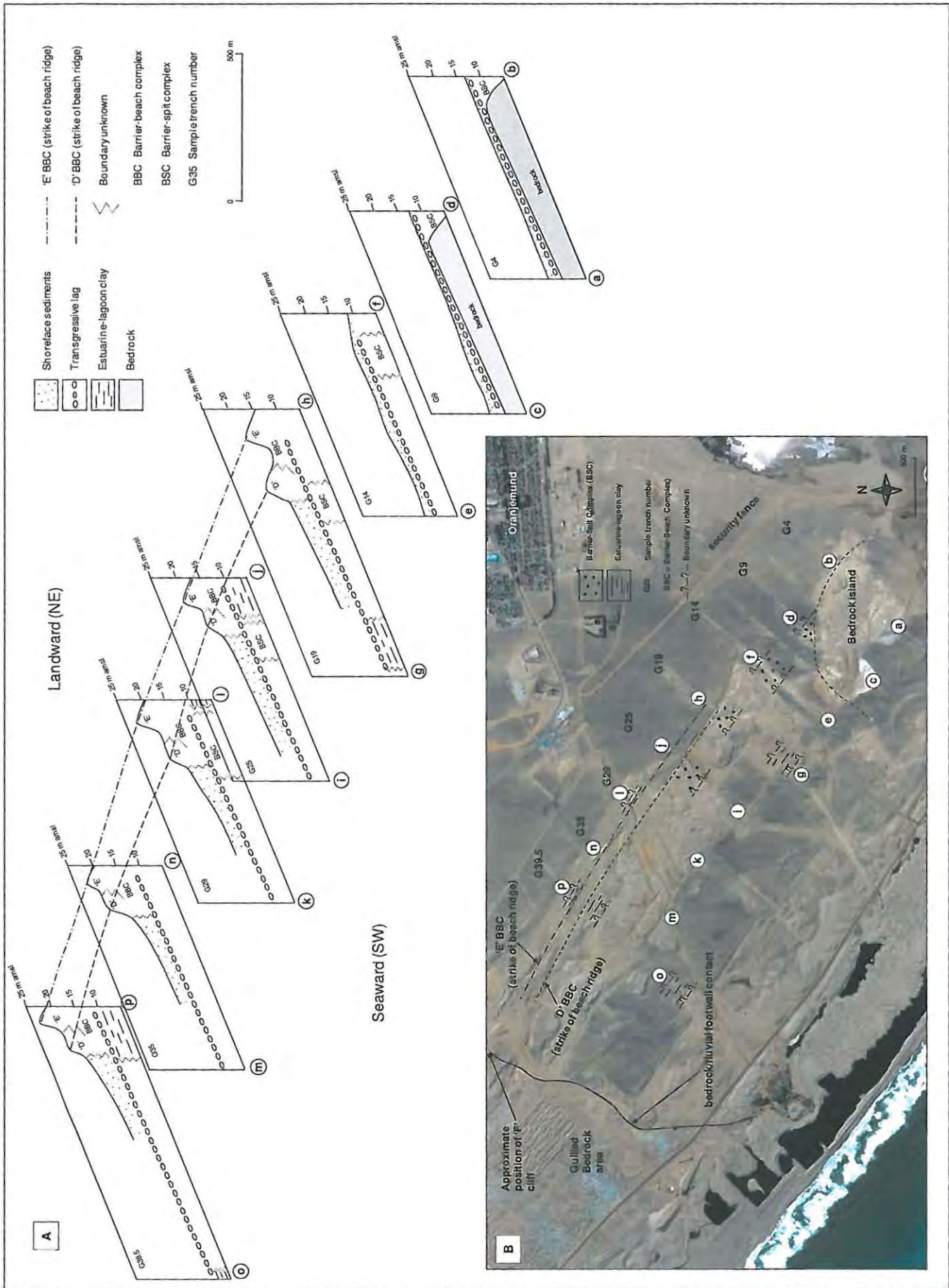
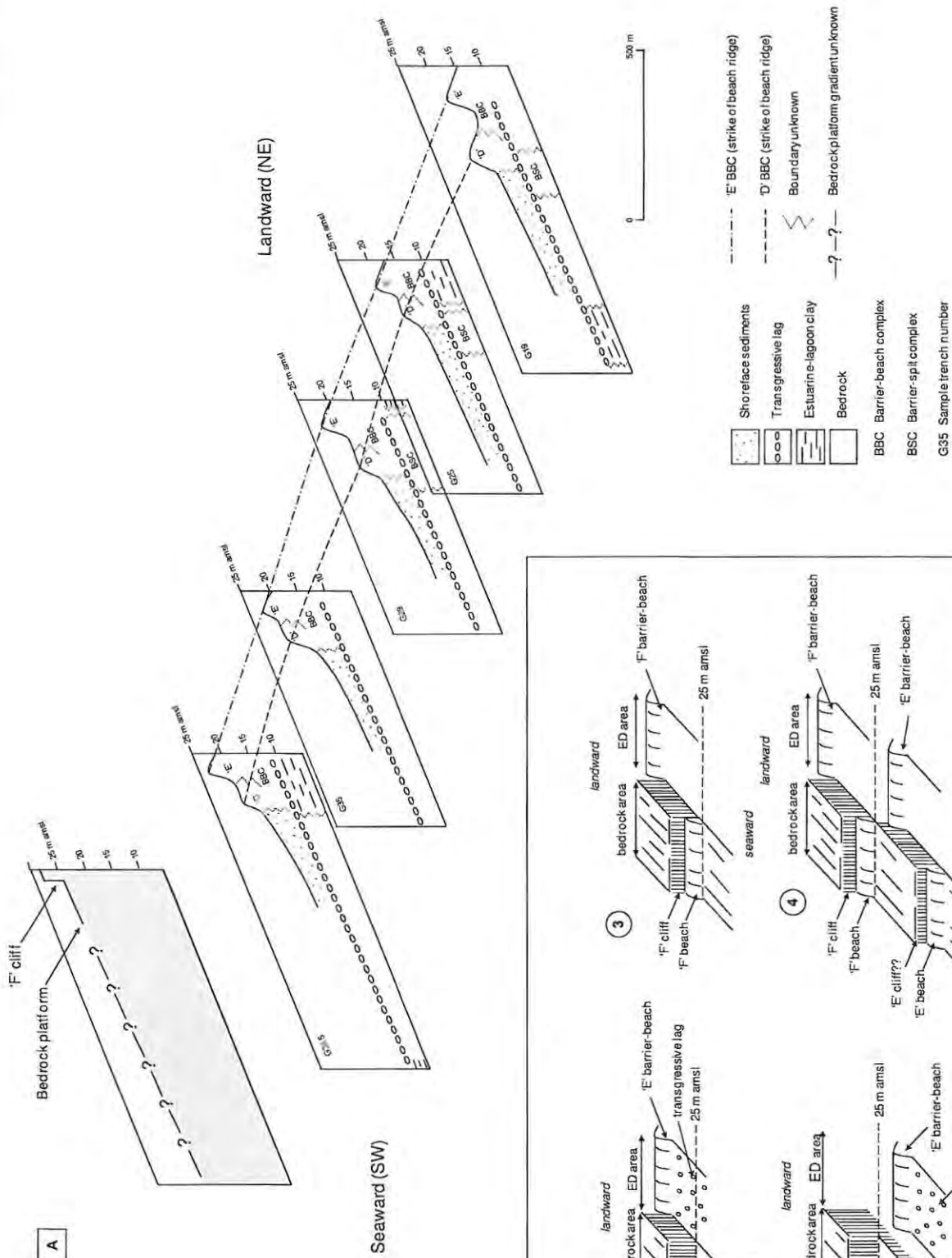


Figure 4.2: Fence diagram and conceptual models illustrating relationship of beach forms to bedrock 'F' cliff. Note the elevation difference between the bedrock platform and transgressive lag in the fence diagram (A). Conceptual models in (B) to explain elevation difference as discussed in text. (B1) Elevations for both the bedrock platform and base of barrier beach (which includes transgressive lag) should be similar if their development was contemporaneous. (B2) Where the 'F' cliff and associated bedrock platform are positioned landward and considerably higher than the barrier beach as seen in the study area, their emplacement was not contemporaneous. (B3) Contemporaneous emplacement of 'F' beaches resulting in a disjointed configuration at the bedrock/palaeo-river mouth boundary. The barrier beach is emplaced farther landward due to a higher migration rate than the 'fixed' beach fringing the bedrock cliff. (B4) Emplacement of the 'E' beach at a lower elevation with an associated disjointed configuration where the 'E' barrier beach is positioned slightly seaward of the 'F' cliff. Note that although evidence for a second cliff ('E' cliff) is lacking, it is not unlikely that this cliff feature would have been cut during the 'E' transgression (see Section 4.3, Stage 4 on 'E' transgression).



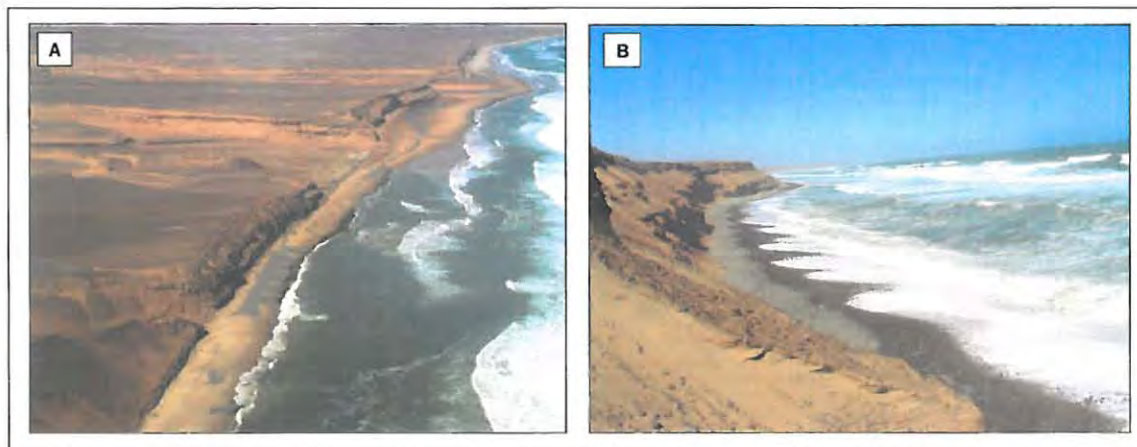
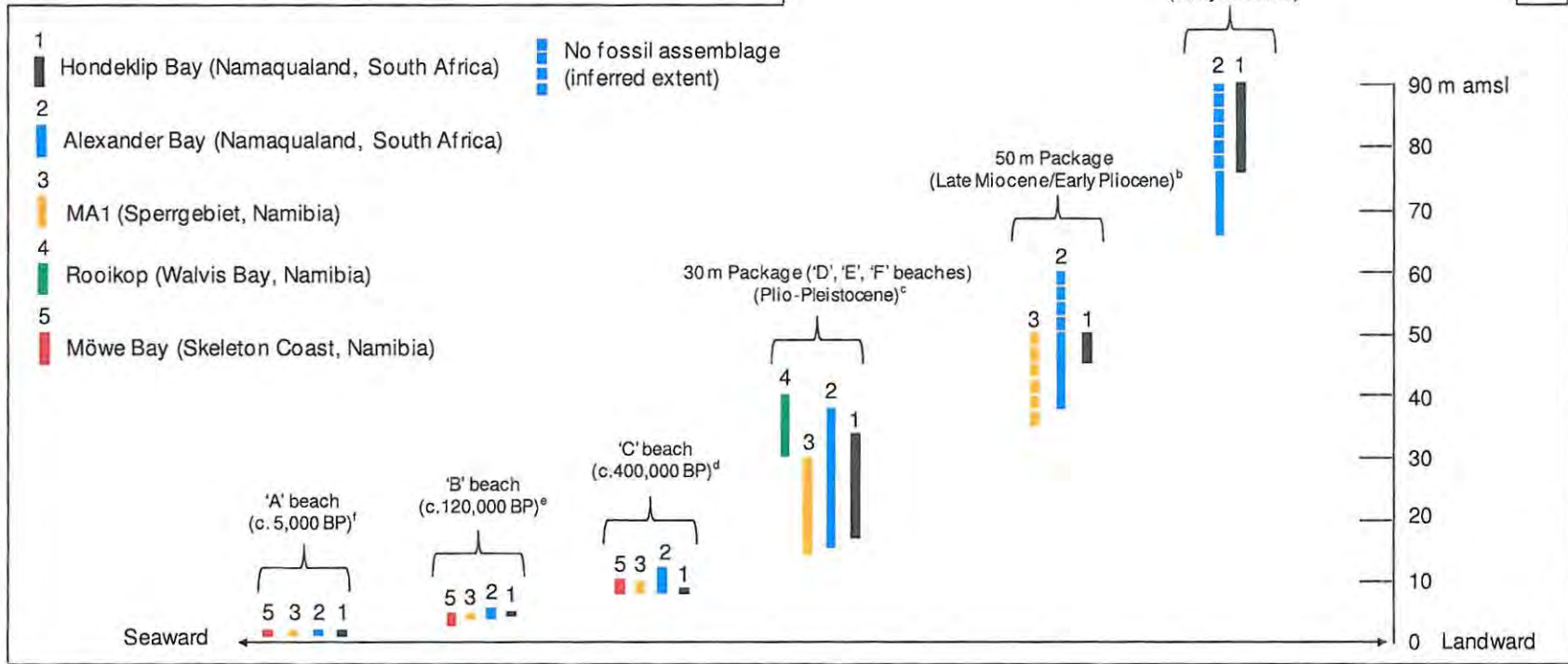
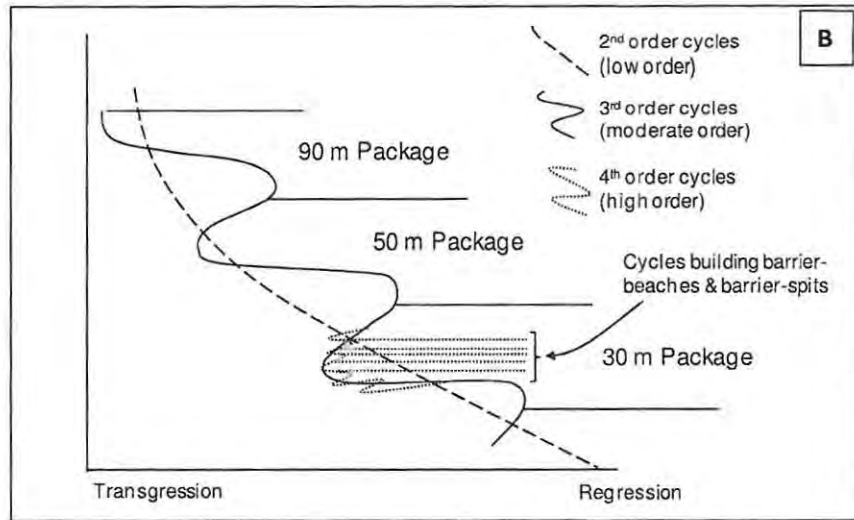
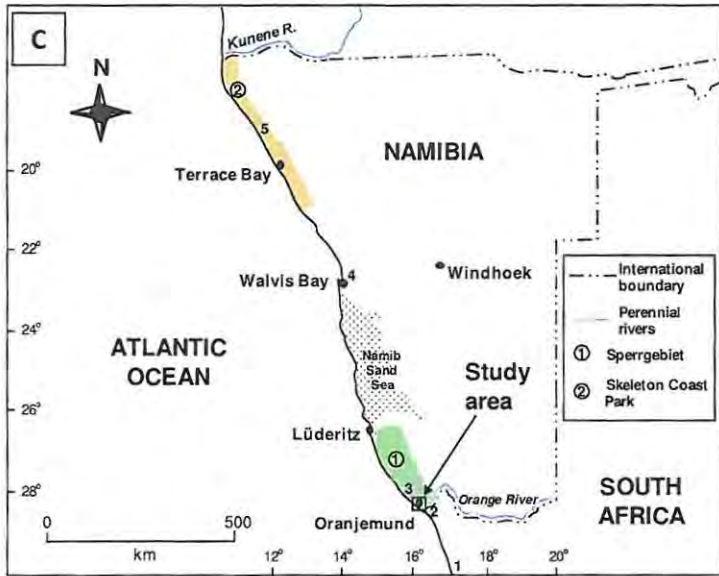


Figure 4.3: Uniab Delta, Skeleton Coast, Namibia. (A) Oblique aerial view of the fan-delta showing a prominent wave-cut cliff. Source, and with kind permission, Krapf (2003). (B) Closer view of the fan-delta and fringing gravel beach that forms the shoreline. Gravel is supplied to the beach through erosion of the fan-delta sediments.

Figure 4.4: General stratigraphic setting of Neogene and Quaternary age coastal deposits from some localities along the Atlantic coastline of South Africa and Namibia. **(A)** Stratigraphic correlation of deposits of different locations and ages illustrating decreasing age with diminishing elevation. The representation illustrates the difficulty in elevation correlation for similar-age deposits older than 400,000 BP, whilst a tighter correlation is evident in the younger deposits. The MA1 90 m Package deposits are not included as they are absent within this area. Note that the representation is not to scale. Sources of information are Hallam (1964), Ward (1984), ^{bc}Pether (1994, 2000), Gresse (1988), ^{abc}Pickford & Senut (1999), ^dRogers *et al.* (1990), ^{ef}Millad (2004) and ^fCompton (2006). **(B)** Simplistic diagram illustrating the superimposition of sea-level cycles in order of priority. See text for explanation. **(C)** Locality map depicting general positions of deposits illustrated in the stratigraphic representation.



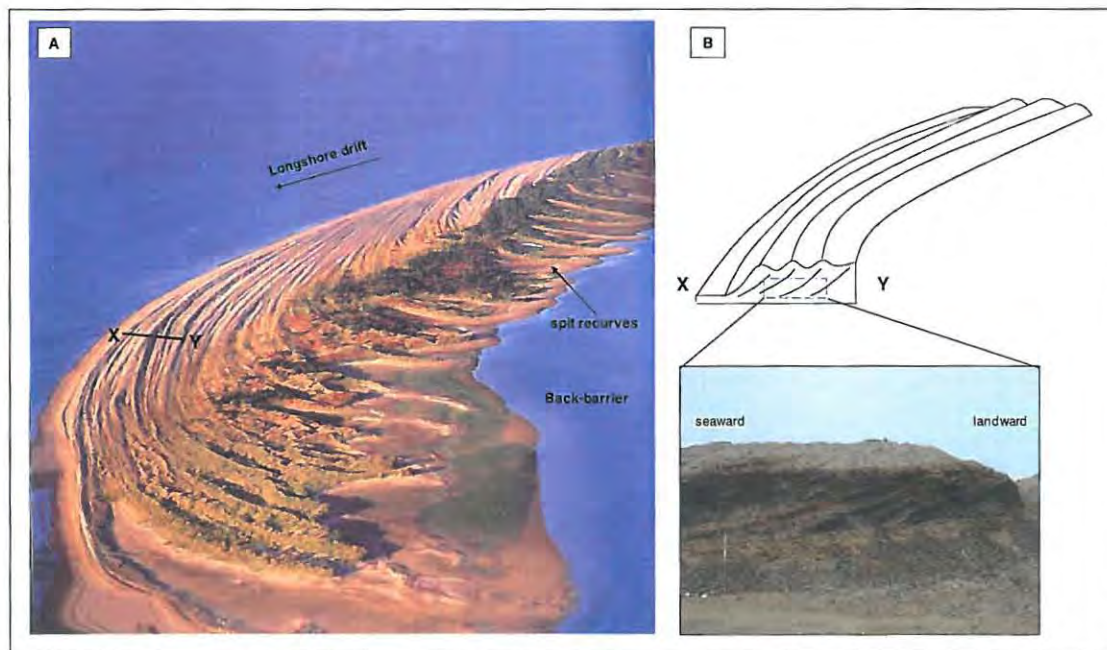


Figure 4.5: Beach-ridge plain. (A) Modern example of a beach-ridge plain in Findhorn, Scotland, developed during barrier spit progradation (image by courtesy of B. Bluck). Although, the image is of a sand-dominated spit, similar coastal features in gravel would have existed within the study area during Plio-Pleistocene times. (B) A schematic diagram (not drawn to scale) illustrating a cross-sectional view (X to Y in A) of the beach-ridge plain and the internal structure if the sediment is gravel-dominated as seen within the study area.

Figure 4.6: Conceptual models for river mouth deposition in a wave-dominated setting. (A) Deposition within a setting where high river discharge is frequent and exerts a groyne effect. Slightly modified after Bhattacharya & Giosan (2003) with the incorporation of amalgamated barrier ridges after Rodriguez *et al.* (2000).

(1) Deposition on subaqueous part of delta during flood. Channel levee deposition from riverine plume generates strong groyne effect, blocking up-drift sediment to induce beach-ridge plain deposition. Thus longshore drift feeds beach-ridge plains, whilst river input is the source to coastal features down-drift of river mouth. Note that the beach-ridge plain progrades in concert with channel extension. (2) Bar formation at the mouth forces distributaries to bifurcate and subaqueous linear barrier-bars are moulded by the wave energy. (3) Linear barrier-bars coalesce and emerge as a barrier island to 'roll' landward, attaching to the mainland. A new bay-head delta may develop in the sheltered lagoon behind the barrier island. Note that the direction of longshore drift is represented by the white arrow.

(B) Deposition in a setting where high river discharge is infrequent and incompetent against a strong unidirectional longshore drift as envisaged for the Orange River setting. Compilation from Bhattacharya & Giosan (2003), Seetharamaia *et al.* (2005) and Rey *et al.* (2009).

(1) Formation of channel margin bars on ebb-shoal during flooding. Bars coalesce to nourish migrating spit and confine inlet channel landward of spit. Note that the main channel in the ebb-shoal can be unconfined and hence migrate. A preferential accumulation of sediment on the up-drift side of the ebb-shoal due to the dominant longshore drift direction results in a down-drift deflection of the river mouth. (2) Down-drift spit growth continues with the inlet and ebb-shoal migrating in the same direction. (3) Once channel loses gradient, a loss in transport power promotes deposition (channel back-filling) and encourages the channel to occupy a more direct route to regain gradient through spit breaching. (4) New spit develops and growth is re-initiated with a down-drift deflection of the river mouth. Coupled with the destruction of the old ebb-shoal, the older spit is deactivated and its attendant inlet is sealed with time. Note, white arrow = direction of longshore drift; black stippled arrow = direction of channel flow; stippled black lines = submerged features such as ebb shoal (rounded polygon) and inlet channel (parallel lines); light grey stippled feature = former positions of ebb-shoal.

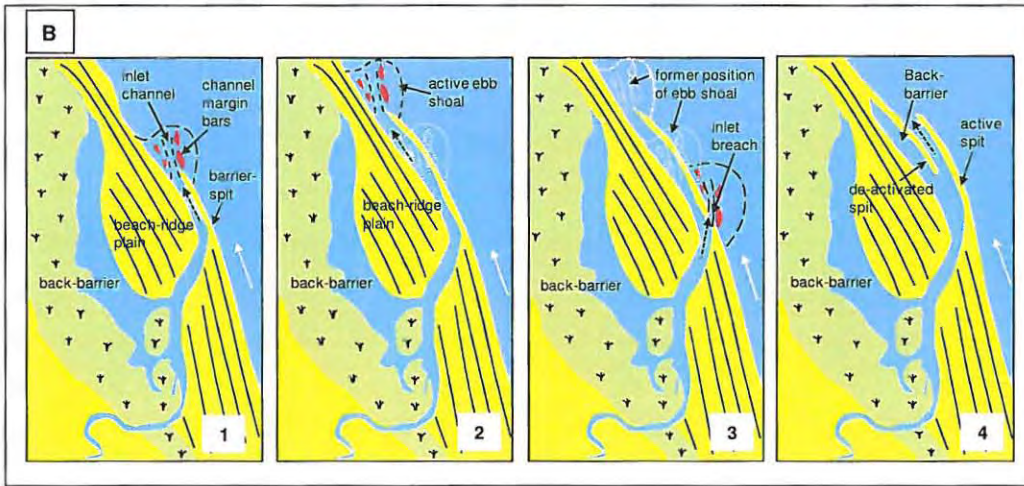
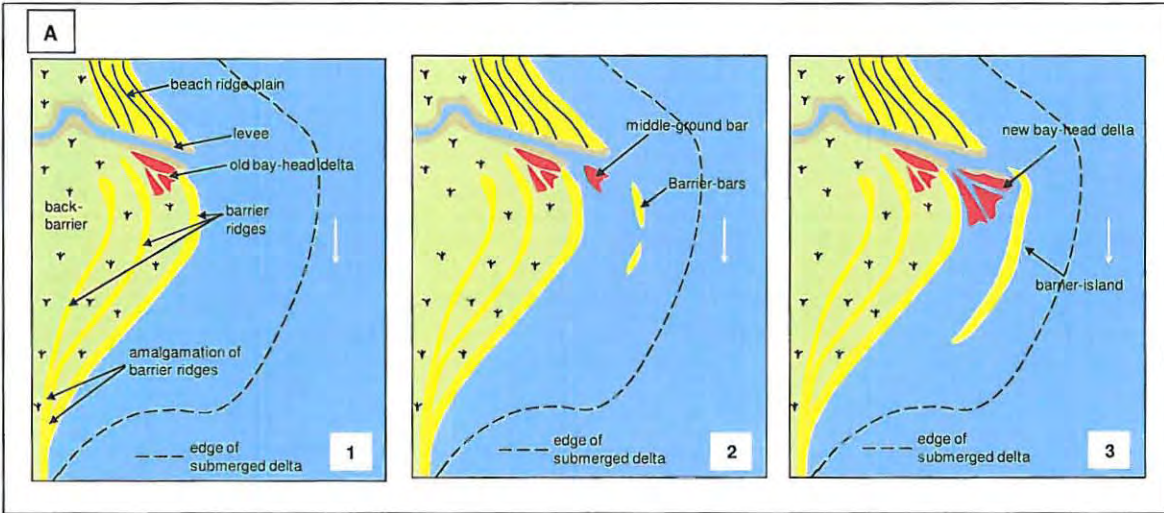
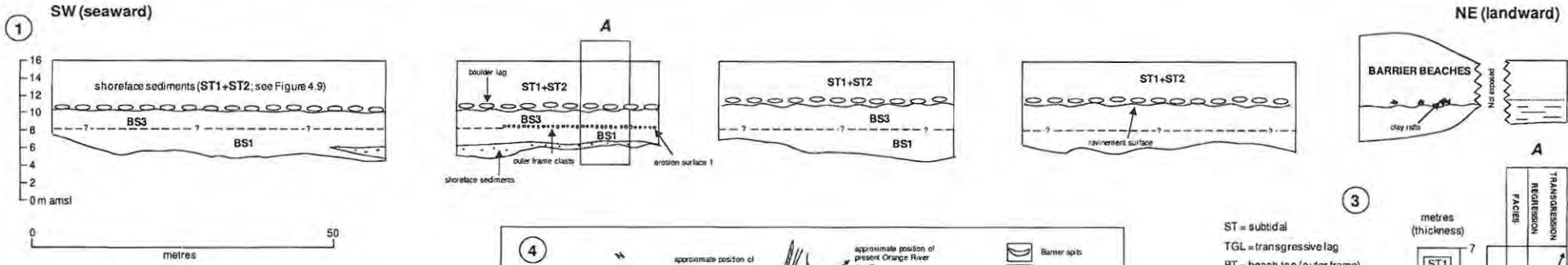




Figure 4.7: Modern example of a deactivated barrier in Oranjemund, Namibia. Oblique aerial view (2003) of the present Orange River mouth setting, looking northwards towards the study area. A deactivated barrier, now an abandoned remnant, is positioned landward and protected from the wave energy by a younger, active barrier feature. Note that current sea-level along the west coast of South Africa and the Namibian coast is rising (see Hughes *et al.*, 1991) and thus the shoreline depicted in the aerial photograph is an expression of a transgressive system, which is also evidenced from the washover deposits. A similar setting of barrier abandonment and isolation is envisaged for the study area. Solid black arrow in photograph depicts river flow direction. For measure of scale, length of de-activated barrier is approximately 700 m.

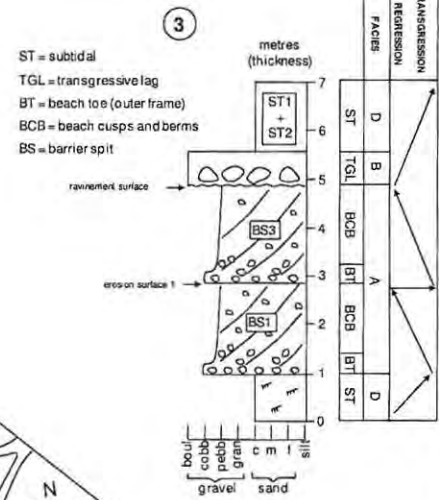
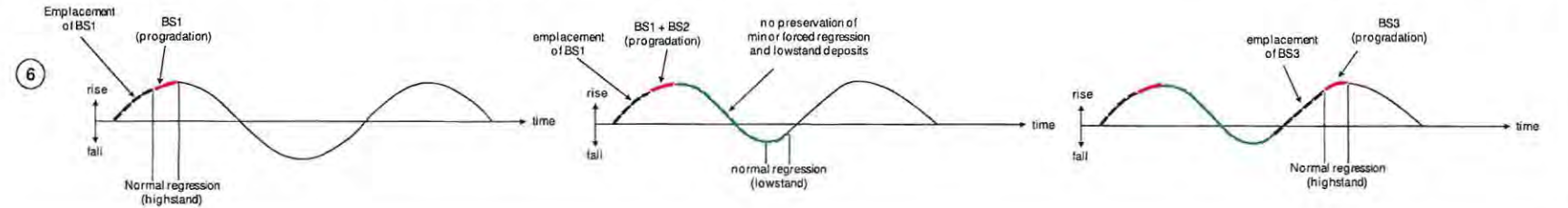
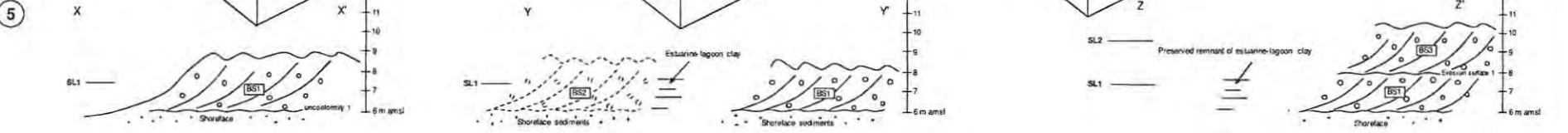
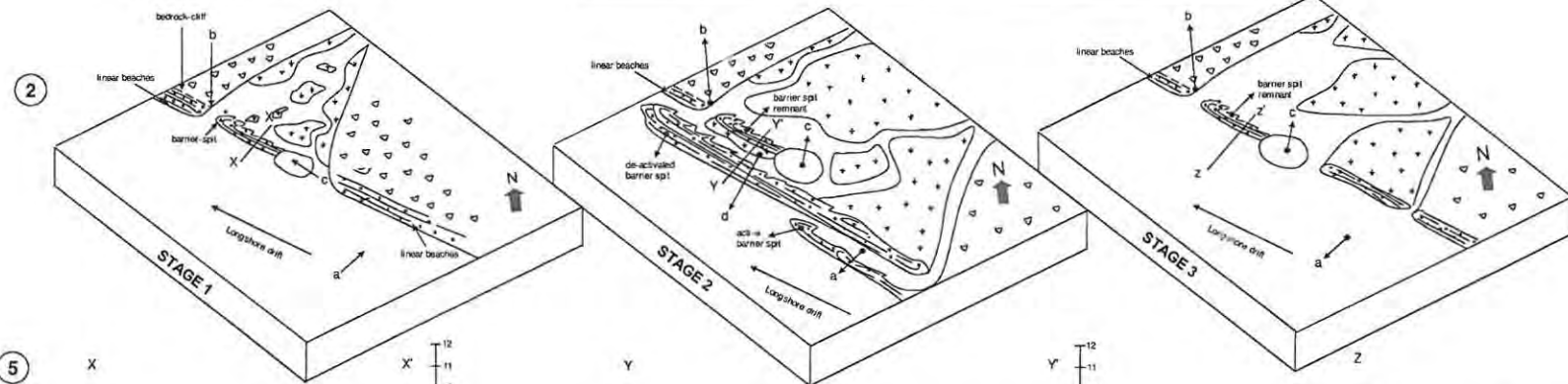
Figure 4.8: Hypothetical model for the genesis of the barrier spit stratigraphy. Cross-section of trench (1) and conceptual block models (2) illustrate development of a vertical stratigraphic sequence (3). Note that ebb-tidal and flood-tidal deltas have been omitted from the block diagrams. In river-dominated estuaries, as in the case of the Orange River, these features are poorly developed or absent due to strong wave energy and weak tidal currents (Cooper, 2002). Block models depict the evolutionary path of the study area only. The preserved deposits are therefore a small representation of the greater coastal feature as shown in the schematic diagram (4) that illustrates a lowstand phase, following a forced regression. The depositional signatures of the last two were not preserved. Information for diagram sourced from Dominguez *et al.* (1987). Cross-sections of each depositional model are shown in (5), whilst the sea-level and sedimentation behaviour is illustrated in sine curve diagrams (6).



- a = position of present Orange River mouth = 28° 37' 54" S; 16° 27' 12" E
- b = position of F cliff/palaeo-Orange River sediment contact = 28° 33' 15" S; 16° 22' 28" E
- c = position of bedrock island = 28° 34' 55" S; 16° 24' 58" E
- d = position of back-barrier clay in G19 trench = 28° 34' 30" S; 16° 24' 04" E

position of present coastline

- ▲ sand dunes
- vegetated estuarine-lagoon sediments



Barrier spit deposits not preserved

Preserved barrier spit deposits

SL2

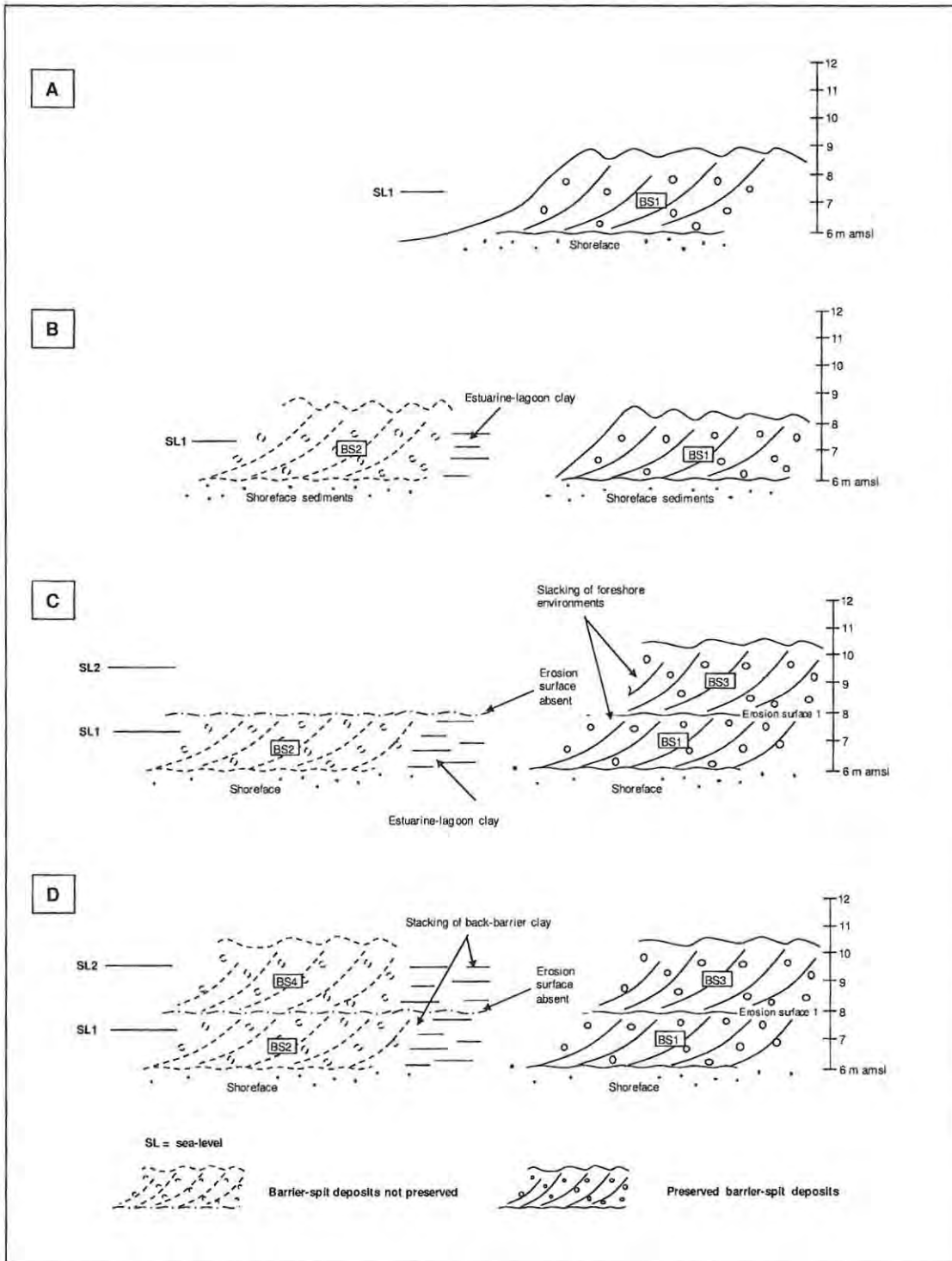
SL1

Shoreface

6 m amsl

Figure 4.9: Hypothetical model for the genesis of the barrier beach stratigraphy. Cross-section of key trench (1) and conceptual block models (2) illustrate development of a vertical stratigraphic sequence (3). Note that ebb-tidal and flood-tidal deltas have been omitted from the block diagrams. In river-dominated estuaries, as in the case of the Orange River, these features are poorly developed or absent due to the strong wave energy and weak tidal currents (Cooper, 2002). Cross-sections of each depositional model are shown in (4), whilst the sea-level and sedimentation behaviour is illustrated in sine curve diagrams (5).

Figure 4.10: Schematic illustration explaining the genesis of barrier spit deposits as discussed in Section 4.4. (A) Emplacement and progradation of most landward barrier spit (BS1). (B) Growth of emerging barrier (BS2) seaward of and isolating barrier BS1 from open coast. Estuarine-lagoon setting develops seaward of BS1. (C) Transgression and erosion of older barrier spit features, leading to emplacement of barrier spit BS3 and stacking of foreshore environments. Note that the only evidence of this erosive event is limited to the foreshore gravels. (D) Isolation and abandonment of barrier spit BS3 by emerging barrier feature (BS4) seaward of BS3. The development of an estuarine-lagoon allows stacking of back-barrier sediments into a 5 m thick clay sequence.



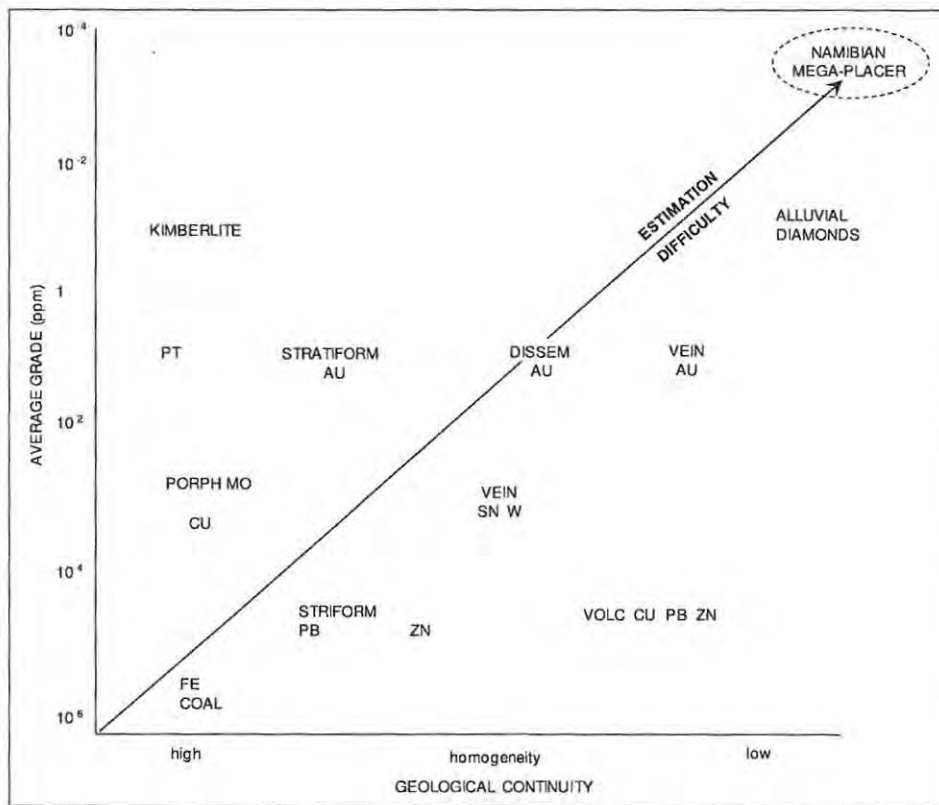


Figure 5.1: Comparison of grade with geological continuity to illustrate estimation difficulty of ore deposits (modified after King *et al.*, 1982; cited in Prins, 2000). Note the position of the Namibian mega-placer (onshore littoral deposits; circled by stippled line).

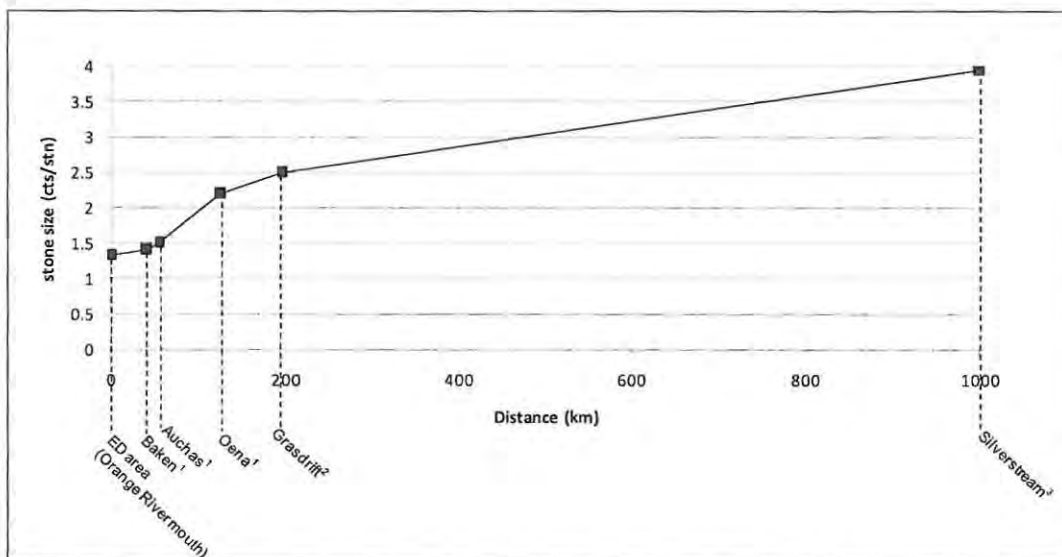


Figure 5.2: Diamond size comparison (cts/stn) in a downstream direction from proximal Meso-Orange River deposits at Silverstream to distal marine deposits of similar age at the Orange River mouth. Source of information – ¹J. Ward (pers. comm., 2009), ²Ward *et al.* (2002) and ³Venmyn (2007).

