A GEOLOGICAL EVALUATION OF MARINE DIAMOND PLACER DEPOSITS ON THE CENTRAL NAMIBIAN INNER SHELF: A CASE STUDY OF THE HOTTENTOT BAY AREA.

By

GRANT RAU

Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of
MASTER OF SCIENCE
in the Department of Geological Sciences
RHODES UNIVERSITY

June, 2003

ABSTRACT

This study focusses on the marine diamond placers within Exclusive Prospecting Licence 1950 and Mining Licence 103a, located northwest of the north-facing Hottentot Bay which is 60 km north of Lüderitz, along the central Namibian coastline. The thesis follows the natural geological evolution of the marine placer deposit from primary source, through alluvial and/or glacial transportation, concentration along the coastline by wave, aeolian and alluvial/sheet-wash processes and finally marine diamond placer preservation. All of these processes are reviewed as they are important in understanding of the evolution marine placer deposits. The poly-cyclic role of coastal aeolian, alluvial, and marine processes, in marine placer enrichment is shown to be particularly important in considered target identification and prioritisation.

A detailed bathymetric, sonographic and seismic interpretation, is an integral part of diamond placer exploration, and was used to examine and describe surficial and sub-bottom characteristics within the study area. Marine placers are formed along palaeo-strandlines during periods of marine transgression and regression and are therefore fundamental in marine placer exploration. A detailed bathymetry map, compiled for this study, of the area between Lüderitz Bay and Clara Hill, provides the foundation for a detailed terrace level investigation. Regionally, twelve well-developed stillstand levels are identified, nine of which fall into the study area. These interpretations are compared with global eustatic as well as terrace and resource/reserve levels in the Lüderitz area and are found to correlate well.

Sediment dynamic studies involve the use of accredited application software for wave refraction modelling, to determine the wave angle and orbital wave velocity at the seabed. Bedload velocities, required to move diamonds of specific sizes, can be empirically determined and therefore areas of diamond entrainment and deposition can be modelled and target features delineated and prioritised.

These detailed interpretations provide a sound platform for evaluating diamond placer process models in the study area. By integrating both previously published and newly formulated ideas, a revised, holistic model for the formation of marine diamond placer deposits in central Namibian is postulated. The proposed model is tested by comparing it to the lateral distribution of presently defined resource/reserve areas in the Lüderitz area and shows a close correlation with most of these enriched deposits. Based on this model, a matrix for the delineation and prioritisation of marine placer deposits is developed and the best target features within the study area are identified.

DECLARATION

I hereby declare that all the work presented in this dissertation is my own, except where otherwise stated and that this thesis has not been submitted for a degree at any other University.

Grant Rau

TABLE OF CONTENTS

LIST OF FIGURES

Note: Unless otherwise stated geodetic information relating to all maps is as follows: WGS84, UTM Zone 33, Central Meridian 15^{0}E.

Figure Number **Diagram Follows Text Page Number**

LIST OF TABLES

LIST OF FREQUENTLY USED ACRONYMS AND ABBREVIATIONS

MCG - Marine and Coastal Geoscience (pty) Ltd
DFI - Diamond Fields International
DKG - Duetsche Kolonial Gesellschaft fur Suidwestafrika
CDM - Centennial Diamond Mines
TDC - Tidal Diamond Corporation
OPIC - Overseas Private Investment Corporation
MDC - Marine Diamond Corporation
ODM - Ocean Diamond Mines
BHP - Broken Hill Proprietary
MDS - Marine Data Solutions CC
EPL - Exclusive Prospecting Licence
ML - Mining Licence
HBG - Hottentot Bay Grant - colloquial name for EPL 1950 and ML103a
BMP - Blue Mountain Prospect - southern portion of EPL 1950
HBP - HB Prospect Area - eastern edge of ML103a
HB-S - southern portion of HB Prospect Area
HB-C - central portion of HB Prospect Area
HB-N - northern portion of HB Prospect Area
CHP - Clara Hill Prospect - northeastern portion of EPL 1950
SHP - Saddle Hill Prospect - formerly the central portion of EPL 1950, subsequently converted to ML 103a

HDP - HD Prospect Area - northwestern portion of EPL 1950
ES - Single beam echo-sounder
B - Boomer sub-bottom profiler
CH - Chirp sub-bottom profiler
SS - Sidescan sonar
SSS - Sidescan sonar
AG - Airgun sub-bottom profiler
P - Pinger sub-bottom profiler
SB - Swath bathymetry
T - TOPAS - Topagraphic Parametric Sonar
MRU - Motion Reference Unit
TVG - Time Varied Gain
AUV - Autonomous Underwater Vehicles
MWR - Main Western Ridge
GIS - Geographical Information System
UTM - Universal Transverse Mercator
WGS - World Geodetic System 1984
A0 - Paper Size 841 mm X 1189 mm
CAD - Computer Aided Design
DTM - Digital Terrain Model
DEM - Digital Elevation Model
A, B, C......AA, AB.....AM - Refer: Figure 25 - Letters allocated to target features in ML103a and EPL 1950 to enable easy referencing during descriptions in the text.
N - North
S - South
E - East
W - West
NNW, NNE etc - North-north west etc.
NW, NE etc - North west etc.
cpht - carats per hundred tons
fs - fine sediment
cs - coarse sediment
rcs - rippled coarse sediment
csv - coarse sediment veneer
SR - Subdued rock
LR - Low rock
MR - Moderate rock
RR - Rugged rock
DSDP - Deep Sea Drilling Programme
MHWS - Mean High Water Springs
bpsl - below present sea level

APPENDICES

ACKNOWLEDGEMENTS

Completing a Masters thesis, outside of working hours, places severe strain on the mind, body and soul. The long hours and associated stress, requires a sacrifice, not only on the part of the candidate, but also impacts on loved ones, friends and work colleges. I would like to thank all those who have encouraged and supported me during this time. I would like to give special thanks to the following:

My wife, Dr A. J. Rau, who has supported and helped me through thick and thin and my 3 year old daughter Sasha who was a shining light no matter what the circumstances.

Mr R. H. De Decker who has offered guidance and input not only during this thesis but throughout my career as a consulting marine geologist.

Mr W. M. Woodborne who offered guidance and was a great inspiration while we were working together at Marine and Coastal Geo-Consultants CC during the earlier part of my career.

Mrs S. S. Smith who has been highly supportive throughout and who was responsible for most of the CAD work and, together with Mrs G. Jones, compiled a number of the diagrams presented in this thesis.

To Mr R. H. De Decker, Dr A. J. Rau and Mrs S. S. Smith for reading drafts of this thesis and their valuable contributions to the quality of the final product.

Dr J. M. Moore who encouraged me to pick up where I left off years ago and keep going to the end, and who's dedication to the science of geology can be an inspiration to all in this field.

To Namibian Minerals Corporation, and in particular to Mr A. Holberton, Mr M. W. Woodborne and Dr C. Morrison who gave me permission to use their data for this thesis. Sadly, NAMCO went into liquidation last year and is unlikely to benefit directly from their contribution.

Lastly, thanks to all the companies prospecting for marine diamonds on the inner shelf that have supported Marine and Coastal Geoscience (Pty) Ltd over the last decade. I hope that this thesis will be of benefit to you in future prospecting for marine placer deposits along the inner shelf.

1. INTRODUCTION

This thesis presents a revised, holistic hypothesis for the concentration of diamonds along the central Namibian coastal plain into discrete, placer deposits. Based on this model a method for the delineation and prioritisation of marine placer deposits on the inner shelf is developed.