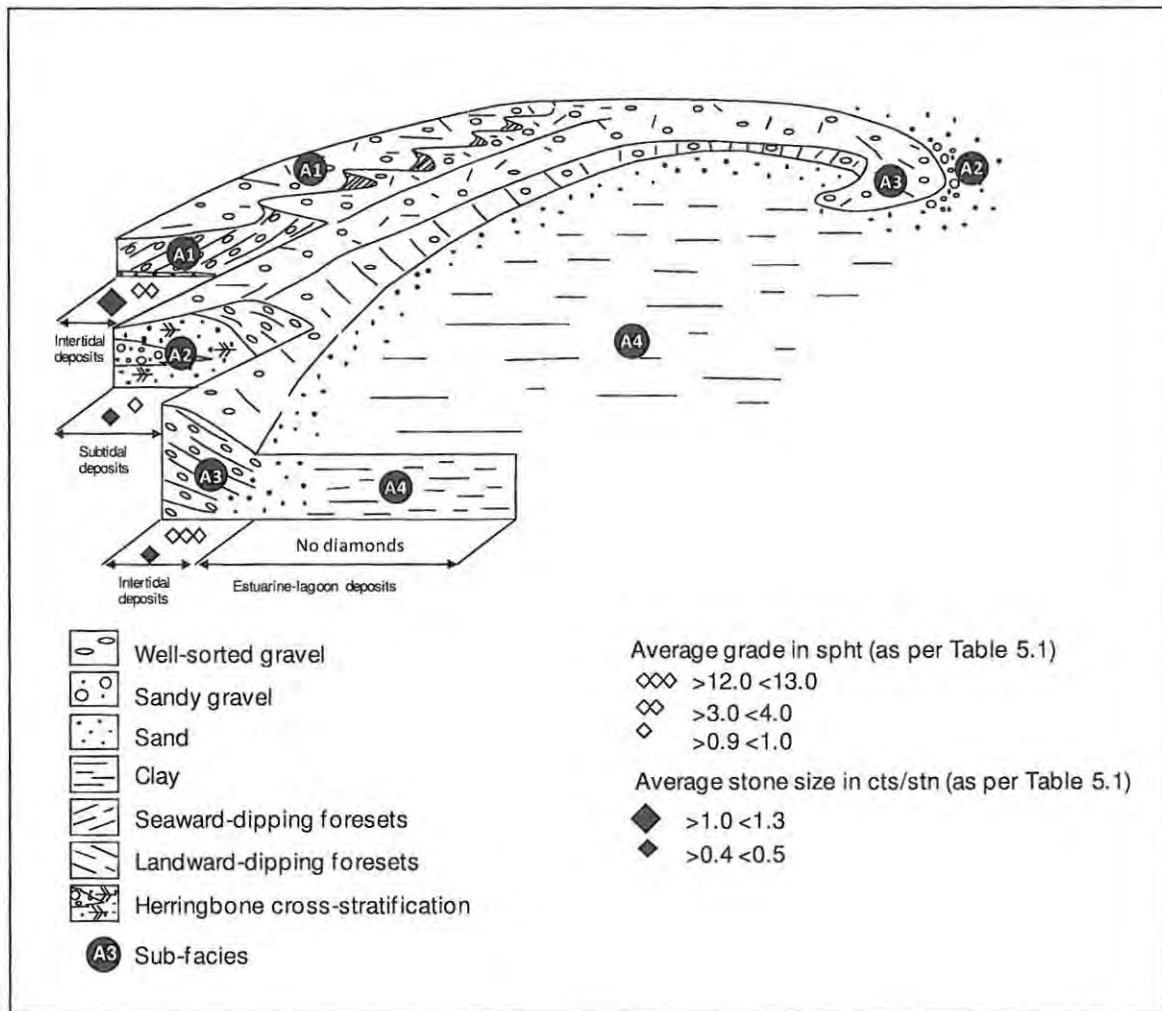


Figure 5.3: Schematic representation of a gravel barrier spit (Facies A) showing distribution of average grade (spht) and stone size (cts/stn) within the different depositional sub-environments (source Spaggiari *et al.*, 2006)

Figure 5.4: Average grade distribution in Facies B (transgressive lag). Illustrations depict stone density in intervals of 1 spht (A), whilst broad contouring (B) depicts zones of grade variation. Block diagram (C) and locality plan (D) portrays position of mineralised area.

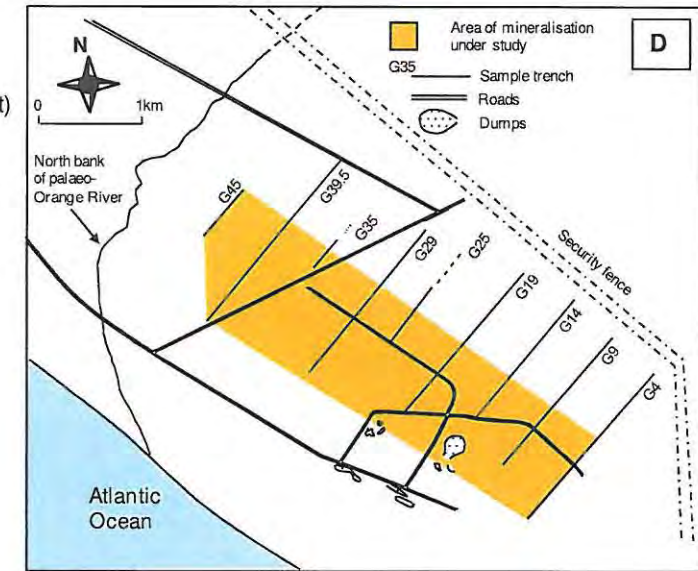
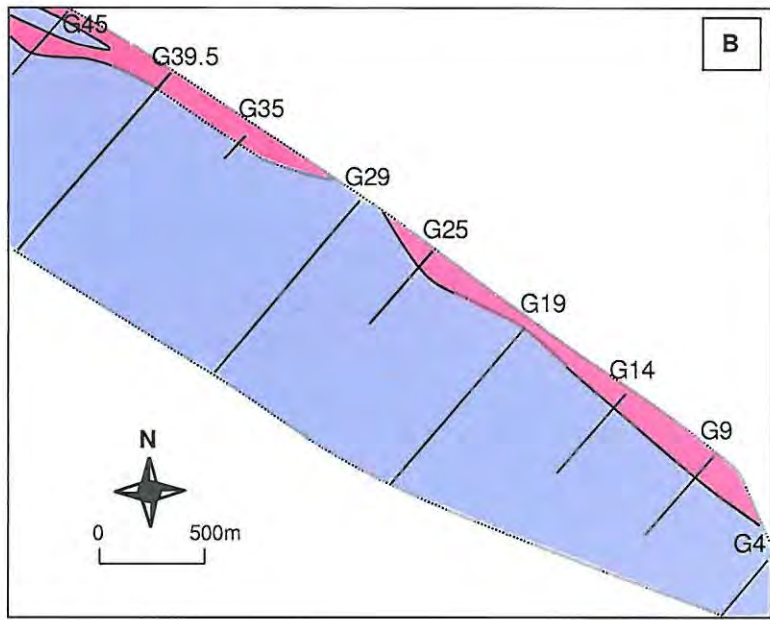
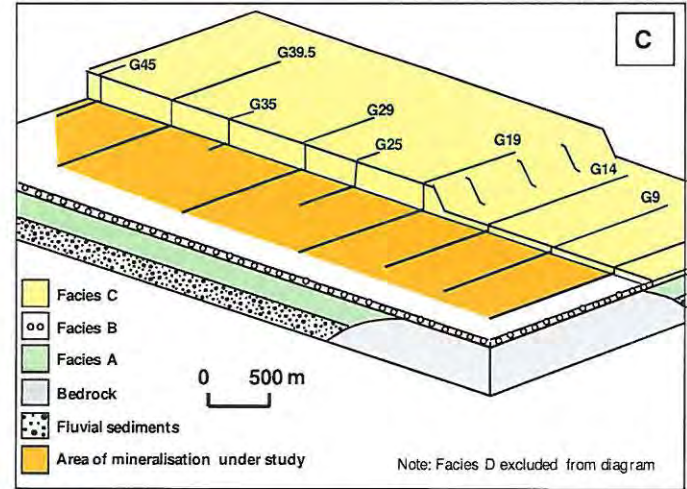
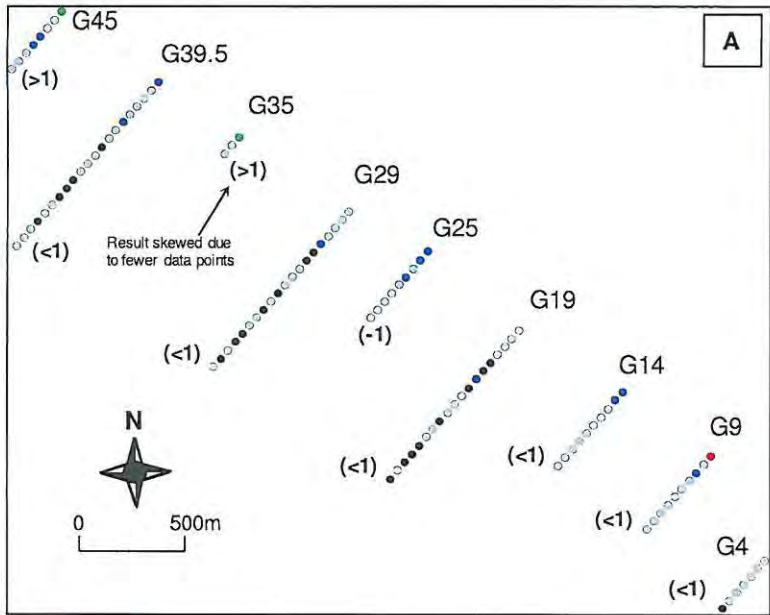
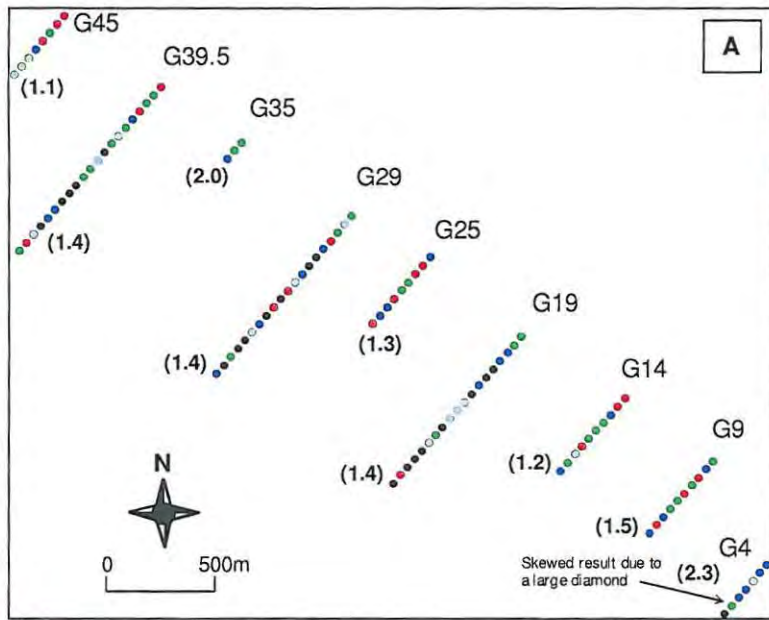


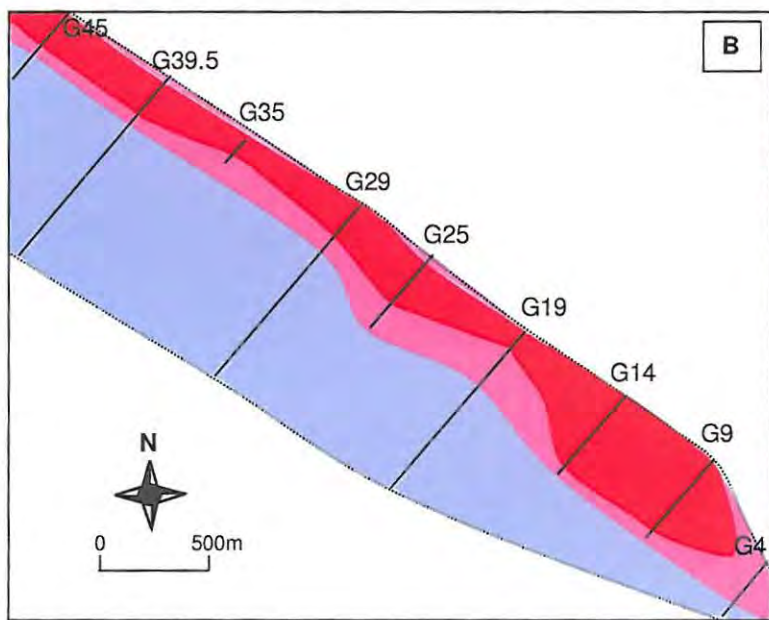
Figure 5.5: Average stone size distribution in Facies B (transgressive lag). Illustrations depict average size in intervals of 0.5 cts/stn (A), whilst broad contouring (B) depicts zones of average stone size. Block diagram (C) and locality plan (D) portrays position of mineralised area.



Stone size (cts/stn)

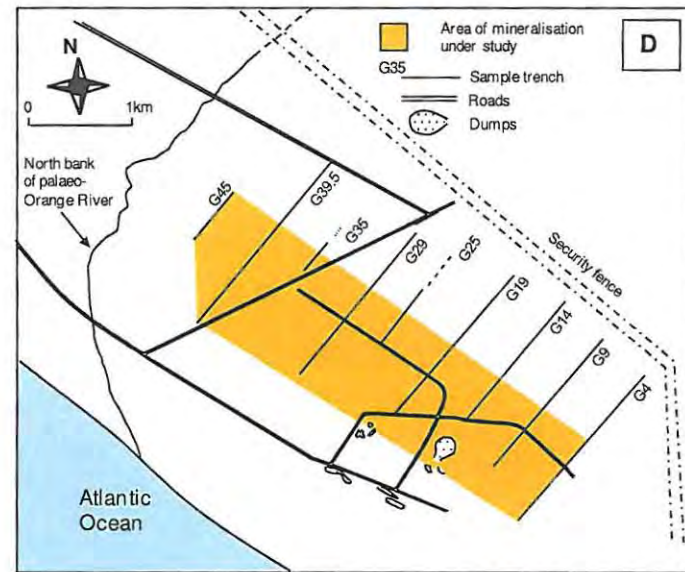
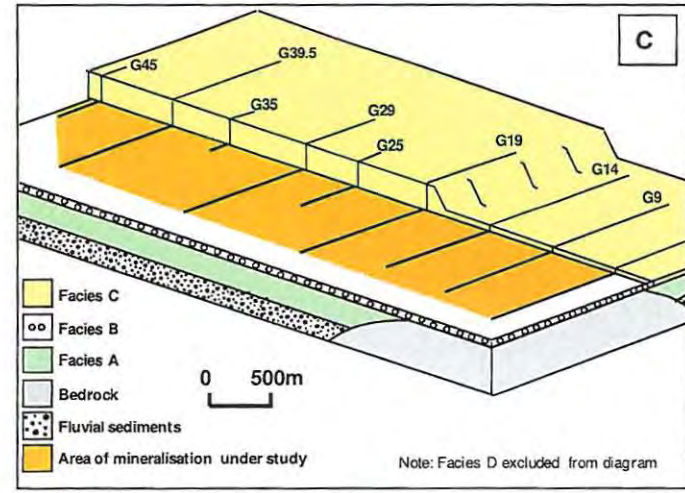
- >1.5
- 1.0-1.5
- 0.5-1.0
- 0.1-0.5
- 0.0

(1.6) – Average cts/stn per sample trench



Average diamond size (cts/stn)

- Exceptionally large average size (>1.0)
- Large average size (0.5-1.0)
- Small average size (<0.5)
- G29 — Sample trench



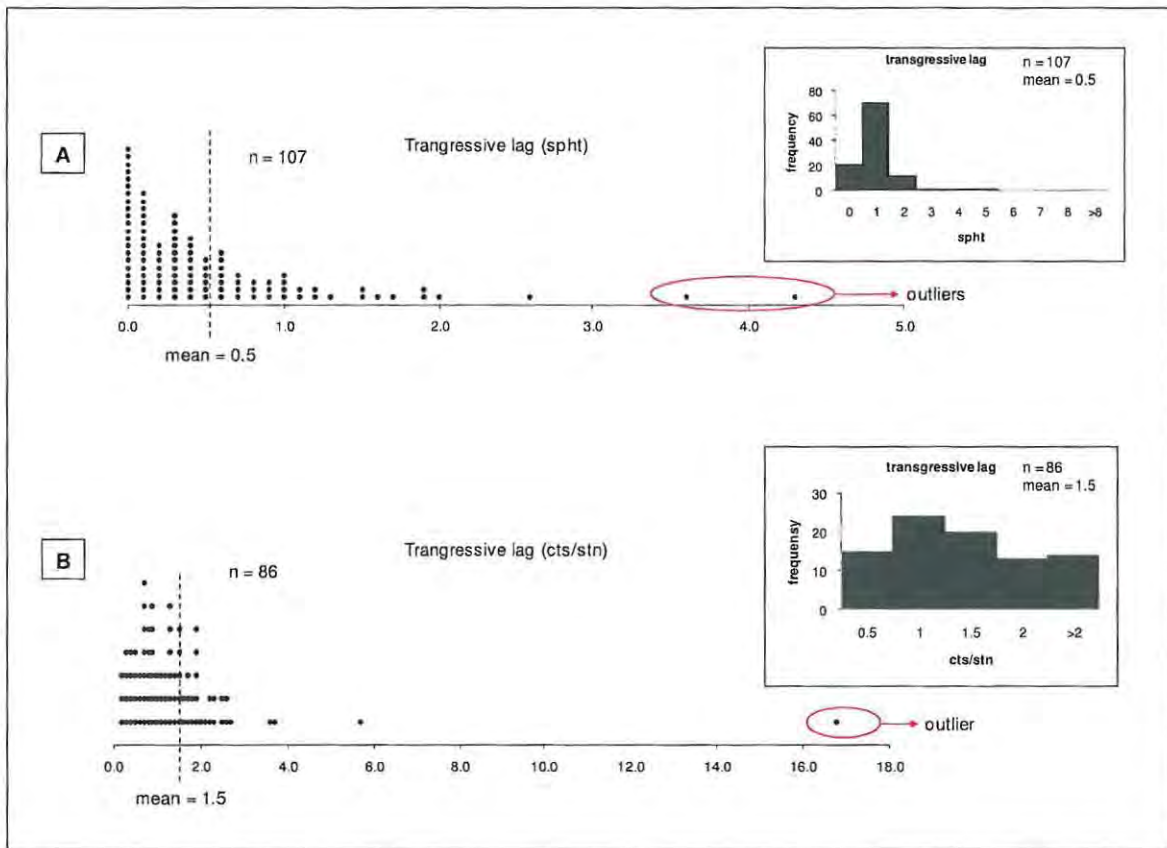


Figure 5.6: Dispersion graphs for Facies B (transgressive lag) grade and stone size data. The graphs illustrate dispersion about the mean for both grade (A) and stone size (B) with frequency distribution graphs included as insets.

Figure 5.7: Average grade distribution in Facies C (gravel barrier beach). (A) Vertical coloured lines illustrate stone density (spht) in intervals of 1 spht, whilst broad contouring (B) depicts zones of grade variation. Block diagram (C) portrays position of mineralised area.

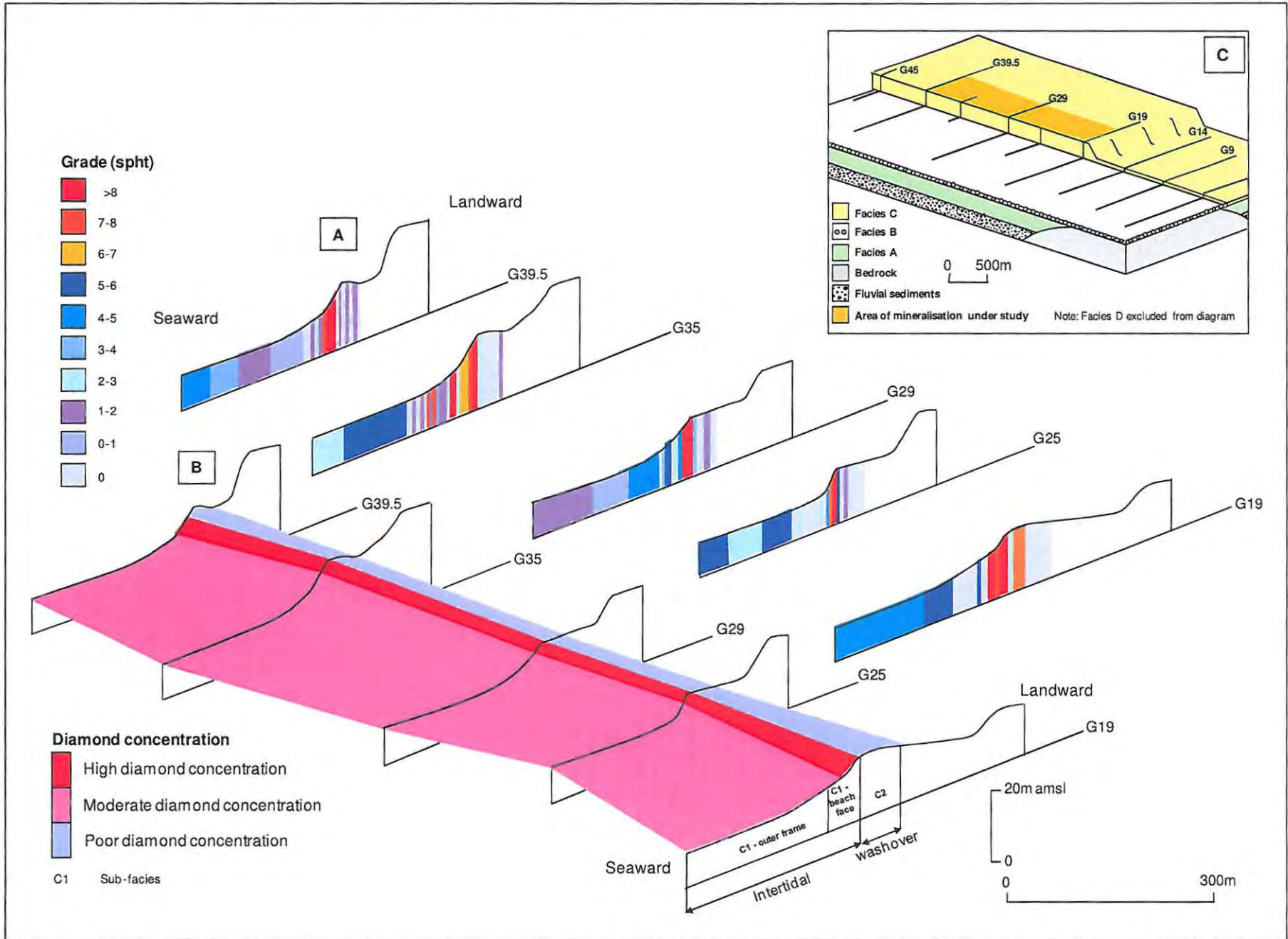
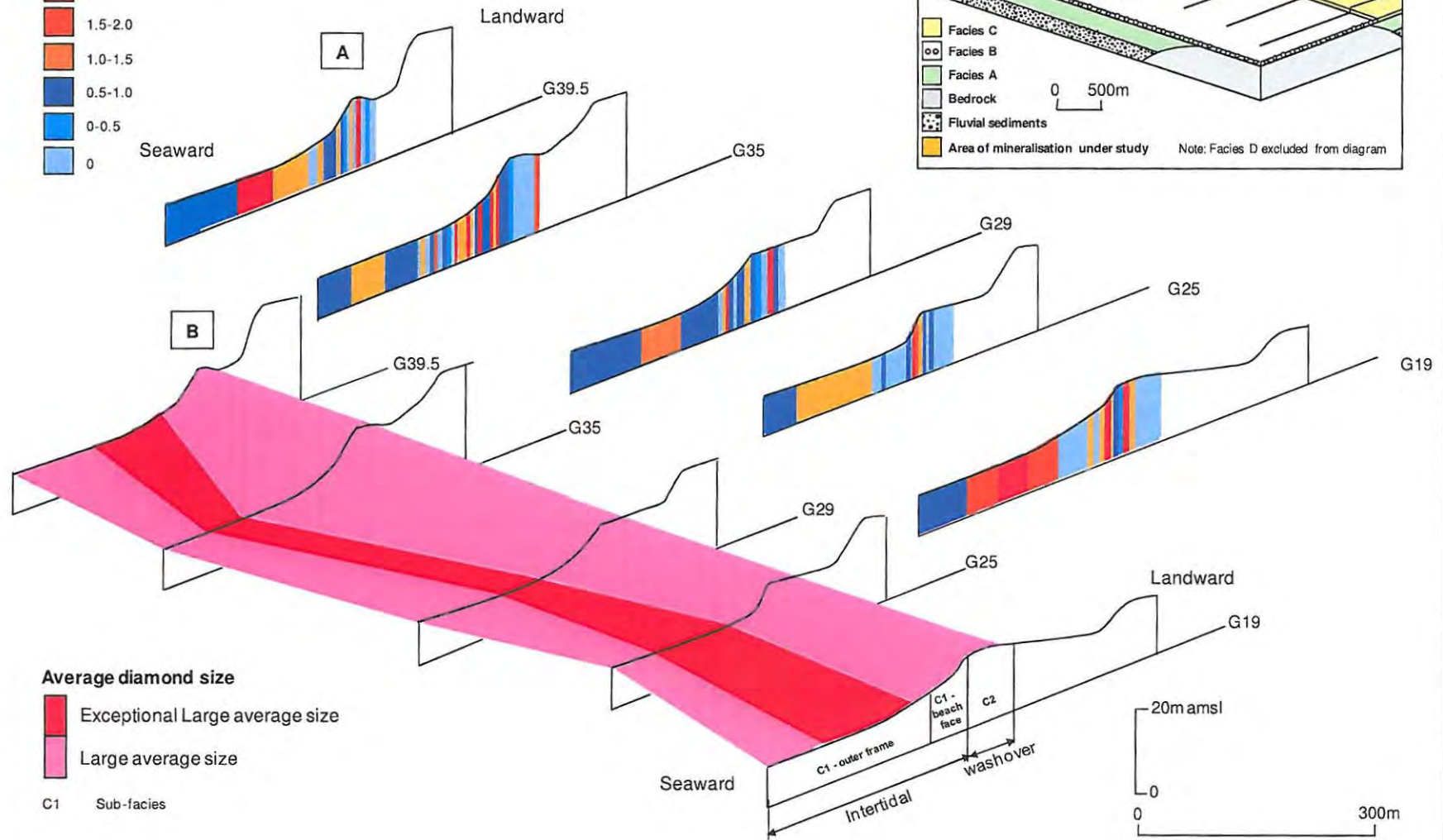
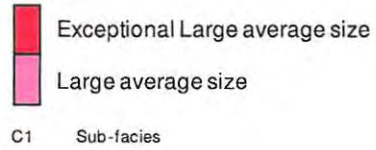


Figure 5.8: Average stone size distribution in Facies C (gravel barrier beach). (A) Vertical coloured lines illustrate distribution of average stone size (cts/stn) in intervals of 0.5 cts/stn, whilst broad contouring (B) depicts zones of average stone size. Block diagram (C) portrays position of mineralised area.

Stone size (cts/stn)

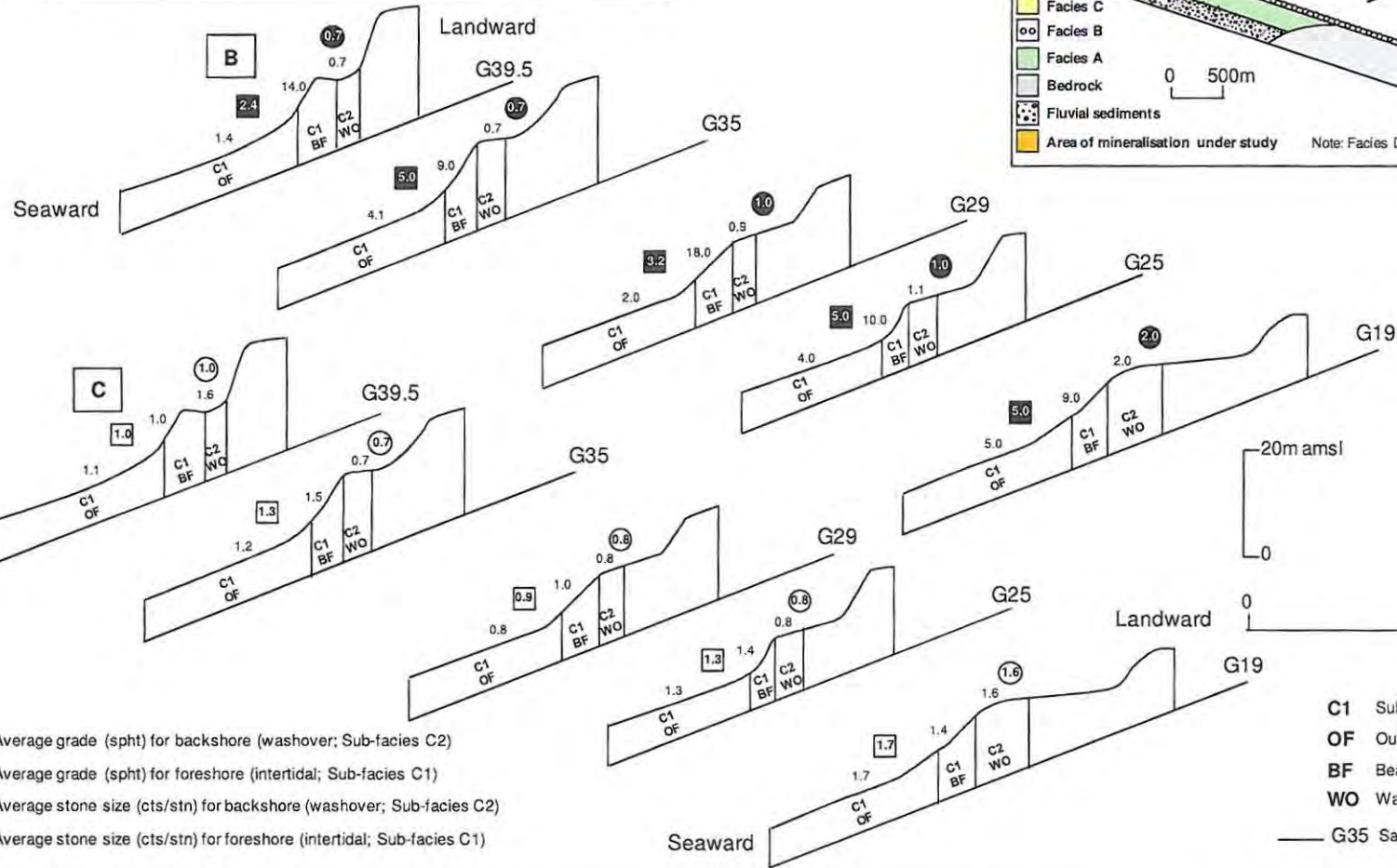
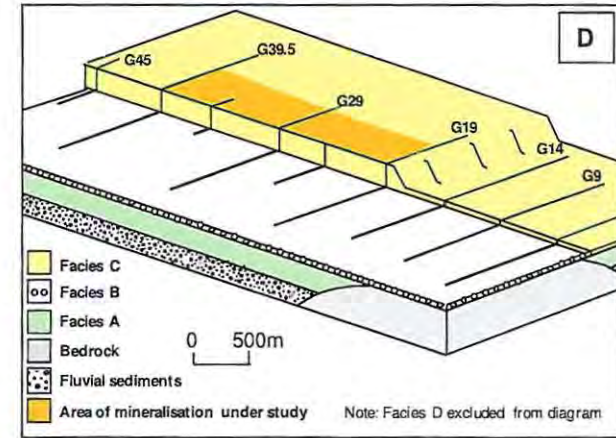
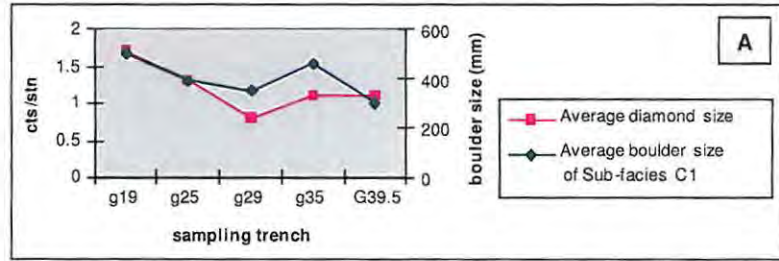


Average diamond size



C1 Sub-facies

Figure 5.9: Comparison of diamond results from foreshore and backshore settings in Facies C (barrier beach). **(A)** Graph illustrating diamond and boulder size association in Sub-facies C1 (beach toe). **(B)** Comparison of grade (spht) and **(C)** stone size (cts/stn) in foreshore and backshore depositional sub-environments. **(D)** Map illustrating locality of mineralised area.



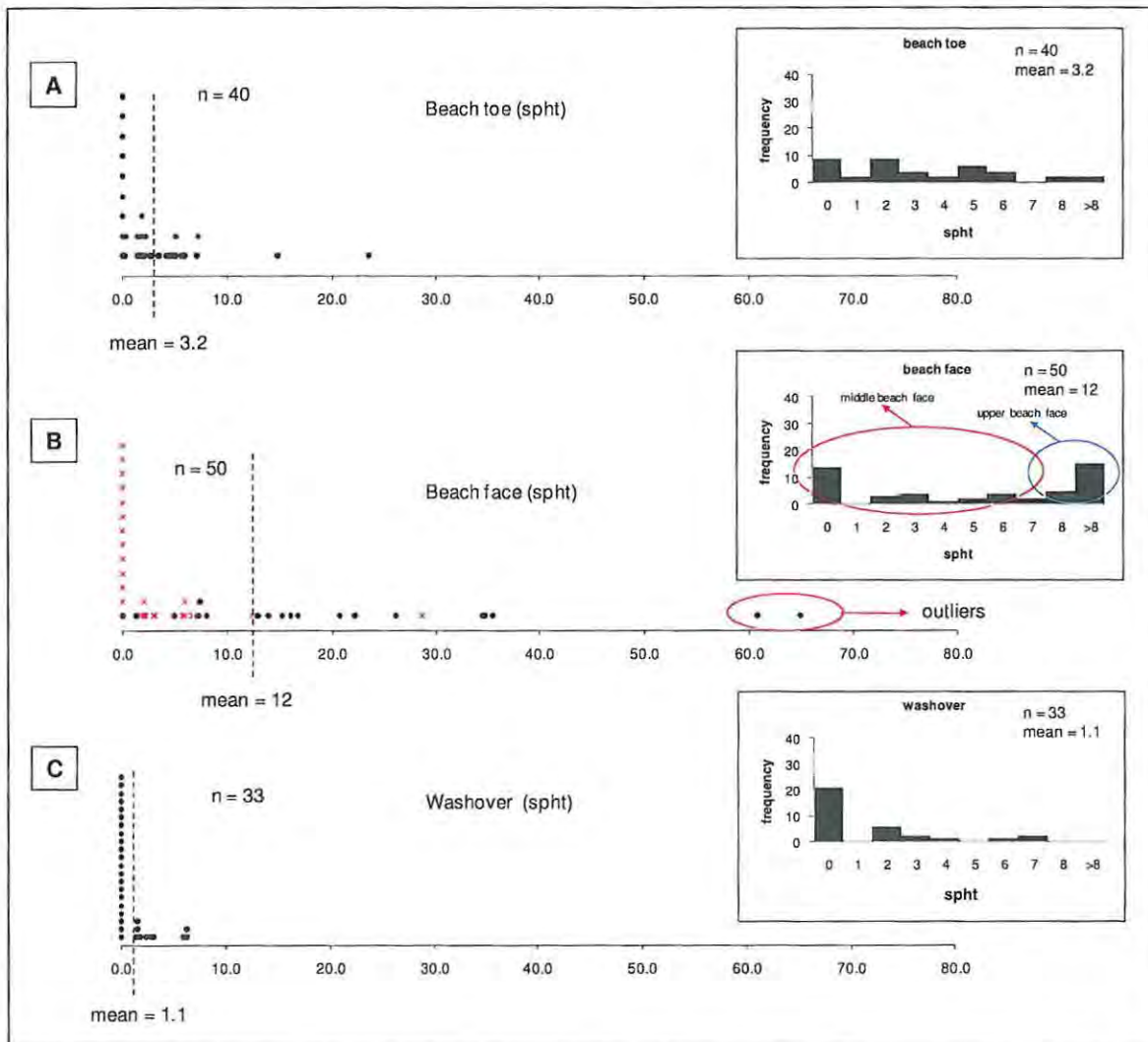


Figure 5.10: Dispersion graphs for Facies C (barrier beach) grade (spht) data. The graphs illustrate dispersion about the mean for outer frame (beach toe; **A**), beach face (**B**) and washover sub-environments (**C**) with frequency distribution graphs included as insets. In the beach face graph (**B**), red crosses represent the middle sector of the beach face, whilst black dots correspond to the upper beach. The higher values correlate mostly to the upper beach face as discussed in the text and circled blue in the frequency distribution graph. Note the high number of zero values within the washover data.

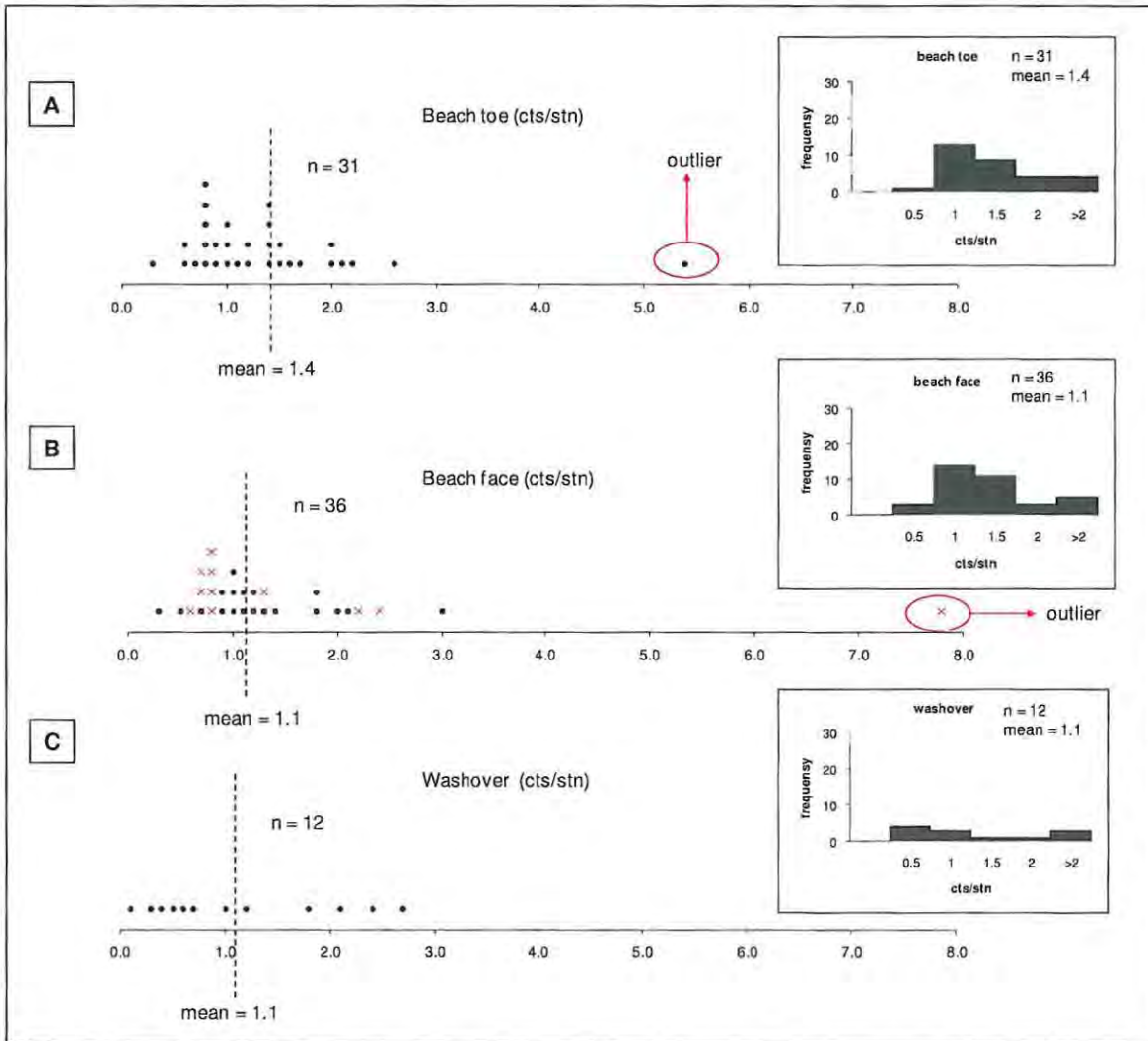


Figure 5.11: Dispersion graphs for Facies C (barrier beach) stone size (cts/stn) data. The graphs illustrate dispersion about the mean for outer frame (beach toe; **A**), beach face (**B**) and washover sub-environments (**C**) with frequency distribution graphs included as insets. In the beach face graph (**B**), red crosses represent the middle sector of the beach face, whilst black dots correspond to the upper beach face. Note the similarities in the frequency distributions of the beach face and outer frame (beach toe) with the influence of outliers.

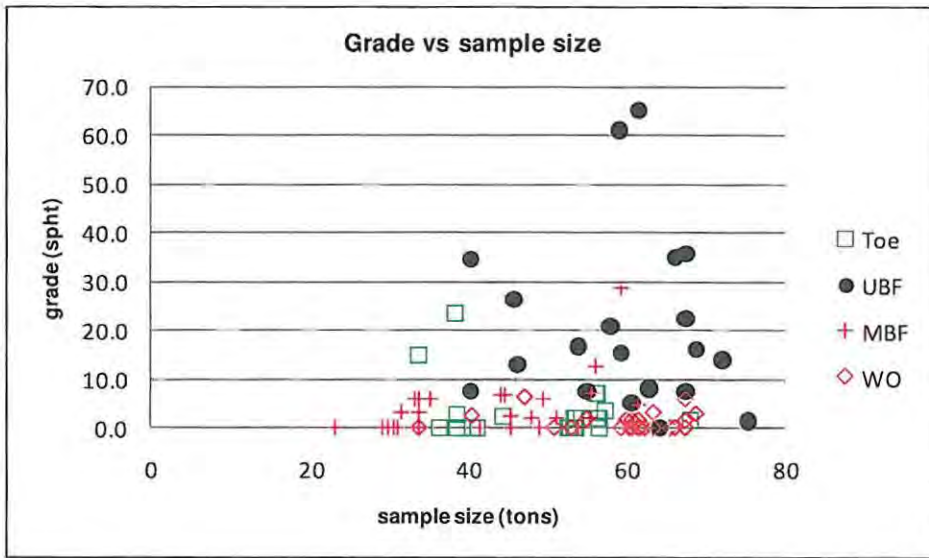
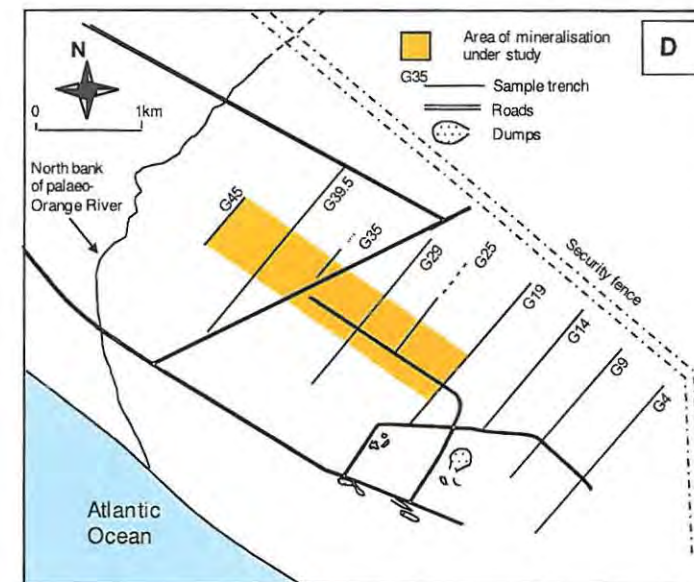
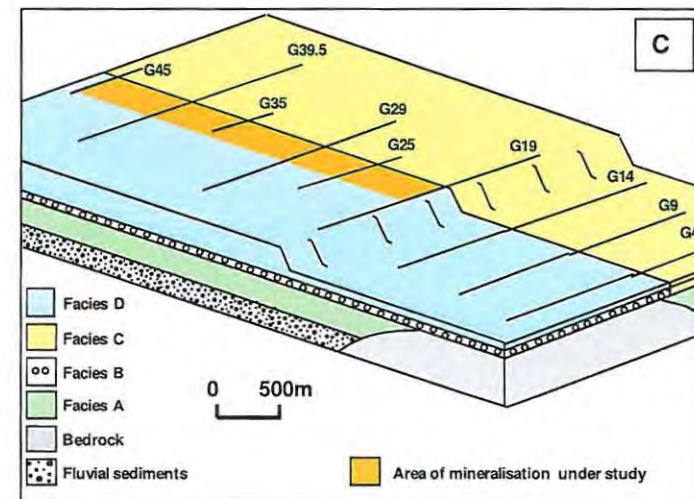
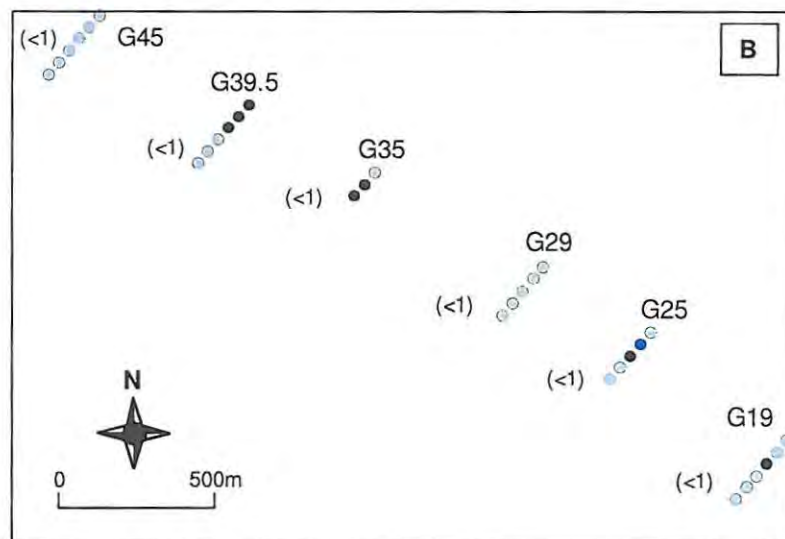
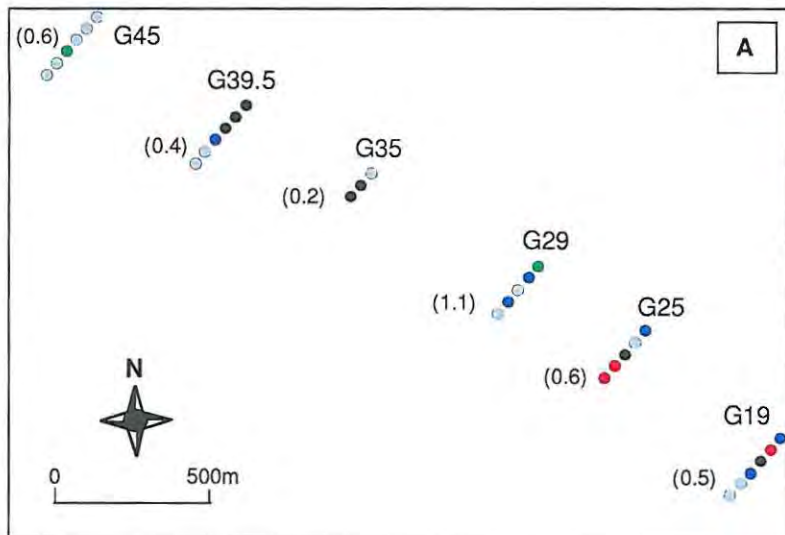


Figure 5.12: Grade versus sample size for barrier beach settings. Note that the sample support size is generally similar and although considered small for alluvial diamond sampling, the graph nonetheless depicts a dominance of higher grades in the upper beach face as demonstrated through basic statistics in Section 5.2.3. Note, Toe = beach toe (outer frame), UBF = upper beach face, MBF = middle beach face, WO = washover.

Figure 5.13: Average stone size and grade distribution in Sub-facies D3 (storm gravel sheets). Illustrations depict average size in intervals of 0.5 carats per stone (**A**) and stone density in intervals of 1 stone per hundred ton (**B**). Note that broad zonation of results is not depicted due to the lack of mineralization trends. Block diagram (**C**) and locality plan (**D**) portrays position of mineralised area.



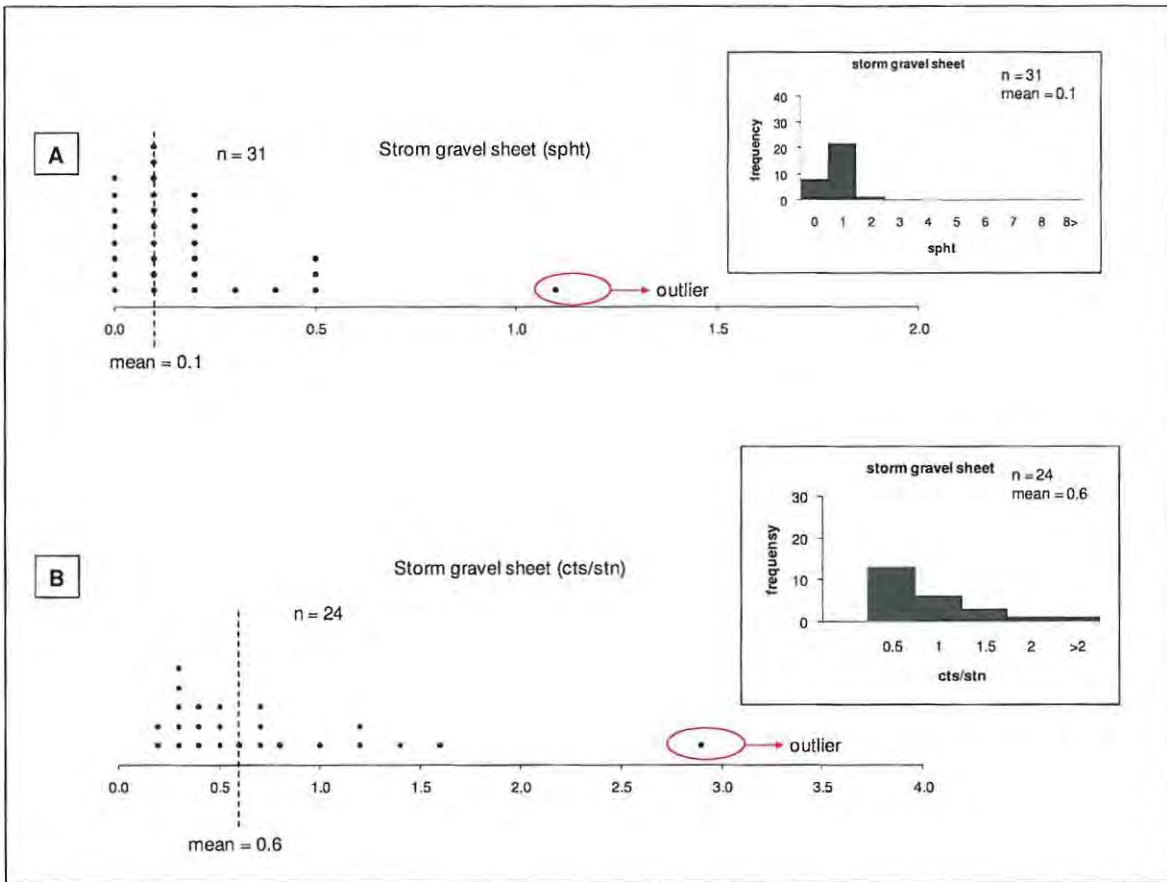


Figure 5.14: Dispersion graphs for the Sub-faces D3 (storm gravel sheet) grade and stone size data. The graphs illustrate dispersion about the mean for both grade (A) and stone size (B) with frequency distribution graphs included as insets.

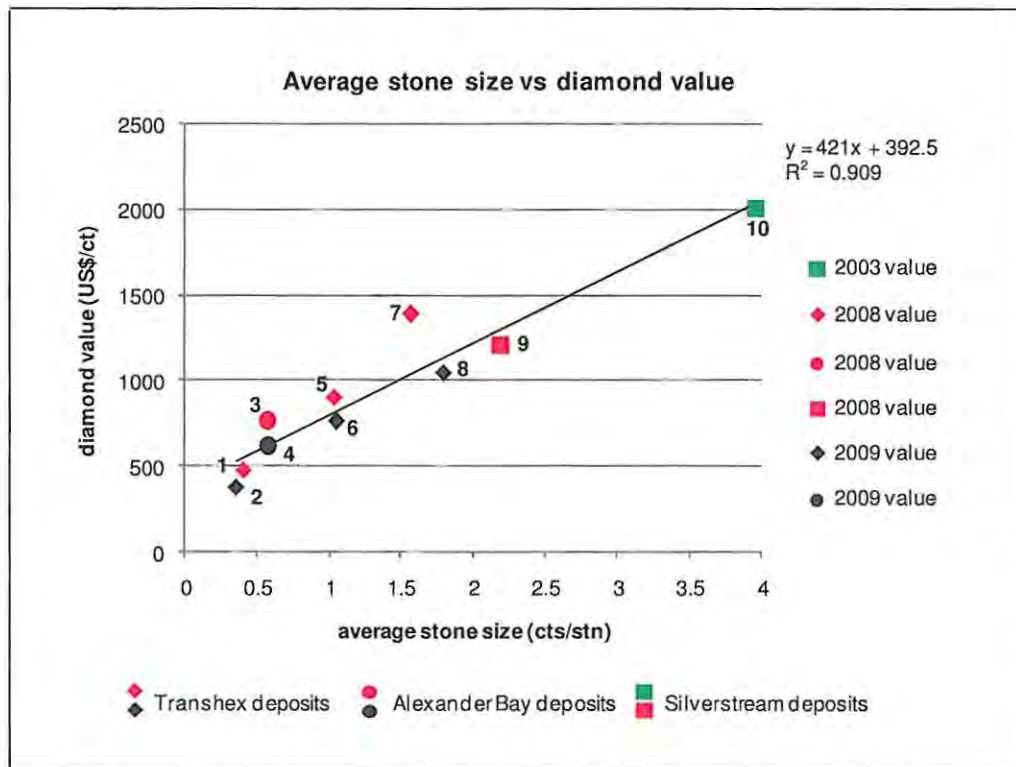


Figure 5.15: Diamond value (US\$/ct) baseline data for estimating ED Area diamond values. The graph illustrates diamond values (2003, 2008 and 2009 tenders) from palaeo-Orange River and marine deposits. The latter is immediately south of the study area in Namaqualand, South Africa. 1 to 2 = shallow marine deposits along Atlantic Coast, 3 and 4 = onshore littoral deposits along Atlantic Coast, 5 and 6 = Baken Mine Orange River deposits, 7 and 8 = Richtersveld Orange River deposits, 9 and 10 = Silverstream Orange River deposit. Diamond values are sourced from: Trans Hex (2009) for 1 to 2 and 5 to 8, Alexkor (2009) for 3 and 4, Martineau (2008) for 9 and Venmyn (2007) for 10.

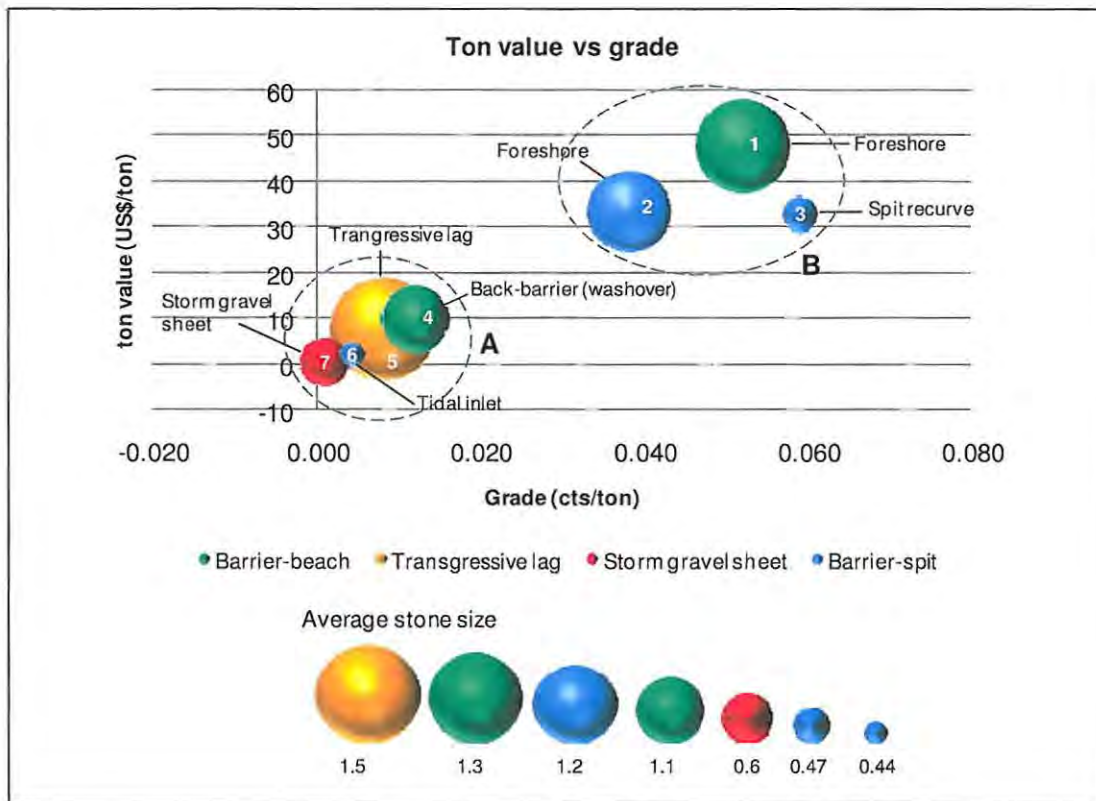


Figure 5.16: Bubble chart illustrating ED Area deposits ton value (US\$/ton) against grade (cts/ton). Note that the grade is expressed as carats per ton (cts/ton) in this instance to allow for establishing ton values. Size of bubble is related to average stone size, whilst white numbers correlate to ranking of facies potential presented in Table 5.9. Grey stippled circles designated **A** and **B** correspond to populations of lower and higher potential, respectively, as discussed in the text.

Figure 5.17: Composite mineralisation diagram illustrating overall average grade and stone size for different depositional sub-environments in barrier spit and barrier beach deposits. The diamond results recorded in Tables 5.1, 5.2, 5.4 and 5.7 were combined to illustrate the composite mineralisation diagram (source Spaggiari *et al.*, 2006).

BARRIER BEACH

Facies/Sub-facies	B	D3	C1		C2
Diamond concentration (grade)	◇	◇	◇◇◇	◇◇◇◇	◇◇
Diamond size (stone size)	◆	◇	◆	◇	◇

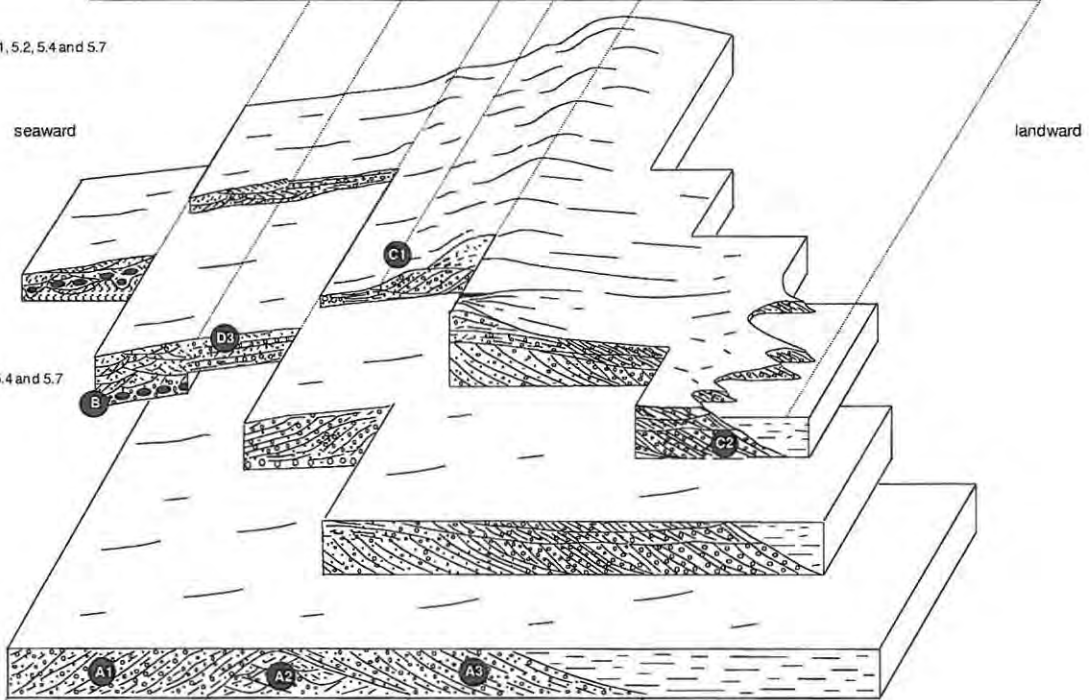
Average stone size (cts/stn) as per Tables 5.1, 5.2, 5.4 and 5.7

- ◆ >1.4<1.6
- ◆ >1.3<1.4
- ◇ >1.0<1.3
- ◇ >0.5<0.9
- ◇ >0.4<0.5

Average grade (spt) as per Tables 5.1, 5.2, 5.4 and 5.7

- ◇ <1.0
- ◇◇ >1.0<2.0
- ◇◇◇ >3.0<4.0
- ◇◇◇◇ >12.0<13.0

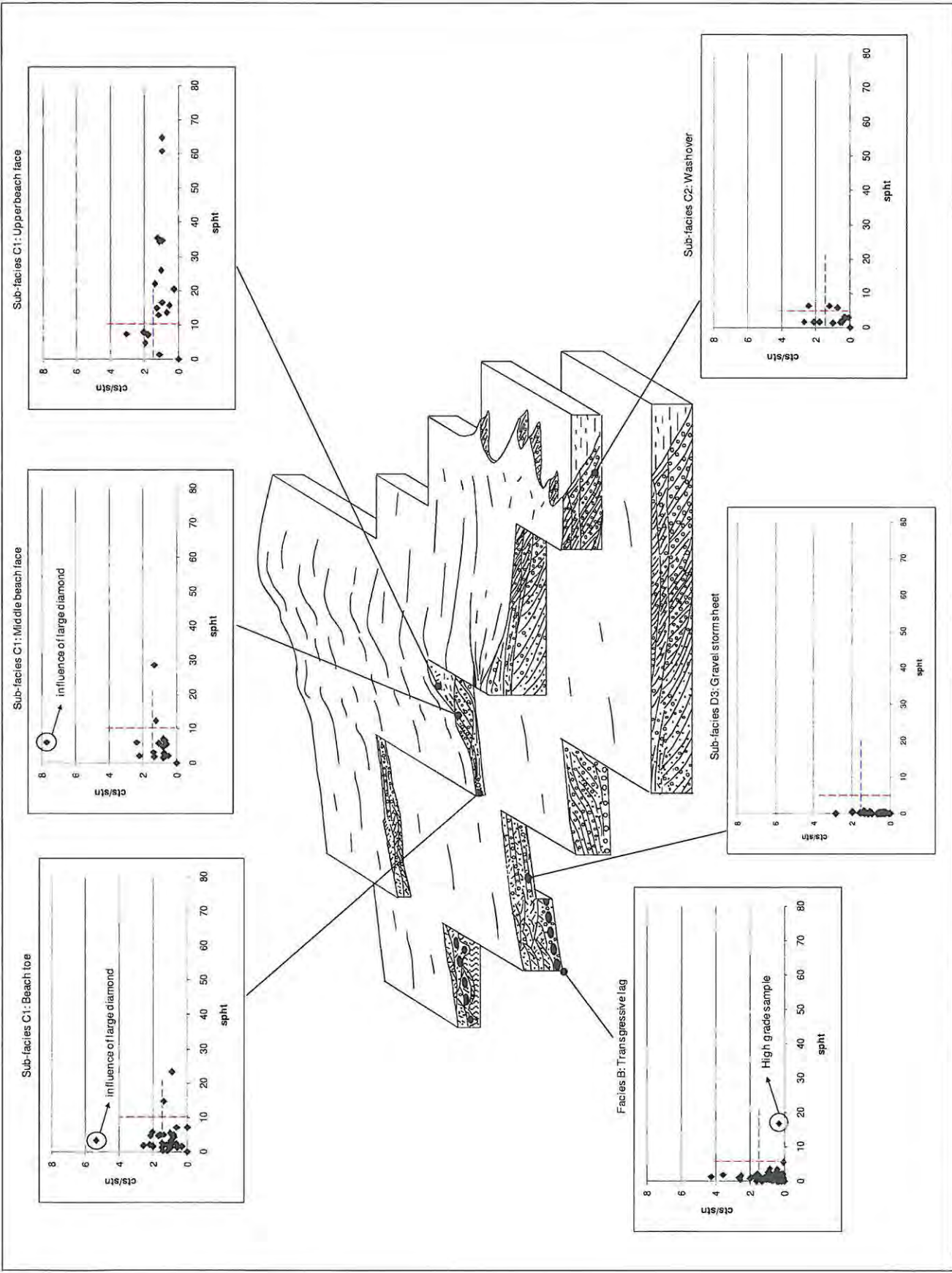
- ⓑ Facies
- ⓒ Sub-facies



BARRIER-SPIT

Facies/Sub-facies	A1	A2	A3
Diamond concentration (grade)	◇◇◇	◇	◇◇◇◇
Diamond size (stone size)	◇	◇	◇

Figure 5.18: Composite mineralisation diagram illustrating statistical summary of average grade (spht) against average stone size (cts/stn). Mention must be made that the barrier spit data have been excluded given the small number of samples that do not allow a statistical comparison. Note that the plots for the beach toe (outer frame) and middle beach face are similar where the distribution is confined predominantly to less than 10 spht (left of red, vertical, stippled line), whereas the distribution for the upper beach face is greater than 10 spht (right of red vertical stippled line). The transgressive lag, storm gravel sheet and washover plots are similar with distributions predominantly less than 5 spht (left of red vertical stippled line). The first two are shoreface sheet-like bodies. However, both the transgressive lag and beach toe (outer frame) plots illustrate a greater occurrence of stones larger than 1.5 cts/stn (above blue, horizontal, stippled line). These sub-environments are considered contiguous where the transgressive lag has its origin in the outer frame setting.



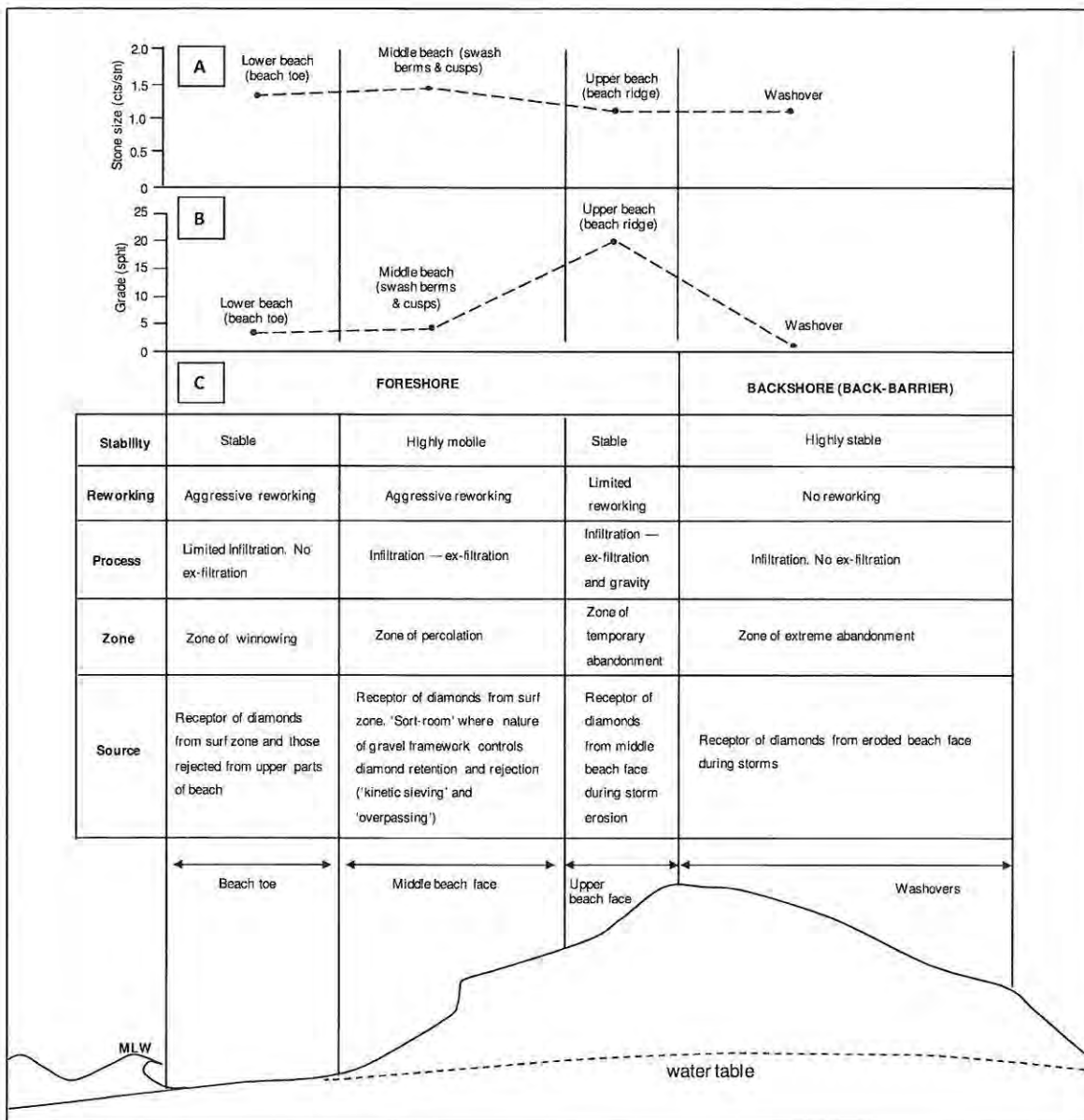


Figure 5.19: Summary of hypothetical diamond mineralisation processes in a barrier beach. Average diamond size (A) and diamond concentration (B) for the barrier beach sub-environments are graphically presented. The characteristics of diamond accumulation are tabulated for each depositional sub-environment in (C). Note acronym MLW = mean low water.

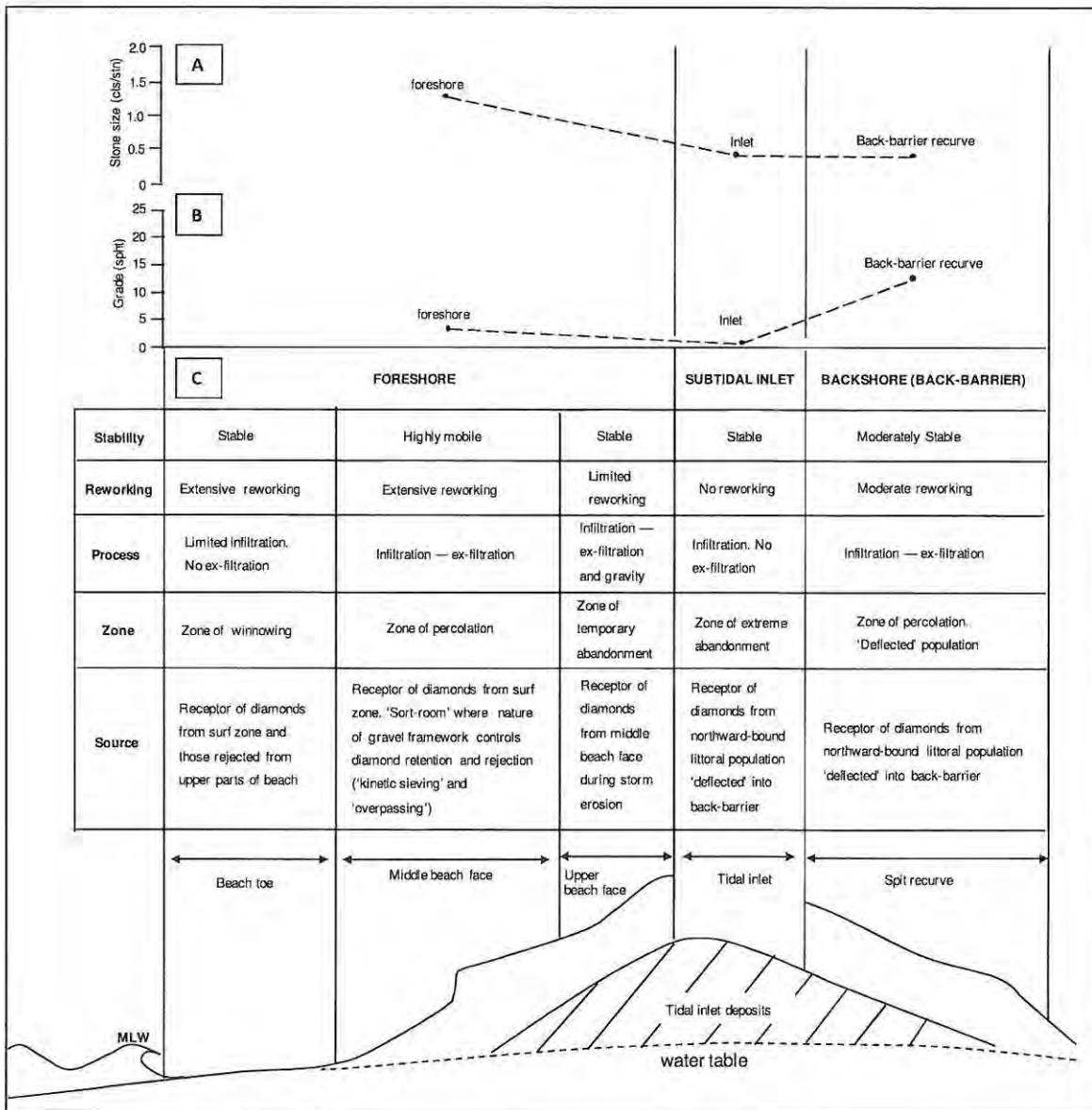


Figure 5.20: Summary of hypothetical diamond mineralisation processes in a barrier spit. Average diamond size (**A**) and diamond concentration (**B**) for the barrier spit environment are graphically presented. (**C**) The characteristics of diamond accumulation are tabulated for each depositional sub-environment of a barrier spit. Note acronym MLW = mean low water.

Figure 6.1: Regional distribution of onshore diamondiferous palaeo-littoral deposits. The general distribution encompasses their entire stratigraphy, ranging from Eocene to Holocene age. Information sourced from Hallam (1964), Keyser (1972), Tankard (1975), Miller & Seely (1976), Ward (1984, 2000), Pether (1986, 1994, 2000), Gresse (1988), Schneider & Miller (1992), Pickford & Senut (1999), Roberts & Brink (2002), Franceschini & Compton (2004), Spaggiari & Ward (2004), Miller (2008).

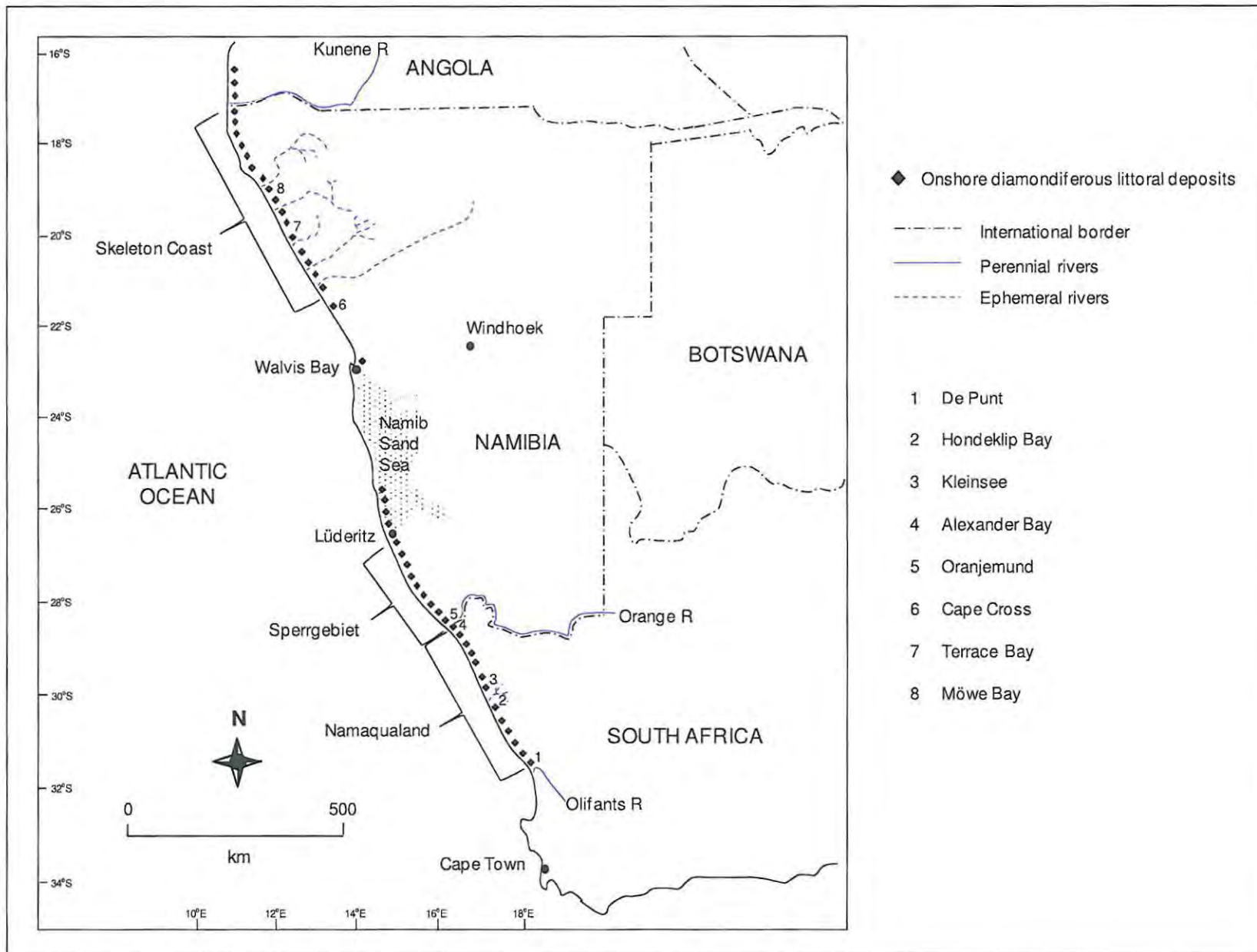
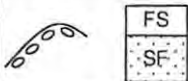
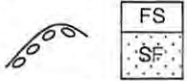

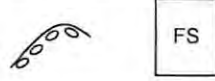




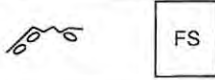
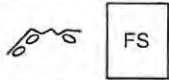
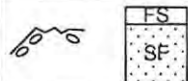
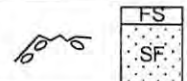
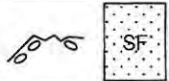


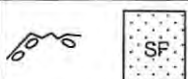
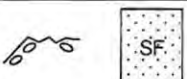
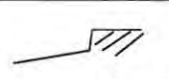



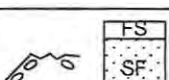

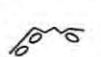
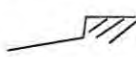


Figure 6.2: Stratigraphic representation of diamondiferous palaeo-shorelines along the Atlantic Coast of South Africa and Namibia. A generalised perspective of the degree of preservation and dominance of depositional environments are also shown. Information sourced from Hallam (1964), Keyser (1972), Pether (1986, 1994, 2000), Ward (1984, 2000), Gresse (1988), Corbett (1989), Pickford & Senut (1999), Roberts & Brink (2002), Franceschini & Compton (2004), Miller (2008), P. Gresse (pers.com., 2010), W. Macdonald (pers.com., 2010) and J. Ward (pers.com., 2010).

Approximate age	Marine package	Zone Fossil	Namaqualand S (South Africa)	Namaqualand N (South Africa)	Sperrgebiet (Namibia)	Walvis Bay and north (Namibia)	Skeleton Coast (Namibia)
0.007-0.4 Ma	Sub 10 m beaches	<i>Donax serra</i>					
3-2.5 Ma	30 m Package	<i>Donax rogersi</i>					
7-5 Ma	50 m Package	<i>Donax haughtoni</i>					
18-17.6 Ma	90 m Package	<i>Isognomon gariesensis</i>				???	
37-40 Ma	Buntfeldschuh Formation	???				absent	absent

 Well developed deposits
  Vestiges of deposits
  No deposits. Geomorphic feature.

FS = foreshore deposits SF = shoreface deposits

Figure 6.3: Regional distribution of 30 m Package (Plio-Pleistocene) onshore palaeo-littoral deposits. Their general distribution and the dominant depositional environments are also presented (see also Figure 6.2). Note that where two depositional environments are recorded, the first is dominant. Information sourced from Hallam (1964), Keyser (1972), Miller & Seely (1976), Ward (1984, 2000), Pether (1986, 1994, 2000), Gresse (1988), Schneider & Miller (1992), Pickford & Senut (1999), Franceschini & Compton (2004), Millad (2004), Spaggiari & Ward (2004), Compton (2006) and Miller (2008).

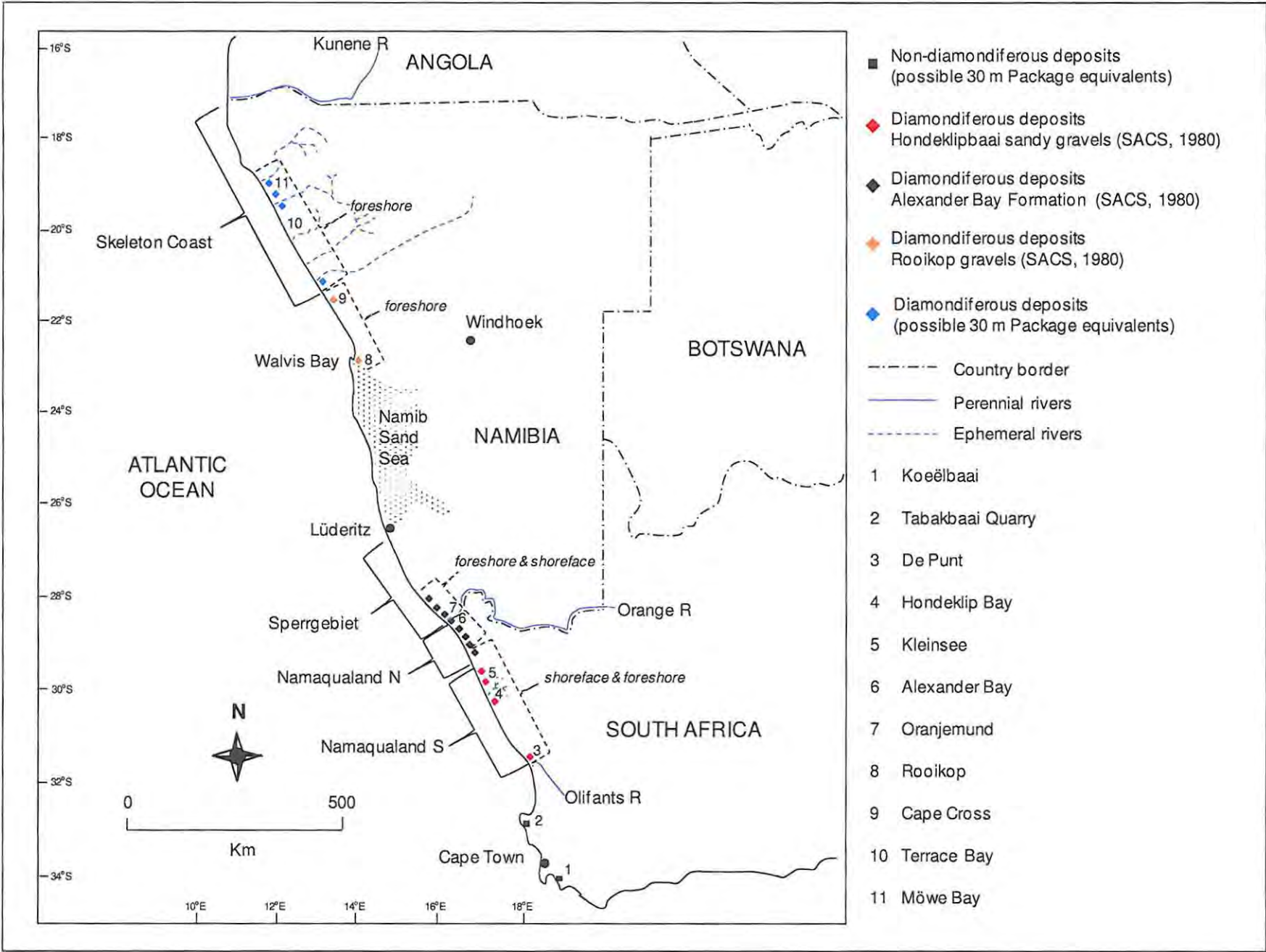
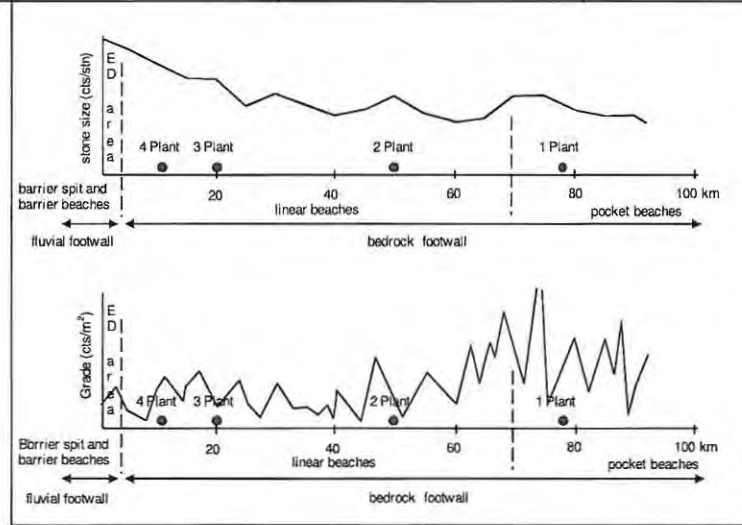
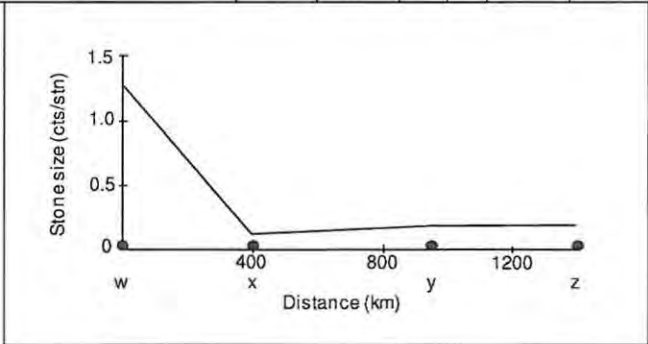
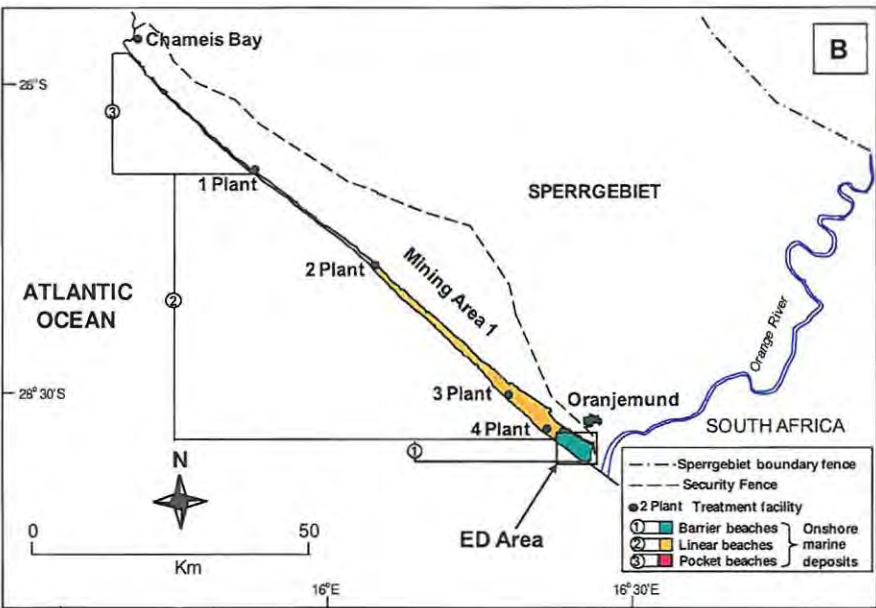
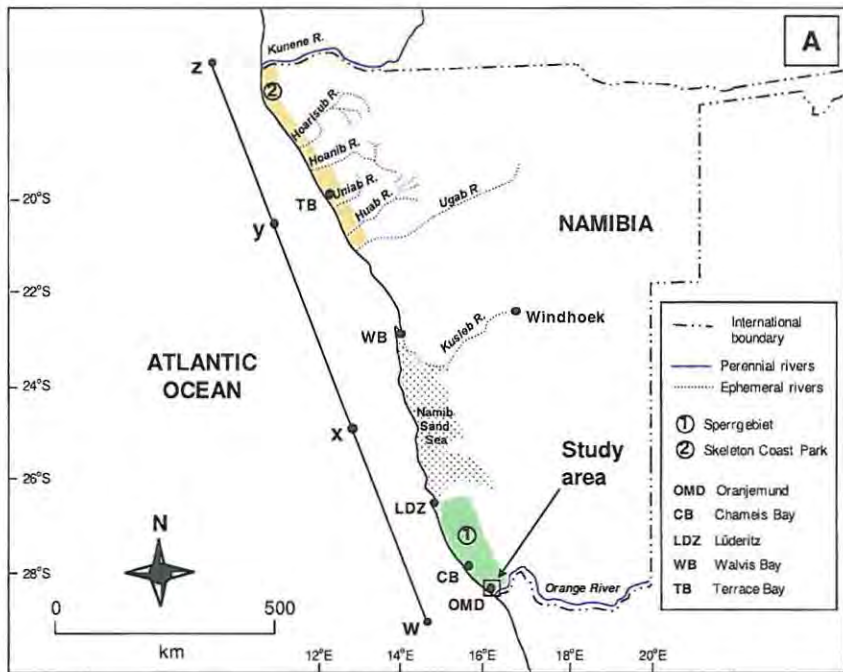


Figure 6.4: Average diamond size and average grade distribution within Plio-Pleistocene and younger littoral deposits along the Namibian coast. (A) Regional perspective of the down-drift diamond size decline from the Orange River mouth to southern Angola. Data sourced from Schneider & Miller (1992), Spaggiari & Ward (2004) and Bluck *et al.* (2005). Note that the average diamond size trend is a combination of data from different age shorelines and thus does not reflect a particular shoreline age. (B) Diamond size and grade trend for only MA1 within the Sperrgebiet, southern Namibia. The map illustrates different deposit types in a down-drift direction, whilst the graph depicts factorised diamond size and grade trends (modified after Schneider & Miller, 1992). Note the 'spiky' trends with an overall size decrease and increase in grade. The last is expressed as grade in carats per square metre (cts/m²; after Schneider & Miller, 1992). Similar to the graph in (A), the trends are a combination of data from different age shorelines and thus do not reflect a particular shoreline age.