This study reviews the processes and methods currently being employed to delineate and prioritise diamond placer deposits on the inner shelf along the west coast of southern Africa. It has evolved as part of the work that Marine and Coastal Geoscience (Pty) Ltd (MCG) has been undertaking over the last 12 years, for the marine diamond industry. The concepts and ideas derive from the author's work done as a consultant geologist in the company. It is the aim of this thesis to provide those actively involved in the exploration and mining of these deposits with a better understanding of their evolution and, in so doing, improve their success in delineating economical marine diamond placer deposits on the inner shelf in the future.

Many detailed investigations on the economic aspects of marine diamond placers have been undertaken internally by companies actively mining along the west coast. Although a large proportion of the wealth of information gathered from mining activities is proprietary, more information has been made and is becoming available, as companies seeking to raise public funding are obligated to release data in order to gain approval from stock exchange listing commissions. Most published studies have centred on the less economically sensitive aspects of the marine placer deposits e.g. the micropalaeontology or oceanography of the areas.

Exclusive Prospecting Licence 1950 (EPL 1950) and Mining Licences 103A (ML 103A), colloquially known as the Hottentot Bay Grants (HBG), ML 50, and the adjacent onshore area, have been selected as a type-area, as all the processes involved in the evolution of the central Namibian marine diamond placer deposits are demonstrated in this region.

Studies associated with the search for drinking water for the town, Lüderitz, as well as the historical mining of the raised terraces at Saddle Hill, adjacent to EPL 1950 provide geo-hydrological, geological and geophysical information from beneath the overlying Namib Sand Sea. The detailed examination of the onshore and offshore regions at HBG and in the areas immediately to the south (Mining Licence Areas ML 51 and ML 111 and EPL 1607 B), provide the framework from which interpretations and conclusions regarding the evolution of marine placer deposits in this region can be drawn.

Previous published studies on the formation of placer deposits along the west coast have centred on either marine or on aeolian processes. This thesis examines the combined role of aeolian, marine and local fluvial processes and presents a revised, holistic hypothesis for the formation of diamond placer deposits along the Namibian coastal plain.

1.1 LOCALITY OF THE STUDY AREA

Exclusive Prospecting Licence 1950 (EPL 1950) is located northwest of the north-facing Hottentot Bay that is about 60 km north of Lüderitz, along the central Namibian coastline. To the west lies EPL 2002, the east EPL 1930 and ML50, the south EPL 1607 and to the north EPL 2495.

In order to assess and interpret the placer evolution within the detailed study area, an understanding of the processes that are/were active on the coastal plain from the Orange River Mouth to the Kuiseb River, south of Walvis Bay, is required (Figure 1). Within this large frame-work, the area from Elizabeth Bay to Clara Hill (Figure 1) is of particular importance and is included in many of the interpretations and process modelling discussions. Marine geophysical maps of the area from Lüderitz Bay to Clara Hill (Figure 1) have been compiled and are examined to augment interpretations and conclusion drawn within the study area.

Lüderitz is a natural harbour, in a large north facing embayment, situated approximately 250 km north of Orange River Mouth, South Africa's border with Namibia (Figure 1). Exclusive Prospecting Licence 1950 (**EPL 1950**) is situated 60 km north of Lüderitz. A rocky headland formed by the Gallovidia Reef and Hottentot Point, immediately to the south, creates the southern lip of the north-facing Hottentot Bay (Figure 1). During sea-level lowstands, Hottentot Bay would have formed a significant re-entrant more pronounced than its current form. The southern boundary of the study area, extends offshore opposite Hottentot Point, and it stretches over 40 km to the northern boundary, that is situated west of Clara Hill (Figure 1). The eastern boundary is located 3 km from the coast and the western boundary 12 km further westward (Figure 1). The water depth in EPL 1950 ranges from approximately 35 metres to 120 metres below present mean sea level. EPL 1950 originally had an area of 526 km^2 but has been reduced to approximately 167 km^2 following the granting of Mining Licence 103A (**ML 103A**) which covers an area of approximately 359 km^2. ML 103A is situated between Blue Mountain Prospect (BMP) in the south and Clara Hill Prospect (CHP) in the north (Figure 1). ML 103A was formerly the central section, Saddle Hill Prospect (SHP), of EPL 1950 and extends from the vicinity of Black Rocks in the south to Saddle Hill in the north (Figure 1).

EPL 2002, lies offshore of EPL 1950, extending from the seaward boundary of the HBG to 30 to 50 km off the Namibian coast (Figure 1). The property covers an area of 994 km^2 and lies in water depths ranging from 96 to 200 m. Both EPL 1950 and EPL 2002 are held by Namco (Pty) Ltd.

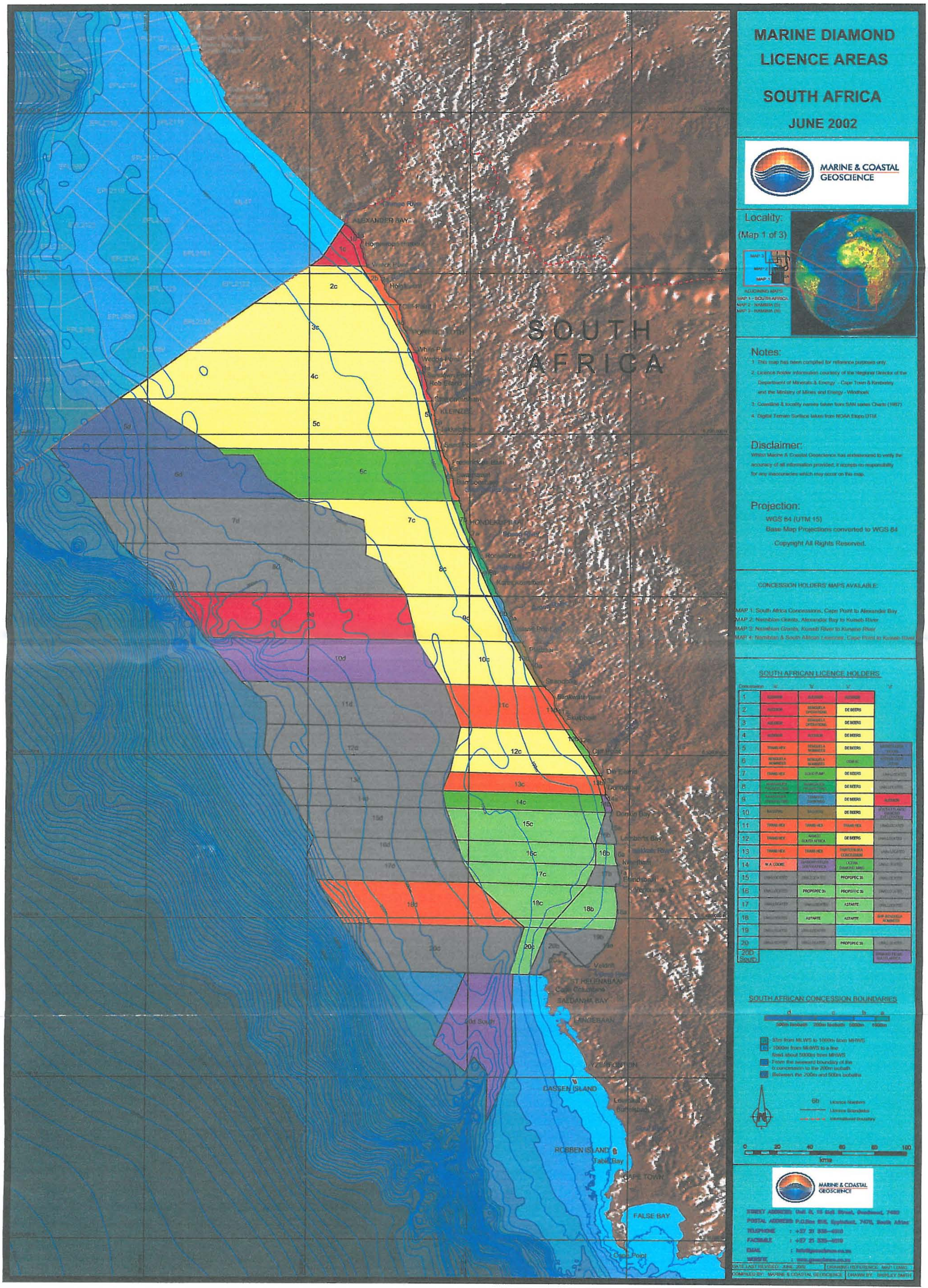
Tidal Diamonds (Pty) Ltd, a subsidiary of Namdeb (Pty) Ltd, are currently the licences holders of **EPL 1944** and **ML 50**. These concessions form the 3 km strip between EPL 1950, at about 35 m water-depth, and the coast (Figure 1). The ML 50 area was the "jack pot" site where in 1964, Mr Sammy Collins, recovered 390 000 carats in just four months.