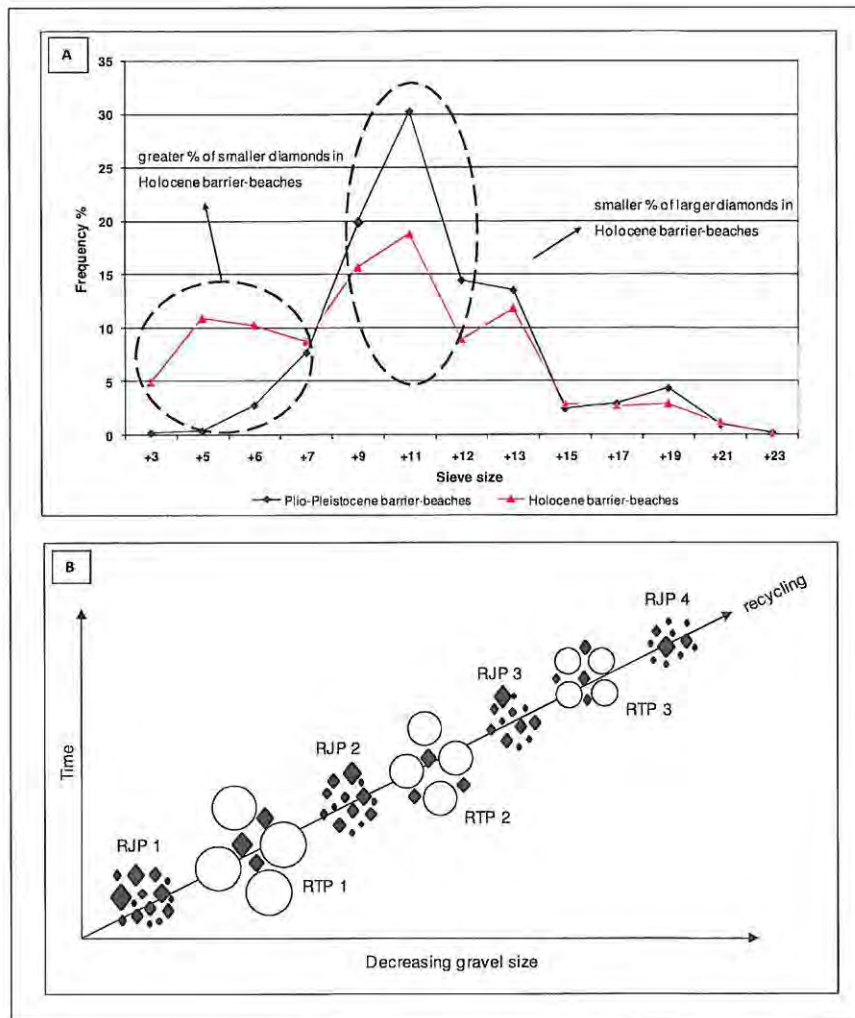


Figure 6.5: Diamond size decline since the Plio-Pleistocene. **(A)** Comparison of diamond size frequency distribution from study area (Plio-Pleistocene barrier beaches) with that from Holocene barrier beaches within the same palaeo-river mouth setting. Note the higher percentage of smaller stones in the Holocene barrier frequency distribution. The size frequency distribution data are tabulated in Appendix B, Section 1.3.2, Table B2. **(B)** Hypothetical model for diamond size decrease through time since the Plio-Pleistocene with changing gravel size. Rejected diamond pool (RJP1) is recycled into a coarse gravel barrier where the larger than average diamond size is retained (RTP1). The rejected pool of smaller diamonds (RJP2) from this barrier beach is recycled into a younger barrier having a smaller gravel size where the retained diamond population is smaller (RTP2). This recycling and trapping process promotes a progressive decline in diamond size allied with decreasing gravel size. Note that where larger diamonds are not trapped in the coarsest gravel framework (i.e. rejected from RTP1), they will be rejected throughout the recycling process through time. RJP = rejected diamond population, RTP = retained diamond population.

Figure 6.6: Hypothetical model for diamond recycling process during sea-level fluctuations. (A) Delivery of coarse sediment during highstand (normal regression) induces shoreline progradation at sea-level position 1 (SL1). Note that the older submerged diamondiferous deposits are confined to shelf regions. (B) Older deposits on shelf are reworked and diamonds recycled into regressive shorelines that 'step down' seaward as regression proceeds (sea-level positions SL1-4). Each regressive shoreline will have a diamond size and concentration trend similar to the shoreline at SL1 in (A). Note that there is no significant diamond introduction from the Orange River at this time, but sediment supply is at its maximum. There is some diamond contribution from the erosion of older higher-lying, landward shorelines. These are eroded in concert with the rejuvenation of ephemeral streams. (C) Subsequent to a lowstand (normal regression), the entire suite of regressive shorelines are reworked on the transgression (sea-level positions SL5-8). In addition to this, the transgressive barrier that is stationary at a particular point in time and space (SL5-8) is also reworked as barrier 'rollover' proceeds landward under a rising sea-level. Therefore, multi-recycling of diamonds are seen during the transgressive phase where diamonds 'leak' out into the littoral and others finally accumulate in barrier sediments once sea-level is stationary to perpetuate shoreline growth on a normal regression. Note that the shoreline at SL8 has transgressed beyond that at SL1. (D) Position of the shoreline at SL8. Here, diamond preservation will be greatest if the next sea-level cycles do not extend beyond sea-level 8 on a subsequent transgression.

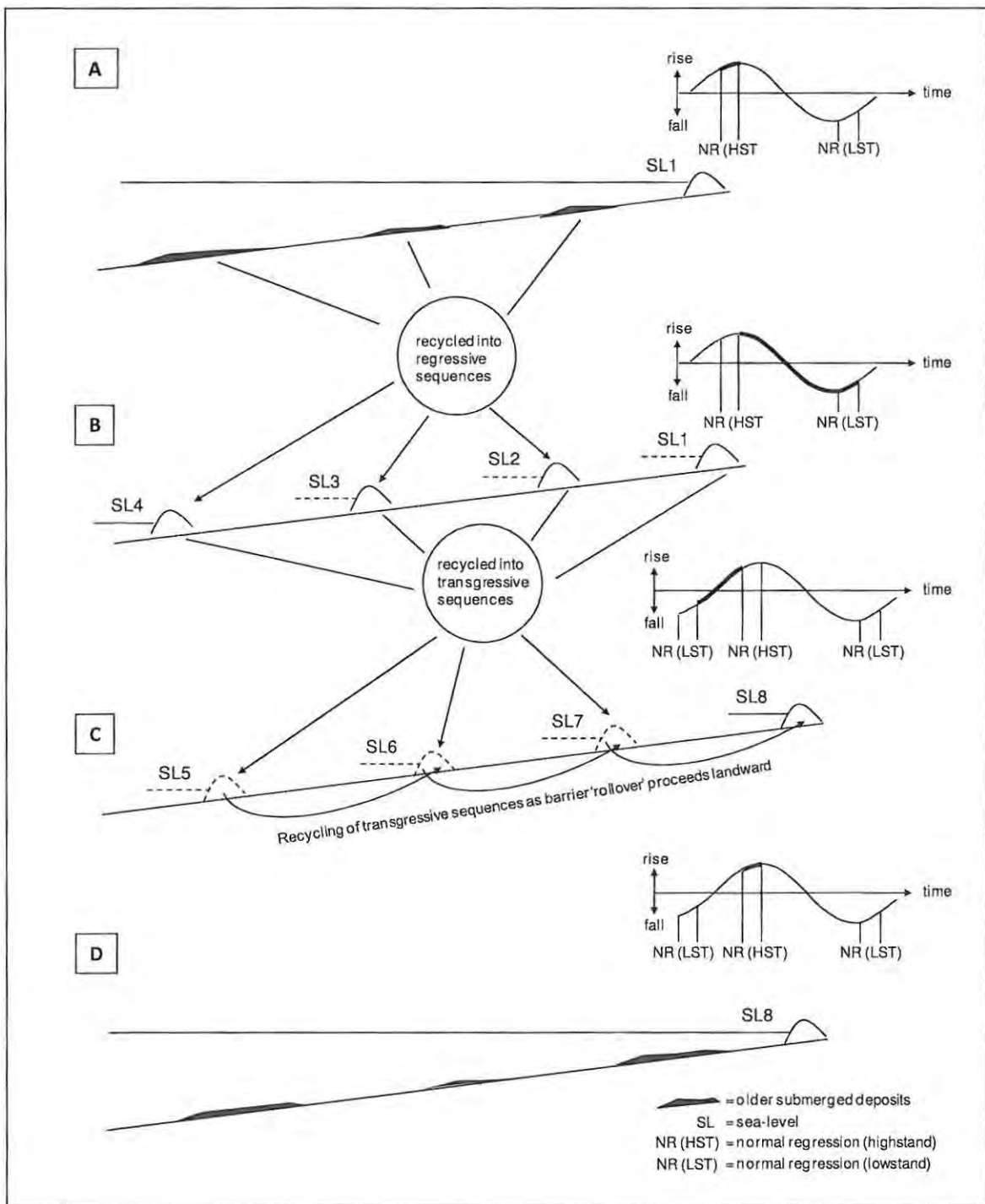


Figure 6.7: Hypothetical model for diamond emplacement in barrier deposits confined to river mouth settings where fixed trapsites are absent. (A) Representation of the 16 m stacked barrier deposits within the ED area showing zones of expected higher diamond concentrations. Note that the diamond concentration in this figure is expressed as carats per hundred tons (cpht). (B) General sea-level curves depicting growth of barrier deposits and time frames of maximum diamond input. (C) Diamond emplacement model when there is minor diamond contribution from the palaeo-Orange River. (1) Diamonds are sourced from pre-existing submerged shorelines during sea-level fall and introduced to an evolving shoreline on a transgression. (2) Maximum preservation of the diamond pool is achieved at the onset of barrier beach progradation when there is an increase in sediment delivery. Here the diamonds are 'sealed' off from further 'leakage' to the littoral as the coastline extends seaward, abandoning the earlier prograded sequences. (3) During the establishment of a younger shoreline on the next transgressive cycle, diamonds are recycled from the older barrier beach through erosion as the younger barrier beach migrates landward. (4) Maximum preservation of the diamond pool is once again achieved at the onset of progradation. Note that the pool of diamonds preserved in the younger barrier beach is less than that in the older barrier considering the lack of replenishment. Consequently, as the barrier beach complex youngs, sediment accumulation increases with a concomitant decrease in diamond quantity. The minor regressions that are in part responsible for barrier build up have not 'farmed' a significant reservoir of diamonds.

APPENDIX A
PUBLICATIONS BY AUTHOR

DECLARATION OF CO-AUTHOR CONTRIBUTION

Part of the work presented in this thesis has been previously published. Although some of these publications have co-authors, the work appearing in this thesis is entirely my own. Mention must be made that these publications prior to the thesis undertaking were presented for peer-review to test the ideas on gravel barrier beach and barrier spit diamond mineralisation; a first of their kind. All study material was collected, analysed and interpreted by the principal author, and were expanded on by him in the thesis. This expansion has evolved the thesis considerably, introducing new concepts on barrier preservation and stratigraphy at the fluvial/marine interface, sea-level behaviour during 30 m Package (Plio-Pleistocene) times and diamond mineralisation processes within barrier structures. These new concepts and models are to date, unpublished.

The role of co-authors and their contributions throughout the study are as follows:

- 1) Co-authors provided assistance during the initial stages of the project when the study area was identified as an economic target requiring evaluation for future mining. This formed part of Namdeb's exploration programme. During this exploration phase the author identified the area as a potential economically biased post-graduate study and developed the exploration work to an academic study.
- 2) Consequently, co-authors took on supervisory roles and were not part of the research once the academic study commenced. Both had specific areas of speciality and input relating to (i) the regional setting and (ii) detailed gravel beach assemblages as seen in the publications.
- 3) Co-authors continued to provide scientific rigour to Namdeb's exploration programme, as well as teach and supervise company staff. In the course of these duties, they also co-supervised and/or assisted a number of M.Sc. projects and a Ph.D. dissertation related directly to the Namibian mega-placer. These joint publications provided the setting initially of the OR mouth to marine transition and also recorded some of the progress made during the course of unravelling the Namibian mega-placer which, by nature of the various postings (see list in acknowledgements), took quite a few years to finish.
- 4) During this extended period, the co-authors did not continue working on the study area after the author was transferred to another country.



Characteristics of diamondiferous Plio-Pleistocene littoral deposits within the palaeo-Orange River mouth, Namibia

R.I. Spaggiari^{a,*}, B.J. Bluck^b, J.D. Ward^c

^a NAMDEB Diamond Corporation, P.O. Box 253 Oranjemund, Namibia

^b Division of Earth Sciences, University of Glasgow, Glasgow G12 8QQ, Scotland, UK

^c De Beers Africa Exploration, P.O. Box 7383 Centurion 0046, South Africa

Received 10 October 2003; received in revised form 18 March 2004; accepted 9 March 2005

Abstract

The Orange River, the principal conduit transporting diamonds from hinterland sources to the Namibian coast in post-Cretaceous times, is characterised by an extreme wave dominated delta that has given rise to a progression of coarse rudaceous littoral deposits preserved onshore for >150 km north of the mouth. Under the long-lived, prevailing vigorous wave, wind and northward longshore drift regimes, the Orange River outfall has been reworked into, amongst others, a series of economically viable, diamondiferous Plio-Pleistocene onshore gravel beach deposits. These placers comprise spits and barrier beaches in the proximal reach within the palaeo-Orange River mouth that, after ca. 5 km northwards, merge into extensive but narrow linear beaches that, in turn after ca. 70 km, give way to pocket beaches. Gravel and diamond size decreases northwards away from the ancestral Orange River mouth. The linear and pocket beach types have considerably higher diamond content but lower average diamond stone size than the two proximal units that are characterised by low diamond grade but comparatively large average diamond size. Given the risk of delineating low grade alluvial diamond deposits accurately, we present here sedimentological reconstructions of the subtidal, intertidal and supra-tidal facies that constitute the spit and barrier beach sequences, based largely on face mapping of exploration trenches and open-cast, mine cuts, as well as the results of large tonnage, sampling campaigns. Diamond distribution is also linked convincingly to basic littoral processes that were operational within the palaeo-Orange River mouth during the complex transgression that gave rise to the +30 m package in Plio-Pleistocene times. In both the spit and barrier beach settings, the intertidal deposits prove to be the most promising targets whereas the subtidal sediments are the least economic. The constant raking associated with coarse, cobble–boulder-sized gravel foreshore deposits in an energetic micro-tidal wave regime increased the average diamond stone size in the intertidal deposits to 1 to 2 carats per stone (cts/stn), but the lack of fixed trapsites (no competent footwall within the palaeo-Orange River mouth at that level) prohibited the accumulation of substantially enriched diamondiferous gravels. Consequently, grades of only 1.5 to 6 carats per 100 tons (cpht) are realised. The highest grades (2 to 6 cpht) are found in the landward-facing, intertidal beach deposits on the spits where gentle reworking in that sheltered environment had somewhat enriched and preserved the diamond content. Significantly, the low average stone size of ca. 0.5 cts/stn in this lower energy setting probably reflects that of the general diamond population available at that time. In contrast, the sand-rich subtidal deposits in the spit sequence return the lowest grades (0.1 to 0.5 cpht), similar to those in the slightly younger, subtidal transgressive boulder lags of the barrier beaches. However, the stone size in the spit subtidal sediments is also low (0.1 to 0.5 cts/stn) due to the highly mobile, fine-grained character of those deposits, whereas that in the subtidal transgressive lag is large (2 to 3 cts/stn) as a result of the local, semi-permanent turbulence associated with the boulder-sized clasts in these gravel sheets.

* Corresponding author.

E-mail address: Spaggiari.Renato@debeersgroup.com (R.I. Spaggiari).

Diamond distribution is therefore also influenced by littoral facies and associated beach types, in addition to the spatial and temporal parameters that have already been documented for the onshore marine placers of the southern Namibian coast.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Marine diamond placer; Namibia; Orange River; Plio-Pleistocene; Gravel

1. Introduction

Along the southwest African coast, diamonds were first recorded at Lüderitz on the Namibian sector in 1908 and on the South African side of the Orange River in 1909, although it was only in 1925 that this latter find led to subsequent development (Hallam, 1964). In Namibia, mining operations have extended for ca. 300 km northwards from the Orange River mouth (Fig. 1), producing over 75 million carats of diamonds over some 94 years — 95% of which are gem quality, making this the richest diamond placer known (Schneider and Miller, 1992; Oosterveld, 2003). Up to the late 1990s, this portion of the

Namibian coast (“Sperrgebiet”) had produced more than 55% of the +130 million carats of alluvial diamonds mined in southern Africa, the bulk of which (ca. 73%) has been derived from Cainozoic littoral marine deposits (Oosterveld, 2003). To date, the most economic of these deposits have been the Late Cainozoic onshore “raised beach” placers lying in the narrow, ca. 110 km long strip between the Orange River mouth and Chameis Bay that, today, forms Mining Area No. 1 for which a mining licence is held by Namdeb Diamond Corporation (Pty) Ltd (Hallam, 1964; Ward et al., 1998). In response to the vigorous longshore marine and southerly wind regimes (Rogers, 1977), a distinct gradation in these onshore

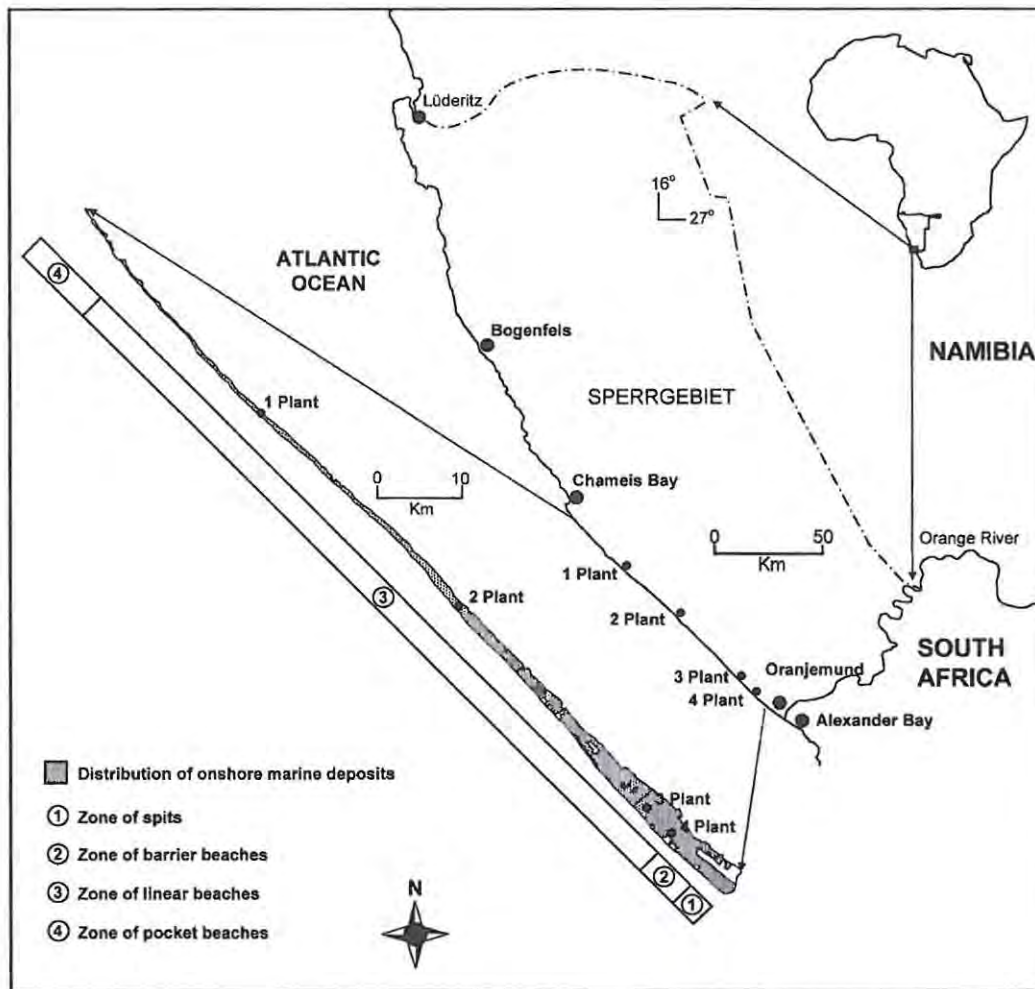


Fig. 1. Locality map of the Sperrgebiet showing northward tapering sediment wedge of onshore Late Cainozoic marine deposits.

littoral deposit types is evident northwards away from the Orange River mouth. In the proximal setting for some 5 km north of the palaeo-Orange River mouth, gravel spits and barrier beaches predominate, giving way to linear beaches for another 70 km or so, that in turn grade farther northwards into pocket beaches that typify the distal extremity (Fig. 1; Apollus, 1995; Spaggiari et al., 1999, 2002; Bluck et al., 2001). This down-drift pattern is also reflected in a decrease in gravel and diamond size northwards away from the mouth of the Orange River (Hallam, 1964; Sutherland, 1982; Schneider and Miller, 1992; Apollus, 1995).

Apart from confidential internal reports and field guides (e.g., Rogers et al., 1990; Ward et al., 1998, 2002), little has been available to the public on this remarkable placer deposit. Early publications (e.g., Merensky, 1909; Kaiser, 1926; Williams, 1932), were concerned mainly with the deposits on the northernmost tail of the diamond distribution in the areas around Bogenfels and Lüderitz prior to the discovery of the main linear beach deposits in 1928. Consequently, the first overall substantial contributions were made by Hallam (1964) and Stocken (1978). Subsequent reviews (e.g., Sutherland, 1982; Schneider and Miller, 1992) largely used these earlier data to, inter alia, highlight the northward logarithmic size decline in the diamond population along the Namibian coast away from the Orange River mouth.

In this paper, we focus on the proximal setting, presenting the sedimentary facies and diamond distribution in the gravel spits and barrier beaches that formed within the accommodation space provided by the palaeo-Orange River mouth during the Late Pliocene to Earliest Pleistocene. From the rare presence of the zone fossil, *Donax rogersi*, these coarse-grained deposits are correlated with the +30 m marine package preserved intermittently elsewhere along much of the southwestern African coast (SACS, 1980; Pether, 1986; Ward, 1987; Gresse, 1988; Pether et al., 2000; Marais et al., 2001; De Beer et al., 2002).

2. Regional setting

Since at least Middle Eocene times, the Orange River has transported diamonds in its coarse sediment load from kimberlitic and sedimentary sources in the hinterland of southern Africa to the Namibian sector of the Atlantic Coast (inter alia, Cornell, 1920; Kaiser, 1926; Stocken, in press; Van Wyk and Pienaar, 1986; Corbett, 1996; De Wit, 1999; Ward et al., 2002). In contrast, the Late Cretaceous outfall of the precursor Orange River was fine-grained, feeding into a large delta offshore that was well developed by ca. 90 Ma (Wickens and McLachlan, 1990; Ward and

Bluck, 1997; Aizawa et al., 2000), and was thus unlikely to be diamond bearing. This shift from fine- (silt to clay) to coarse-grained (gravel to sand) deposition at the mouth of the ancestral Orange River reflected a regional sub-continental uplift in the Late to End Cretaceous that initiated deep fluvial incision that has continued intermittently through much of the Cainozoic. By this time, all of the known diamond-bearing kimberlite pipes in southern Africa had already been emplaced, many of which, notably those of Cretaceous age, were within the drainage network of the Orange basin (Gurney et al., 1991). These, and the diamonds yielded by the erosion of older kimberlites and sedimentary sources within the Orange River drainage basin, thus provided the supply to the southern Namibian coast. This fluvial incision, particularly that in Early to Middle Tertiary times, was instrumental in the erosion of the landscape and the accelerated distribution of the diamonds to the coast (Jacob et al., 1999; Ward et al., 2002).

The modern Orange River has a wave-dominated delta that is subjected to a vigorous northward longshore drift under the prevailing southerly wind regime (Rogers, 1977), a setting that has persisted for much of its Middle to Late Tertiary history when coarse-grained sediment was being debouched into the Atlantic Ocean. In the present coastal regime, 90% of the waves have a height which falls in the range 0.75 to 3.25 m with an average of 1.75 m for winter and 1.5 m for summer (Rossouw, 1981; De Decker, 1988). The persistence of high energy conditions throughout most of the year (Hay and Brock, 1992) highlights the vigorous regime of this coastline and the adjacent shelf. In contrast to the extreme wave energy, the tidal range is only 1.8 m at Oranjemund, making this a micro-tidal coast (Davis, 1972). Significantly, from examinations of the internal structures of older, Cainozoic beaches there is no reason to assume a different tidal range during their formation from the Late Tertiary to Quaternary (Gresse, 1988; Pether, 1994; Spaggiari et al., 1999). The present coastal redistribution system, active for at least the last 43 Ma, has thus separated the coarser and finer sediment fractions from the Orange River outfall (Fig. 2). The fine fraction is believed to move largely north (Birch et al., 1991; Grey et al., 2000) and west out to the continental shelf edge where it forms extensive mud sheets (Bagguley, 1996). The sand, much of which is retained within the breaker zone, moves northwards along the coast in a belt that is usually not more than 3 km wide. At a number of points, and particularly at changes in the orientation of the coast, sand is blown off the beaches onto the land where it accumulates, under desert conditions, in the main Namib Sand Sea (Rogers,

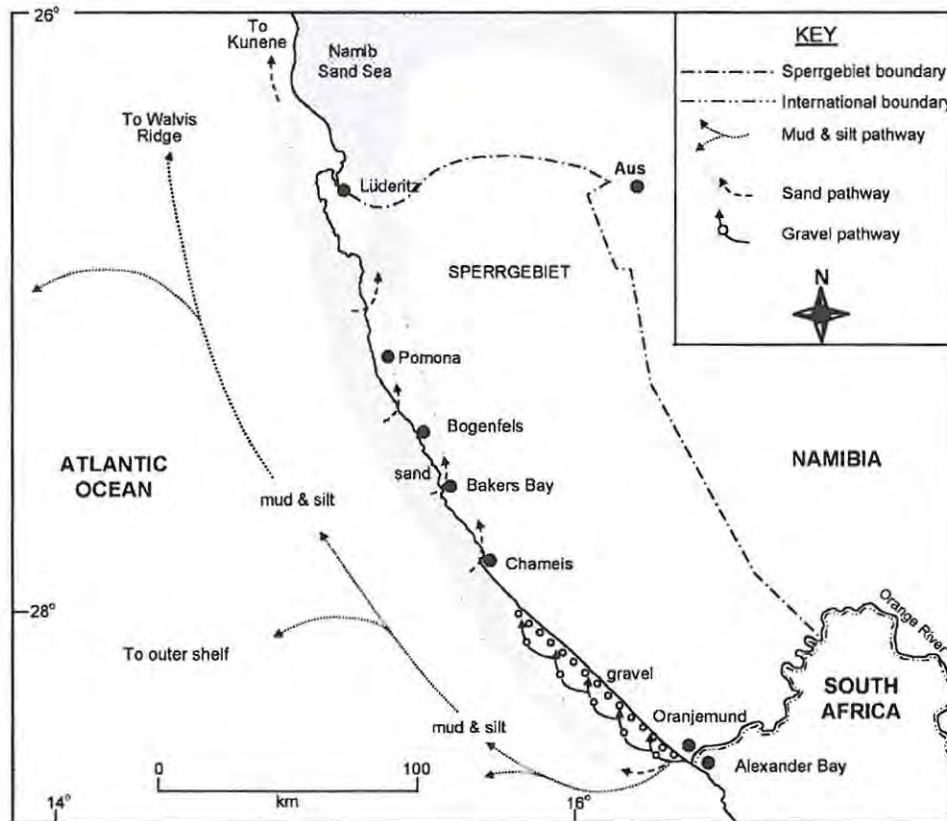


Fig. 2. Map showing the sediment dispersal paths for gravel, sand and finer sediment on the continental shelf.

1977; Corbett, 1989, 1996). The gravel fraction, however, has accreted as a series of narrow beaches which, in their various forms, have built up the coast for over 150 km north of the Orange River mouth (Hallam, 1964; Bluck et al., 2001).

Since the Middle Eocene, there have been substantial changes in sea level from a high at ca. 180 metres above sea level (masl) followed by a regional and well documented Oligocene low which is thought to have had a profound effect on the western African drainages and their supply of sediment to the coast (Serrane, 1999). Younger fluctuations between +90 masl and about -120 masl occurred between the Miocene and the Late Pleistocene, with current sea level being reached after a short-lived, +2 masl Holocene high at ca. 5000 years BP (Siesser and Dingle, 1981; Dingle et al., 1983; Pether, 1986; Pether et al., 2000). With there being a copious supply of gravel following the post-Cretaceous incision, particularly in Neogene times, accompanied by a vigorous coastal wave system, the littoral sediment dispersal and accretion pattern typical of the Quaternary is no different to that of the Tertiary. The effect of the sea-level changes on a fairly wide continental shelf was to repeat the Present to Pliocene gravel beach accretions over a substantial width of this shelf. In Mining Area

No. 1, the onshore expression of the Plio-Pleistocene sea level high stands is demarcated by a series of distinctly rudaceous littoral marine deposits at elevations ranging from an older Pliocene suite at +10 to ca. 30 masl, to a Mid-Pleistocene unit at 8 to 10 masl through to a Late Pleistocene record at +4 masl and the Holocene high at +2 masl (summarised in Pether et al., 2000).

3. Results of recent mining and sampling programmes

Onshore, in Mining Area No. 1 (Fig. 1), the Cainozoic marine deposits have been well-exposed in extensive sampling trenches that are > 1000 m long, 1 to 10 m wide, and, in places, > 15 m deep. There are also excellent exposures in the retreating mine faces dug during current diamond mining operations. In our study area close to the palaeo-Orange River mouth, we have monitored and mapped mine faces and sample trenches intermittently over the last 8 years. In addition, old records and mine plan sections for this area are available since 1947. This unusually extensive and detailed dataset has been combined to yield composite cross-sections which extend from the highest gravel beaches in the east to the shoreface deposits in the west, enabling accurate

reconstructions of the internal structures of the rudaceous spits and barrier beaches in the proximal setting close to the palaeo-Orange River mouth (Spaggiari et al., 1999, 2002). Diamond data were derived from 200 to 1500 ton samples taken in the various littoral facies making up the two principal marine gravel deposits within the palaeo-Orange River mouth setting. These samples were treated through a dedicated sampling facility and their concentrates sorted in a secure geological laboratory on Mining Area No. 1. As there is little or no known subsidence recorded for the southern Namibian coast during the Late Pliocene to Holocene interval, the development of sedimentary sequences depends primarily on sea-level changes for accommodation space, aided in this instance by the presence of the palaeo-Orange River mouth. The beach structures are also related principally to the interaction between Orange River sediment supply and sea-level fluctuations.

4. Marine deposits, and their inferred sub-environments along the Southern Namibian Coast

The morphology, dynamics and growth of gravel beaches have been investigated by a number of workers (see Pye, 2001; Orford et al., 2001, for reviews). After an initial and preliminary study by Bluck (1967) the internal structure of gravel beaches has been recognised only within the last few decades (Orford, 1975; Maejima, 1982; Massari and Parea, 1988; Williams and Caldwell, 1988; Postma and Nemeč, 1990; Sherman et al., 1993; Bluck, 1999; Bluck et al., 2001; Neal et al., 2001). There

now exist a number of criteria for the recognition of such beaches and Bluck (1999) recently established a hierarchy in beach sedimentation, beginning with *clast assemblages* (sheets of gravel classified according to the various clast shapes and sizes) that were then combined into *beds and bed assemblages* (a series of structurally related clast assemblages), the resultant pattern of their association in turn characterising known gravel beach bed forms. This identification procedure enables diamond grade (expressed here as carats per hundred tons = cpht) and average diamond size (expressed here as carats per stone = cts/stn) to be related to beach structure and hence, ultimately, littoral processes building such gravel units (*sensu* Bluck, 1999). Not only is a visual aid to diamond placer quality thus generated, but a better understanding of marine placer formation is also gained. In this regard, further insight was gleaned from the formation and structure of modern gravel beaches derived from the destruction of the Unjab delta along the northern (Skeleton) coast of Namibia in the vicinity of Terrace Bay. These Skeleton Coast beaches are formed under similar wave and tidal conditions as envisaged for the palaeo-beaches in Mining Area No. 1 farther south.

Gravel at the shore accumulates in three major regimes and their deposits are divided into three main units (Bluck et al., 2001):

- Unit A Subtidal deposits of gravel and sand;
- Unit B Intertidal deposits, which includes all the gravel beaches, including the supra-tidal areas;
- Unit C Back barrier/beach deposits, such as lagoonal sediment found landward of the beaches.

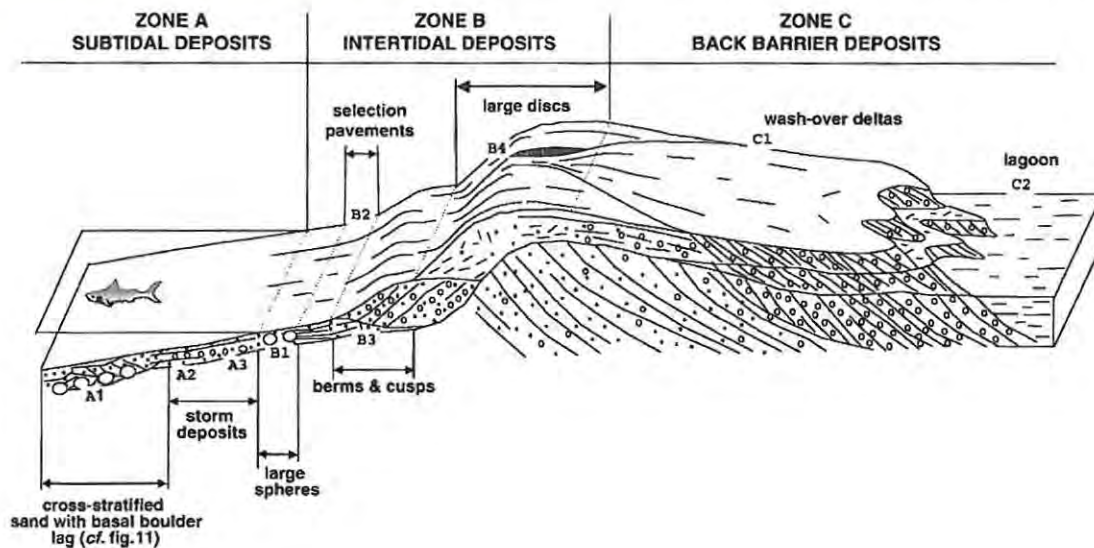


Fig. 3. Schematic representation of the various depositional environments of a barrier beach. A = Subtidal deposits, with A1–A3 representing depositional sub-units discussed in the text. B = Intertidal deposits (see text). C = back barrier (see text).

4.1. Unit A: subtidal deposits

A range of subtidal deposits was exposed in the sampling trenches, as well as in the active mine faces, and these could be traced into the ancient gravel beaches. Deposits at the fine end of the range comprise sands, commonly with cross-strata that may display a bimodal dip orientation. Those beds, sometimes with abundant shell debris (much of which is broken), are thought to be the equivalent of the shallow marine, mega-rippled sand fields described south of the Orange River mouth by De Decker (1988). In addition there are sand sheets up to 3 m thick which are heavily bioturbated but with sufficient internal structure remaining to be identified as subtidal in origin. These latter deposits suggest that there were situations in the aggressive shelf where there was sufficient protection for sands to accumulate, or for older sand sheets to have escaped erosion for long enough to have supported in-fauna.

At the other extreme of the range and with many gradations between, are deposits comprising an alternation of sand and gravel sheets that contain progressively more gravel towards the toes of the ancient gravel beaches. These sheets of gravel are thought to have been displaced principally from the seaward edges of the gravel beaches during storm conditions, and as such, are often enriched in large spherical clasts which represent the most mobile of clasts on the beach. In some exposures they are clearly seen to occupy broad channels in which the gravel is lenticular rather than sheet-like. These channel deposits are likely to have been generated by rip currents. The schematic association of these various units is outlined in Fig. 3, where the subtidal deposits (e.g. sub-unit A1 in Fig. 4A) are seen to dominate the western exposures, in the direction of the present-day ocean.

4.2. Unit B: intertidal (beach) deposits

The structurally complex intertidal unit has a great range of bed assemblages and sub-environments of deposition. Not only is there a range of foreshore deposits, but the morphology and structure of the gravel bars themselves (of which the foreshore forms part) are also quite diverse. Along the Sperrgebiet coast, Bluck et al. (2001) recognised essentially four gravel beach types which, in order of decreasing sediment accretion rate are: spits, barrier beaches, linear beaches and pocket beaches — all identified on the basis of the range and combinations of bed assemblages. However, the one characteristic that links them all and serves as a clear factor in their identification is the degree of shape

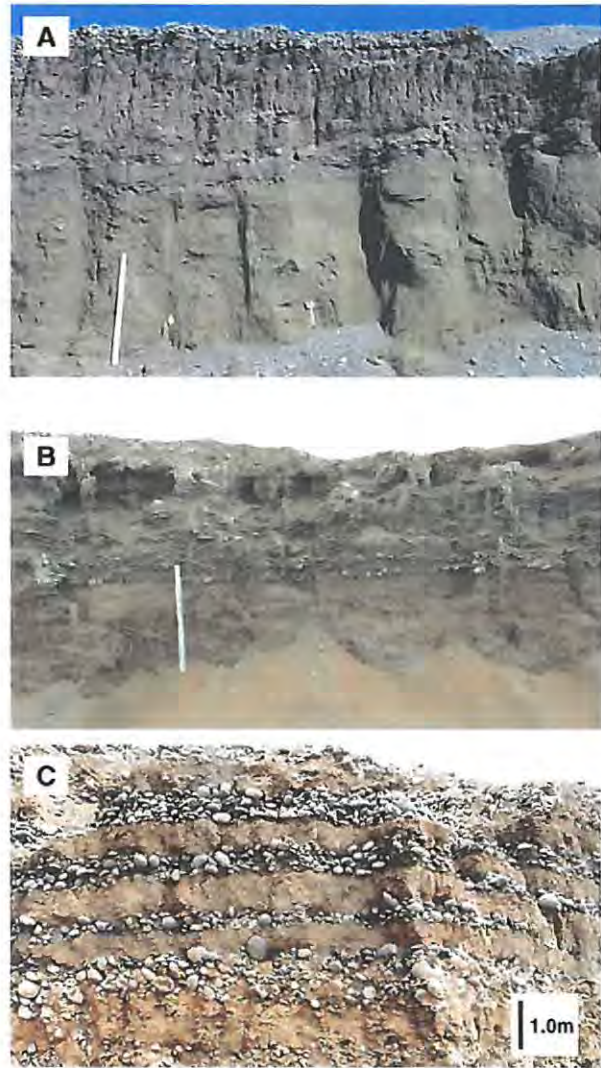


Fig. 4. Examples of Plio-Pleistocene subtidal units, southernmost Mining Area No. 1, Namibia. (A) Distal shoreface sand deposits (A1 sub-unit), in places with bi-polar cross stratification and thin beds of gravel. Measuring staff=1.2m. (B) Sand sheets with abundant bioturbation and thin gravel sheets (A2 sub-unit). (C) Storm deposits of sand and inter-stratified gravel (A3 sub-unit). The gravel, with coarse spherical clasts and a mixture of shapes in the finer fraction, is probably recycled off the seaward margins of beaches during storm periods. A1–A3 refer to the depositional units shown in Fig. 3.

sorting of the gravel clasts. Most gravel beaches show a remarkable clast shape segregation where large oblate to discoidal clasts together with small clasts of various shapes accumulate at the beach crest, and large equant or spherical clasts and small discoidal and other shaped clasts accumulate at the base of the intertidal zone. The beach surface can then be seen as a wide zone of varying steepness where particle selection according to shape and size is taking place in response to the vigorous wave swash and backwash energy. Beach progradation consequently deposits a sequence containing large

discs at the top and large spheres at the base (Bluck, 1967, 1999).

Gravel beaches differ substantially in morphology and therefore in sedimentary environments that influence the distribution of coarse and fine sediment (Figs. 3, 5 and 6). The following zones have been recognised (cf. Bluck, 1967, 1999):

- near the seaward toe of the beach is the infill zone, where clasts, raked from the beach, fill the open framework of large spherical clasts that comprise the outer frame (sub-unit B1 in Figs. 3 and 6). Large spherical clasts, because of the ease with which they roll on the steep beach surface, are segregated and displaced seaward onto the toe of the beach. In the record, these are commonly recognised by clast-supported framework gravels that display comparatively poor clast shape and size sorting and also by flat stratification where large, in-filled sphere frameworks alternate with beds of smaller spheres and sand. There is a considerable range in the degree of clast shape and

size sorting, dependent largely on sediment supply and the reworking of older beach gravels.

- the infill zone commonly merges landward into an inclined surface that is often a mixture of sand and gravel. This is the zone of selection pavements where clasts of various sizes and shapes are sorted hydraulically to accumulate on the beach in the form of seaward inclined strata with good size and shape segregation (sub-unit B2 in Figs. 3 and 6). Stratified marine gravels normally originate in this zone. Cusps may develop here but are more commonly found in the next landward zone.
- landward of the selection pavements, lies the zone of cusps and berms (sub-unit B3 in Figs. 3 and 6; Fig. 5) that have steep surfaces and construct beds far steeper than those of the selection pavements; consequently the degree of sorting achieved is much higher (Fig. 5D). These fairly steep beds dip seaward, in the direction of beach progradation and are characterised by extreme shape/size sorting. These structures, invaluable in determining the

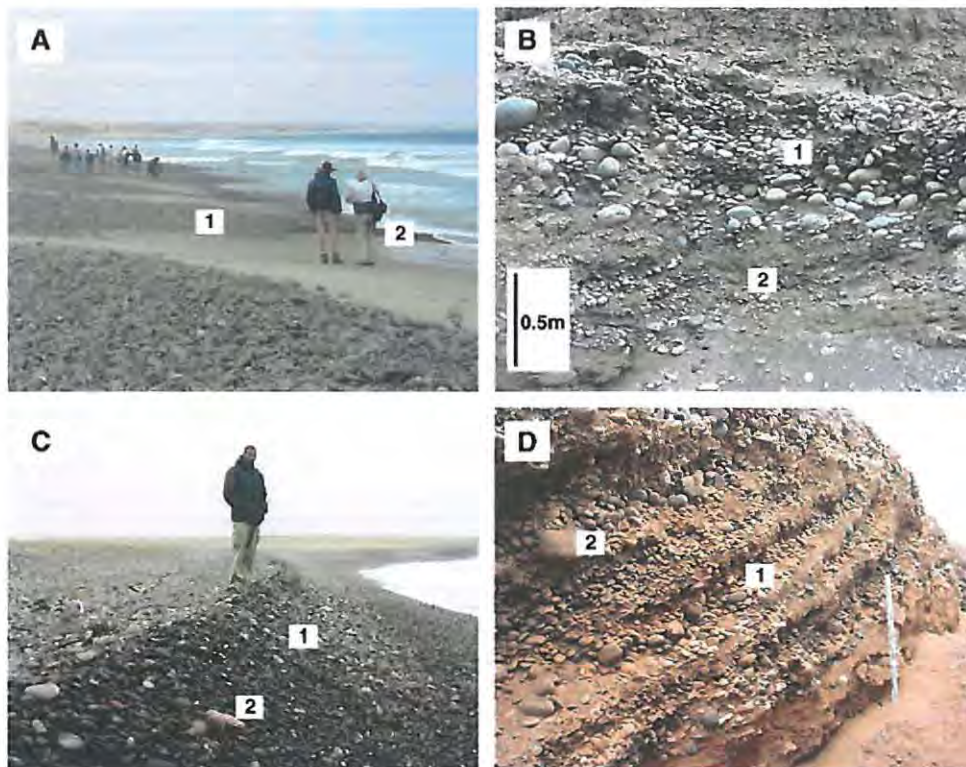


Fig. 5. Cusp and berm structures (B3 sub-unit) from Recent and Pleistocene gravel beaches, Namibia. (A) Cusp development in modern gravel beaches with 1 = coarse assemblage of spherical and rod shaped clasts (crown); 2 = finer assemblage of discs and blade shaped clasts (imbricate shadow), Unjab delta, Skeleton Coast. (B) Section of prograding cusp in Pleistocene beaches showing coarse crown (1) and fine shadow (2), southernmost Mining area No. 1. (C) Modern gravel berm with steep seaward dipping face (1). Note the displacement of coarse clasts by the more dominant and uniformly sized finer gravel in a process of fabric rejection (2), Terrace Bay, Skeleton Coast. (D) Section of seaward dipping progradational berms (1) in Plio-Pleistocene gravel beaches, southernmost Mining Area No. 1. Displaced cobble-sized clasts (2) are isolate in the dominant finer-sized clasts. Measuring staff=1.2m.