The rights to the area **EPL 1607** to the south have been allocated to Namibian West Coast Diamonds, a subsidiary of Diamond Fields International (Pty) Ltd (DFI). This area lies in the 20 m to 130 m water depth range (Figure 1). It is a relatively rocky area which forms the submarine extension of the large Hottentot Point headland that shelters HBG from southerly storms, particularly during periods of sea-level regression.

MARINE DIAMOND LICENCE AREAS

SOUTH AFRICA

JUNE 2002



Notes:

1. This map has been compiled for reference purposes only.
2. Licence holder information courtesy of the Regional Director of the Department of Minerals & Energy - Cape Town & Kimberley and the Ministry of Mines and Energy - Windhoek.
3. Coastline & locality names taken from SAN series Charts (1987)
4. Digital Terrain Surface taken from NOAA Etopo UTM

Disclaimer:

Whilst Marine & Coastal Geoscience has endeavoured to verify the accuracy of all information provided, it accepts no responsibility for any inaccuracies which may occur on this map.

Projection:

WGS 84 (UTM 15)
Base Map Projections converted to WGS 84

Copyright All Rights Reserved.

CONCESSION HOLDERS' MAPS AVAILABLE:

MAP 1: South Africa Concessions, Cape Point to Alexander Bay
MAP 2: Namibian Grants, Alexander Bay to Kuiseb River
MAP 3: Namibian Grants, Kuiseb River to Kunene River
MAP 4: Namibian & South African Licences, Cape Point to Kuiseb River

SOUTH AFRICAN LICENCE HOLDERS

Concession	'a'	'b'	'c'	'd'
1	ALEXKOR	ALEXKOR	ALEXKOR	
2	ALEXKOR	BENGUELA OPERATIONS	DE BEERS	
3	ALEXKOR	BENGUELA OPERATIONS	DE BEERS	
4	ALEXKOR	ALEXKOR	DE BEERS	
5	TRANS HEX	BENGUELA NOMINEES	DE BEERS	[illegible]
6	BENGUELA NOMINEES	BENGUELA NOMINEES	[illegible]	[illegible]
7	TRANS HEX	SOLID PUMP	DE BEERS	UNALLOCATED
8	[illegible]	[illegible]	DE BEERS	UNALLOCATED
9	[illegible]	[illegible]	DE BEERS	ALEXKOR
10	[illegible]	[illegible]	DE BEERS	SOUTH ATLANTIC DIAMOND EXPLORATION
11	TRANS HEX	TRANS HEX	TRANS HEX	UNALLOCATED
12	TRANS HEX	NAMCO SOUTH AFRICA	DE BEERS	UNALLOCATED
13	TRANS HEX	TRANS HEX	THIRTEEN SEA CONCESSION	UNALLOCATED
14	W.A. COOKE	DIAMOND FIELDS SOUTH AFRICA	OCEAN DIAMOND MINING	UNALLOCATED
15	UNALLOCATED	UNALLOCATED	PROPSPEC 35	UNALLOCATED
16	UNALLOCATED	PROPSPEC 35	PROPSPEC 35	UNALLOCATED
17	UNALLOCATED	UNALLOCATED	ASTARTE	UNALLOCATED
18	UNALLOCATED	ASTARTE	ASTARTE	BHP BENGUELA NOMINEES
19	UNALLOCATED	UNALLOCATED		
20	UNALLOCATED	UNALLOCATED	PROPSPEC 35	UNALLOCATED
20D South				DIAMOND FIELDS SOUTH AFRICA

SOUTH AFRICAN CONCESSION BOUNDARIES

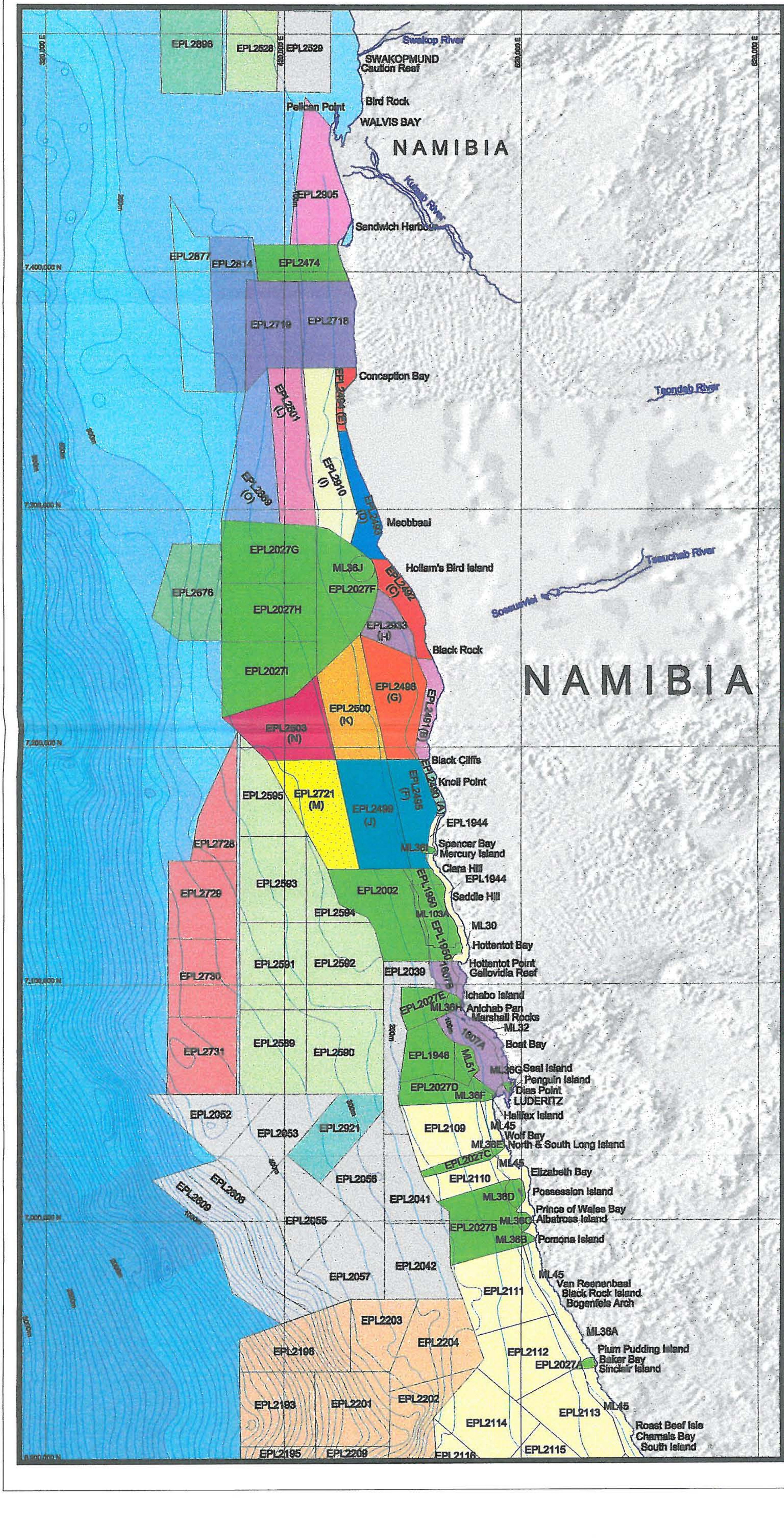
a - 33m from MLWS to 1000m from MHWS
b - 1000m from MHWS to a line fixed about 5000m from MHWS
c - From the seaward boundary of the b concession to the 200m isobath
d - Between the 200m and 500m isobaths