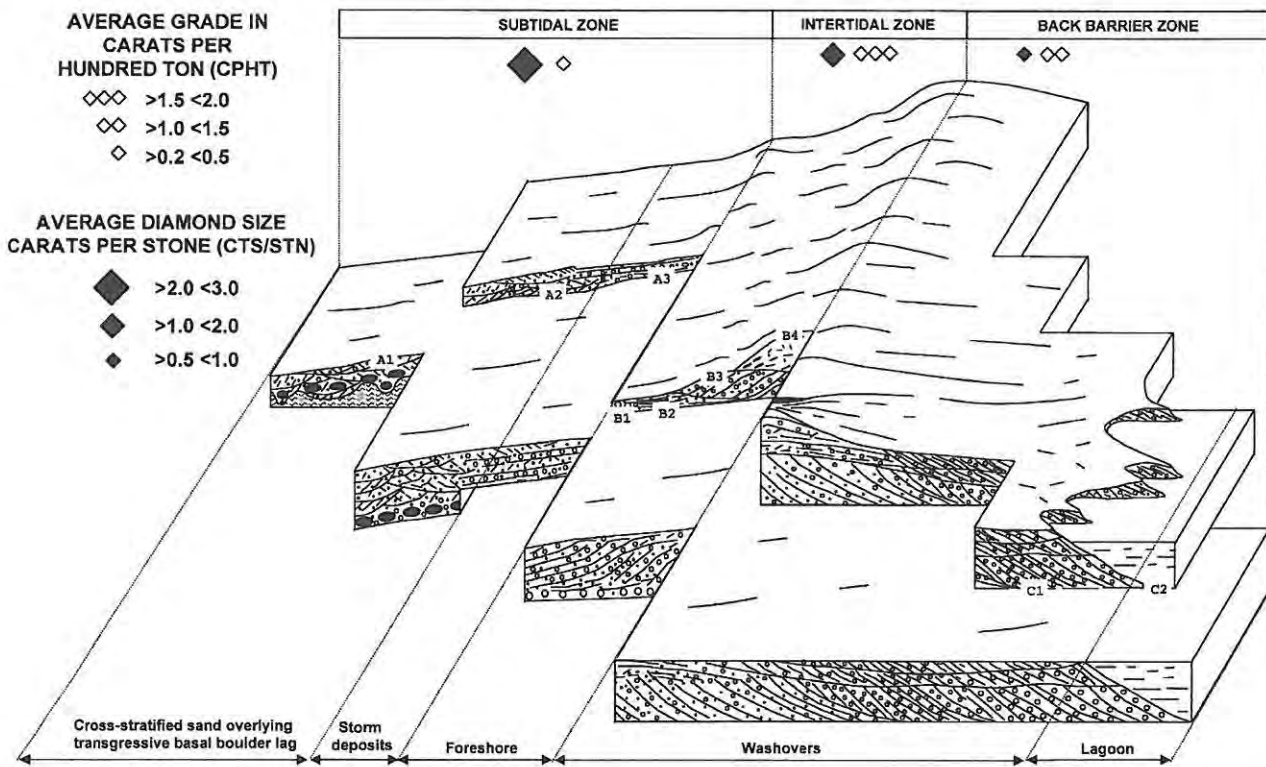


Fig. 6. Schematic representation of average diamond grades (carats per hundred tons = cpht) and sizes (carats per stone = cts/stn) within a Plio-Pleistocene gravel barrier sequence, based on data collected within the palaeo-Orange River mouth, southernmost Mining Area No. 1, Namibia. A1–A3, B1–B4 and C1–C2 refer to depositional sub-units shown in Fig. 3.

accretion directions of beach gravel sheets when seen in section, are also useful in gravel beach reconstruction. At the beach crest, large disc and blade clasts accumulate to yield a large-disc zone (sub-unit B4 in Figs. 3 and 6).

Variations on this pattern of zones are quite common, not only in the beach surfaces seen along the Namibian coast, but also in sample and mine cut sections. The area where the pavements and cusps

form may be replaced by a single, steep zone (berm) which is strike-aligned along the coast with very little sign of cusped development. Wave action here is vigorous and the persistent steep slope generates a backwash that is so strong that maximum clast shape and size sorting is achieved.

The distribution of diamond grades (cpht) and sizes (cts/stn) in the Late Pliocene–Early Pleistocene +30 m intertidal beach sequence preserved within the palaeo-Orange River mouth is illustrated schematically in Fig. 6.

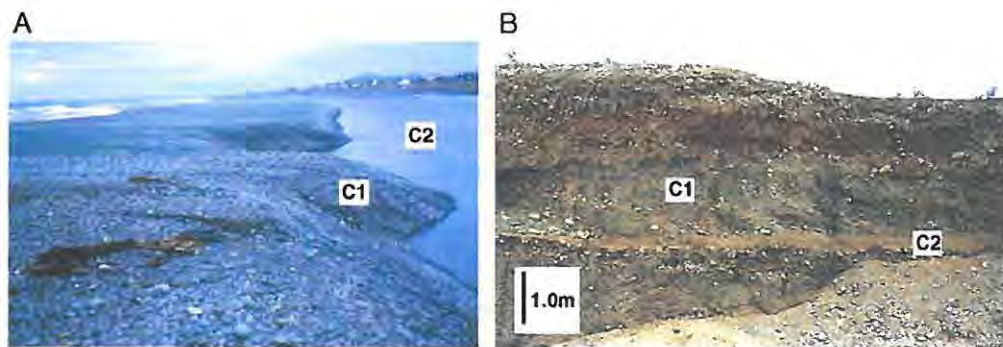


Fig. 7. Wash-over deposits (C1 sub-unit) in Modern and Pleistocene gravel beaches. (A) Modern wash-over delta, Ballantrae, Scotland. (B) Section of a Plio-Pleistocene wash-over sequence, C1, exhibiting landward dipping foresets interfingering with finer lagoonal sediments, C2. Southernmost Mining Area No. 1, Namibia. C1 and C2 refer to depositional units shown in Fig. 3.

4.3. Unit C: back-barrier/beach deposits

In contrast to the foreshore, back beach deposits — found landward of the large-disc zone and beach crest — comprise mainly landward dipping surfaces (cf. Orford and Carter, 1982; Massari and Parea, 1988; Blair, 1999). On modern barriers, gently inclined surfaces, beginning at the beach crest terminate in wash-over deltas characterised by steeply dipping foresets prograding towards the land (Fig. 7). These foresets often lack the size and shape sorting of the cusp and berm deposits with which they could otherwise be confused (cf. Fig. 5B and D; C1 in Fig. 7). Moreover, the more gently inclined surfaces (top-set equivalents) also tend to lack the extremes of size and shape sorting seen in foreshore deposits. The delta gravels, which commonly interfinger with the sands deposited in the low ground behind the barrier (C2 in Fig. 7), are essentially the product of wash-over during high tide, accompanied by storm conditions where the back-barrier area is filled with water.

5. Proximal gravel palaeo-beaches of Southern Mining Area No. 1

As mentioned earlier, and on the basis of their internal structure, four types of gravel beaches have been recognised in the Plio-Pleistocene littoral record along the southern Namibian coast (Fig. 8; Spaggiari et al., 1999, 2002). In the south, gravel spits are present, as are barrier beaches, in this ca. 5 km wide proximal setting within the palaeo-Orange River mouth. Northwards, beyond these deposits, are the extensive linear beaches that, after some 70 odd km, give way to pocket beaches (Fig. 8). Of these beach types, only spits and barrier beaches that are developed within the palaeo-Orange River mouth are discussed further (1 and 2 in Fig. 8). Moreover, these southern, proximal deposits also host related boulder-cobble gravel sheets that cut across the local stratigraphy, forming additional important potential trapsites for diamonds.

5.1. Gravel spits

Gravel spits are recognised in a series of trench sections where their 3-D geometry has been fully established (Fig. 9; Spaggiari et al., 1999). Landward they are replaced by, and are seen to interdigitate with, thick and fairly extensive mud and silt deposits of lagoonal origin (C2 in Fig. 9). The gravel spits are characterised, at their tips, by hemispherical radial gravel-growth building to the north-northwest and

parallel with the coast (cf. Nielsen et al., 1988; Hiroki and Masuda, 2000; Bluck et al., 2001; Fig. 9). The gravel, in sections which bisect this hemisphere of growth (i.e., at the north-northwestward migrating tip of the spit), interfingers with, and partly overlies, subtidal gravelly sands with bi-polar cross-stratification. This is the principal growth point of the spit which builds over the sand bars created by tidal currents in the channel that connects the lagoon, formed as a result of its development (sub-unit A1 in Fig. 9B), to the open sea.

The gravel deposits accumulating both landward and seaward of the coast-parallel spine of the spit (sub-unit B3 in Fig. 9B) have amongst the longest and steepest foresets on the southern beaches within the palaeo-Orange River mouth. These foresets also display some of the most mature gravel fabrics on the Namibian beaches, both past and present, with sphere-rich and disc-rich clast assemblages in a whole range of grain sizes. Such well-developed sub-units are interpreted to have formed on steep foreshores, such as those seen at Terrace Bay on the Skeleton Coast in northern Namibia (see Fig. 5). As commonly found on present-day active spit heads, the gravel strata that envelop the lens of subtidal sand are often mixed with gravel sheets slumped into the spit-head channel. The textural maturity of the gravel on the landward dipping foresets is partly achieved by wave refraction around the spit head.

Landward of this gravel structure, and partly interfingering with it, lies an extensive sheet of red (aerobic) and green (anaerobic) mud deposited in the lagoon formed by the extending spit (Fig. 9). The spits, building to the north, cut off large sectors of the coast to convert them into lagoons. Spits are known to be amongst the fastest growing of the gravel bar forms: recorded rates of growth for short periods running at >150 m/year (e.g., Steers, 1937; Carr, 1969).

Gravel spits may undergo morphological change during their growth (cf. Orford et al., 1991), commonly becoming narrower on continued extension. When the supply of gravel is finally cut off or reduced considerably, the spit may become detached from the land, converting to a barrier beach which may then migrate onshore. This type of evolution is recognised in some of the Plio-Pleistocene beach sections where gravels, ascribed to barrier beaches that are not known to pond extensive lagoons, are seen to rest on eroded and extensive lagoonal deposits (Fig. 11).

The distribution of diamonds in the spits (Fig. 10) shows a clear decreasing stone size through the sedimentary units when traced landward. The greater stone size in the intertidal zone is probably related to the

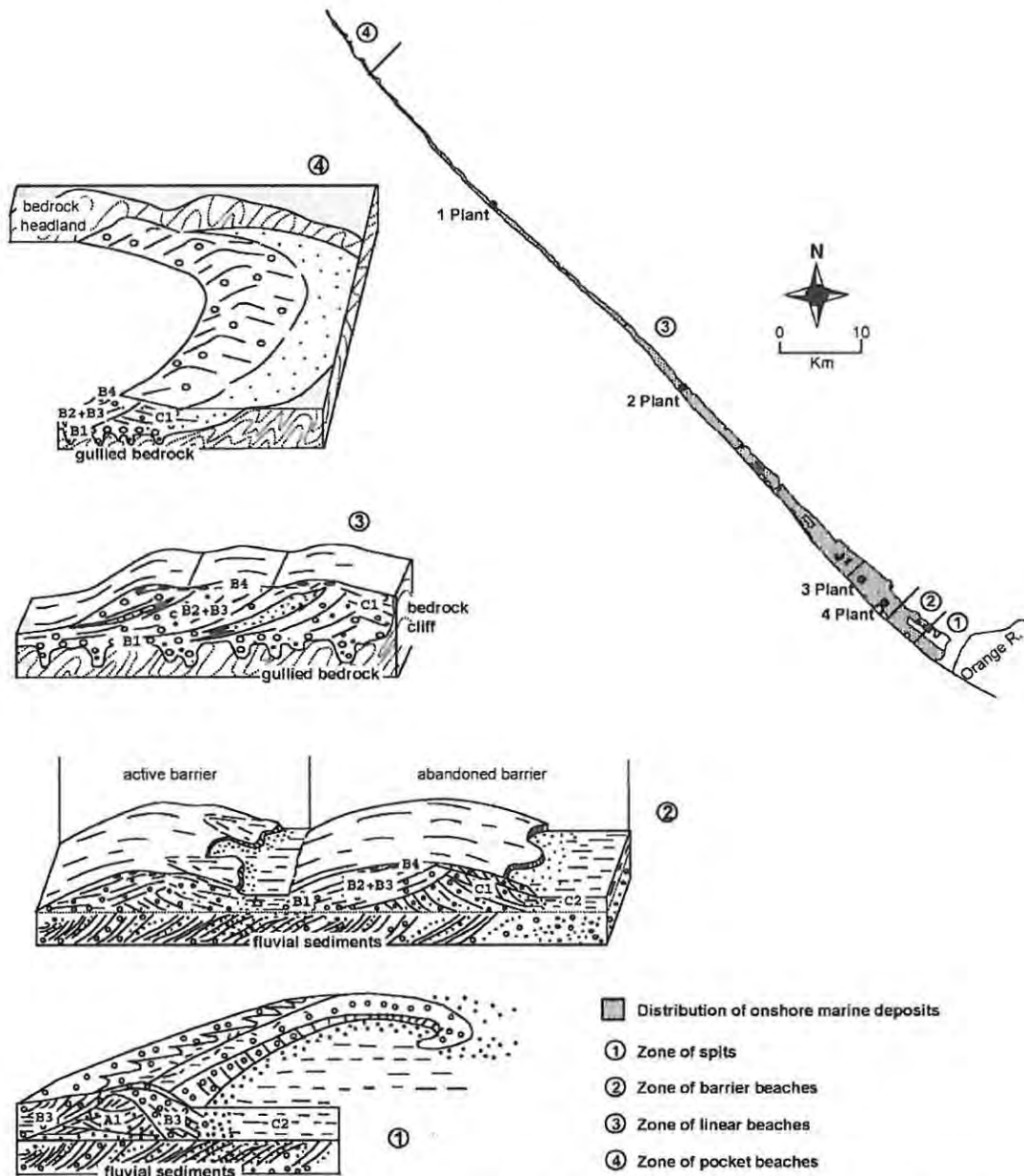


Fig. 8. Distribution of four main Pio-Pleistocene gravel beach types along the southern Namibian coast. Spits (1) are found, along with barrier beaches, in a zone of rapid sediment supply and where the area of beach accretion is widest. Barrier beaches (2) dominate the proximal setting whereas linear gravel beaches (3) follow in a trend where the width of gravel beach accretion and sediment supply is reduced. Pocket beaches (4) terminate the coastal gravel accretions to the north-northwest.

higher energy conditions persisting there, as will be discussed later. The maximum grade is found in the landward dipping foresets.

5.2. Barrier beaches

Barrier beaches are characterised by landward dipping foresets produced by wash-over deltas and by berms and cusps that grow in the opposite, seaward direction (Bluck, 1999; Bluck et al., 2001; Fig. 3; '2' on

Fig. 8). This type of gravel beach is seen in the higher-lying, slightly younger parts of the southern, proximal sections and mostly to the north of the zone hosting the spits. Barrier beaches are also characterised by containing cores of sediment that are often finer-grained than the beach itself. The sediment cores may be cross-stratified and are considered to have been produced by subtidal barriers migrating landward and building intertidal bars. In places, and probably also related to the initiation of the beach, the barrier is cored with a sandy foreshore deposit.

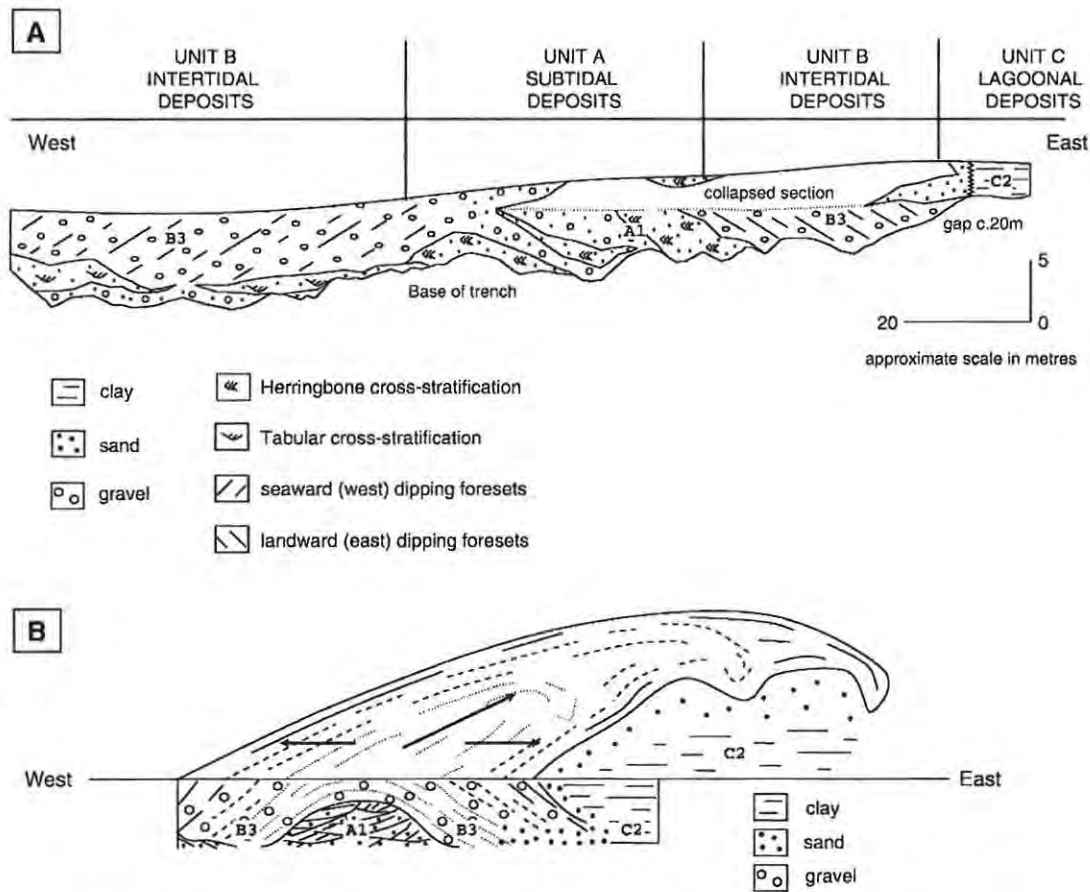


Fig. 9. Section and interpretation of Plio-Pleistocene spit deposits within the palaeo-Orange River mouth, southernmost Mining Area No. 1, Namibia. (A) Simplified trench section through Plio-Pleistocene gravel spit showing different units of sedimentation. A1 = subtidal deposits, B3 = intertidal deposits and C2 represents lagoonal clays and silts. (B) Interpretation of A, showing schematic plan and section of spit. A1, B3, and C2 refer to depositional sub-units discussed in A. Arrows schematically demarcate longshore extension of the gravel spit, accompanied by seaward and landward progradation of intertidal deposits.

Farther to the north-northwest, the barrier beaches are replaced by almost continuous coastal accretion backed by a bedrock cliff. In contrast to the situation at the palaeo-Orange River mouth, the accommodation space here was limited and wash-over fan deposits are rare. Farther south, on the Namaqualand coast near Port Nolloth, wash-over deposits related to bedrock ridges have been reported where accommodation space was created by embayments in the coastline (Gresse, 1988).

This lateral, northward change along the coast from spits and barrier beaches in the southernmost proximal setting to linear beaches farther north, is accompanied by an overall reduction in the width of the Plio-Pleistocene accretionary beaches (Figs. 1 and 8). This is taken to indicate a northward decrease in sediment supply to the beaches, a factor that may be the dominant control on the change in growth form of the gravel beaches away from the palaeo-Orange River mouth (Bluck et al., 2001).

5.3. Gravel sheets produced during transgression

Two different types of deposits record transgressive events in these Plio-Pleistocene gravel beaches (Fig. 11). The first type, generally found associated with the proximal, southernmost beaches, comprises sheets of coarse cobble- to boulder-sized gravel, mostly <2m thick, with three important characteristics:

- host patches of gravel with a disorganised fabric;
- no recognisable internal structure; and
- commonly incorporating large (<1 m size) clasts of partly lithified mud (Fig. 11B).

These coarse gravel sheets truncate the underlying strata at a low, but distinctly landward-rising, angle (Fig. 11). Such gravel sheets are interpreted to have been produced during transgression, where marine erosion at the base of a shoreward-migrating gravel beach or spit has cut into the lagoonal mud lying behind a barrier or spit. Although the mud could also have come from mud

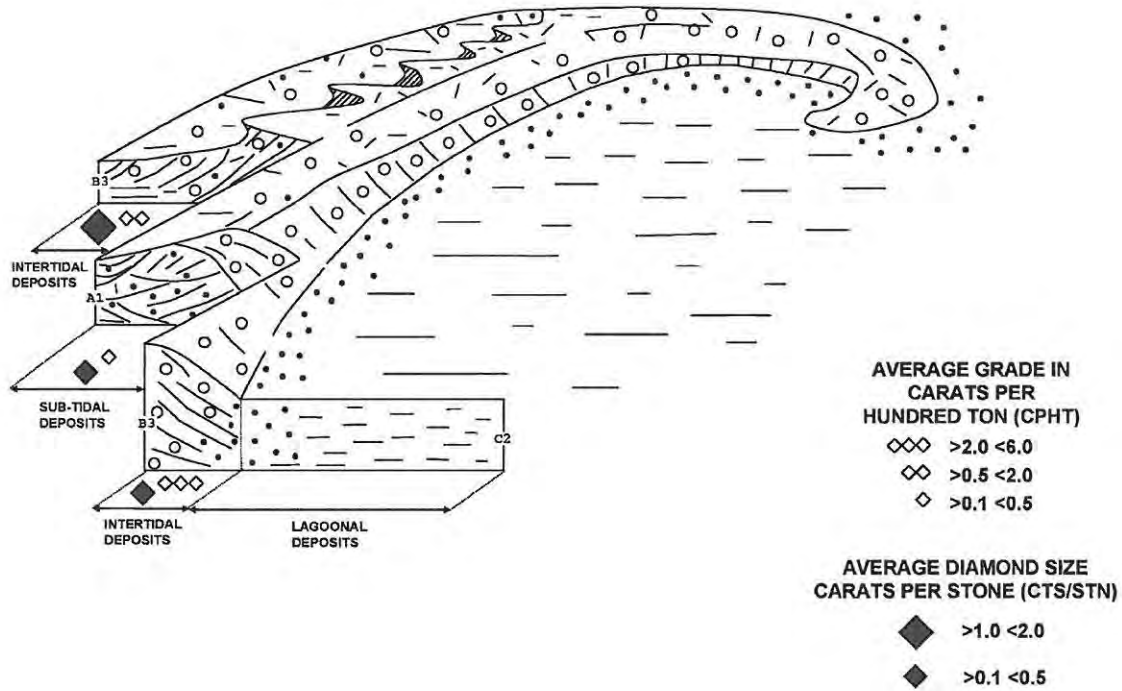


Fig. 10. Schematic representation of Plio-Pleistocene spit showing distribution of average diamond grades (carats per hundred tons = cpht) and sizes (carats per stone = cts/stn), based on data collected from within the palaeo-Orange River mouth, southernmost Mining Area No. 1. A1, B3 and C2 refer to the depositional units shown in Fig. 9.

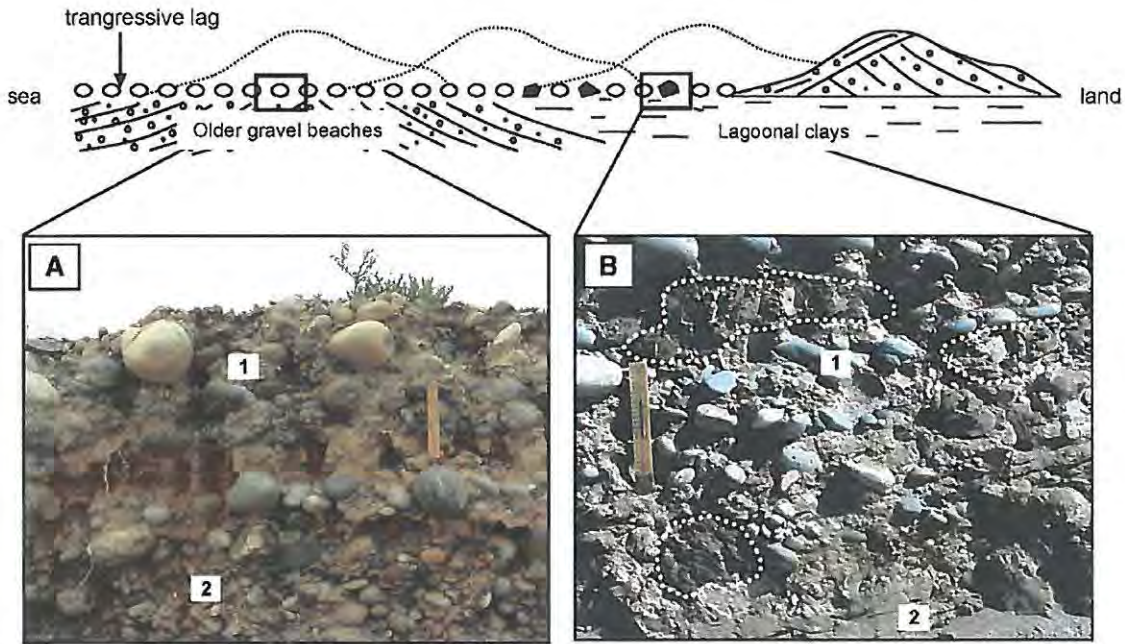


Fig. 11. Schematic section and photographs of Plio-Pleistocene transgressive beach deposits produced during barrier migration on rising sea level, southernmost Mining Area No. 1, Namibia. The seaward part of the barrier is marked by a coarse gravel sheet containing large spheres rejected from the landward migrating barrier. (A) Boulder gravel (1) truncating older deposits (2). (B) Mixture of cobble-gravel and boulders (1) truncating lagoonal clays (2). Dotted lines highlight large, rip-up clay clasts. Scale=0.25m.

flats developed at the palaeo-Orange River mouth, long distance transport in this vigorous coastal regime seems unlikely. The disorganised fabric is probably the result of the rapid reworking of the older gravel during transgression, and the enrichment in discs observed in places may be the result of the preferential movement of these clasts towards the shore during that transgressive event.

The second type of gravel sheet is distinctively different in that it comprises clasts that are often conspicuously larger than those of the adjacent, related beach and display exceptionally mature fabrics (Fig. 11A). This gravel type rarely incorporates clay–silt beds and invariably can be traced landward into a barrier or linear beach that marks the point of maximum transgression. Commonly, these gravel sheets also grade vertically into a regressive (seaward growing) beach system and, in that sense, mark the beginning of a new phase of beach building. In these circumstances, the transgressive lag sheet becomes the outer frame of the seaward building beach and, in both transgression and regression, represents the gravel sheet constituting reworked coarse, spherical and easily rolled clasts of the pre-existing beach(es). Such gravel sheets are thus a composite deposit, being the combined product of both transgression and regression.

In some instances (e.g., in Fig. 11), these coarse sheets are areally extensive, cutting across a wide variety of footwall types ranging from silt to gravel and, in general, dipping gently towards the present coastline. It is possible that such gravel sheet deposits represent major marine transgressions that characterise the coastal deposits of the Pleistocene world-wide. However, their distribution near to the palaeo-Orange River mouth, and hence the product of fluvial outfall, may also reflect a fluctuating sediment supply.

6. Diamond concentration in the Plio-Pleistocene littoral deposits within the palaeo-Orange River Mouth

6.1. General considerations

As indicated earlier, there is now general consensus that the bulk of the southern Namibian diamonds were introduced to Atlantic littoral environments via the Orange-Vaal drainage since at least Middle Eocene (ca. 42Ma) times (inter alia, Cornell, 1920; Kaiser, 1926; Stocken, 1978; Van Wyk and Pienaar, 1986; Corbett, 1996; De Wit, 1999; Ward et al., 2002). During this time, both diamond supply and average diamond size varied considerably, with clues to these changes being

recorded in the terraces and incision periods of the Lower Orange Valley (Van Wyk and Pienaar, 1986; Jacob et al., 2001). Available evidence suggests that the diamond population in the Eocene was generally finer-grained and possibly less abundant than that recovered from the younger Neogene deposits. Maximum diamond outfall appears to have occurred just prior to a main aggradational phase dated to the early Middle Miocene at ca. 17.5Ma (Pickford et al., 1996a,b), whereafter grades dropped throughout the rest of the Miocene and Plio-Pleistocene to a minimum in the present day. In partial contrast, the average stone size increased after the maximum outfall, peaking in the Pliocene–Early Pleistocene. Consequently, the great abundance of diamonds recovered from the Plio-Pleistocene beaches north of the river could therefore not have been sourced directly from the Orange River and an alternative, more local source has to be found for them. The principal, immediate source for these diamonds is interpreted as the reworking of pre-existing Cainozoic beaches, which in turn represented the destruction of former Orange River fan-delta deposits. These are known to be present in the offshore and, in places, thought to have been present onshore but have since been reworked into younger deposits.

The northward longshore drift system that created the onshore Plio-Pleistocene gravel beaches, and displaced the former Orange delta(s), has existed since at least the Middle Eocene (summarised in Pether et al., 2000). Recent sampling of relict fluvial sediments with a characteristic Eocene clast assemblage (*sensu* Kaiser, 1926) in the palaeo-Orange mouth has returned a diamond grade (0.5cph) and an average stone (0.4cts/stn) size that is less than 50% of that found in the overlying Plio-Pleistocene beaches (J. M. Loubser, pers. comm., 2002). This trend continues northwards into the Kolmanskop area of the northern Sperrgebiet where Eocene-derived diamonds run at ca. 0.1 cts/stn, in contrast to the 0.2 to 0.3 cts/stn returned from younger Late Cainozoic deposits along the current coast and immediately offshore (Merensky, 1909; Kaiser, 1926; Hallam, 1964). It is therefore inferred that all the deposits formed during the transgressions and regressions that have taken place since the Eocene potentially had a similar diamond size decline to the north as is evident in the onshore Pliocene–Holocene beaches.

It also follows that the data assembled by Hallam (1964), Sutherland (1982) and Schneider and Miller (1992), demonstrating a size decline in the diamonds northward along the coast from the Orange River mouth, are characterising an older pattern with geologically

younger manifestations thereof. Thus the present northward decrease in diamond size is a modification by Plio-Pleistocene processes of a diamond size trend that characterises a pre-existing suite of beaches deposited and destroyed by repeated transgressions and regressions which affected this coast, as well as the adjacent shelf, in post-Cretaceous times. In addition, diamond supply via the Orange River into the Atlantic Ocean has also fluctuated since the Eocene. The Eocene deposits are characterised by low grades and small average stone sizes, whereas those of Early to Middle Miocene age host the peak in both grade and average stone size, that is followed by a marked decline through the Plio-Pleistocene to the modern river setting. The diamonds have therefore been re-distributed onto the Plio-Pleistocene beaches from a complex source, but under varying conditions of strong northward longshore drift in an energetic littoral setting since at least the Eocene.

Data, particularly from onshore but also supported by offshore results, demonstrate that, in addition to a south to north variation in stone size and grade, there is also an east to west trend. As demonstrated by Hallam (1964), beaches that developed at different levels, and hence at different times, yield different diamond grades—a feature that is evident along much of the Namaqualand and southern Namibian coasts (cf. Gresse, 1988; Rogers et al., 1990; Marais et al., 2001).

The Namibian subaerial littoral placer is therefore seen as a ca. 300 km long, northwards tapered wedge of sediment showing two significant variables in diamond distribution, namely, an overall diamond size decrease to the north and subsidiary to this, a heterogeneous distribution of diamonds recycled from past sea-level stands. However, from the mining and sampling operations, a third important control on diamond size and grade distribution can be discerned — one related to sub-environments of deposition within the host littoral setting. With the recognition of sub-units of beach sedimentation as discussed above it is now possible to explore the significance of this third variable.

6.2. Variation in diamond grade (carats per 100 tons = cpht) and stone size (carats per stone = cts/stn) of the Plio-Pleistocene littoral deposits within the palaeo-Orange River mouth

In the Pliocene to Holocene onshore littoral deposits of Mining Area No. 1, good grades (>100cpht) with average stone sizes ranging from 1 to 0.5cts/stn are found within the linear and pocket beaches that are floored and/or cliffed with competent Late Proterozoic rock types conducive to fixed trap site formation

(Hallam, 1964; Apollus, 1995; Jacob, 2001). In contrast, the gravel spits and barrier beaches within the palaeo-Orange River mouth rest on an incompetent fluvial sedimentary footwall that does not promote the development of fixed trapsites. Significantly, but unsurprisingly, therefore, gravel spits and barrier beaches have considerably lower diamond grades than the linear and pocket beaches (Figs. 6 and 10).

Within the beach environment, Hallam (1964) noted that the best grades occur at the top and bottom of these deposits, analogous to heavy mineral concentrations on the present beaches. The results of the sampling campaigns in the palaeo-Orange River mouth area (summarised in Figs. 6 and 10) provide new insights into the diamond distribution of gravel spit and barrier beach settings during the Plio-Pleistocene. Using the criteria already discussed, these gravel beach deposits are ascribed to the various zones of accumulation as seen on present-day beaches along the Skeleton Coast and elsewhere. This approach has the advantage of being able to infer the conditions under which the gravel accumulated and therefore the conditions under which diamonds were retained.

6.3. Intertidal (beach-face) deposits

Within the palaeo-Orange River mouth, the proximal seaward-facing intertidal deposits in the spit and barrier beach settings (beach face, zone B, Figs. 6 and 10) have some of the higher grades of the littoral deposits (0.5 to 2cpht), as well as a larger than average stone size (1 to 2cts/stn). This zone is subject to the highest wave energy, with swash and backwash raking sediment continuously over the rough gravel surface. Turbulence generated here, particularly when backwash runs over a rough surface, makes these sites ideal areas for intensive sorting. This is clearly demonstrated by the extreme clast shape-size-sorting seen there and by the thick accumulations of garnets observed in this setting on the gravel beaches along both Mining Area No. 1 and the Skeleton Coast.

Sediment erosion within the intertidal zone is common. Replacement of beach gravel, sometimes to depths of up to a meter in storm conditions, means that the sediment exchange with the offshore, or with other regions of the beach, is considerable. Consequently, there are few places where diamonds can accumulate, after repeated sorting events over a long period, in order to ultimately generate an unusually rich placer deposit. Here, and elsewhere on the beach, the main method of diamond retention is therefore considered to be by percolation through the often very large gravel

framework pore-space. Diamonds may then descend through this framework until they reach a level where the pore-size is too small to allow them further passage.

The main role played by the intertidal zone is thus likely to be in concentrating diamonds on the beach surface by an intensive sorting processes when wave conditions are favourable. Such concentrates produced on the beach may then be moved into the immediate offshore during beach breakdown or thrown higher up on the beach. From there, the diamonds may remain as a relatively concentrated assemblage, be diluted by additional sediment introduced to those sub-environments or even be removed completely by longshore drift currents.

6.4. Back-barrier and landward-facing spit deposits

Whilst the intertidal deposits of the beach face and toe are subject to a great deal of reworking, those of the wash-over deltas, the crests of beach ridges and, to some extent, the landward regions of spits are usually either storm produced or developed during spring tides. Once deposited, these sediments are rarely reworked, implying that their diamond population represents a reasonable measure of the ratio of diamond to gravel transported within waves that break periodically over the crest of the beach. In the back-barrier zone, wash-over delta grades are generally low at 1 to 1.5 cpht with a small average stone size of 0.5 to 1 cts/stn (Fig. 6).

In the case of spits, the landward-facing beaches have the highest grades (2 to 6 cpht) but the smallest average stone size (0.1 to 0.5 cts/stn; Fig. 10). These deposits are subject to more reworking than the wash-over deltas because waves refracted around the spit-head produce orthogonal waves running parallel to the beach face, but in a southerly direction. These southward moving waves, albeit with greatly reduced wave height, gently rework the steep, landward-facing beaches, often washing out the finer-grained sediments, resulting in only moderate concentration of the placer. Once deposited, diamonds appear to accumulate without significant further modification by large-scale erosion — an observation supported by the minimal upgrading in average stone size of the landward-facing beaches (0.1 to 0.5 cts/stn) compared to the seaward-facing beaches on the spit (1 to 2 cts/stn).

6.5. Subtidal, transgressive boulder lags

During the landward migration of a beach, the coarsest and most mobile clasts, notably the large

spheres, accumulate at the beach toe. As this landward migration proceeds, e.g., during a transgression or a period of minimal sediment input and hence local erosion, this area of coarse clast accumulation progressively becomes the depositional surface of the subtidal zone. Diamonds washed seaward from the steep intertidal zone, as well as those that might accumulate from subtidal sorting, are retained here. With the local turbulence being controlled by clast size, which in this proximal setting is of boulder size (Fig. 11), only the largest diamonds (2 to 3 cts/stn) are retained but grades are invariably poor (0.2 to 0.5 cpht).

Given the mobility and fine-grained nature of the sand-dominated subtidal deposits associated with spit elongation, it is not surprising that these deposits return the poorest results from both a grade (0.1 to 0.5 cpht) and average stone size (0.1 to 0.5 cts/stn) perspective. Even in the proximal setting within the palaeo-Orange River mouth, clast and grain size play an important role in determining diamond concentration.

The sampling campaign, combined with a detailed analysis of sedimentary facies, therefore highlighted several important points:

1. Diamonds are abundant in littoral sediments that migrate northwards. They are derived from multiple sources, including the Orange River, its former fan-deltas and associated beach deposits.
2. Gravel spits and barrier beaches within the palaeo-Orange River mouth are ineffective in retaining diamonds — they ultimately move northward under the vigorous longshore drift regime.
3. Where there are permanent trapsites, which create sufficient turbulence, diamonds are extracted from this passing bed-load and concentrated.
4. Beaches are not as efficient in trapping diamonds as other surfaces, in particular, fixed bedrock trapsites such as those found in the Late Proterozoic bedrock underlying the linear and pocket beaches (Hallam, 1964; Apollus, 1995; Jacob, 2001) or those preserved in terraces of the ancestral Lower Orange River (Jacob et al., 1999). Thus, by generating long-lived sites of turbulence, fixed trapsites accumulate and retain many generations of diamond within that portion of the sedimentary system, thereby increasing both grade and average stone size significantly in those, invariably small, areas.

7. Summary of conclusions and core interpretations

1. The Plio-Pleistocene +30m littoral package within the palaeo-Orange River mouth is a low grade, large

average stone size diamond placer that was deposited at a time when there was a minimal input of diamonds from the Orange River. In order to account for the diamonds in these deposits, it is postulated that additional diamonds were sourced from pre-existing beaches, dominantly from the seaward—but also, in places, from the landward-side. These pre-existing beaches had a northward decrease in diamond size that was probably inherited, but enhanced, during their accumulation on the Pliocene–Holocene beaches.

2. The low grades of the littoral deposits within the palaeo-Orange River mouth, lower by several orders of magnitude compared to the classic linear and pocket beaches farther north along the littoral drift system, are attributed to the incompetent footwall and consequent paucity of fixed trapsites, as well as a general northward movement of the smaller diamonds through longshore drift. In contrast to the grades, therefore, the higher average diamond size in these southernmost deposits is linked to their close proximity to the palaeo-Orange River outfall both prior to, and during, the Pliocene–Pleistocene.
3. In the proximal littoral setting within the palaeo-Orange River mouth, the Pliocene–Pleistocene seaward-facing intertidal deposits in both barrier beaches and spits provide the most promising targets with grades ranging from 0.5 to 2 cpht and average stone sizes ranging from 1 to 2 cts/stn. Although effectively a mobile trapsite, this placer owed its accumulation largely to the intense sorting associated with a coarse gravel foreshore environment. Maximum concentration (2 to 6 cpht) was recorded in the landward-facing intertidal deposits of the gravel spits but the low average stone size (0.1 to 0.5 cts/stn) affects these better grades adversely. The subtidal transgressive boulder lags yielded grades of similar range (0.2 to 0.5 cpht) but the average diamond size of 2 to 3 cts/stn is the largest of all the sub-units sampled in this proximal setting, thus increasing their interest rating substantially. The lowest, currently sub-economic grades (0.1 to 0.5 cpht) and stone sizes (0.1 to 0.5 cts/stn) were returned from subtidal settings associated with gravel spits.
4. By identifying and relating internal sedimentary structures to depositional facies regimes in this way, more accurate sampling, evaluation and mining of such low grade littoral placers can therefore now be undertaken.
5. On the Namibian coast, therefore, diamond distribution and average stone size is shown to be linked

directly to sedimentary facies in the Pliocene–Pleistocene beach types preserved within the palaeo-Orange River mouth. This additional control must be incorporated, along with the already known spatial decrease in diamond size northwards from the Orange River outfall and the east to west temporal heterogeneity in grade between Late Cainozoic beaches of different ages, in any evaluation of the Namibian coastal placer.

Acknowledgements

We thank Namdeb Diamond Corporation (Pty) Limited, in particular the former Mineral Resource Manager, Mr. Mike Lain, and the current Manager, Mr. Bob Burrell, for their unstinting support and encouragement over the years. Dr. Mike de Wit, General Manager, De Beers Africa Exploration, is also thanked for his interest, as are the Geolab personnel, SASP sampling team and Security of Namdeb who assisted with the collection of the diamond data. Reviews by Dr. P. Gresse and Mr. A. van der Westhuizen (Trans Hex Group) are acknowledged with gratitude—their comments greatly improved our earlier draft. The late Dr. G. Els is thanked for his patience in allowing us to complete this paper.

References

- Aizawa, M., Bluck, B., Cartwright, J., Milner, S., Swart, R., Ward, J., 2000. Constraints on the geomorphological evolution of Namibia from the offshore stratigraphic record. *Communications of the Geological Survey of Namibia* 12, 337–346.
- Apollus, L., 1995. The distribution of diamonds on a Late Cainozoic gravel beach, southwestern Namibia. Unpublished M.Sc. thesis, Department of Geology and Applied Geology, University of Glasgow. 170 pp.
- Bagguley, J.G., 1996. The application of seismic and sequence stratigraphy to the post-rift megasequence, offshore Namibia. Unpublished Ph.D. thesis, Oxford-Brookes University. 370 pp.
- Birch, G.F., Day, R.W., Du Plessis, A., 1991. Nearshore Quaternary sediments on the west coast of southern Africa. *Geological Survey of South Africa, Bulletin* 101, 1–14.
- Blair, T.C., 1999. Sedimentology of gravelly Lake Lahontan highstand shoreline deposits, Churchill Butte, Nevada, USA. *Sedimentary Geology* 123, 199–218.
- Bluck, B.J., 1967. Sedimentation of beach gravels: examples from South Wales. *Journal of Sedimentary Petrology* 37, 128–156.
- Bluck, B.J., 1999. Clast assembling, bed forms and structure in gravel beaches. *Transactions of the Royal Society of Edinburgh. Earth Sciences* 89, 291–323.
- Bluck, B.J., Ward, J.D., Spaggiari, R.I., 2001. Gravel beaches of southern Namibia. In: Packham, J.R., Randall, R.E., Barnes, R.S. K., Neal, A. (Eds.), *Ecology and Geomorphology of Coastal Shingle*. Westbury Academic and Scientific Publishing, Otley, West Yorkshire, U.K., pp. 56–76.

- Carr, A.P., 1969. The growth of Orford Spit: cartographic and historical evidence from the sixteen century. *Geographical Journal* 135, 28–29.
- Corbett, I.B., 1989. The sedimentology of the diamondiferous deflation deposits, Namibia. Unpublished Ph.D. thesis, University of Cape Town. 430 pp.
- Corbett, I.B., 1996. A review of diamondiferous marine deposits of western southern Africa. *Africa Science Review* 3, 1–18.
- Cornell, F.C., 1920. Reprinted 1992 *The Glamour of Prospecting*. Creda Press (Pty) Ltd., Cape Town. 336 pp.
- Davis, J.L., 1972. *Geographical Variation in Coastal Development*. Oliver and Boyd, Edinburgh. 204 pp.
- De Beer, C.H., Gresse, P.G., Theron, J.N., Almond, J.E., 2002. The Geology of the Calvinia area. Explanation of 1:250,000-scale map sheet 3118 Calvinia. Council for Geoscience, South Africa. 92 pp.
- De Decker, R.H., 1988. The wave regime on the inner shelf south of the Orange River and its implications for sediment transport. *South African Journal of Geology* 91, 358–371.
- De Wit, M.J.C., 1999. Post-Gondwana drainage and the development of diamond placers in west South Africa. *Economic Geology* 94, 721–740.
- Dingle, R.V., Siesser, W.G., Newton, A.R., 1983. Mesozoic and Tertiary geology of southern Africa. A.A. Balkema, Rotterdam. 375 pp.
- Gresse, P.G., 1988. Washover boulder fans and reworked phosphorite in the Alexander Bay Formation. *South African Journal of Geology* 91, 391–398.
- Grey, C.E.D., Meadows, M.E., Lee-Thorp, J.E., Rogers, J., 2000. Characterising the Namaqualand mud belt of southern Africa. *Palynology and Palaeoenvironments. Southern African Geographical Journal* 82, 137–142.
- Gurney, J.J., Moore, R.O., Otter, M.L., Kirkley, M.B., Hops, J.J., McCandless, T.E., 1991. Southern African Kimberlites and their Xenoliths. In: Kampunzu, A.B., Lubala, R.T. (Eds.), *Magmatism in Extensional Structural Settings*. Springer-Verlag, Berlin, pp. 495–536.
- Hallam, C.D., 1964. The geology of the coastal diamond deposits of southern Africa (1959). In: Haughton, S.H. (Ed.), *The Geology of Some Ore Deposits in Southern Africa*, vol. 2. Geological Society of South Africa, pp. 671–729.
- Hay, W.W., Brock, J.C., 1992. Temporal variation in intensity of upwelling off southwest Africa. In: Summerhays, C.P., Prell, W.L., Emeis, K.C. (Eds.), *Upwelling Systems: Evolution since the Early Miocene*. Geological Society of London Special Publication, vol. 63, pp. 463–497.
- Hiroki, Y., Masuda, F., 2000. Gravelly spit deposits in a transgressive systems tract: the Pleistocene Higashikanbe gravel, central Japan. *Sedimentology* 47, 135–149.
- Jacob, J., 2001. Late Proterozoic bedrock geology and its influence on Neogene littoral marine diamondiferous trapsites, MA1 — Sperrgebiet, Namibia. Unpublished M.Sc. thesis, University of Cape Town. 140 pp.
- Jacob, R.J., Bluck, B.J., Ward, J.D., 1999. Tertiary-age diamondiferous fluvial deposits of the Lower Orange River Valley, southwestern Africa. *Economic Geology* 94, 749–758.
- Jacob, R.J., Bluck, B.J., Ward, J.D., 2001. Incision and aggradation in the Orange River valley, southwestern Africa. 7th International Conference on Fluvial Sedimentology, University of Nebraska, August 2001, Abstract Volume, p. 138.
- Kaiser, E., 1926. *Die Diamantenwürste Südwestafrikas*. Deitrich Reimer (Ernst Vohsen), Berlin. Volumes 1 and 2. 535 pp.
- Maejima, W., 1982. Texture and stratification of gravelly beach sediments. *Japan Journal of Geoscience* 25, 35–51.
- Marais, J.A.H., Agenbacht, A.L.D., Prinsloo, M., Basson, W.A., 2001. The geology of the Springbok area. Explanation of 1:250,000-scale map sheet 2916 Springbok. Council for Geoscience, South Africa. 103 pp.
- Massari, F., Parea, G.C., 1988. Progradational gravel bed sequences in a moderate-to-high energy, micro-tidal environment. *Sedimentology* 35, 881–913.
- Merensky, H., 1909. The diamond deposits of Lüderitzland, German South West Africa. *Transactions of the Geological Society of South Africa* 12, 13–23.
- Neal, A., Dackcombe, R.V., Roberts, C.L., 2001. Applications of ground penetrating radar (GPR) to the study of coarse elastic (shingle) coastal structures. In: Packham, J.R., Randall, R.E., Barnes, R.S.K., Neal, A. (Eds.), *Ecology and Geomorphology of Coastal Shingle*. Westbury Academic and Scientific Publishing, Otley, West Yorkshire, U.K., pp. 77–106.
- Nielsen, L.H., Johannessen, P.N., Surlyk, F., 1988. A Late Pleistocene coarse-grained spit-platform sequence in Northern Jylland, Denmark. *Sedimentology* 35, 915–937.
- Oosterveld, M.M., 2003. Evaluation of alluvial diamond deposits. Workshop: alluvial diamonds in South Africa, 2 April 2003, Johannesburg. Directorate of Professional Programmes of the Geological Society of South Africa. Geological Society of South Africa. 17 pp.
- Orford, J.D., 1975. Discrimination of particle zonation on a pebble beach. *Sedimentology* 22, 441–463.
- Orford, J.D., Carter, R.W.G., 1982. Crestal overtop and overwash sedimentation on a fringing sandy gravel barrier coast, Carnsore Point, southeast Ireland. *Journal of Sedimentary Petrology* 52, 265–278.
- Orford, J.D., Carter, R.W.G., Jennings, S.G., 1991. Coarse elastic barrier environments: Evolution and implications for Quaternary sea level interpretation. *Quaternary International* 9, 87–104.
- Orford, J.D., Jennings, S.C., Forbes, D.L., 2001. Origin, development, reworking and breakdown of gravel-dominated coastal barriers in Atlantic Canada: future scenarios for the British coast. In: Packham, J.R., Randall, R.E., Barnes, R.S.K., Neal, A. (Eds.), *Ecology and Geomorphology of Coastal Shingle*. Westbury Academic and Scientific Publishing, Otley, West Yorkshire, U.K., pp. 23–55.
- Pether, J., 1986. Late Tertiary and early Quaternary marine deposits of the Namaqualand coast, Cape Province: new perspectives. *South African Journal Science* 82, 464–470.
- Pether, J., 1994. The sedimentology, palaeontology and stratigraphy of coastal-plain deposits at Hondeklip Bay, Namaqualand, South Africa. Unpublished M.Sc. thesis, University of Cape Town. 313 pp.
- Pether, J., Roberts, D.L., Ward, J.D., 2000. Deposits of the West Coast. In: Partridge, T.C., Maud, R.R. (Eds.), *The Cenozoic of Southern Africa*. Oxford University Press, pp. 33–49.
- Pickford, M., Senut, B., Mein, P., Gommery, D., Morales, J., Soria, D., Nieto, M., Ward, J., 1996a. Preliminary results of new excavations at Arrisdrift, Middle Miocene of southern Namibia. *Comptes Rendus de l'Académie des Sciences (Series IIA, Earth and Planetary Science)*, vol. 322, pp. 991–996.
- Pickford, M., Senut, B., Mein, P., Morales, J., Soria, D., Nieto, M., Ward, J., Bamford, M., 1996b. The discovery of Lower and Middle Miocene vertebrates at Auchas, southern Namibia. *Comptes Rendus de l'Académie des Sciences (Series IIA, Earth and Planetary Science)*, vol. 322, pp. 901–906.

- Postma, G., Nemec, W., 1990. Regressive and transgressive sequences in a raised Holocene gravelly beach, Southwestern Crete. *Sedimentology* 27, 907–920.
- Pye, K., 2001. The nature and geomorphology of coastal shingle. In: Packham, J.R., Randall, R.E., Barnes, R.S.K., Neal, A. (Eds.), *Ecology and Geomorphology of Coastal Shingle*. Westbury Academic and Scientific Publishing, Otley, West Yorkshire, U.K., pp. 2–22.
- Rogers, J., 1977. Sedimentation on the Continental Margin off the Orange River and the Namib Desert: Bulletin Geological Survey and /University of Cape Town Marine Geoscience Unit 7. 212 pp.
- Rogers, J., Pether, J., Molyneux, R., Genis, G., Kilham, J.L.C., Cooper, G., Corbett, I.B., 1990. Cenozoic Geology and Mineral Deposits Along the West Coast of South Africa and the Sperrgebiet: Guidebook, Geocongress '90. Geological Society of South Africa. PR1. 111 pp.
- Rossouw, J., 1981. Wave conditions at Oranjemund: summary of wave rider data March 1976–April 1980. Unpublished Report, Council for Scientific and Industrial Research, Stellenbosch, T/SEA 8106, 1–4.
- Schneider, G.I.C., Miller, R.McG., 1992. *Diamonds, The Mineral Resources of Namibia*, 1st edition. Ministry of Mines and Energy, Windhoek, Namibia, pp. 5.1-1–5.1-32.
- Serrane, M., 1999. Early Oligocene stratigraphic turnover on the west Africa continental margin: a signature of the Tertiary greenhouse-to-icehouse transition? *Terra Nova* 11, 135–140.
- Sherman, D.J., Oxford, J.D., Carter, R.W.G., 1993. Development of cusp-related, gravel size and shape facies at Malin Head, Ireland. *Sedimentology* 40, 1139–1152.
- Siesser, W.G., Dingle, R.V., 1981. Tertiary sea-level movements around southern Africa. *Journal of Geology* 89, 83–96.
- South African Committee for Stratigraphy (SACS), 1980. *Stratigraphy of South Africa*, Kent, L.E. (Compiler): Part 1. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophutatswana, Transkei and Venda. Handbook of the Geological Survey of South Africa 8. 690 pp.
- Spaggiari, R.I., Bluck, B.J., Ward, J.D., 1999. Beaches, barriers and bars: sedimentary facies of Early Pleistocene diamondiferous deposits within the Orange River mouth, Namibia. In: Lee-Thorp, J., Clift, H. (Eds.), *The Environmental Background to Hominid Evolution*, XV International Congress International Union for Quaternary Research, 3–11 August 1999, Durban, South Africa, Abstract Volume, pp. 169–170.
- Spaggiari, R.I., Ward, J.D., Bluck, B.J., 2002. Quaternary diamond bearing beaches of southern Namibia. IAS 16th International Sedimentology Congress, Rand Afrikaans University, Johannesburg, July 2002. Abstract Volume, p. 341.
- Steers, J.A., 1937. The Culbin Sands and Burghead Bay. *Geographical Journal* 90, 498–528.
- Stocken, C.G., 1978. A review of the later Mesozoic and Cenozoic deposits of the Sperrgebiet. Unpublished Report, Consolidated Diamond Mines of South West Africa (Pty) Ltd. 38 pp.
- Sutherland, D.G., 1982. The transport and sorting of diamonds by fluvial and marine processes. *Economic Geology* 77, 1613–1620.
- Van Wyk, J.P., Pienaar, L.F., 1986. Diamondiferous gravels of the Lower Orange River, Namaqualand. In: Anhaeusser, C.R., Maske, S. (Eds.), *Mineral Deposits of Southern Africa*, vol. II. Geological Society of South Africa, pp. 2309–2321.
- Ward, J.D., 1987. The Cenozoic succession in the Kuseib Valley, central Namib Desert. *Geological Survey of South West Africa/Namibia Memoir* 9 (124 pp.).
- Ward, J.D., Bluck, B.J., 1997. The Orange River: 100 million years of fluvial evolution in southern Africa. 6th International Conference on Fluvial Sedimentology, University of Cape Town, South Africa, September 1997, Abstract Volume, p. 222.
- Ward, J.D., Van der Westhuizen, A., Jacob, R.J., Apollus, L., Spaggiari, R.I., Nicholas, G., 1998. West Coast Field Excursion. 7th International Kimberlite Conference. University of Cape Town, South Africa. 23 pp.
- Ward, J.D., Jacob, R.J., De Wit, M.C.J., Spaggiari, R.I., Bluck, B.J., 2002. Post-Gondwana evolution of the Vaal-Orange drainage system: economic implications. Excursion Guide, 16th International Sedimentological Conference. Rand Afrikaans University, Johannesburg, South Africa. 75 pp.
- Wickens, H. deV., McLachlan, I.R., 1990. The stratigraphy and sedimentology of the reservoir interval of the Kudu 9A-2 and 9A-3 boreholes. *Communications of the Geological Survey of Namibia* 6, 9–22.
- Williams, A.F., 1932. *The Genesis of the Diamond*, Vol. II. E. Benn, Ltd., London. 636 pp.
- Williams, A.T., Caldwell, N.E., 1988. Particle size and shape in pebble beach sedimentation. *Marine Geology* 82, 199–215.

Quaternary diamond bearing beaches of southern Namibia

R.I. SPAGGIARI¹, J.D. WARD² & B.J. BLUCK³

¹Namdeb Diamond Corporation, Pty (Ltd), Oranjemund, Namibia (E-mail: rspaggiari@namdeb.com.na)

²De Beers Africa Exploration, Centurion, South Africa

³Division of Earth Sciences, University of Glasgow, Glasgow G12 8QQ, Scotland

In southern Namibia, diamond bearing gravel beaches accumulated north of the Orange River under a highly energetic coastal regime during the Quaternary. The Orange River has transported diamondiferous sediment from the Kaapvaal craton, and its associated cover deposits, to the Atlantic Ocean since at least the Early Tertiary. A north-northwestward directed coastal dispersal system, driven by a vigorous southerly wind regime, has fractionated these sediments such that:-

- (i) Fine sediment (silt & clay) is transported onto the continental edge and northward in the offshore;
- (ii) Sand is dispersed along an inshore linear corridor, tapped by suitably oriented take-off points, which return much of it to the land as aeolian dunes in a desert setting;
- (iii) Coarse clasts accrete to the shoreline as a series of beaches that begin immediately north of the Orange River and then extend along the coast for >200 km.

These beaches and the re-worked residues thereof, trap the diamond fraction brought down by the Orange River and constitute the main placer in this unique diamond bearing deposit. Thus, the northward-dispersal results in a characteristic logarithmic decline in grain size of both gravel and diamond size down-drift (to the NNW). In the main placer, a variety of gravel beaches have recently been recognised, differing from each other in the arrangement and type of basic gravel building blocks. These are defined on both texture and structure, which are attributed to sub-environments of deposition. The beaches

have variable average diamond sizes, as well as variable grades within each building block and gravel bar type. The highest diamond grades are found in linear and pocket beaches; the lowest in barrier beaches and spits. On these low-grade barrier type gravel beaches, the highest diamond concentrations are confined to the intertidal zone, particularly in the beach face. Here the main method of diamond retention is thought to be by percolation through a large gravel (cobble-boulder) framework pore-space. In contrast, the landward margins of gravel spits are characterised by high grades but with a reduced stone size. Deposition there was due to wave refraction around the spit head which, because of attenuation, were long wave constructive rather than short wave destructive settings.

The wash-over deltas, usually storm produced or developed during high spring tides, are repositories of repeated diamond influx from the beach face. With very little sorting and re-erosion after deposition at the site of their accumulation, the diamond population in wash-over deltas was not subjected to further upgrading and thus displays the lowest grades of the barrier beach sub-environments. The seaward facing beach surface is a zone of effective clast shape sorting, where diamonds are also sorted and retained. However, it is notably a mobile surface, subject to much erosion and rebuilding. Consequently, the retention of diamonds on this surface is limited compared with the total amount sorted in this littoral environment.

sediments associated with several marker tephra layers and ^{14}C dates. Combined with the lithic typology, the following cultural sequence, characterised by "type-fossil" stone tools has been established: edge polished axes (30-25 ka), knives (27-16 ka), small-size points (16-14 ka), microliths (14-12 ka) and large-size points (12-10 ka). Today, comparisons of regional chronology using widespread tephra layers as time markers, reveal common features and regional differences in the Upper Palaeolithic cultures. In addition, three potsherds discovered below the Asama-Okubozawa Pumice 2 (ca. 16 ka) at the Shimomouchi site stimulate a debate on the time of pottery emergence. Since 1980s, the extended application of this research method to the continental part of eastern Eurasia, has established among many archaeologists recognition of the common leptozone in this region. Widespread tephra layers with Japanese and Korean origins have been traced to Russia and China, as well as to Japan and Korea. For example, AT ash (24-25 ka) of Japanese origin was identified at some Palaeolithic sites in South Korea, and the relationships between the AT ash and archaeological occurrences have been discussed. In the near future, it will be possible to study Palaeolithic chronology using these same marker tephra layers, even over a more extended area, including the Kuril Islands and the Kamchatka Peninsula.

Changqing SONG & Xiangjun SUN

Institute of Botany, Chinese Academy of Sciences, Beijing China

POLLEN RECORDS ON THE HISTORY OF MIXED CONIFER AND HARDWOOD FOREST IN NORTHEAST CHINA

This paper deals with history of the mixed conifer and hardwood forest in Northeast China. Dated pollen records published so far indicated that forests of this kind were distributed in north and east parts of Changbai Mountain above 900m a.s.l. during the warm period of Holocene, ca. 10 000 to 5 000-4 000 BP. During the same period the lower altitude of the region was covered with hardwood forest. From about 5 000 BP in accordance with general climatic cooling, pine (mainly *Pinus koraiensis*) began to migrate.

R SORESENSEN (1), A MURRAY (2), AK KAAVA (3) & M KILASARA (3)

(1) Department of Soil & Water Sciences, Agricultural University of Norway, Aas. (2) Department of Geology, University of Aarhus. (3) Department of Soil Science, Sokoine University of Agriculture, Morogoro, Tanzania.

STRATIGRAPHY AND FORMATION OF A LATE PLEISTOCENE COLLUVIAL APRON IN MOROGORO DISTRICT, CENTRAL TANZANIA

Thick sandy colluvium has formed at the footslopes of an inselberg of granitic gneiss in Central Tanzania. Maximum observed thickness is 13 m. Medium to fine massive and light coloured sand underlay a thin soil horizon. At approximately 4.5 m depth a discontinuous calcrete occurs at the top of a brownish, medium to coarse sand with an irregular upper boundary interpreted as a strongly eroded surface. Such cut and fill structures were described by Botha (1996). The calcrete and the brownish sand may represent remnants of a palaeosol, approximately 40 ka old (^{14}C -dating). TL/OSL datings give similar results. Down to 12.5 m depth the deposit show occasional weak layering of fine granules and very coarse sand in a generally medium to coarse massive sand. At 13 m depth a ca. 0.3 m thick siltcrete layer occurs. This is near the present day groundwater seepage-zone, which is found approximately 1 m above the underlying unweathered gneiss at this location. The fine sand (125 - 63 m) is only slightly weathered, with 'fresh' microcline and oligoclase feldspars. The mineralogy is determined by XRD- and thin-section analyses, confirmed by total chemical analyses of selected samples. The 'lines' (< 10 m) contain also considerable amounts of slightly weathered mineral material mixed with kaolinite. A series of five TL/OSL-datings indicate that the deposit has formed over a period of approximately 90 ka. Luminescence dating has proven successful in similar sediments in Kwazulu-Natal. It is assumed that sheet-wash is the dominant type of sediment transport, but some of the fine sand and silt may have an aeolian origin. The calcrete and corresponding palaeosol may represent an interstadial around 40 ka. During the Holocene the colluvial apron has undergone degradation by a combination of surface erosion and episodic ground-water ravination. Preliminary results from this section have been published. Similar investigations have been carried out further north in Central Tanzania.

A SOWUNMI & PA OYELARAN

Department of Archaeology & Anthropology, University of Ibadan, Ibadan, Nigeria.

HOLOCENE ENVIRONMENTS IN WEST AFRICA, WITH PARTICULAR EMPHASIS ON NIGERIA

Based on the limited available palynological, oceanographic, sedimentological and archaeological data, the human and non-human Holocene environments in West Africa have been reconstructed. There were changes in the nature and extent of the lowland rain forest and its edaphic variants on the one hand and the savanna vegetations on the other. These changes in the non-human environments from the beginning of the Holocene to the period ca. 3 500 yr BP seemed to have been mainly due to climatic fluctuations; but there are strong indications from geophysical, sedimentological and palynological evidence that subsequent changes were compounded and accentuated by human activities related to plant cultivation.

RI SPAGGIARI (1), BJ BLUCK (2) & JD WARD (1)

(1) Namdeb Diamond Corporation, Oranjemund, Namibia. (2) Department of Geography and Topographic Science, University of Glasgow, Scotland.

BEACHES, BARRIERS AND BARS: SEDIMENTARY FACIES OF EARLY PLEISTOCENE DIAMONDFEROUS DEPOSITS WITHIN THE ORANGE RIVER MOUTH, NAMIBIA

In Namibia, the bulk of the diamond production to date has been derived from Quaternary marine deposits preserved between about +30masl and -20masl. These marine deposits, which extend north of the Orange River mouth for some 100 km, rest unconformably on, and are backed by, late Proterozoic Gariep Complex metasediments. In contrast, the accommodation space

within the Orange River valley has promoted the preservation of a *Donax rogersi* bearing (Early Pleistocene zone fossil), gravel barrier package as a distinct geomorphic feature some 4 km long. These barrier sediments directly overlie fluvial deposits of an earlier course of the Orange River. A number of principal facies comprising this feature have been recognised and are described here:- 1. Shoreface gravel and sand deposits: reflect the influence of a northward-directed longshore drift system and the vigorous coastal storm conditions that prevailed during the Early Quaternary. 2. Intertidal gravel and sand deposits: accretionary beaches and washovers deposited under conditions of high sediment input in a tidal regime similar to that of the present day. 3. Course gravel sheets: laterally persistent beds that truncate sediments of pre-existing barrier systems and are the transgressive lag product of extensive reworking as the barriers migrated landward. 4. Gravel spits: seaward and landward dipping gravel beaches, separated by sandy tidal inlet deposits displaying a northward-directed growth record. 5. Back barrier deposits: fine-grained sediments of the lagoonal environment that in places contain marine foraminifera, which is indicative of marine flooding. Thus the large barrier complex preserved within the Orange River Valley mouth area comprises stacked accretionary marine deposits of a coast-parallel system correal with the +30m marine package that is well distributed along the southwestern African coast. Based on the clast assemblage, most of the sediment for this barrier complex was derived from the outfall of a Pliocene to Early Pleistocene palaeo-Orange River.

Matt SPONHEIMER (1, 2) & Julia LEE-THORP (1)

(1) Dept of Archaeology, University of Cape Town, RSA. (2) Dept of Anthropology, Rutgers University, USA.

A C_3/C_4 BOVID CRITERION FOR RECONSTRUCTING PLIO-PLEISTOCENE ENVIRONMENTS

Bovids are among the most frequently used palaeoenvironmental indicators at Plio-Pleistocene hominid sites. This stems partly from their ubiquity in the fossil record, and because contemporary bovid species are adapted for life in diverse habitats, including deserts, wetlands, and forests. This, bovids can provide a broad array of environmental information for many early hominid sites. Frequently, researchers use the percentage of "arid-adapted" bovids (alcelaphines and antelopines) among the total bovid assemblage as a habitat proxy: assemblages dominated by ostensibly arid-adapted, grazing species are assumed to be indicative of "open" environments (e.g. grasslands) while those that have few are thought to indicate more "closed" environments (e.g. woodlands). Recent morphological and isotopic studies suggest, however, that the habitat preferences of modern day bovids may not have been shared by their distant ancestors, making it difficult to distinguish between "arid/open" and "woodland/closed" loving species in a fossil context. Thus, methods of palaeoenvironmental reconstruction that take advantage of the ubiquity of bovids in the fossil record, without making undue assumptions about the behaviour which clarify the diets, and hence habitat requirements, of bovids, without making assumptions about the behavior of fossil taxa, are needed. One approach is to use the percentages of C_3 (trees, bushes, and forbs) and C_4 (tropical grasses) plant consuming bovids at a site, which can be measured directly using stable carbon isotope analysis. Analysis of bovids in modern environments shows that relatively "closed" environments always comprise more than 20% C_3 plant consuming specialists, while relatively "open" environments always have more than 35% C_4 plant specialists. Application of this method to the Makapansgat Limestone sites shows that it clusters well within "closed" habitats, and completely outside the range of modern "open" habitats. This result is in accordance with recent habitat reconstructions based upon community ecology. Analysis of the Swartkrans bovids, however, suggests that it may have been less "open" at times than previously supposed.

Shaune SPRECKLEY (1), Julia LEE-THORP (1) (Presenter) & Karin HOLMGREN (2)

(1) Dept. of Archaeology, Univ. of Cape Town, RSA. (2) Dept of Physical Geography, University of Stockholm, Sweden.

A PALAEOENVIRONMENTAL RECORD FROM FICUS CAVE, NORTHERN PROVINCE

Continuous, high-resolution palaeoclimatic records for Southern Africa are rare. Recently, several high-resolution speleothems studies have been reported for sites in the Makapansgat Valley, Northern Province. A stalagmite from Ficus Cave, Makapansgat Valley, known as F2, was analysed for stable light oxygen and carbon composition and grey scale (colour banding) using standard sampling and analytical techniques. Absolute palaeotemperatures were not determined in this study because the oxygen isotopic content of the seepage water could not be determined, but the $^{18}\text{O}/^{16}\text{O}$ record indicated a great deal of variability, likely the result of frequent shifts in $\delta^{18}\text{O}$ of rain. Furthermore, a change in coloration in the grey level plot due to the amount of trapped humics within the calcium carbonate of the stalagmite, showed variation related to the $\delta^{13}\text{C}$ record. In general, there was a noticeable correlation between enriched $\delta^{13}\text{C}$ values and darker bands, suggesting a greater proportion of C_4 grass cover at those times. Two alpha spectrometer thorium-uranium dates were determined, giving 2050±320 BP near the top of the stalagmite and 4380 ± 610 BP near the bottom. The stalagmite had ceased growing before removal. A noticeable characteristic of stalagmite F2 was the many crust- or porous-like internal layers which resembled the outer crust of the stalagmite, once it had stopped growing. These layers likely represent hiatus periods, although the scarcity of dates makes the number and duration of hiatuses unclear. The mineral form of F2 is calcite, as determined by FTIR spectroscopy. Both the oxygen and carbon isotope records are characterised by cyclical fluctuations that are broadly in phase with one another. We deduce that warm, moist and grassy conditions prevailed during the oldest period (4400BP and older) and the youngest period of growth (2050 BP and younger). Conditions between 2000 and 4000 BP and around 4400 BP were dry and cool, with a higher proportion of C_3 woodland vegetation. At c. 4000BP, a brief moist period is observed coupled with a higher proportion of C_4 grass cover. In comparison with stalagmites T7 and T5 from nearby Cold Air Cave, the Ficus stalagmite shows a similar response to warm, wet, conditions, indicated by the greater proportions of C_4 grass cover. On the other hand, it reflects greater proportions of C_3 plants between 2000 and 4000 yrs BP, perhaps reflecting woodier vegetation in the vicinity of Ficus Cave, at that time.

APPENDIX B
METHODS

TABLE OF CONTENTS

1	METHODS	B1
1.1	TRENCH EXCAVATION	B1
1.2	FIELD MEASUREMENTS	B1
1.2.1	Palaeo-current measurements	B1
1.2.2	Data presentation	B2
1.2.3	Palaeo-current data	B4
1.2.4	Grain scale chart	B13
1.2.5	Class shape discrimination	B14
1.2.6	Class size data.....	B16
1.3	SAMPLE TREATMENT	B18
1.3.1	Sample treatment process	B18
1.3.2	Sample results – diamond data	B20
1.3.3	Diamond data.....	B26

LIST OF FIGURES

B1	Inclinometer, based on Dasgupta's (1995) design, used for palaeo-current measurements.....	B2
B2	Comparison of stereographic projections with rose diagrams.....	B3
B3	Udden-Wentworth grade scale.....	B13
B4	Ternary plots for clast shape discrimination.....	B15
B5	Sample treatment flow diagram.....	B19
B6	Graphic illustration of the range of sample support sizes.....	B21
B7	Grade versus sample support size.....	B22
B8	Grade versus sample support size for beach toe	B23
B9	Corrected average grades for transgressive lag and storm gravel sheets.....	B24

LIST OF TABLES

B1 Sampling data summary..... B25

B2 Stone size frequency data from barrier beaches of different ages B26

1. METHODS

1.1 TRENCH EXCAVATION

Trenches were excavated using a Caterpillar (CAT) 375 excavator with a boom reach of six metre and in all instances the entire marine successions were exposed. Where sediment thicknesses were greater than the reach of the excavator's boom, benching was necessary to expose the entire marine sequence. In some instances, subsidiary trenches were excavated at right angles to and intersecting the main trench to create a 'T-piece'. This provided a three-dimensional view to facilitate mapping of the sedimentary sequences.

1.2 FIELD MEASUREMENTS

1.2.1 Palaeo-current measurements

An inclinometer based on a technique proposed by Dasgupta (1995) was constructed out of durable Perspex and the relevant parts were secured with aluminium rivets; the dipmeter and spirit level were glued to the base plate (Figure B1).

The accuracy of this technique was checked by comparing a number of readings using the inclinometer against readings derived from a different technique such as a Brunton compass. With a Brunton compass the line of strike was established and the attendant direction and dip angle were measured. Using the inclinometer, the line of strike and dip angle were determined using the instrument and the direction was measured with a Brunton compass. The comparison (10 readings) was conducted on exposed bedrock schist with good planar features and demonstrated that the inclinometer was 99.6% accurate.

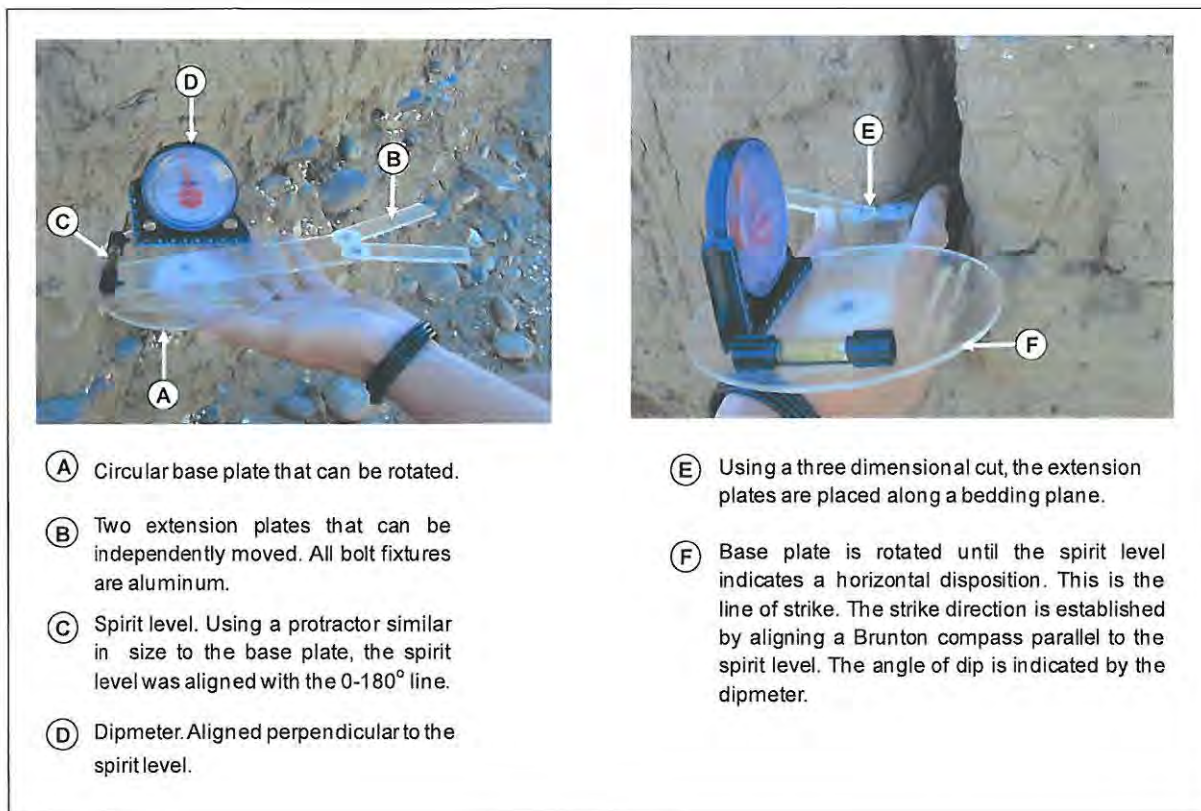


Figure B1: Inclinometer, based on Dasgupta's (1995) design, used for palaeo-current measurements. The main components of the instrument and method of determining the attitude of a planar feature are described above.

1.2.2 Data presentation

The technique proposed by DeCelles *et al.* (1983) to ascertain the azimuth of trough cross-stratification was used to test the authenticity of palaeo-current results measured randomly from such structures. Where opposing limbs (left and right) of a trough structure were measured in the field, these were plotted on a stereo net using GEOrient © 2009 (version 9.4.4; Holcombe, 2009). Two stereographic methods were applied as per DeCelles *et al.* (1983) proposal which yielded the same result. The first method considers the plotting of poles to planes where pole clusters represent opposing limbs. Thus, by determining the best-fit girdle (great circle) of the poles, the azimuth of the trough is established where it is 90° to the best-fit girdle (pole to best-fit girdle).

The second method incorporates the intersection of great circles that correspond to the individual poles. This provides an appreciable estimate of the trough axis orientation. Note

that corrections for tectonic effects are not required in both methods given that tectonics conditions were reasonably stable. The stereo net results showed that random measurements of trough limbs using the inclinometer, regardless of whether they were opposing limbs, were not significantly erroneous. In fact, when comparing the stereo net plots to the rose diagrams (representing measurements of numerous limbs from different trough structures), a variance of some 8° to 9° was noted (Figure B2).

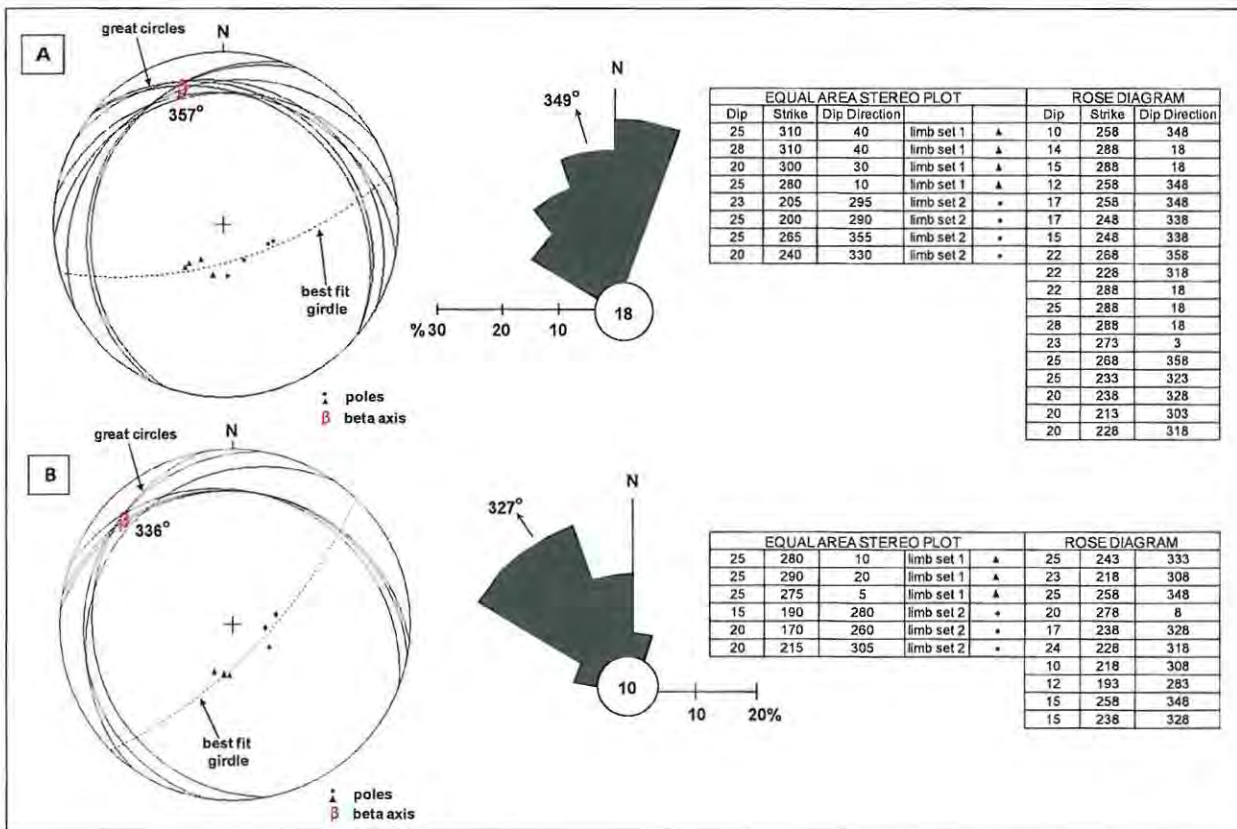


Figure B2: Comparison of stereographic projections with rose diagrams. Trough cross-stratification measurements for Sub-Facies D2 sand (A) and for Sub-facies D3 sand (B). Note that the β axis, representing the resultant direction, is the line of intersection of great circles and also perpendicular to the best fit girdle (see DeCelles *et al.*, 1983).

1.2.3 Palaeo-current data

Facies A

Sub-facies A1 (beach face)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G25. Gravel forests (seaward facing beach)			
1	23	154	244
2	17	132	222
3	19	131	221
4	22	139	229
5	22	144	234
6	14	142	232
7	20	146	236
8	16	141	231
9	16	135	225
10	23	137	227
11	18	133	223
Trench G15. Gravel foresets (seaward facing beach)			
1	26	135	225
2	20	124	214
3	25	136	226
4	25	137	227
Trench G19. Gravel foresets (seaward facing beach)			
1	20	128	218
2	26	128	218
3	15	188	278
4	25	88	178
5	16	153	243
6	20	148	238
7	21	158	248
8	22	133	223
9	13	166	256
10	15	163	253
11	15	173	263
12	22	153	243
Trench G9. Gravel foresets (seaward facing beach)			
1	13	178	268
2	14	132	222
3	14	147	237
4	10	158	248
5	22	128	218

6	12	133	223
7	14	173	263
8	17	133	223
9	4	183	273
10	19	131	221
11	10	184	274

Sub-facies A2(tidal inlet)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G25. Herringbone cross-stratified sand foresets			
1	20	170	260
2	28	158	248
3	26	160	250
4	29	128	218
5	20	153	243
6	20	174	264
7	20	175	265
8	21	173	263
9	21	182	272
10	26	133	223
11	26	182	272
12	21	130	220
13	24	293	23
14	20	312	42
15	16	293	23
16	29	298	28
17	17	315	45
18	22	308	38
19	22	278	8
20	21	291	21
21	10	308	38
22	11	303	33
23	11	287	17
24	26	128	218
25	23	135	225
26	29	134	224
27	25	303	33
28	25	280	10
29	22	290	20
30	24	293	23
31	30	163	253
32	20	306	36

33	24	323	53
34	18	321	51
35	17	313	43
36	20	312	42
37	25	324	54
38	20	133	223
39	16	132	222
40	18	146	236
41	17	178	268
42	19	283	13
43	23	306	36
44	25	306	36
45	22	308	38
46	25	283	13
47	20	295	25
48	15	121	211
49	20	128	218
50	35	165	255
51	32	162	252
52	35	158	248
53	31	175	265
54	15	274	4
55	10	289	19
56	20	288	18
57	18	313	43
58	10	268	358
59	22	143	233
60	20	133	223
61	20	121	211
62	11	132	222
63	25	148	238
64	18	138	228
65	24	118	208
66	15	123	213
67	22	146	236
68	20	144	234
69	20	113	203
70	15	138	228
71	23	153	243
72	20	148	238
73	23	138	228
74	20	304	34

75	16	328	58
76	20	288	18
77	20	294	24
78	20	278	8
79	17	283	13
80	18	293	23
81	20	288	18
82	10	278	8
83	30	258	348
Trench G25. Herringbone cross-stratified sand. Bounding planes			
1	19	248	338
2	15	263	353
3	15	250	340
4	20	263	353
5	15	248	338
6	12	278	8
7	20	258	348
8	10	260	350
9	8	278	8
10	15	261	351
11	14	283	13
12	13	265	355
13	14	261	351

Sub-facies A3(spit recurve)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G25. Gravel foresets (landward facing beach)			
1	13	8	98
2	13	8	98
3	27	8	98
4	20	353	83
5	14	350	80
6	18	353	83
7	18	18	108
8	14	353	83
9	20	38	128
10	20	48	138
11	20	68	158
12	13	33	123
13	21	58	148
14	26	38	128

15	5	108	198
Trench G19. Gravel foresets (landward facing beach)			
1	17	320	50
2	12	318	48
3	13	327	57
4	13	310	40

Facies C

Sub-facies C1 (beach face)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G29. Sand foresets (seaward facing beach)			
1	20	183	273
2	20	198	288
3	20	173	263
4	20	158	248
5	15	143	233
Trench G29. Gravel foresets (seaward facing beach)			
1	25	168	258
2	25	118	208
3	23	178	268
4	30	188	278
5	15	168	258
6	20	148	238
Trench G25. Gravel foresets (seaward facing beach)			
1	22	108	198
2	20	128	218
Trench G19. Gravel foresets (seaward facing beach)			
1	19	163	253
2	20	138	228

Sub-facies C2 (washover)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G25. Sand foresets			
1	5	332	62
2	11	287	17
3	10	272	2
4	9	329	59
5	8	312	42
6	11	332	62

7	16	303	33
8	20	292	22
9	9	331	61
10	10	282	12
11	14	302	32
12	10	299	29
13	11	283	13
14	12	297	27
15	5	296	26
16	10	294	24
17	11	272	2
18	12	288	18
19	15	306	36
20	14	305	35
21	18	282	12
22	15	302	32
23	9	299	29
24	14	304	34
Trench G19. Gravel foresets			
1	20	248	338
2	22	248	338
3	20	253	343
4	10	268	358
5	10	223	313
6	12	278	8
7	15	248	338
Trench G39.5. Gravel foresets			
1	15	315	23
2	10	340	48
3	15	315	23

Facies D***Sub-facies D1(lower shoreface)***

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G39.5. Planar cross-stratified sand foresets			
1	5	332	62
2	10	283	13
3	9	352	82
4	8	300	30
5	12	327	57
6	9	357	87

7	10	322	52
8	15	297	27
9	8	307	37
10	5	300	30
11	10	297	27
12	8	337	67
13	12	322	52
14	10	330	60
15	12	322	52
16	10	322	52
17	10	322	52
18	9	352	82
19	12	287	17
20	10	302	32
21	7	322	52
22	12	322	52
23	6	352	82
24	6	352	82
25	8	352	82
26	11	332	62
27	14	277	7
28	24	252	342
29	7	342	72
30	7	322	52
31	10	307	37
32	11	302	32
33	10	302	32
34	5	297	27
35	15	307	37
36	5	297	27
37	25	312	42
38	25	322	52

Sub-facies D2 (middle shoreface)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G39.5. Trough cross-stratified sand foresets			
1	10	258	348
2	14	288	18
3	15	288	18
4	12	258	348
5	17	258	348
6	17	248	338

7	15	248	338
8	22	268	358
9	22	228	318
10	22	288	18
11	25	288	18
12	28	288	18
13	23	273	3
14	25	268	358
15	25	233	323
16	20	238	328
17	20	213	303
18	20	228	318
Trench G39.5. Trough cross-stratified granule foresets			
1	18	263	353
2	12	248	338
3	30	278	8
4	15	208	298
5	25	248	338
6	22	253	343
Trench G39.5. Trough cross-stratified gravel foresets			
1	10	308	38
2	20	276	6
3	20	303	33

Sub-facies D3 (upper shoreface)

n	dip (x°)	strike (x°)	dip direction (x°)
Trench G39.5. Trough cross-stratified sand foresets (base of D3)			
1	25	243	333
2	23	218	308
3	20	163	253
4	20	278	8
5	25	258	348
6	12	153	243
7	24	158	248
8	17	238	328
9	24	228	318
10	10	218	308
11	12	193	283
12	15	258	348
13	15	238	328

14	10	168	258
Trench G39.5. Planar cross-stratified sand foresets (top of D3)			
1	20	228	318
2	18	218	308
3	15	222	312
4	22	217	307
5	25	222	312
6	15	232	322
7	20	237	327
8	25	219	309
Trench G39.5. Trough cross-stratified gravel foresets (base of D3)			
1	24	163	253
2	20	213	303
3	15	213	303
4	10	198	288
5	14	163	253
6	27	168	258
7	20	158	248
8	18	128	218
Trench G39.5. Planar cross-stratified gravel foresets (top of D3)			
1	18	128	218
2	20	158	248

Sub-facies D3 (upper shoreface clast imbrication)

n	strike (x°)	dip direction of pebble (x°)	palaeo-flow direction (x°)
Trench G39.5. Imbrication of gravel discs and blades (top of D3)			
1	330	60	240
2	310	40	220
3	320	50	230
4	330	60	240
5	340	70	250
6	360	90	270
7	330	60	240
8	298	28	208
9	330	60	240
10	360	90	270

1.2.4 Grain scale chart

The Udden-Wentworth grain scale (Udden, 1914; Wentworth, 1922) is universally accepted by most geologists as a means of classifying sediment grain size (see Packham & Neal, 2001). The chart presented in Figure B3 is taken from Packham & Neal (2001). In addition to the Udden-Wentworth class-size terminology, the chart also includes the modified terminology of Friedman & Sanders (1978). Note that where particles relate to a size of greater than 2 mm, but less than 4 mm, they are referred to as granules in this study as per the Udden-Wentworth terminology.