MARINE & COASTAL GEOSCIENCE

STREET ADDRESS: Unit [illegible], 15 [illegible] Street, Goodwood, [illegible]
POSTAL ADDRESS: P.O.Box [illegible], [illegible], [illegible], South Africa
TELEPHONE : +27 21 [illegible]
FACSIMILE : +27 21 [illegible]
EMAIL : [illegible]
WEBSITE : [illegible]

DATE LAST REVISED: JUNE 2002 | DRAWING REFERENCE: MAP 1.DWG
COMPILED BY: MARINE & COASTAL GEOSCIENCE | DRAWN BY: SHIRLEY SMITH

FIGURE 1A



MARINE DIAMOND LICENCE AREAS NAMIBIA

Walvis Bay to Chamais Bay

LICENCE HOLDERS

Afri Namibia Mining Company (Pty) Ltd
2493 BLOCK D

Auas Diamond Company (Pty) Ltd
2495 BLOCK F

Bogenfel Diamond Corporation (Pty) Ltd
2728 2729 2730 2731

Cape Ocean Namibia (Pty) Ltd
2490 BLOCK A

C-Fos Namibia (Pty) Ltd
2809 BLOCK O

Cristal Colours (Pty) Ltd
2910 BLOCK I

Diamarine Mining Corporation (Pty) Ltd
2528

Diamond Fields (Namibia) (Pty) Ltd
ML32 1607A & B

Guinas Angonam Mining (Pty) Ltd
2501 BLOCK L

Karas Mining Holdings (Pty) Ltd
2503 BLOCK N

Kuvelai Delta Mining Company (Pty) Ltd
2721 BLOCK M

Le Ro Marine Diamonds (Pty) Ltd
2593 2589 2594 2590 2595 2591 2592

Manyoka Trading Company (Pty) Ltd
2814

Marine Phosphates Namibia (Pty) Ltd
2676

Moonstone Diamonds Namibia (Pty) Ltd
2496 BLOCK G

Namco Namibia (Pty) Ltd
1950 1946 2002 ML36 A–J ML51 ML 103A

Island Diamonds Ltd

North Long Island	Hollam's Bird Island
South Long Island	Halifax Island
Posession Island	Seal Island
Albatross Island	Penguin Island
Pomona Island	Ichabo Island
Sinclair Island	Mercury Island
2027A–I	Plumpudding Island
	2474

Namib Env. Health & Waste Man & Mining
2877

Namdeb Diamond Corporation (Pty) Ltd
2109–2116 ML45

Namibian Gemstone Mining
2193, 2195, 2196, 2201, 2202, 2203, 2204, 2209

Namibian Minerals Exploration (Pty) Ltd
2933 BLOCK H

Okakoverua Coast Diamonds (Pty) Ltd
2492 BLOCK C 2494 BLOCK E

Okawe Minerals (Pty) Ltd
2921

Rose Gems cc
2905

Tidal Diamonds (Pty) Ltd
1944 ML30

Together Ouando Mining Consortium (Pty) Ltd
2491 BLOCK B

Trans Atlantic Mining (Pty) Ltd
2608 2609 2667

Tritonova (Pty) Ltd
2718 2719

Tsondab Gem Exploration (Pty) Ltd
2500 BLOCK K

Waduma Mining Corporation (Pty) Ltd
2499 BLOCK J

Unallocated

V/O Zarubezhgeologia
2896

0 50kms

EPL2493	Licence Numbers
───	Licence Boundaries
▬ ▬ ▬	International Boundary
───	Water Depth Contours

MARINE & COASTAL GEOSCIENCE

STREET ADDRESS: Unit 8, 15 Mall Street, Goodwood, 7460
POSTAL ADDRESS: P.O.Box 818, Eppindust, 7475, South Africa
TELEPHONE : +27 21 535–4510
FACSIMILE : +27 21 535–4519
EMAIL : info@geoscience.co.za
WEBSITE : www.geoscience.co.za

DATE LAST REVISED: MARCH 2003
COMPILED BY: MARINE & COASTAL GEOSCIENCE

Figure 18

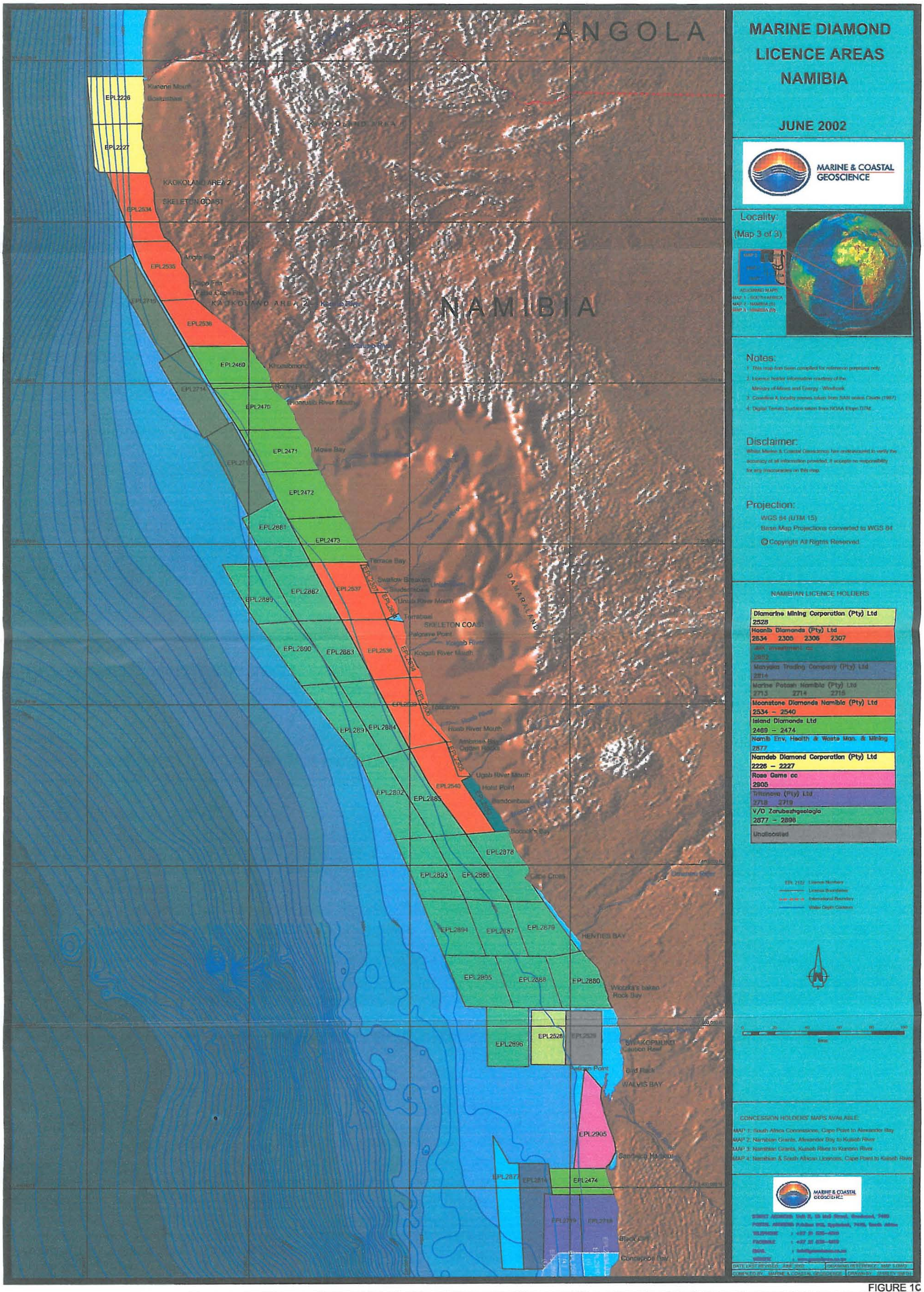

MARINE DIAMOND LICENCE AREAS NAMIBIA
JUNE 2002
MARINE & COASTAL GEOSCIENCE
Locality:
(Map 3 of 3)
ADJOINING MAPS
MAP 1 - SOUTH AFRICA
MAP 2 - NAMIBIA (S)
MAP 3 - NAMIBIA (N)
Notes:
1. This map has been compiled for reference purposes only.
2. Licence holder information courtesy of the Ministry of Mines and Energy - Windhoek.
3. Coastline & locality names taken from SAN series Charts (1987)
4. Digital Terrain Surface taken from NOAA Etopo DTM.
Disclaimer:
Whilst Marine & Coastal Geoscience has endeavoured to verify the accuracy of all information provided, it accepts no responsibility for any inaccuracies on this map.
Projection:
WGS 84 (UTM 15)
Base Map Projections converted to WGS 84
© Copyright All Rights Reserved.
NAMIBIAN LICENCE HOLDERS
Diamarine Mining Corporation (Pty) Ltd 2528
Hoanib Diamonds (Pty) Ltd 2534 2305 2306 2307
Investment cc 2852
Manyaka Trading Company (Pty) Ltd 2814
Marine Potash Namibia (Pty) Ltd 2713 2714 2715
Moonstone Diamonds Namibia (Pty) Ltd 2534 – 2540
Island Diamonds Ltd 2469 – 2474
Namib Env, Health & Waste Man. & Mining 2877
Namdeb Diamond Corporation (Pty) Ltd 2226 – 2227
Rose Gems cc 2905
Tritonova (Pty) Ltd 2718 2719
V/O Zarubezhgeologia 2877 – 2896
Unallocated
EPL 2122 Licence Numbers
Licence Boundaries
International Boundary
Water Depth Contours
km
CONCESSION HOLDERS' MAPS AVAILABLE:
MAP 1: South Africa Concessions, Cape Point to Alexander Bay
MAP 2: Namibian Grants, Alexander Bay to Kuiseb River
MAP 3: Namibian Grants, Kuiseb River to Kunene River
MAP 4: Namibian & South African Licences, Cape Point to Kuiseb River
MARINE & COASTAL GEOSCIENCE
DATE LAST REVISED: JUNE 2002
DRAWING REFERENCE: MAP 3
COMPILED BY: MARINE & COASTAL GEOSCIENCE
DRAWN BY: SHIRLEY SMITH
ANGOLA
NAMIBIA
KAOKOLAND AREA
KAOKOLAND AREA 2
SKELETON COAST
DAMARALAND
Kunene Mouth
Angra Fria
Cape Frio
Khumib River Mouth
Möwe Bay
Terrace Bay
Swallow Breakers
Unjab River Mouth
Torrabaai
Palgrave Point
Koigab River Mouth
Huab River Mouth
Ugab River Mouth
Hoist Point
Cape Cross
HENTIES BAY
Wlotzka's baken
Rock Bay
SWAKOPMUND
Pelican Point
WALVIS BAY
Sandwich Harbour
Black Cliff
Conception Bay
EPL2226
EPL2227
EPL2534
EPL2535
EPL2536
EPL2715
EPL2714
EPL2713
EPL2469
EPL2470
EPL2471
EPL2472
EPL2473
EPL2881
EPL2882
EPL2889
EPL2890
EPL2883
EPL2537
EPL2538
EPL2884
EPL2891
EPL2892
EPL2885
EPL2540
EPL2878
EPL2893
EPL2886
EPL2894
EPL2887
EPL2879
EPL2895
EPL2888
EPL2880
EPL2896
EPL2528
EPL2529
EPL2905
EPL2877
EPL2814
EPL2474
EPL2719
EPL2718

FIGURE 1C

The licence for **EPL 2495**, to the north (Figure 1), is held by Auas Diamond Company (Pty) Ltd, who had a joint venture arrangement with Trans Hex (Pty) Ltd. Water depth ranges in this concession are similar to that of HBG varying from approximately 30 m to 120 m depth.

The coastal strip just south of Saddle Hill adjacent to HBG was mined by Tidal Diamonds South West Africa (Pty) Ltd and Industrial Diamonds of South Africa Ltd.

1.2 AIMS AND OBJECTIVES

The goal of this thesis is to present a revised, holistic model for the formation of the west coast diamond placers which can be used to delineate and prioritise further high potential targets along the inner shelf, during marine diamond prospecting programmes.

The author has, over the last 8 years, through work as a consultant for MCG, been exposed to a wealth of information regarding the diamond placer deposits along the southern African west coast. This includes geophysical, sedimentological, geotechnical and resource data from a number of companies who currently hold concessions, exclusive prospecting licences and/or mining licences along the west coast, both on-land and offshore. Using this publically available information, as well as knowledge accumulated working as a a consultant geologist, focussing largely on marine and alluvial placer deposits, this thesis aims to achieve the following:

- Examine models that deal with the origin of the west coast diamonds and evolution of the alluvial systems that transported them to the Atlantic Ocean. Particular emphasis is placed on the relationship to marine diamond placer distribution along the west coast.

- Evaluate the historical geological, geophysical and mining data within the HBG area. These are examined together with the current geophysical, geological and oceanographic interpretations in the area. These data are used together with available prospecting results to formulate a technique to delineate and prioritise marine placer deposits.

- Evaluate and assess the role of the various mechanisms active in the transport, re-distribution, concentration and preservation of diamonds within the coastal environment and present a revised model for diamond placer evolution in central Namibia.

As with most deposits, the understanding of grade distribution is intimately linked to a sound understanding of the formation of the deposit. This study will demonstrate how an integrated geological, geophysical and oceanographic approach can be successfully used to delineated and prioritize high potential marine diamond placer targets. Historical and recent investigations in the HBG area are used to illustrate that a holistic approach must be applied in order to evaluate these deposits effectively.

1.3 ORGANISATION OF THE THESIS

The order of this thesis follows the natural geological evolution of the marine placer deposit from primary source, through alluvial and/or glacial transportation, concentration along the coastline by wave, aeolian and alluvial/sheet-wash processes and finally placer preservation.

A "List of Frequently used Acronyms and Abbreviations" has been included after the "List of Tables" for easy reference. The "List of Figures" gives comprehensive captions should information, additional to that given in the text, be required. Captions on the diagrams were kept succinct in order to have the diagrams as large and legible as possible.

Each Chapter within the thesis has a similar format: 1) there is an introductory summary **(in bold)**, 2) the literature is reviewed or new data are presented, and 3) this is followed by a discussion to conclude. Note that references are not repeated in the introductory summary or discussions presented at the end of each major section, if the concept has been extracted directly from a referenced portion within the body of the main text.

- **Chapter 2 - History of Diamond Mining in Southern Africa**

  This chapter briefly reviews the history of diamond placer discovery and mining in southern Africa. The history of alluvial, aeolian and marine diamond mining places the current study in the context of the century of diamond mining that has preceded it.