Size		Sediment size class terminology of Wentworth (1922)	Sediment size class terminology of Friedman and Sanders (1978)	
mm	phi			
2048	-11		Very Large Boulders	Gravel
1024	-10		Large Boulders	
512	-9	Cobbles	Medium Boulders	
256	-8		Small Boulders	
128	-7		Large Cobbles	
64	-6		Small Cobbles	
32	-5		Very Coarse Pebbles	
16	-4	Pebbles	Coarse Pebbles	
8	-3		Medium Pebbles	
4	-2		Fine Pebbles	
2	-1	Granules	Very Fine Pebbles	
1	0	Very Coarse Sand	Very Coarse Sand	Sand
0.5	1	Coarse Sand	Coarse Sand	
0.25	2	Medium Sand	Medium Sand	
0.125	3	Fine Sand	Fine Sand	
0.063	4	Very Fine Sand	Very Fine Sand	
0.031	5		Very Coarse Silt	Silt
0.016	6	Silt	Coarse Silt	
0.008	7		Medium Silt	
0.004	8		Fine Silt	
0.002	9	Clay	Very Fine Silt	
			Clay	

Figure B3: Udden-Wentworth grade scale (Udden, 1914; Wentworth, 1922) after Packham & Neal (2001).

1.2.5 Clast shape discrimination

Various plots have been advocated for shape discrimination, these being:

- 1) the Folk form triangle (in Sneed & Folk, 1958; cited in Illenberger 1991) using the Disc Rod Index ($DRI = \frac{a-b}{a-c}$) versus c/a ;
- 2) Illenberger's (1991) form triangle using the Corey Shape Index ($CSI = c/\sqrt{ab}$) versus DRI; and
- 3) Zingg's (1935) classification where (b/a) versus (c/b) .

Whilst disadvantages in the use of the above methods have been noted by various authors (Illenberger 1991, 1992; Benn & Ballantyne, 1992; Blott & Pye, 2008), there is a general consensus that ternary plots are the more satisfactory method for discriminating shapes (Sneed & Folk, 1958; cited in Illenberger 1991, 1992; Benn & Ballantyne, 1992).

Consequently, the Folk form triangle modified by Blott & Pye (2008) was used in this study. Mention must be made that Blott & Pye's (2008) modifications were mainly a re-categorisation of the shape classes where different degrees of equancy (sphericity) are introduced and are represented by eight classes. However, their descriptive terms make it difficult to envisage the geometric implications. For ease of visualisation, the eight classes were grouped into four broad categories in this study; namely spheres, discs, blades and rods. For example, Blott & Pye's (2008) classes that show increasing equancy (sphericity), but still maintain a degree of flatness such as those from discoid through very oblate spheroid to oblate spheroid are grouped into a single class for disc-shaped clasts. Figure B4 illustrates this grouping. More significantly such a degree of shape discrimination as per the eight classes is not required for this study. A more general measure to illustrate the dominance of a particular clast shape in beach ridges (disc and blade shapes) and beach toe environments (spherical shapes) as per Bluck's (1967) findings is adequate for this study.

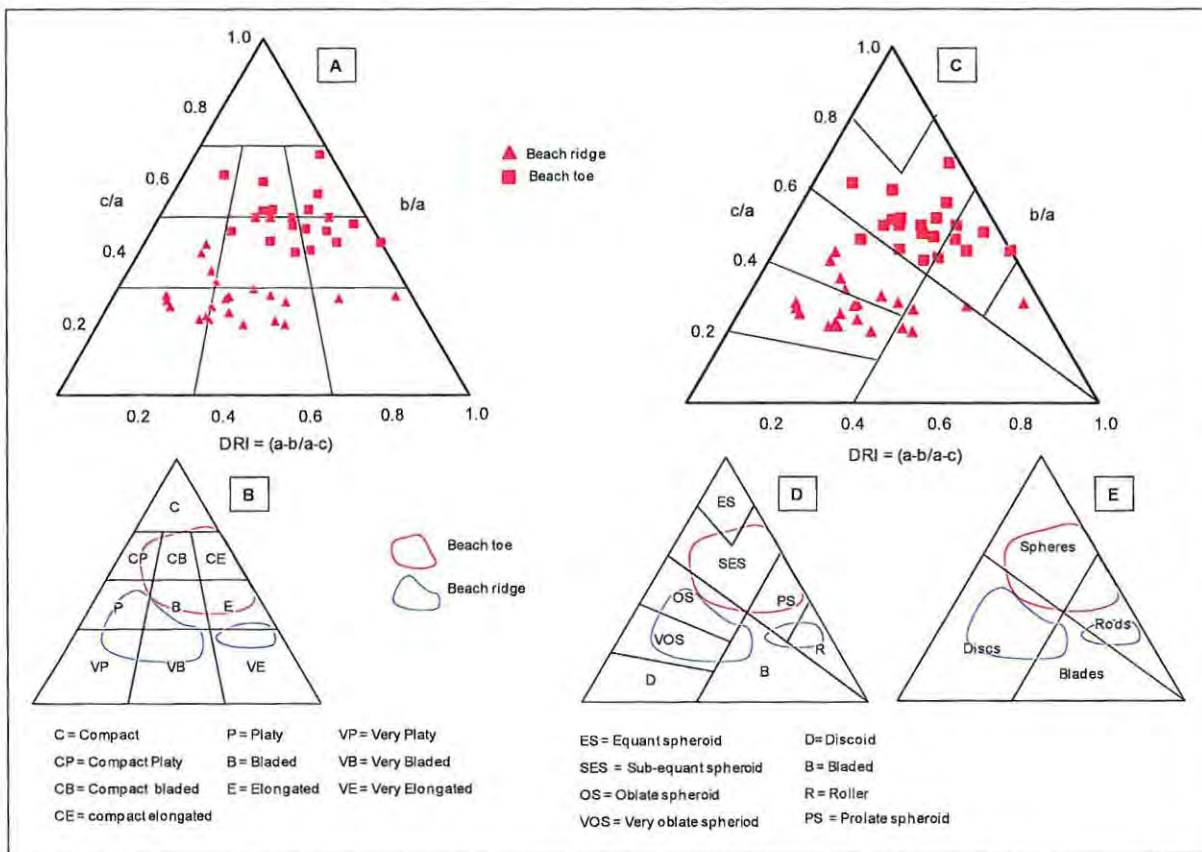


Figure B4: Ternary plots for clast shape discrimination. **(A)** Data for beach ridge and beach toe environments (Sub-facies C1) plotted on a Folk form diagram (Sneed & Folk, 1958). **(B)** Note the number of class types (ten classes) and the two data fields (red and blue polygons for beach toe and beach ridge, respectively) encompassing different clast shapes. **(C)** The same data plotted on a Folk form diagram (Sneed & Folk, 1958) modified by Blott & Pye (2008). **(D)** The diagram better illustrates the dominant clast shapes for the two data fields (red and blue polygons) where the beach toe environment is dominated by spherical clasts, whilst the beach ridge by discoidal clasts. By grouping similar classes as shown in **(E)** to derive at four main classes, a swift and more general appreciation of clast discrimination is gained.

1.2.6 Clast size data

Sub-facies C1 – beach toe

a_axis in cm	b_axis in cm	c_axis in cm
20.0	17.0	5.0
40.0	25.0	16.0
26.0	21.0	12.0
23.0	15.0	12.0
30.0	21.0	13.0
23.0	17.0	12.0
21.0	14.0	10.0
25.0	13.0	12.0
28.0	12.0	12.0
22.0	15.0	11.0
27.0	16.0	11.0
23.0	15.0	13.0
29.0	22.0	15.0
26.0	20.0	13.0
26.0	15.0	12.0
21.0	19.0	13.0
20.0	16.0	12.0
27.0	16.0	13.5
28.0	15.0	12.0
20.0	14.0	13.5
28.0	12.0	12.0
30.0	19.0	14.0
30.0	22.0	15.0

Sub-facies C1 – beach ridge

a_axis in cm	b_axis in cm	c_axis in cm
22.0	17.0	7.0
20.0	15.0	5.0
20.0	11.0	4.0
20.0	15.0	4.5
21.0	16.0	4.5
20.0	17.0	8.5
22.0	16.0	6.0
21.0	15.5	4.5
18.0	13.0	5.0
15.0	13.0	4.0
20.0	13.0	4.0

19.0	11.0	5.0
20.0	13.5	6.0
20.0	16.0	7.0
30.0	21.0	7.0
20.0	17.0	8.0
22.0	10.0	6.0
25.0	8.0	7.0
16.0	14.0	4.5
19.0	11.0	4.0
16.0	10.0	4.5

Sub-facies D3 – storm gravel sheets

a_axis in cm	b_axis in cm	c_axis in cm	Trench section
20.0	8.0	7.5	Eastern part of trench
15.0	9.5	6.0	
10.5	6.5	4.8	
14.0	10.5	4.8	
13.0	7.0	2.5	
11.5	8.0	2.5	
8.5	5.0	4.0	
9.0	7.0	2.5	
13.5	9.0	5.0	
8.5	5.5	3.7	
13.5	7.5	5.5	
8.5	7.5	4.0	
12.5	6.5	4.5	
12.7	5.0	5.0	
14.7	7.0	6.5	
10.0	5.0	4.0	Western part of trench
7.5	5.0	2.4	
6.5	5.0	2.5	
5.5	3.8	2.5	
6.5	4.4	3.2	
8.4	3.5	3.4	
6.0	3.7	3.5	
9.0	3.8	3.5	
6.5	4.2	2.0	
8.0	4.0	1.8	
6.5	5.0	4.0	
8.5	6.0	5.2	
7.0	4.0	2.8	
8.0	4.3	2.8	

1.3 SAMPLE TREATMENT

1.3.1 Sample treatment process

In the diamond industry, Dense Medium Separation (DMS) plants use a heavy medium such as ferrosilicon to achieve an appreciable degree of diamond (specific density of 3.51 g/cm^3 ; Cairncross, 2004) separation from the lighter material (that has a specific density less than 2.8 g/cm^3) through a cyclone (Chaston & Napier-Munn, 1974). Obviously other minerals with a similar or greater specific density than 2.8 g/cm^3 will also be included with diamond during the cyclone separation. The final product is a 'concentrate' consisting of different heavy minerals, including diamond. Note that the term 'concentrate' is used loosely to describe processed material having a specific density greater than 2.8 g/cm^3 . Further processing of the 'concentrate' to remove diamonds only is accomplished by using a Flow-Sort X-ray.

The X-ray processing relies on the unique property of diamond in that it fluoresces (emits light) when bombarded by X-rays (Hart, 2003). This allows effective separation of diamonds from the non-fluorescent material through a process of ejection. The X-ray 'concentrate' comprising diamond and other non-diamond particles caught in the ejection process (Hart, 2003) are dried for final recovery. Here diamonds are removed manually by qualified sorters in a high-security sorting facility.

In mining operations not all diamonds are recovered. It is impractical and uneconomical to recover diamonds of every size fraction, particularly those at the finest end of the size spectrum. Thus, a lower screen size is used in the processing plants to restrict the recovery of a certain lower size. This size is dependent on the nature of the deposit and on the outcome of an optimisation study to determine the minimum size required. Usually this screen size falls within the range of 0.5-2.5 mm (Rombouts, 1995). An optimum screen size also applies to the upper limit for the recovery of large diamonds and the size is set for recovering the largest diamonds that are in appreciable quantities. In Mining Area 1 (MA1), which includes the study area, the upper and lower screen sizes in the treatment plants were set to 2 mm and 25 mm, respectively. The above-mentioned discussion is a general view of the concept of DMS and X-ray treatment and obviously a number of processing procedures have been omitted. These are shown in the flow diagram in Figure B5.

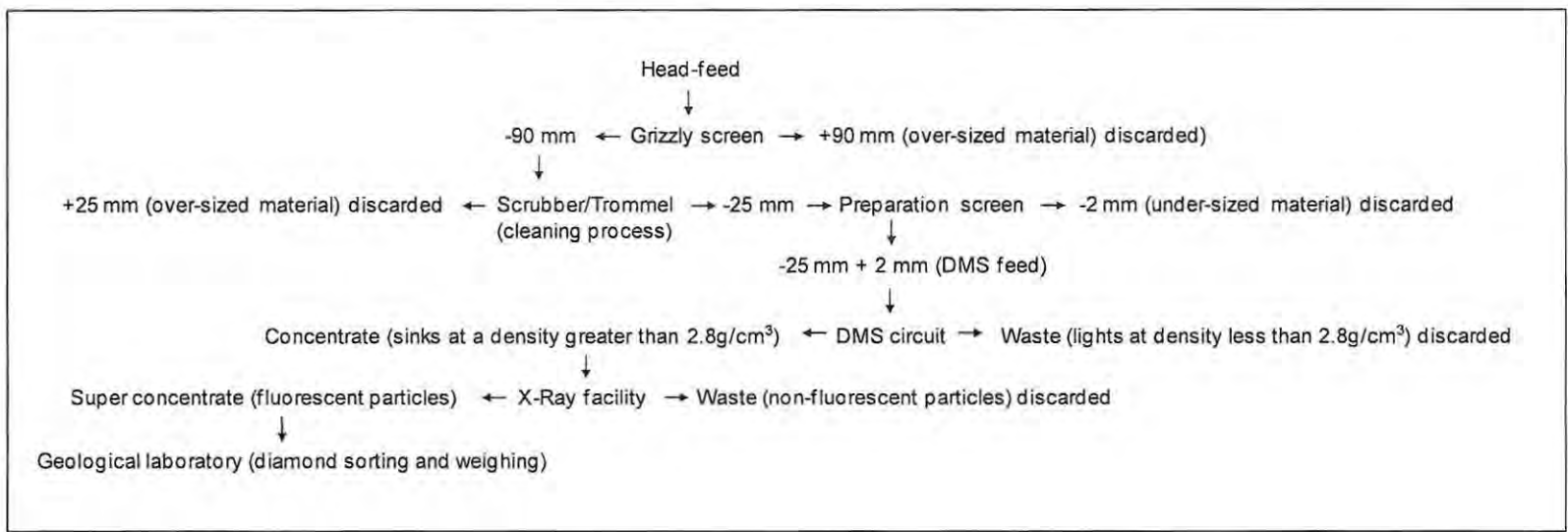


Figure B5: Sample treatment flow diagram. The various processing stations from DMS through to final recovery where diamonds are sorted and weighed are illustrated.

1.3.2 Sample results - diamond data

Samples from the earlier-phases were derived from trench sections that were either 5 m long x 1.5 m wide (the 1950s sampling campaign) or from sections that were 50 m long x 1.5 m wide (the 1970s megatrench sampling). These sampling sections were contiguous and thus the entire trench was sequentially sampled.

Grade and stone size

In this study, grade is calculated based on the stone density distribution (Sichel, 1973; Oosterveld *et al.*, 1987; Rombouts, 1995) and is a measure of the number of diamonds (or number of stones) per sample unit. Note that 'stone' is a term loosely used as a reference to a diamond (Sichel, 1973). A sample unit may be a trench section or a pit and is expressed in terms of volume (in m³) or weight (in tons). The latter is preferred as it eliminates usage of figures with large decimals as would be the case when volume (m³) or area (m²) is applied for low grade deposits. Note that a global density of 1.8 g/cm³ is used to derive at ton figures. Given that density values were not accurately measured for different material types where gravel and sand occur in various proportions, there may be a degree of error in tonnage calculations.

All sample unit values are also normalised to 100 tons. Thus, grade (i.e. number of stones in a 100 tons) irrespective of the weight, colour, shape and quality of the diamonds in a sample unit, is expressed as stones per 100 tons (spht; see also Sichel, 1973) in this study.

Although the conventional approach for reporting grade is carats per hundred tons (cpht) and is an expression of the carat weight (ct) per sample unit, the number of diamonds per sample unit (i.e. stone density as discussed above) is favoured because a single large diamond with an anomalous carat weight is likely to skew a result when carats per hundred ton is considered. Note that carat weight (ct) is a measure of the size of a diamond and one carat is equal to 0.2 grams (Lynn *et al.* 1998). Some of the deposits studied are sheet-like in nature, having a two-dimensional configuration and thus metres squared (m²) should be considered for grade calculations. However, weight (in tons) was used for these deposits to facilitate ease of statistical comparison with three-dimensional type deposits such as barrier beaches.

The average diamond size for each sample unit, expressed as carats per stone (cts/stn), is calculated by dividing the total carat weight (cts) by the total number of diamonds (stones).

Sample support size

The entire spectrum of diamond results, including negative values (barren samples) and outliers (results with values significantly higher than the background) was used in the basic analysis to demonstrate the ‘nugget’ effect that is typical of diamond placers. Although sample support size varies significantly, two broad sizes are evident as illustrated in Figure B6. These encompass the 1950s samples that are less than 100 tons and the 1970s megatrench samples that are larger than 300 tons with a range of sizes. At a smaller support size, such as the 1950s sampling, Duggan *et al.* (2007) point out that the grade distributions are highly skewed due to a large percentage of barren samples, which is evident in this study. A corollary of this is that the estimated grade is generally lower than the actual deposit grade (Duggan *et al.*, 2007). Note that the latter is customarily established from mining operations. Duggan *et al.* (2007) note that this effect does not necessarily imply biased sampling, but merely indicates that the average of such a distribution is likely to fall below, rather than above the actual grade.

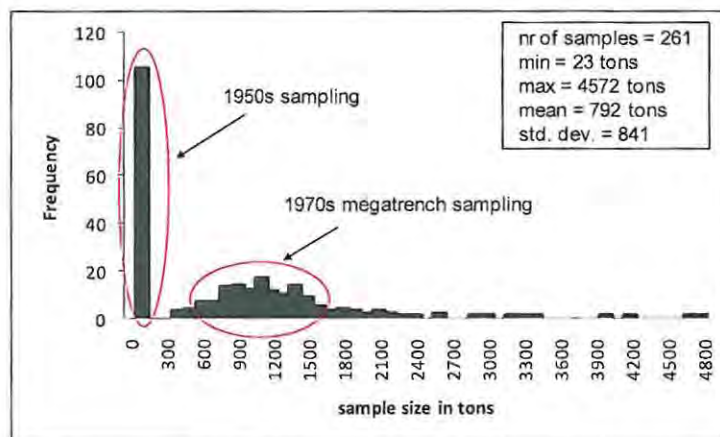


Figure B6: Graphic illustration of the range of sample support sizes. Note the two main groups (circled in red). The size range of the 1970s megatrench samples is clustered between 800 tons and 1,500 tons. Note the high dispersion of values around the mean (large standard deviation).

However, when sample size is compared with grade (spht), the higher grades in this study are mostly associated with smaller samples, whilst the reverse is seen in the larger samples (Figure B7). While this trend may be a result of the variable sample size, a geological influence is considered an alternative explanation (Figure B7). The larger samples yielding lower grades correspond predominantly (90% of the samples) to sheet-like shoreface

deposits, namely storm gravel sheets and the transgressive lag. Moreover, these shoreface deposits have a higher percentage of sand that dilutes the sample material. The better grades in the sheet-like deposits as illustrated in Figure B7 are derived from the foreshore beach toe (outer frame) sub-environment. In contrast, the higher grades are returned mainly from gravel beach deposits, more specifically the foreshore beach face, which comprises thick accumulations of gravel.

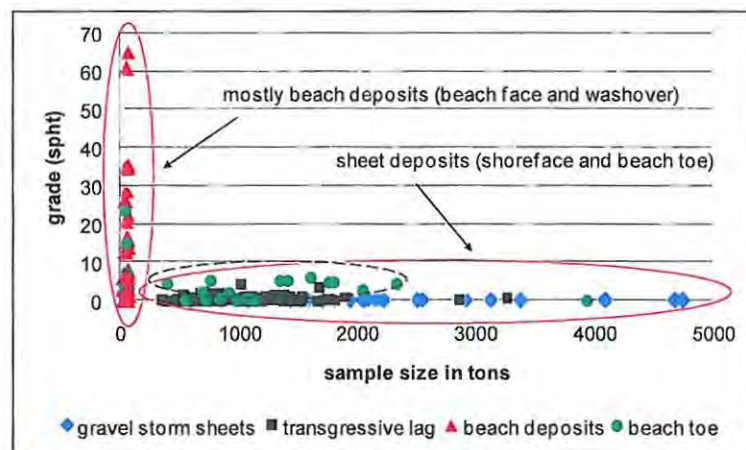


Figure B7: Grade (spht) versus sample support size. Note that the higher grades are mostly associated with smaller samples (foreshore beach face deposits), whilst the larger samples (sheet like deposits) yield lower grades. Better grades in the larger samples (black stippled circle) are the foreshore beach toe deposits. Note spht = stones per hundred tons.

This geological influence is also apparent where a depositional sub-environment has been discreetly sampled using a range of sample support sizes, as illustrated in Figure B8. Here, samples from less than 80 tons to over 2,000 tons were collected from a beach toe (outer frame) sub-environment. When grades are compared with different sample sizes, the results show that the grades (spht) are broadly similar regardless of sample support size (Figure B8). Approximately 45% of all larger samples have grades (0-4 spht) similar to those from smaller samples, whilst the remaining percentage is only slightly higher (4-6 spht). Of interest is that the highest grades (>6 spht) are returned from the smaller support size.

concentrations of diamonds (see Chapter 5, Section 5.4) and for this reason, Millad (2004) excluded such deposits from his study.

- 3) Of all the environments, the transgressive lag has been better sampled given the large number of samples and support size, and a high stone count. Note that the sampling targeted the entire sheet of gravel with samples positioned contiguously along the full length of each trench. Although, the sampling is considered representative, the grade results may in fact be lower than the actual grade. The reason for this is the inclusion of barren material that dilutes the sample. Gravel extraction from these sheet-like deposits is difficult and in most instances a large amount of the enclosing sand would be incorporated into the sample.
- 4) Sampling of the storm gravel sheets is equally representative. Notwithstanding the low number of samples, the areal sample coverage of these deposits is high with samples positioned in a similar fashion as discussed for the transgressive lag. In fact, the number of samples is related to the extent of the storm gravel sheet, which has a limited distribution. Unlike the other depositional environments, these results are supported by a high number of samples (as much as 81%) that are greater than 1,000 tons. However, as in the case of the transgressive lag, sample dilution is expected.
- 5) Even if the diluting sand in the transgressive lag and storm gravel sheet samples is removed, no appreciable grade increase is evident. The grade still remains below 1 spht, which is considered a poor result. Figure B9 illustrates the change in grade where sand dilution of 5%, 15% and 30% is removed.

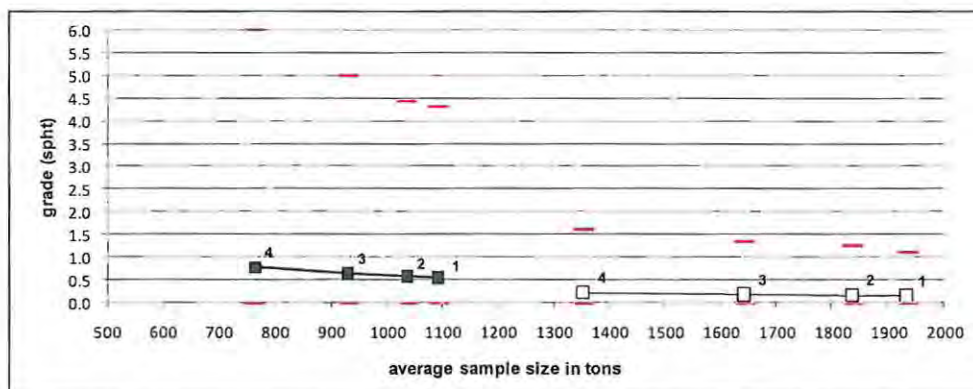


Figure B9: Corrected average grades for transgressive lag (solid squares) and storm gravel sheets (open squares). Red bars denote range of average grades. 1 = uncorrected average grade, 2 = removal of 5% dilution, 3 = removal of 15% dilution and 4 = removal of 30% dilution.

Table B1: Sampling data summary

Environment	Geological setting	Total no of stones	Total carats	Total no of samples	No of barren samples	Average sample size	Min sample size	Max sample size
Barrier spit	Beach face	61	69.00	3	0	1034	990	1067
	Tidal inlet	2	0.88	1	0	NA	NA	207
	Spit recurve	220	104.43	3	0	590	230	1131
Barrier beach	Beach toe	817	113.53	40	9	636	34	3940
	Beach face	295	338.45	50	14	49	23	75
	Washover	21	24.00	33	21	60	34	69
Shoreface	Transgressive lag	632	916.73	107	21	1093	345	3274
	Storm gravel sheet	82	51.06	31	7	1933	459	4752

Ton value (or in situ value)

When the value of a deposit is considered, its ton value must be determined. Basically, it is the *in situ* value and is expressed as US dollars per ton (US\$/ton; Hanson Westhouse, undated). To derive at the ton value two factors must be known; these being the average value or price of the diamond population within the deposit expressed as US dollars per carat (US\$/ct) and the grade of the deposit expressed as carats per ton (cts/ton). The last determines the average carat weight per ton of ground. Note this grade application is different to stones per hundred ton (spht) as discussed earlier as it must be aligned with the method to calculate ton value. The basic formula for calculating ton value is therefore expressed as:

$$\text{Ton value (US$/ton)} = \text{average diamond value (US$/ct)} \times \text{average grade (cts/ton)}.$$

Data presentation

As mentioned in Chapter 1, Section 1.7, only basic statistical computations were undertaken. The raw data are merely presented in geographical space to gain an appreciation of spatial trends, which are displayed as broad contours for grade with intervals of one stone per one-hundred ton (1spht) and stone size with intervals of 0.5 carats per stone (0.5 cts/stn).

Stone size frequency distribution (SFD)

In order to derive at a stone size frequency distribution (SFD), diamonds are sized according to different sieve classes using screens with specific apertures. Thus, sieve

numbers that are commonly recorded in stone size frequency plots (see Figure 6.5) refer to standard round-aperture sieves. Higher sieve numbers correspond to larger apertures and in turn, to larger diamonds (see Millad, 2004). Stone size frequency is determined by the quantity of diamonds within each sieve class. The data used for comparing the stone size frequency distribution of Plio-Pleistocene barrier beaches (within the study area) with their Holocene equivalents are presented in Table B2.

Table B2: Stone size frequency data from barrier beaches of different ages

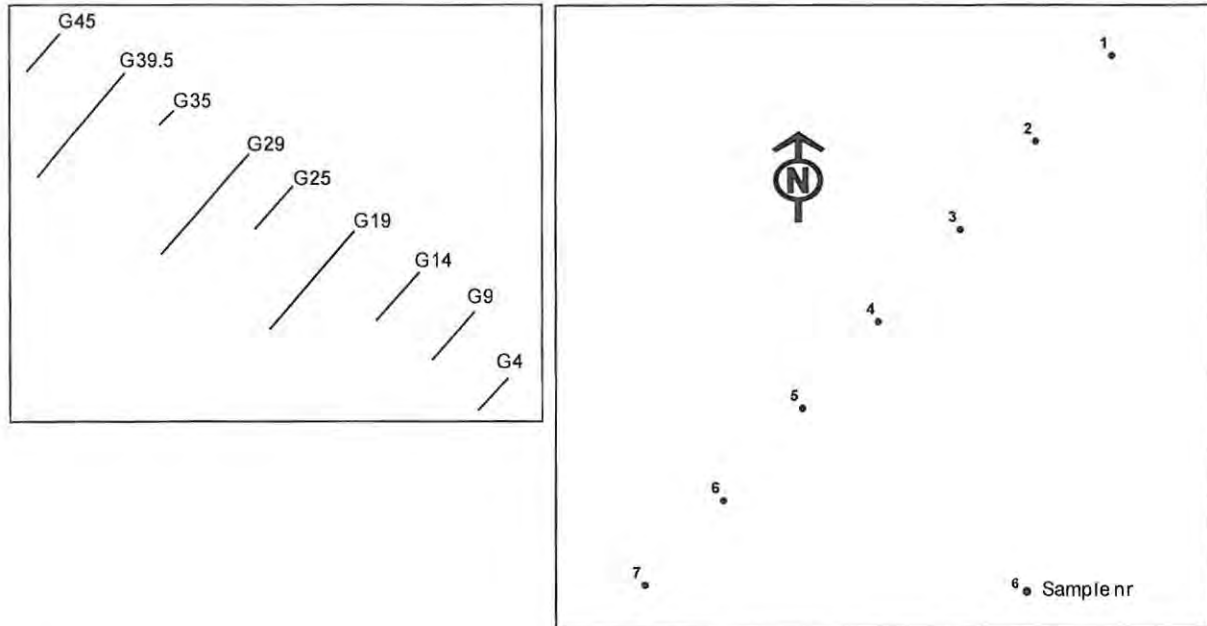
Sieve size	Plio - Pleistocene age		Holocene age	
	Stns	% freq	Stns	% freq
+23	2	0.2	5	5
+21	10	0.9	11	11
+19	46	4.3	10	10
+17	31	2.9	9	9
+15	26	2.5	16	16
+13	143	13.5	19	19
+12	153	14.5	9	9
+11	320	30.2	12	12
+9	210	19.8	3	3
+7	81	7.7	3	3
+6	30	2.8	3	3
+5	4	0.4	1	1
+3	2	0.2	0	0
Total	1058	100	3136	100

1.3.3 Diamond data

Facies A (barrier spit)

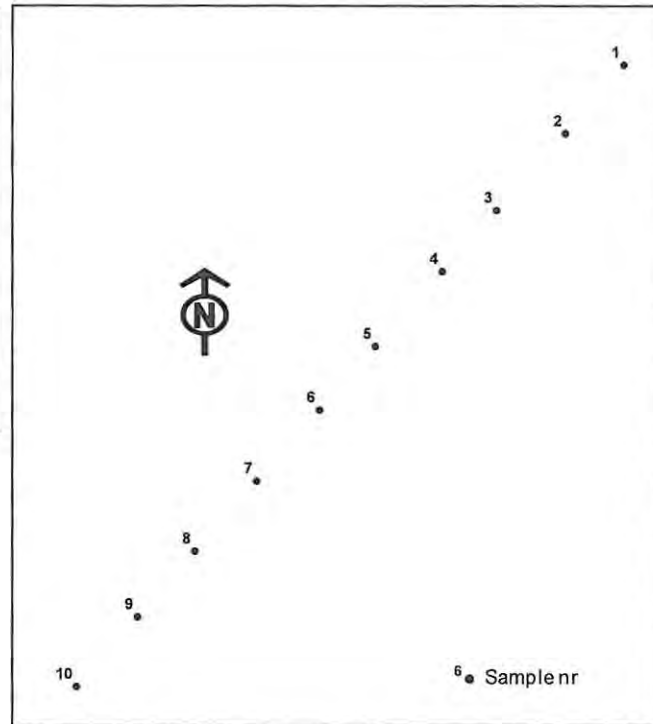
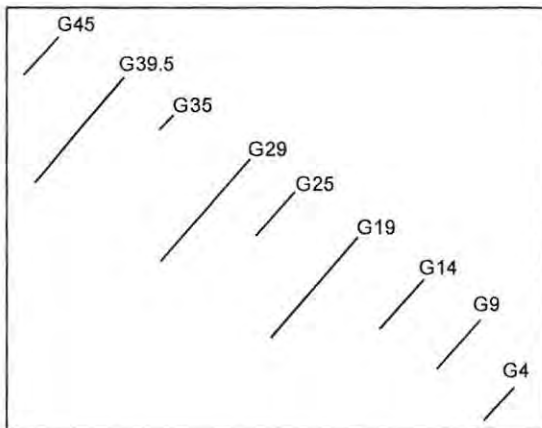
Trench G25

sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	17.90	13	1067	10.670	1.2	1.4	intertidal (seaward facing beach)
2	14.85	13	1046	10.460	1.2	1.1	intertidal(seaward facing beach)
3	36.38	35	990	9.900	3.5	1.0	intertidal (seaward facing beach)
4	0.88	2	207	2.070	0.9	0.4	tidal channel
5	81.93	173	1311	13.110	13.2	0.5	recurve (landward facing beach)
6	15.42	39	230	2.300	17.0	0.4	recurve (landward facing beach)
7	7.08	8	230	2.300	3.5	0.9	recurve (landward facing beach)

Facies B (transgressive lag)***Trench G4***

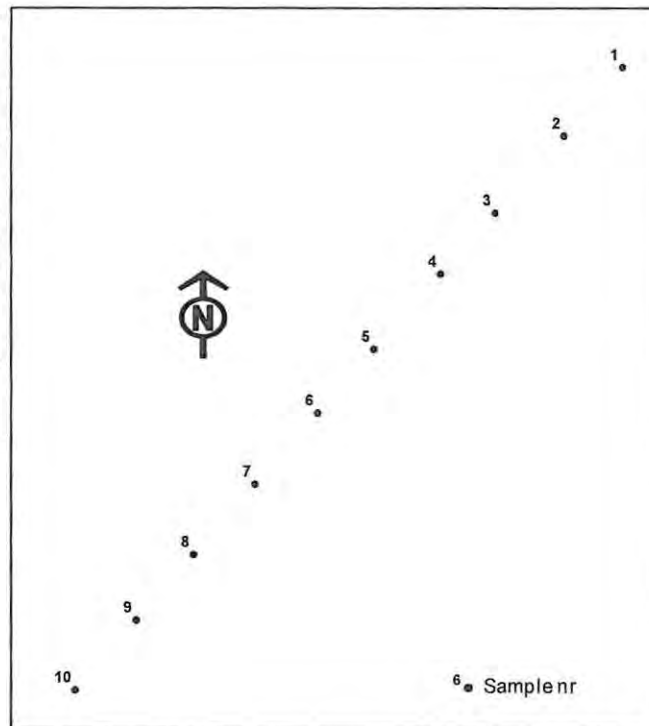
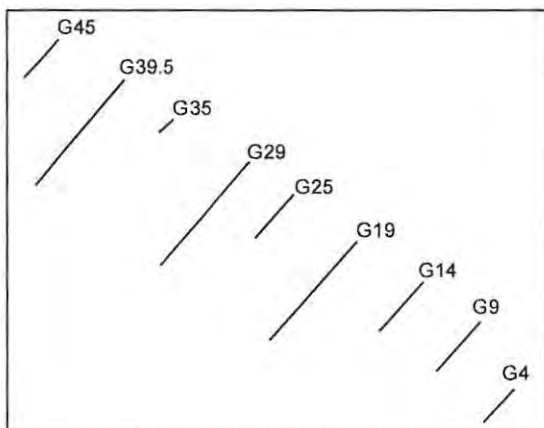
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	4.31	5	1377	13.770	0.4	0.9	Transgressive lag
2	6.08	9	1132.2	11.322	0.8	0.7	Transgressive lag
3	1.87	4	1407.6	14.076	0.3	0.5	Transgressive lag
4	6.8	7	1254.6	12.546	0.6	1.0	Transgressive lag
5	2.85	3	918	9.180	0.3	1.0	Transgressive lag
6	50.38	3	864	8.640	0.3	16.8	Transgressive lag
7	0	0	1378.8	13.788	0.0	0.0	Transgressive lag

Trench G9



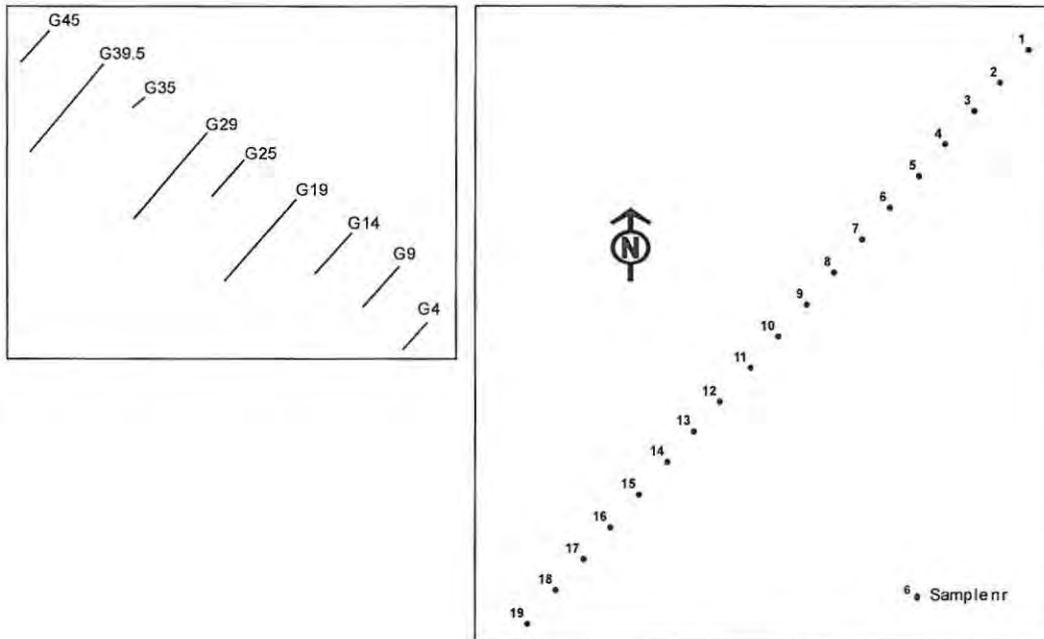
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	32.36	18	703.8	7.038	2.6	1.8	Transgressive lag
2	7.19	8	1071	10.710	0.7	0.9	Transgressive lag
3	19.04	13	1224	12.240	1.1	1.5	Transgressive lag
4	8.12	5	948.6	9.486	0.5	1.6	Transgressive lag
5	8.69	8	1315.8	13.158	0.6	1.1	Transgressive lag
6	9.89	4	734.4	7.344	0.5	2.5	Transgressive lag
7	6.21	4	856.8	8.568	0.5	1.6	Transgressive lag
8	1.88	2	1009.8	10.098	0.2	0.9	Transgressive lag
9	1.16	1	1315.8	13.158	0.1	1.2	Transgressive lag
10	1.8	2	1132.2	11.322	0.2	0.9	Transgressive lag

Trench G14



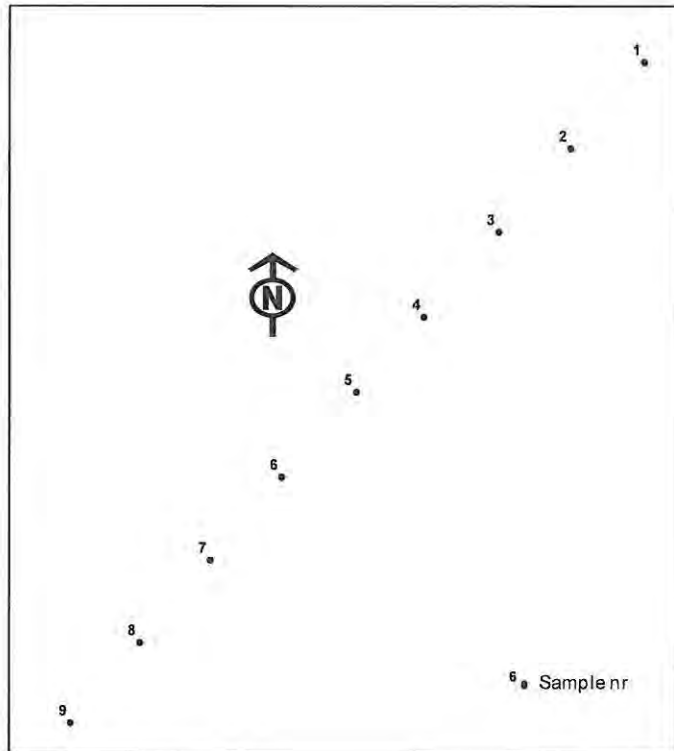
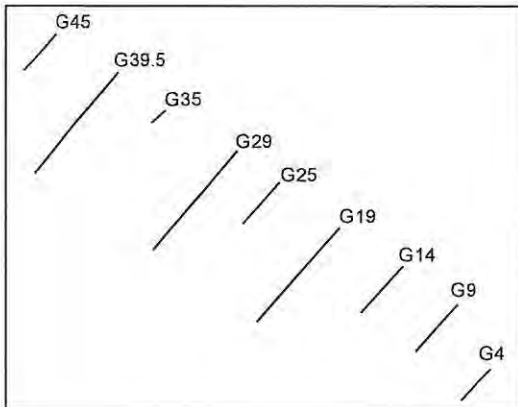
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	33.58	24	1377	13.770	1.7	1.4	Transgressive lag
2	24.68	20	1297.8	12.978	1.5	1.2	Transgressive lag
3	11.25	17	1900.8	19.008	0.9	0.7	Transgressive lag
4	17.04	9	1121.4	11.214	0.8	1.9	Transgressive lag
5	14.27	7	1207.8	12.078	0.6	2.0	Transgressive lag
6	6.72	4	1364.4	13.644	0.3	1.7	Transgressive lag
7	7.37	5	759.6	7.596	0.7	1.5	Transgressive lag
8	4.15	10	1539	15.390	0.6	0.4	Transgressive lag
9	4.67	2	1398.6	13.986	0.1	2.3	Transgressive lag
10	3.38	5	1211.4	12.114	0.4	0.7	Transgressive lag

Trench G19



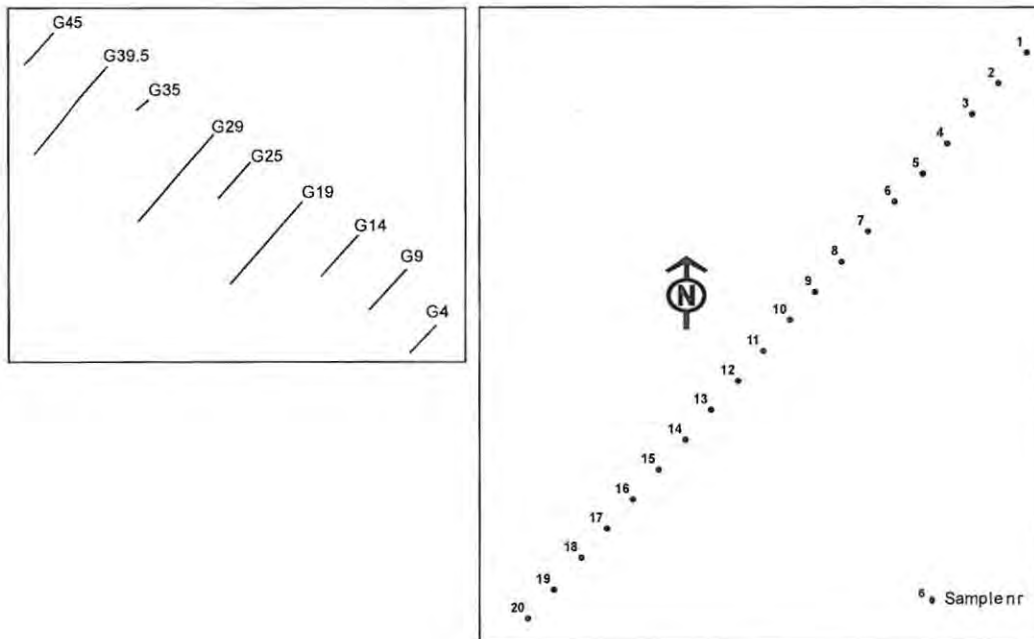
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	28.78	11	1053	10.530	1.0	2.6	Transgressive lag
2	18.27	7	1081.8	10.818	0.6	2.6	Transgressive lag
3	3	4	660.6	6.606	0.6	0.8	Transgressive lag
4	1.44	2	473.4	4.734	0.4	0.7	Transgressive lag
5	0	0	424.8	4.248	0.0	0.0	Transgressive lag
6	0	0	621.0	6.210	0.0	0.0	Transgressive lag
7	6.19	10	831.6	8.316	1.2	0.6	Transgressive lag
8	0	0	379.8	3.798	0.0	0.0	Transgressive lag
9	0.36	1	1287	12.870	0.1	0.4	Transgressive lag
10	1.36	5	1380.6	13.806	0.4	0.3	Transgressive lag
11	0.65	2	1092.6	10.926	0.2	0.3	Transgressive lag
12	0	0	840.6	8.406	0.0	0.0	Transgressive lag
13	3.3	2	984.6	9.846	0.2	1.7	Transgressive lag
14	0.17	1	927	9.270	0.1	0.2	Transgressive lag
15	0	0	1175.4	11.754	0.0	0.0	Transgressive lag
16	0	0	1002.6	10.026	0.0	0.0	Transgressive lag
17	0	0	1526.4	15.264	0.0	0.0	Transgressive lag
18	1.33	1	1117.8	11.178	0.1	1.3	Transgressive lag
19	0	0	1387.8	13.878	0.0	0.0	Transgressive lag