- **Chapter 3 - Regional Setting**

  The regional setting of the Namibian coastline and the morphology of the continental shelf are described in Chapter 3 to place subsequent, more detailed descriptions and interpretations, in context.

- **Chapter 4 - Large-Scale Processes Influencing the Formation of Marine Placers**

  The origin and transport of the diamonds from the southern African interior forms an integral part of the understanding of marine diamond placer distribution along the coast. Early and current models proposed for the origin of the west coast diamonds are critically reviewed within the overall context of potential primary and secondary point sources.

  The examination of the models pertaining to primary and secondary diamond sources, coastal processes and the landscape evolution is relatively detailed, but is fundamental in formulating the considered model for the evolution of marine diamond placers in central Namibia, presented in the latter part of the thesis. Particular emphasis is placed on the roles of the poly-cyclic processes on the coastal plain, in central Namibia, responsible for the formation of the diamond placers.

- **Chapter 5 - Landscape Evolution in Southwestern Africa**

The evolution of the west coast marine placers must conform to the broader parameters developed for the landscape and drainage evolution of southern Africa as well as that for the west coast plain. The role and significance of the poly-cyclic coastal processes active in the transport, deposition, concentration, re-distribution and preservation of diamond placers along west coast are assessed.

- **Chapter 6 - Review of Early Investigations Undertaken in Hottentot Bay Grant**

In order to place the case study area into context geological and geophysical exploration and historical prospecting and mining data, onshore and in the shallow water adjacent to HBG, prior to 1975 are reviewed and discussed.

- **Chapter 7 - Recent Geophysical and Oceanographical Investigations in the Study Area**

Geophysical data form the foundation of marine exploration. As no detailed visual inspection of deposit is usually possible, good quality, positionally accurate records are essential. The equipment, data acquisition and interpretation methods used for the assessment of the geophysical data in the case study area, as well as the author's role in data acquisition and interpretation, are presented.

- **Chapter 8 - Results from Geophysical and Oceanographical Investigations in the Study Area**

The bathymetric, sonographic, seismic, structural, sediment dynamics and terrace level study results are presented in this chapter.

- **Chapter 9 - An Integrated Approach to Target Selection and Prioritisation**

A revised model for marine placer formation along the inner shelf in central Namibia is presented. The various geological, geophysical and oceanographic methods routinely utilised in assessing, delineating and prioritising marine placer deposits are assessed. The importance of the various target selection and prioritisation criteria are critically reviewed and a weighting matrix derived for inner shelf marine diamond placer deposits;

- **Chapter 10 - Summary and Conclusion**

In conclusion, all results presented in the thesis are summarised. The major sea-levels on the inner shelf are listed, the revised model for marine diamond placer evolution on the inner shelf of central Namibia, presented in bullet form and the top ten ranked features, as derived from the prioritisation matrix, listed.

2. HISTORICAL BACKGROUND

Diamonds were first discovered along the coast of Namibia and South Africa in 1908 and 1926, respectively. Subsequent prospecting and mining, spanning almost a century, has identified the largest known diamond placer in the world, along the west coast of southern Africa. A brief review of the history of alluvial, aeolian and marine diamond mining in southern Africa provides a context for this study.

2.1 INTRODUCTION

It is difficult to ascertain when exactly diamonds were first discovered but it is clear is that from the earliest times mankind has been actively prospecting for diamonds.

As the existence of diamonds has been recorded from the very earliest times it is difficult to ascertain exactly when they were first discovered. Even if, in the Book of Exodus (Chap. 39, v.11), the mention of the diamond amongst the jewels in the high priest's breast-plate is put down to error on the part of the translators, there is evidence that diamonds were possessed by the Hindus and Greeks many centuries before the Christian era (Reunert, 1886). The history of the Koh-i-noor stone can be traced back 5000 years, where it is celebrated in one of the songs of the Vedas as having formed part of the treasures of an old Indian chief. There is little doubt that the earliest known diamonds came from India. During Roman times, writers refer only to the Indian mines when alluding to diamonds and their source. Until the 1800's no other source of supply was known (Reunert, 1886).

Bushman etchings of animals into the hard, fine-grained andesites of the Ventersdorp Lava Group, observed by the author along the western bank of the Schweizer-Reneke dam, may have been carved using diamonds as artistic tools. Diamonds are present in the exposed diamondiferous alluvial gravels readily found in the area. These andesites are too hard to be scratched using the quartzite and vein quartz that is also locally present, even with the application of considerable force.

Since their first discovery in southern Africa, prospecting and mining spanning almost a century has identified the largest known diamond placer in the world, deposited on the inner and middle shelf along the west coast of southern Africa. This predominantly low grade placer stretches from Cape Columbine to the Kunene River (Figure 2), a distance of about 1850 kilometres, and from 160 m above present sea-level (apsl) to an estimated 500 m below present sea-level (bpsl) covering an area of about (216 214) km^2. Detailed exploration and mining of this marine diamond placer deposit has taken place over the last century. Due to current technological constraints, mining is presently restricted to a maximum water depth of 180 m bpsl.

Over the last century vast volumes of information have been written about the primary kimberlitic source, the evolution of the secondary alluvial systems that transported the diamonds to the coast and the aeolian and marine processes associated with the formation of the coastal diamond placer deposits. Doctoral theses by De

Wit, (1993) on the southern African drainage evolution, Corbett, (1989) on the Namibian west coast aeolian deposits and Birch (1975), Rogers (1977) and Bremner (1981) and Masters theses by O'Shea, (1971), De Decker (1986), Woodborne (1987), Pether (1994a) and Jacobs (2001) on the southern African west coast marine geology and marine placer deposits, represent the core of the research completed in this regard. However, the evolution of the public knowledge of the marine diamond industry has been anomalous, in that, early authors like Merensky (1909), Wagner (1914), Wagner and Merensky (1928), Haughton (1931), Gevers (1953), Hallam (1964), and Wright (1964) were relatively free to publish papers based on all available results. In some cases this included information relating to economic aspects of the deposit, like grade, diamond size distributions and values, and factors controlling grade distribution, whilst in recent years economic competition has resulted in restrictions in the publication of data. O'Shea (1971) was only able to document limited results, with respect to the economic aspects of the diamond placers, in his masters thesis, while Keyser (1972 and 1976) used the opportunity of free access to the economic-based information for the state owned State Alluvial Diggings (now Alexkor Ltd), on which to base his studies. Subsequently, companies like De Beers, Namco, Diamond Fields International, Ocean Diamond Mining and Trans Hex, placed strict access limitations to their databases and internal reports in order to protect their proprietary knowledge and economically sensitive data. Though many detailed investigations on marine diamond placers have been undertaken internally, most publically available studies have focussed predominantly on the less economically sensitive aspects of the marine placer deposits, such as sedimentological, micro-palaeontological and climatic variations. A large percentage of the work conducted on the middle shelf has been undertaken by De Beers and Namdeb and information is not readily available to external parties. However, since the early nineties considerable exploration and mining has been conducted within this placer deposit outside of the De Beers group, increasing the knowledge base of both the inner and middle shelf enormously. A recent MSc study by Jacob, (2001) examines diamond concentration mechanisms within the marine placer system. This study focusses on the raised diamond placer deposits from Oranjemund to Chameis Bay. With the large data-base spanning decades of mining that took place in that area, the study presents little in the way of detailed analysis of mining results and how they correlate with high grade occurrence, or field evidence in support of the postulated controls on grade distribution . This may be a function of poor resolution grade information being available because of the large scale mining methods employed or it may be associated with the veil of secrecy that has always shrouded the release of diamond results on the west coast. In spite of attempts to retain secrecy, the updated prescribed stock exchange regulatory body standards have forced public companies to divulge more information regarding their diamond resources over the last few years.

2.2 HISTORY OF DIAMOND MINING IN SOUTHERN AFRICA

In 1867, a 21.25 carat diamond was found by a Bushman youth along the southern bank of the Orange River near Hopetown. A trader, Mr John O'Reilly, saw the diamond and had it verified as a diamond. The first diamond rush started within southern Africa in 1869, after the discovery of the 83.5 carat, "Star of South Africa". Initially the diamond prospectors' focus was on alluvial deposits, but after kimberlites were discovered in the late 1870's, the emphasis moved to these "dry diggings".

Details in accounts of the discovery of the first diamonds in South Africa vary slightly, but the common factors declare that in 1867, a small, shiny stone was found a Bushman youth along the southern bank of the Orange River near Hopetown. A trader, Mr. John O'Reilly, resting his oxen on the farm "De Kalk" saw the diamond and had it verified as a 21.25 carat diamond, worth 500 pounds, by Dr Atherstone from Grahamstown (Reunert, 1886; Joyce and Scannel, 1993). In March 1869, on the farm Zandfontein, a Griqua shepherd named Booi, brought a magnificent white stone to Mr. Schalk van Niekerk, for which he was paid about 400 pounds worth of livestock. This 82.5 carat diamond, which came to be known the "Star of South Africa", was sold to Messrs Lilienfeld of Hopetown for over 10 000 pounds and initiated the first diamond rush. Optimistic prospectors converged on Hopetown, but soon abandoned these alluvial diggings, after finding little, for the more prospective alluvial gravels along the Vaal River. In the late 1870's many moved to the "dry diggings" at DuToitspan and Bultfontein of the Orange Free State (Reunert, 1886). Thus, the claim staking and mining of the kimberlites began, marking the beginning of the multi-billion dollar South African diamond industry (Joyce and Scannel, 1993).

2.2.1 DISCOVERY OF DIAMONDS IN NAMIBIA

After Zacharias Lewala picked up a diamond at a siding near Lüderitzbucht in 1908, the diamond rush in Namibia began. Early mining was concentrated within aeolian deposits but soon spread to raised marine terrace deposits.

A newspaper article entitled "NAMIBIAN DIAMONDS" written by Chris Hinde describes the early history of the west coast diamond discovery as follows; "In 1883, Adolf Lüderitz, a German merchant bought the land extending from the Orange River in the South 137 northwards to latitude 26^0 S from a local chief. Adolf sold his rights to the Deutsche Kolonial Gesellschaft fur Sudwestafrika (DKG) when South West Africa became a German Protectorate. In the early 1900's, interest in DKG's potential was initiated by the discovery of diamonds on the islands off the coast. In 1905 sovereignty was ceded to the state. DKG retained its right to grant exclusive mining rights and to royalties. In 1908, after Zacharias Lewala picked up a diamond at a siding near Lüderitzbucht the diamond rush began. August Stauch, Zacharias's foreman and the Inspector of Permanent Works on the Kolmanskuppe section of railway, obtained the licences to stake six 1 kilometre radius claims between Lüderitzbucht and Pomona from DKG. This culminated in Stauch's discovery of the exceptionally rich Idatal valley. By 1909 mining had spread to Kolmanskuppe, Stauchslager, Charlottental, Bogenfels, Elisabethbucht and Pomona in the (DKG), Sperrgebiet area. During the period 1909 to 1921, 6.7 million carats were mined from these deposits, situated predominantly within aeolian corridors. At the end of World War One in 1918, South Africa took over the mandate of SWA. Anglo American Corporation bought out DKG together with eight other German-controlled companies mining in the Lüderitz area, and formed Consolidated Diamond Mines (CDM) in 1920. Mining of the raised beach deposits north of the Orange River was carried out on a large scale by CDM, with the exception of the curtailing of operations during the depression and modest production throughout the Second World War".

2.2.2 DISCOVERY OF RAISED MARINE AND AEOLIAN DIAMONDS ALONG THE WEST COAST

Diamonds were discovered along the Namaqualand coast north of the Olifants River in 1925. However, the real diamond rush started when Captain Jack Carstens, an officer in the Indian Army, discovered diamonds, in quantity, in 1926, while spending a vacation with his father, a trader, in Port Nolloth. Soon afterwards, in September of 1927, Dr Hans Merensky recovered 2762 diamonds at Alexander Bay, including 487 diamonds from beneath one flat stone. The discovery of diamonds on the northern bank at Oranjemund soon followed.

Tidal Diamond Corporation (TDC), held the lease for the onshore and shallow water coastal strip between Hottentot Point north of Lüderitz, and Sandwich Harbour south of Walvis Bay (Gevers, 1953). Wind concentrated diamonds had been mined in Diamond Area II up to 1923 (Gevers, 1953). Mining of the raised marine terrace resumed in 1944 and continued until 1963. During 1965, further prospecting in the Saddle Hill area, including drilling, trenching and dump and beach sampling recovered 585 diamonds weighing 35 carats (Sullivan, 1966). Other discoveries have been made north of Lüderitz at Spencer Bay, Meob Bay, Conception Bay, Terrace Bay, Charlottenfelder, Toscanini, Rocky Point and Möwe Bay (Refer: Figure 1).

In 1928, Mr. W. Beetz discovered the diamondiferous emerged marine terraces on the northern side of the Orange River, that are continuous for almost 100 km northward to Affenrucken (Corbett, 1996). After the demise of the original Lüderitz diamond fields in the 1930's, recoveries of diamonds were concentrated in this southern coastal zone between the Orange River and Chameis Bay (Corbett, 1996). Diamond production along these emerged marine terrace deposits reached its zenith when 2 001 217 carats of diamonds were recovered along the west coast, in 1977 (De Beers Annual Reports). This figure has since declined to about 750 000 carats per year in 2000 (De Beers Annual Reports).

2.2.3 HISTORY AND GROWTH OF THE OFFSHORE MARINE DIAMOND INDUSTRY

A few early, unsuccessful attempts to mine diamonds from the sea-floor were made by Mr van Diggelen off Oranjemund on the salvage vessel *Arpione* and Mr Wilson, on the *Nautilus*, off Possession Island (Williams, 1996). In 1958, Mr Vivier acquired the first offshore diamond concession between the Orange River and Diaz Point, 450 km further north, from the high-water mark to the 200 m isobath. He recovered a small number of diamonds from the swash zone.

In 1959, Sammy Collins, a Texan contractor laying an offshore diesel delivery pipe wondered whether the onshore diamond placer deposits could extend offshore (Corbett , 1996). Mr Collins and Mr Emerson Kailey purchased the prospecting concern operated by Mr Vivier and the Van Zyl brothers in 1961 (Williams, 1996) and established Marine Diamond Corporation (MDC). MDC took the lead in marine diamond mining when, in 1961, they began marine prospecting in licence areas they held north of the Orange River. The first offshore diamonds were recovered at Wolf Bay, near North and South Long Islands (Refer: Figure 1), in the same year, using a converted Royal Navy salvage tug the *Emerson K* (Corbett, 1996). In 1963, MDC applied for the rights to mine to the edge of the Namibian shelf and in 1964, De Beers contracted Ocean Science and Engineering to evaluate the economic potential of the inner shelf between the Olifants River and Meob Bay using the *MV Rockeater* (Corbett, 1996). This was the first comprehensive geophysical and sampling programme conducted along the west coast. In the same year MDC produced 90 000 carats from the stretch of coast between the Orange River and Lüderitz Bay and expanded their fleet to the extent that three barges and several other vessels were operating continuously in Chameis Bay and Hottentot Bay (Corbett, 1996). By the end of the sixties MDC had recovered a total of 788 000 carats including a "jack pot" find of 390 000 carats recovered within four months from Hottentot Bay (Williams, 1996).