Trench G25



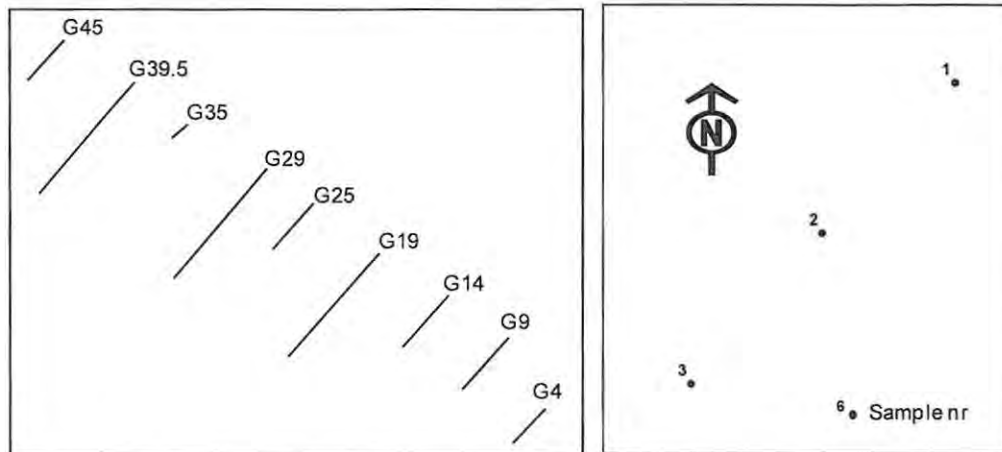
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	14.07	17	856.8	8.568	2.0	0.8	Transgressive lag
2	22.62	18	1530	15.300	1.2	1.3	Transgressive lag
3	15.94	15	1438.2	14.382	1.0	1.1	Transgressive lag
4	29.7	13	819	8.190	1.6	2.3	Transgressive lag
5	6.57	3	948.6	9.486	0.3	2.2	Transgressive lag
6	6.87	5	1254.6	12.546	0.4	1.4	Transgressive lag
7	5.33	7	673.2	6.732	1.0	0.8	Transgressive lag
8	4.58	5	856.8	8.568	0.6	0.9	Transgressive lag
9	4.45	3	702	7.020	0.4	1.5	Transgressive lag

Trench G29



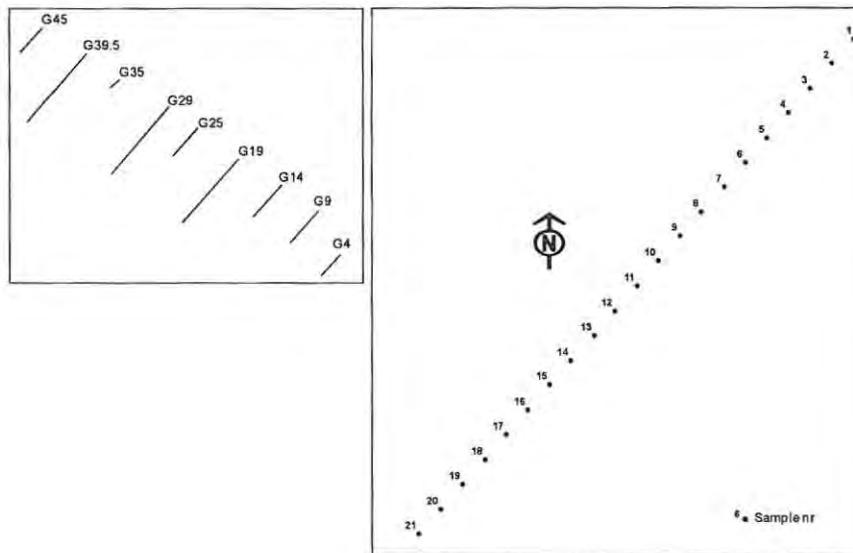
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	15.26	6	725.4	7.254	0.8	2.5	Transgressive lag
2	3.76	7	808.2	8.082	0.9	0.5	Transgressive lag
3	18.1	5	1128.6	11.286	0.4	3.6	Transgressive lag
4	6.04	4	826.2	8.262	0.5	1.5	Transgressive lag
5	12.42	12	1103.4	11.034	1.1	1.0	Transgressive lag
6	0	0	824.4	8.244	0.0	0.0	Transgressive lag
7	0	0	531	5.310	0.0	0.0	Transgressive lag
8	0.83	1	500.4	5.004	0.2	0.8	Transgressive lag
9	0.37	1	680.4	6.804	0.1	0.4	Transgressive lag
10	7.22	5	1090.8	10.908	0.5	1.4	Transgressive lag
11	0	0	732.6	7.326	0.0	0	Transgressive lag
12	1.46	1	745.2	7.452	0.1	1.5	Transgressive lag
13	0	0	694.8	6.948	0.0	0	Transgressive lag
14	4.14	6	1758.6	17.586	0.3	0.7	Transgressive lag
15	0.34	2	1456.2	14.562	0.1	0.2	Transgressive lag
16	0	0	1184.4	11.844	0.0	0	Transgressive lag
17	0	0	1062	10.620	0.0	0	Transgressive lag
18	5.73	1	1422	14.220	0.1	5.7	Transgressive lag
19	0	0	1670.4	16.704	0.0	0	Transgressive lag
20	1.14	2	1800	18.000	0.1	0.6	Transgressive lag

Trench G35



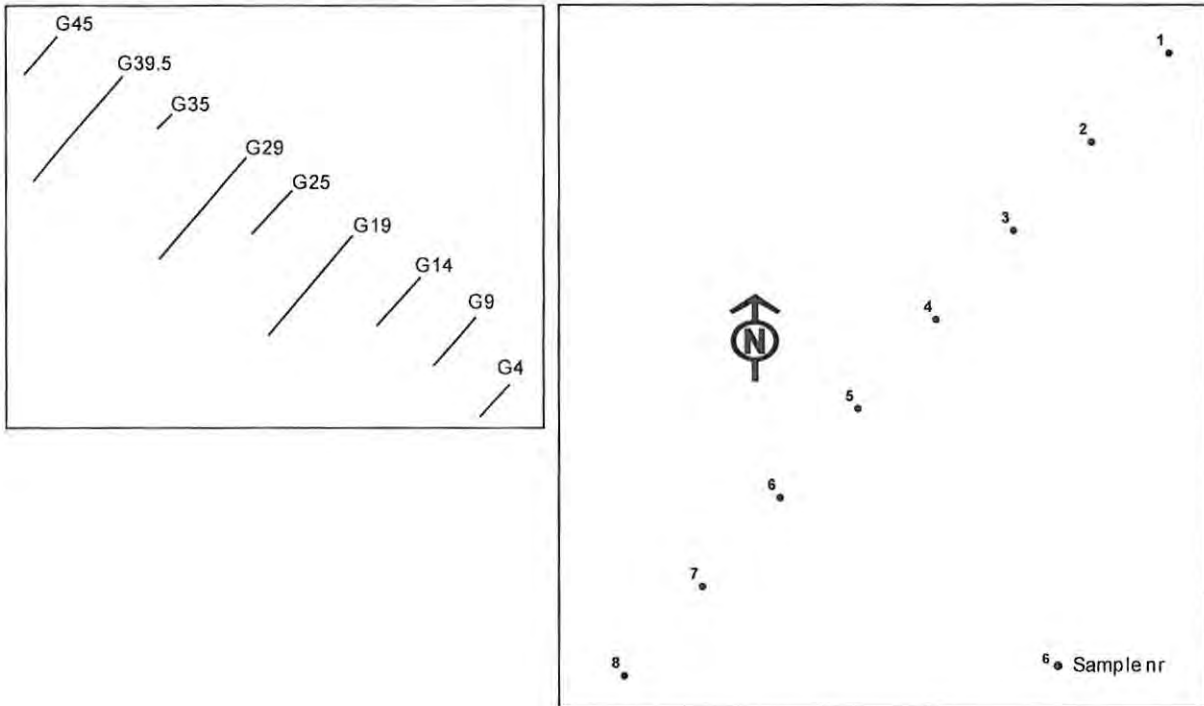
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	111.46	60	1683	16.830	3.6	1.9	Transgressive lag
2	33.05	9	1040.4	10.404	0.9	3.7	Transgressive lag
3	2.23	3	1031.4	10.314	0.3	0.7	Transgressive lag

Trench G39.5



sample nr	carats	stones	tons	tons normalised	sph	cts/stn	environment
1	17.17	15	775.8	7.758	1.9	1.1	Transgressive lag
2	3.62	2	925.2	9.252	0.2	1.8	Transgressive lag
3	42.83	23	3274.2	32.742	0.7	1.9	Transgressive lag
4	12.5	10	2865.6	28.656	0.3	1.3	Transgressive lag
5	2.61	4	925.2	9.252	0.4	0.7	Transgressive lag
6	15.36	8	525.6	5.256	1.5	1.9	Transgressive lag
7	0.82	2	1375.2	13.752	0.1	0.4	Transgressive lag
8	2.14	1	345.6	3.456	0.3	2.1	Transgressive lag
9	0	0	1396.8	0.000	0.0	0.0	Transgressive lag
10	2.16	4	1396.8	13.968	0.3	0.5	Transgressive lag
11	1.73	1	540	5.400	0.2	1.7	Transgressive lag
12	1.93	1	801	8.010	0.1	1.9	Transgressive lag
13	0	0	498.6	4.986	0.0	0.0	Transgressive lag
14	0	0	1031.4	10.314	0.0	0.0	Transgressive lag
15	0	0	768.6	7.686	0.0	0.0	Transgressive lag
16	1.29	2	1258.2	12.582	0.2	0.6	Transgressive lag
17	0.77	1	1819.8	18.198	0.1	0.8	Transgressive lag
18	0	0	1474.2	14.742	0.0	0.0	Transgressive lag
19	0.28	1	1474.2	14.742	0.1	0.3	Transgressive lag
20	4.87	4	1450.8	14.508	0.3	1.2	Transgressive lag
21	2.18	1	1074.6	10.746	0.1	2.2	Transgressive lag

Trench G45

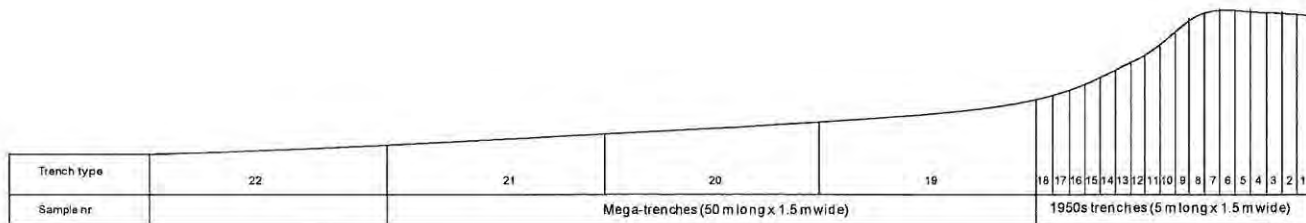


sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	57.01	43	1009.8	10.098	4.3	1.3	Transgressive lag
2	5	4	734.4	7.344	0.5	1.3	Transgressive lag
3	13.45	5	520.2	5.202	1.0	2.7	Transgressive lag
4	16.63	13	673.2	6.732	1.9	1.3	Transgressive lag
5	12.48	14	1101.6	11.016	1.3	0.9	Transgressive lag
6	1.62	3	887.4	8.874	0.3	0.5	Transgressive lag
7	3.07	10	1346.4	13.464	0.7	0.3	Transgressive lag
8	0.94	4	979.2	9.792	0.4	0.2	Transgressive lag

*Facies C (barrier beach)**Trench G19*

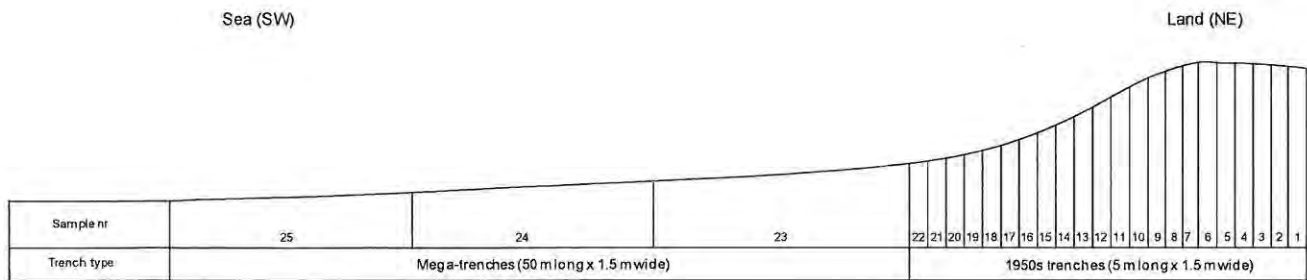
Sea (SW)

Land (NE)



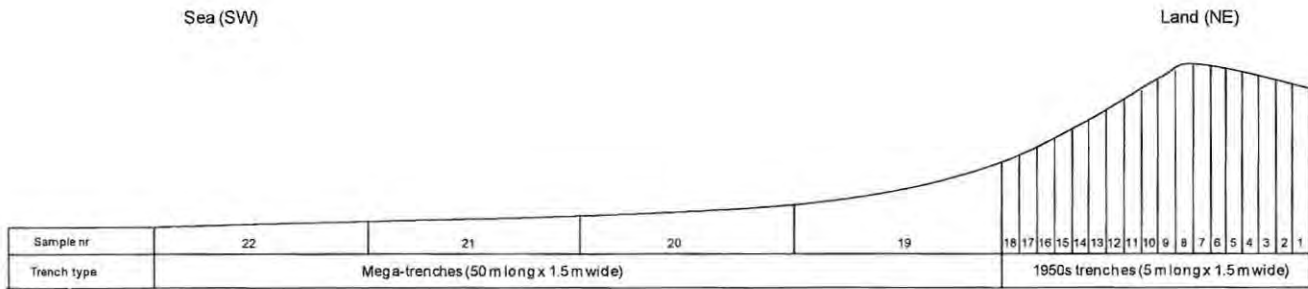
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	0.00	0	33.75	0.338	0.0	0.0	washover
2	0.00	0	59.4	0.594	0.0	0.0	washover
3	0.00	0	59.4	0.594	0.0	0.0	washover
4	0.00	0	53.19	0.532	0.0	0.0	washover
5	3.60	3	47.25	0.473	6.3	1.2	washover
6	7.25	3	47.25	0.473	6.3	2.4	washover
7	0.35	1	40.5	0.405	2.5	0.4	washover
8	12.35	12	45.9	0.459	26.1	1.0	beach face (upper to middle)
9	15.80	14	40.5	0.405	34.6	1.1	beach face (upper to middle)
10	9.10	3	40.5	0.405	7.4	3.0	beach face (upper to middle)
11	6.95	6	46.44	0.464	12.9	1.2	beach face (upper to middle)
12	0.00	0	33.75	0.338	0.0	0.0	beach face (middle to lower)
13	2.10	2	33.75	0.338	5.9	1.1	beach face (middle to lower)
14	0.00	0	22.95	0.229	0.0	0.0	beach face (middle to lower)
15	0.00	0	45.36	0.454	0.0	0.0	beach face (middle to lower)
16	0.00	0	29.16	0.292	0.0	0.0	beach face (middle to lower)
17	0.00	0	41.58	0.416	0.0	0.0	beach face (middle to lower)
18	0.00	0	29.7	0.297	0.0	0.0	beach face (middle to lower)
19	248.77	122	2056	20.556	5.9	2.0	beach toe
20	146.00	68	1415	14.148	4.8	2.1	beach toe
21	135.80	80	1615	16.146	5.0	1.7	beach toe
22	63.82	82	1804	18.036	4.5	0.8	beach toe

Trench G25



sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	0.00	0	65.61	0.656	0.0	0.0	washover
2	0.00	0	66.15	0.662	0.0	0.0	washover
3	0.00	0	67.5	0.675	0.0	0.0	washover
4	0.00	0	67.5	0.675	0.0	0.0	washover
5	1.00	1	67.5	0.675	1.5	1.0	washover
6	0.00	0	67.5	0.675	0.0	0.0	washover
7	2.95	4	67.5	0.675	5.9	0.7	washover
8	28.80	24	67.5	0.675	35.6	1.2	beach face (upper to middle)
9	20.85	15	67.5	0.675	22.2	1.4	beach face (upper to middle)
10	8.90	5	67.5	0.675	7.4	1.8	beach face (upper to middle)
11	5.90	3	60.75	0.608	4.9	2.0	beach face (upper to middle)
12	0.00	0	54	0.540	0.0	0.0	beach face (middle to lower)
13	0.75	1	33.75	0.338	3.0	0.8	beach face (middle to lower)
14	0.00	0	33.75	0.338	0.0	0.0	beach face (middle to lower)
15	0.00	0	49.14	0.491	0.0	0.0	beach face (middle to lower)
16	0.00	0	33.75	0.338	0.0	0.0	beach face (middle to lower)
17	0.00	0	33.75	0.338	0.0	0.0	beach face (middle to lower)
18	0.00	0	36.45	0.365	0.0	0.0	beach toe
19	0.00	0	38.61	0.386	0.0	0.0	beach toe
20	0.65	1	38.61	0.386	2.6	0.7	beach toe
21	0.00	0	40.5	0.405	0.0	0.0	beach toe
22	0.00	0	41.31	0.413	0.0	0.0	beach toe
23	58.89	37	720	7.200	5.1	1.6	beach toe
24	41.87	28	979.2	9.792	2.9	1.5	beach toe
25	31.47	39	765	7.650	5.1	0.8	beach toe

Trench G29

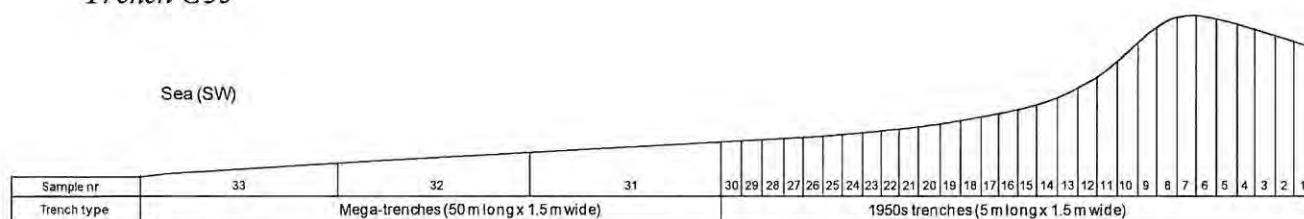


sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	0.00	0	61.56	0.616	0.0	0.0	washover
2	0.00	0	60.48	0.605	0.0	0.0	washover
3	0.60	1	60.08	0.601	1.7	0.6	washover
4	2.10	1	60.75	0.608	1.6	2.1	washover
5	0.00	0	61.83	0.618	0.0	0.0	washover
6	0.00	0	62.37	0.624	0.0	0.0	washover
7	0.60	2	63.45	0.635	3.2	0.3	washover
8	21.50	23	66.15	0.662	34.8	0.9	beach face (upper to middle)
9	38.80	40	61.56	0.616	65.0	1.0	beach face (upper to middle)
10	11.45	9	59.4	0.594	15.2	1.3	beach face (upper to middle)
11	8.50	9	54	0.540	16.7	0.9	beach face (upper to middle)
12	2.40	3	61.56	0.616	4.9	0.8	beach face (middle to lower)
13	0.65	1	45.36	0.454	2.2	0.7	beach face (middle to lower)
14	0.00	0	31.05	0.311	0.0	0.0	beach face (middle to lower)
15	1.20	2	35.1	0.351	5.7	0.6	beach face (middle to lower)
16	4.75	2	33.21	0.332	6.0	2.4	beach face (middle to lower)
17	1.35	1	31.59	0.316	3.2	1.4	beach face (middle to lower)
18	0.00	0	30.51	0.305	0.0	0.0	beach face (middle to lower)
19	58.01	75	1775	17.748	4.2	0.8	beach toe
20	8.65	6	2351	23.508	0.3	1.4	beach toe
21	5.75	6	397.8	3.978	1.5	1.0	beach toe
22	7.69	13	837	8.370	1.6	0.6	beach toe

Trench G35

Land (NE)

Sea (SW)

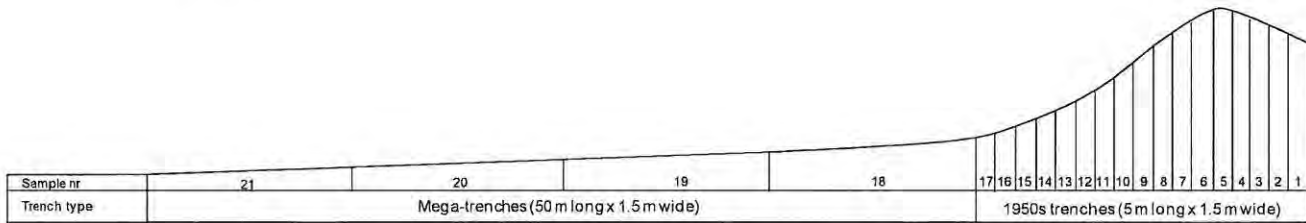


sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	1.80	1	60.75	0.608	1.6	1.8	washover
2	0.00	0	63.45	0.635	0.0	0.0	washover
3	0.00	0	66.15	0.662	0.0	0.0	washover
4	0.00	0	66.15	0.662	0.0	0.0	washover
5	0.00	0	66.15	0.662	0.0	0.0	washover
6	0.00	0	66.15	0.662	0.0	0.0	washover
7	0.20	2	68.85	0.689	2.9	0.1	washover
8	7.10	10	72.09	0.721	13.9	0.7	beach face (upper to middle)
9	6.00	11	68.85	0.689	16.0	0.5	beach face (upper to middle)
10	10.25	5	62.91	0.629	7.9	2.1	beach face (upper to middle)
11	7.15	4	55.08	0.551	7.3	1.8	beach face (upper to middle)
12	23.25	3	49.68	0.497	6.0	7.8	beach face (middle to lower)
13	2.20	3	44.28	0.443	6.8	0.7	beach face (middle to lower)
14	2.00	3	44.82	0.448	6.7	0.7	beach face (middle to lower)
15	2.20	1	48.06	0.481	2.1	2.2	beach face (middle to lower)
16	7.95	9	38.34	0.383	23.5	0.9	beach toe
17	6.85	5	33.75	0.338	14.8	1.4	beach toe
18	2.20	1	44.55	0.446	2.2	2.2	beach toe
19	1.40	1	53.6	0.536	1.9	1.4	beach toe
20	1.50	1	68.04	0.680	1.5	1.5	beach toe
21	10.80	2	57.38	0.574	3.5	5.4	beach toe
22	3.35	4	56.16	0.562	7.1	0.8	beach toe
23	0.30	1	56.3	0.563	1.8	0.3	beach toe
24	2.50	4	56.43	0.564	7.1	0.6	beach toe
25	0.00	0	56.7	0.567	0.0	0.0	beach toe
26	2.00	1	56.7	0.567	1.8	2.0	beach toe
27	1.00	1	54.54	0.545	1.8	1.0	beach toe
28	0.00	0	52.92	0.529	0.0	0.0	beach toe
29	1.10	1	53.46	0.535	1.9	1.1	beach toe
30	0.00	0	52.65	0.527	0.0	0.0	beach toe
31	62.77	46	918	9.180	5.0	1.4	beach toe
32	65.00	64	1132	11.322	5.7	1.0	beach toe
33	36.00	29	1346	13.464	2.2	1.2	beach toe

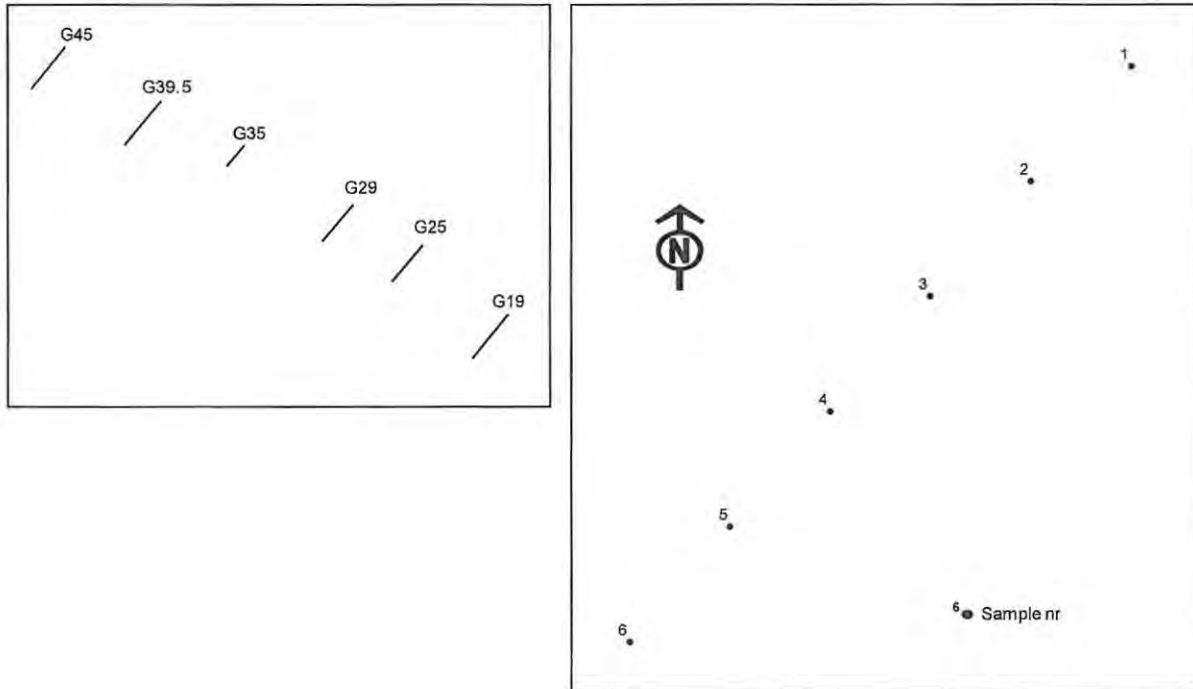
Trench G39.5

Sea (SW)

Land (NE)

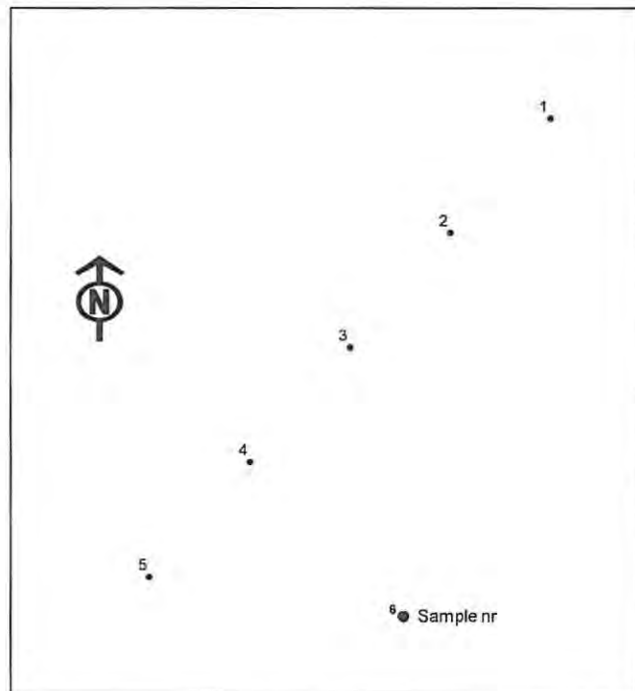
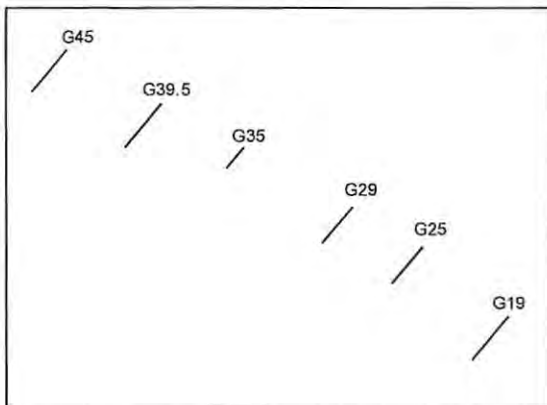


sample nr	carats	stones	tons	tons normalised	stns/100 ton	cts/stn	environment
1	0.00	0	51.03	0.510	0.0	0.0	washover
2	0.50	1	55.08	0.551	1.8	0.5	washover
3	0.00	0	60.75	0.608	0.0	0.0	washover
4	2.70	1	61.56	0.616	1.6	2.7	washover
5	0.00	0	60.75	0.608	0.0	0.0	washover
6	1.10	1	75.33	0.753	1.3	1.1	beach face (upper to middle)
7	0.00	0	64.26	0.643	0.0	0.0	beach face (upper to middle)
8	3.20	12	58.05	0.581	20.7	0.3	beach face (upper to middle)
9	35.15	36	59.13	0.591	60.9	1.0	beach face (upper to middle)
10	22.25	17	59.4	0.594	28.6	1.3	beach face (middle to lower)
11	8.65	7	56.16	0.562	12.5	1.2	beach face (middle to lower)
12	3.25	4	55.62	0.556	7.2	0.8	beach face (middle to lower)
13	0.80	1	55.35	0.554	1.8	0.8	beach face (middle to lower)
14	0.50	1	48.06	0.481	2.1	0.5	beach face (middle to lower)
15	1.30	1	51.3	0.513	1.9	1.3	beach face (middle to lower)
16	0.00	0	53.73	0.537	0.0	0.0	beach toe
17	0.00	0	53.46	0.535	0.0	0.0	beach toe
18	14.25	12	3940	39.402	0.3	1.2	beach toe
19	28.39	11	550.8	5.508	2.0	2.6	beach toe
20	33.57	36	1075	10.746	3.4	0.9	beach toe
21	25.23	31	700.2	7.002	4.4	0.8	beach toe

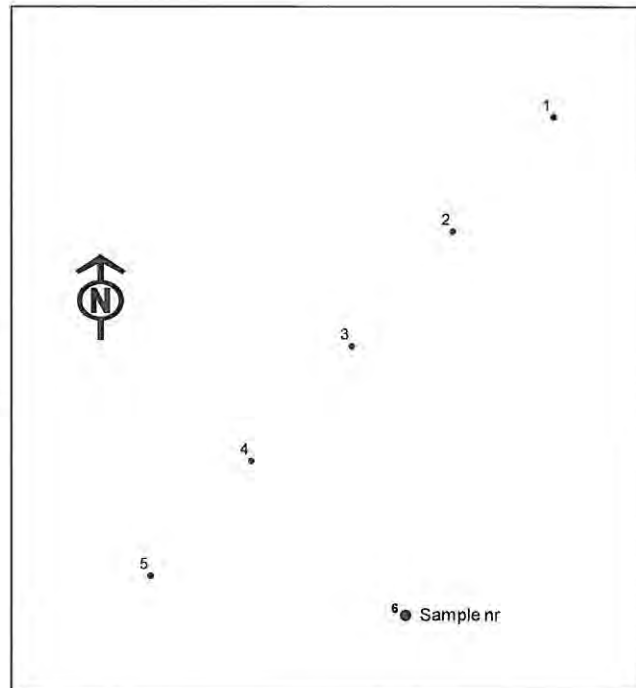
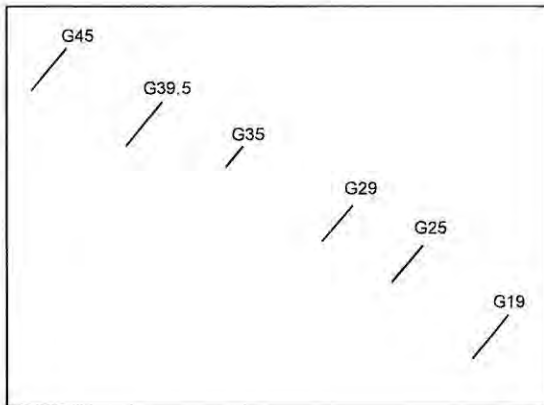
*Facies D (shoreface)**Sub-facies D3 (storm gravel sheets)**Trench G19*

sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	1.3	2	1139.4	11.394	0.2	0.7	storm gravel sheets
2	1.18	1	1531.8	15.318	0.1	1.2	storm gravel sheets
3	0	0	1080	10.800	0.0	0.0	storm gravel sheets
4	0.95	1	1713.6	17.136	0.1	1.0	storm gravel sheets
5	1.56	4	1816.2	18.162	0.2	0.4	storm gravel sheets
6	1.56	5	2563.2	25.632	0.2	0.3	storm gravel sheets

Trench G25

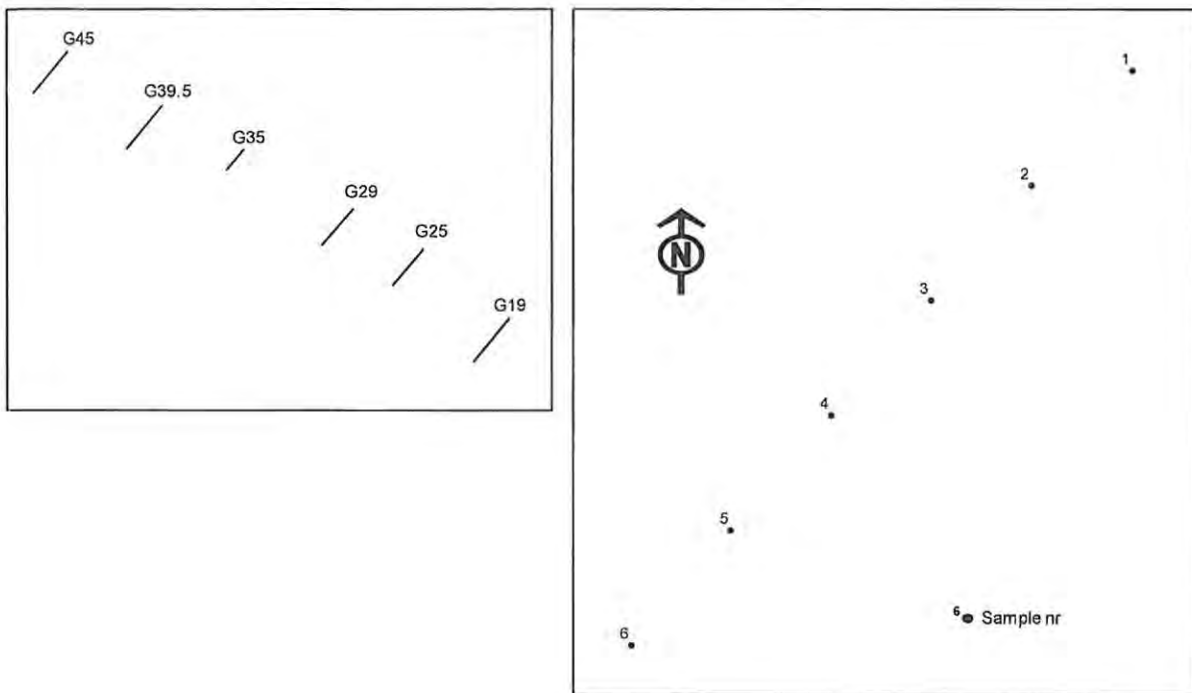


sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	2.27	3	853.2	8.532	0.4	0.8	storm gravel sheets
2	2.27	12	1240.2	12.40.2	1.1	0.2	storm gravel sheets
3	0	0	581.4	5.814	0.0	0.0	storm gravel sheets
4	7.24	5	948.6	9.486	0.53	1.4	storm gravel sheets
5	1.24	1	459.0	4.590	0.22	1.2	storm gravel sheets

Trench G29

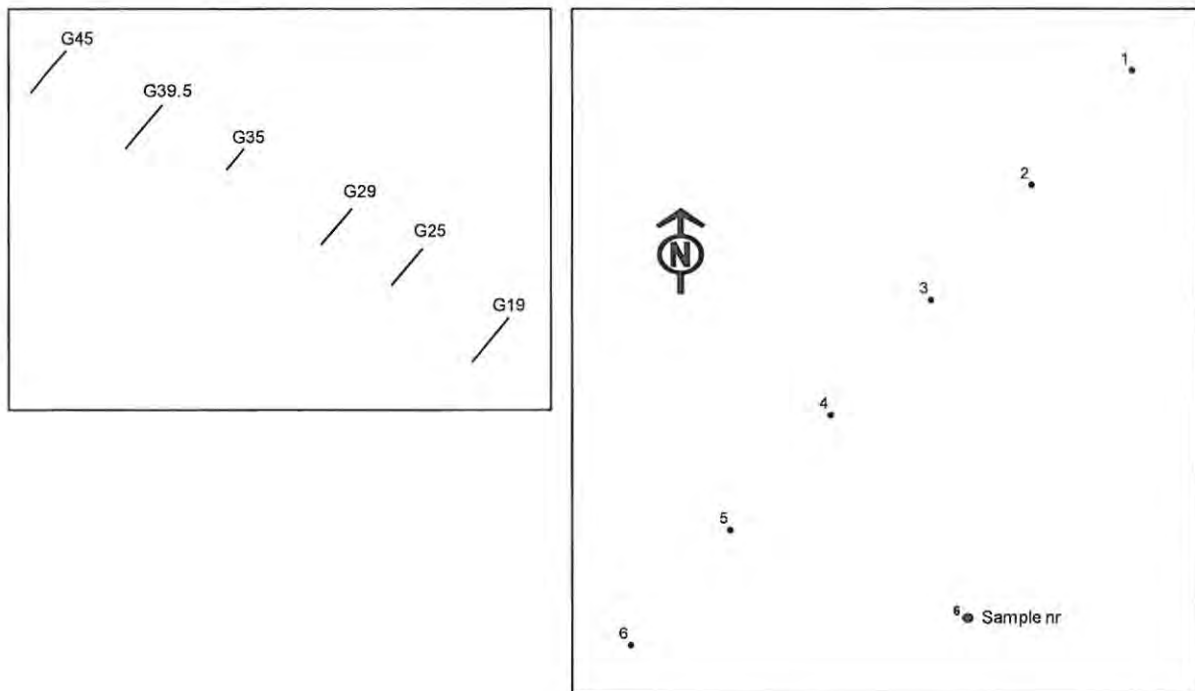
sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	12.75	8	3135.6	31.356	0.3	1.6	storm gravel sheets
2	2.66	4	2100.6	21.006	0.2	0.7	storm gravel sheets
3	0.4	1	2525.4	25.254	0.04	0.4	storm gravel sheets
4	2.02	3	2925	29.250	0.1	0.7	storm gravel sheets
5	0.51	1	1949.4	19.494	0.1	0.5	storm gravel sheets

Trench G39.5



sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	0	0	4690.8	46.908	0.0	0.0	storm gravel sheets
2	0	0	4752.0	47.520	0.0	0.0	storm gravel sheets
3	0	0	4100.4	41.004	0.0	0.0	storm gravel sheets
4	1.73	3	3387.6	33.876	0.1	0.6	storm gravel sheets
5	0.94	2	2071.8	20.718	0.1	0.5	storm gravel sheets
6	1.58	6	1269	12.690	0.5	0.3	storm gravel sheets

Trench G45



sample nr	carats	stones	tons	tons normalised	spht	cts/stn	environment
1	1.08	2	2172.6	21.726	0.1	0.5	storm gravel sheets
2	0.69	2	2233.8	22.338	0.1	0.3	storm gravel sheets
3	1.74	4	2050.2	20.502	0.2	0.4	storm gravel sheets
4	2.86	1	1438.2	14.382	0.1	2.9	storm gravel sheets
5	0.28	1	918	9.180	0.1	0.3	storm gravel sheets
6	1.65	5	1009.8	10.098	0.5	0.3	storm gravel sheets

APPENDIX C
MARINE FOSSIL ASSEMBLAGE

MARINE FOSSIL ASSEMBLAGE

Macro-fauna: conglomerate boulder (30 m Package; Plio-Pleistocene age)

Macro-fauna	Identified by
<i>Burnupena rogersi</i>	Pether (2003)
<i>Spinucella praecingulata</i>	Pether (2003)

Macro-fauna: conglomerate boulder (50 m Package; Early Pliocene age)

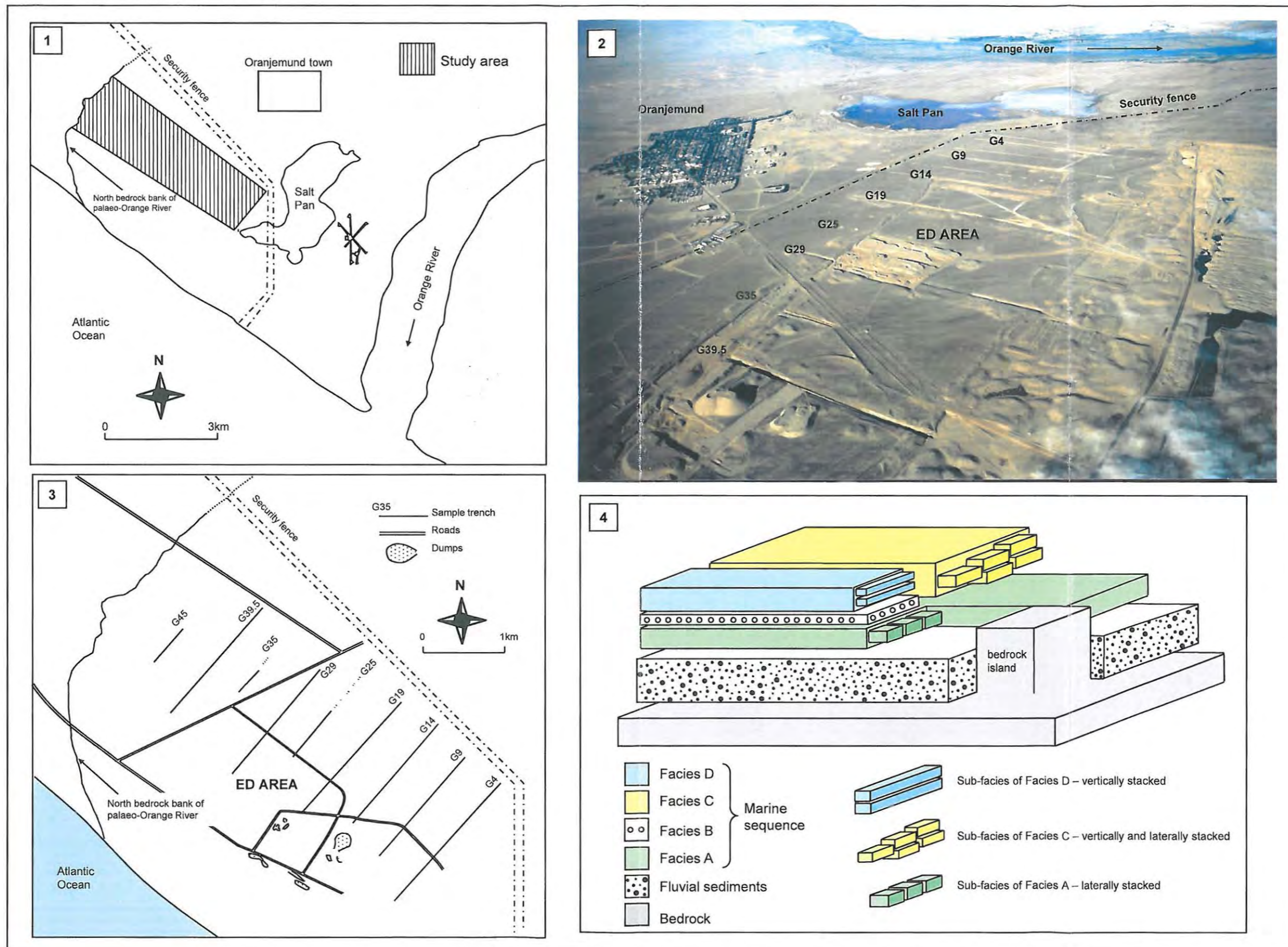
Macro-fauna	Identified by
<i>Chamelea krigei</i>	Pether (2003)
<i>Spinucella praecingulata</i>	Pether (2003)

Micro-fauna: conglomerate boulder (50 m Package; Early Pliocene age)

Foraminifera	Identified by	Estimated age (Ma)
<i>Lobatula lobatula</i> (Walker & Jacob)	Dale & McMillan (2003)	4.9 - 7.4 (see Franceschini & Compton, 2004)*
<i>Quinqueloculina</i> spp.	Dale & McMillan (2003)	
<i>Triloculina</i> sp.	Dale & McMillan (2003)	
<i>Quinqueloculina</i> cf. <i>curta</i>	Dale & McMillan (2003)	
<i>Quinqueloculina</i> cf. <i>vulgaris</i>	Dale & McMillan (2003)	
<i>Ammonia</i> cf. <i>parkinsoniana</i> (D'Orbigny)	Dale & McMillan (2003)	
<i>Pararotalia nipponica</i> (Asano)	Dale & McMillan (2003)	Early Pliocene (Dale & McMillan, 2003)
<i>Spiroplectinella</i> sp	Dale & McMillan (2003)	
<i>Cibicidoides</i> sp	Dale & McMillan (2003)	
<i>Elphidium</i> cf. <i>crispum</i> (Linné)	Dale & McMillan (2003)	
<i>Lagena</i> sp	Dale & McMillan (2003)	

* Note that the 50 m Package along the Namaqualand Coast at Hondeklip Bay was dated by Pickford & Senut (1999) as Late Miocene to Early Pliocene based on the presence of un-abraded mammalian remains of that age within the marine sediments. This age closely correlates to the Strontium isotope date of Franceschini & Compton (2004) from the foraminifer *Lobatula lobatula*; a species that also forms part of the 50 m Package assemblage along the Namaqualand Coast (Dale & McMillan, 2003).

APPENDIX D: Locality of study area (1 & 3) with oblique aerial view of ED Area (2; photograph by courtesy of J Ward). Block diagram depicting the vertical and lateral stratigraphic relationship of facies and sub-facies (4).



APPENDIX E: Reconnaissance map showing stratigraphic sections within ED Area.