By 1990, De Beers had succeeded in delineating large ore reserves in the mid-shelf areas in water depths of 120 m to 150 m off the Namibian coast and had developed the technology to recover these deposits economically (De Decker, 2001). De Decker (2001) notes that in 1991, De Beers Marine produced 170 744 carats in its first year of mining and has maintained annual production increases since then. Offshore diamond production by Namdeb alone reached 514,310 carats per annum in 1999 (De Decker, 2001).

Prior to being acquired by Namco in 2000, Ocean Diamond Mines (ODM) was actively prospecting and mining in their ML 36 areas off the Namibian coast (De Decker, 2001). ODM achieved production of approximately 57,000 carats per annum in 1997 and 1998, and 63,000 carats in the year to March 31, 1999 and 64,000 carats to the end of the same year (De Decker, 2001).

After sampling in the Lüderitz and Hottentots Bay Grants in 1996, Namco declared an inferred resource of 2,36 million carats, and a combined measured and indicated resource of 290 000 carats (De Decker, 2001).

From the sampling completed by the BHP/Benco Joint Venture in DFI's Lüderitz areas ML 32 and EPL 1607 in 1996, an inferred resource of 1.15 million carats was defined in areas that range from 30 to 80 m water depth (De Decker, 2001). In March 1999, DFI completed a sampling and trial mining programme in their EPL 1607A and 1607B areas (De Decker, 2001). Based on these results the resource estimate was revised by Thurston (2001) to 1.6 million carats.

3. REGIONAL COASTAL SETTING - SOUTHERN AFRICA

The morphology and surficial geology of the southern African coastline and the adjacent continental shelf are described in order to place the more detailed descriptions of and interpretations drawn from the case study area into context.

3.1 THE DIAMONDIFEROUS SOUTHERN AFRICAN COASTLINE

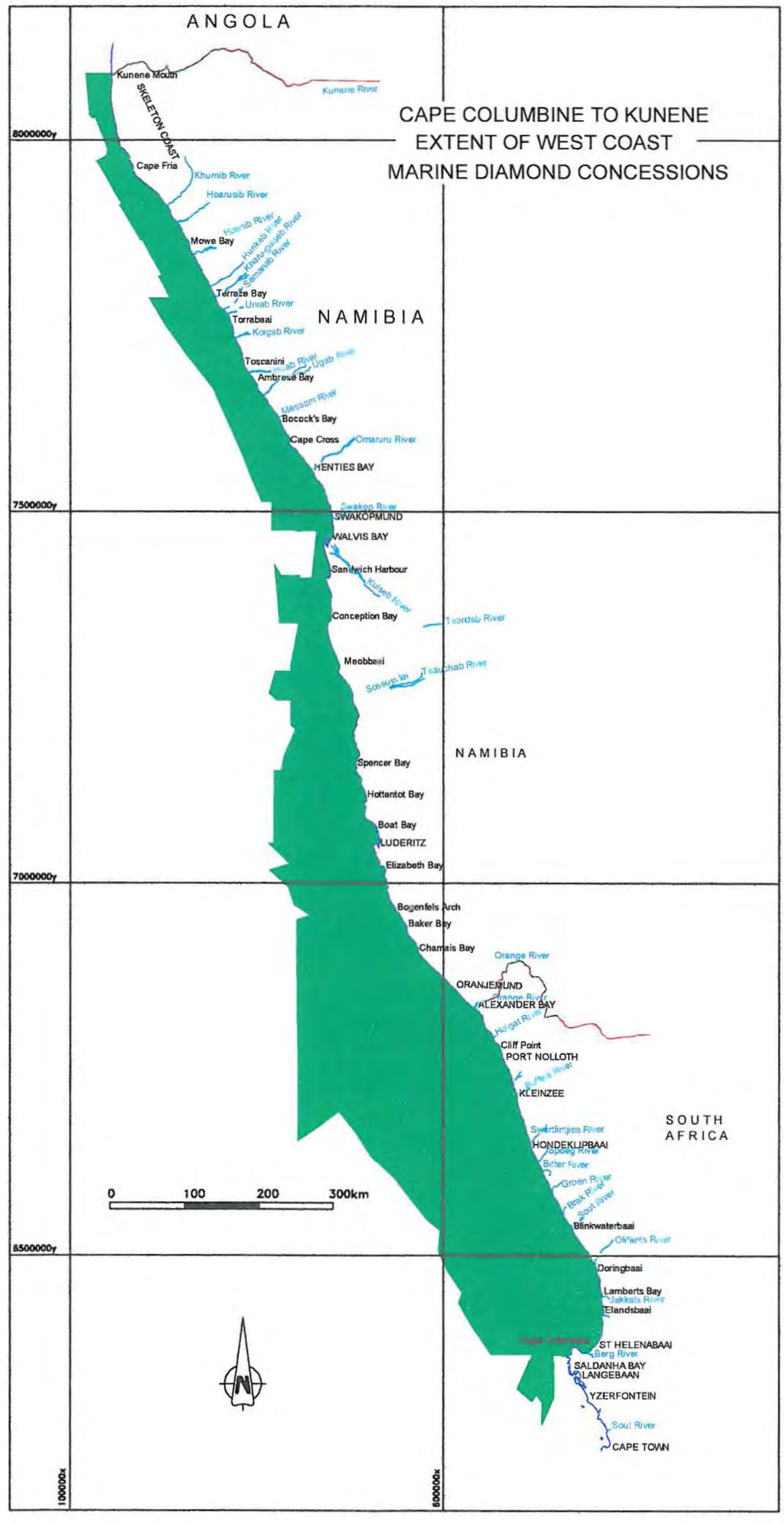
The diamondiferous southern African coastline extends for about 1850 km between Donkin Bay in the south and the Kunene River in the north (Figure 2).

The southern African coastline is generally straight, with small embayments and promontories that break the general NNW trend. The continental shelf extends off the west coast of southern Africa up to 230 km offshore and lies as deep as 500 m below present sea level (Rogers, 1977). The inner continental shelf consists of a narrow, rugged and, generally, sediment-free rocky "platform" with an average depth of -30 m. It extends up to 8 km offshore and is marked on its seaward side by a steeper slope with a gradient that ranges between 1,1° and 1,9° (De Decker and Woodborne, 1996). The inner shelf was incised by palaeo channels as a consequence of base-level lowering during sea level regressions. Except for the Holocene deltaic deposits of the modern Orange River Delta and the Quaternary palaeo-deltaic deposits shoreward of the 200 m isobath, the middle and outer shelves support only a thin veneer of Holocene sediment over much of their surface (De Decker and Woodborne, 1996). Locally, exploration has enabled the delineation of bedrock outcrops and sediment deposits on the inner shelf and the middle shelf to the 200 m isobath (De Decker and Woodborne, 1996).

3.2 SOUTHERN AND CENTRAL NAMIBIAN COASTLINE

The Namibian coastline stretches from the Orange River in the south to the Kunene River in the north (Figure 3). Several north- and south-facing bays occur along this coastline the most significant being Bogenfels, Elizabeth, Lüderitz, Hottentot, Meob, Conception and Walvis Bays. The Namibian coastal zone and hinterland is largely covered by the Namib Desert Sand Sea.

The coastline north of the Orange River to Chameis Bay is unbroken by embayments or promontories, comprising continuous sandy beaches which stretch for approximately 100 km northward from the river's mouth (De Decker, 2001). Chameis Bay is the first of several log-spiral embayments north of the Orange River. Northward of Chameis Bay, the coast is characterised by numerous north-facing log-spiral bays, and promontories with south-facing embayments that check sediment transported northward by littoral drift and that act as the source for the sand dunes being transported inland by the persistent southerly winds (De Decker, 2001).



CAPE COLUMBINE TO KUNENE
EXTENT OF WEST COAST
MARINE DIAMOND CONCESSIONS

Figure 2

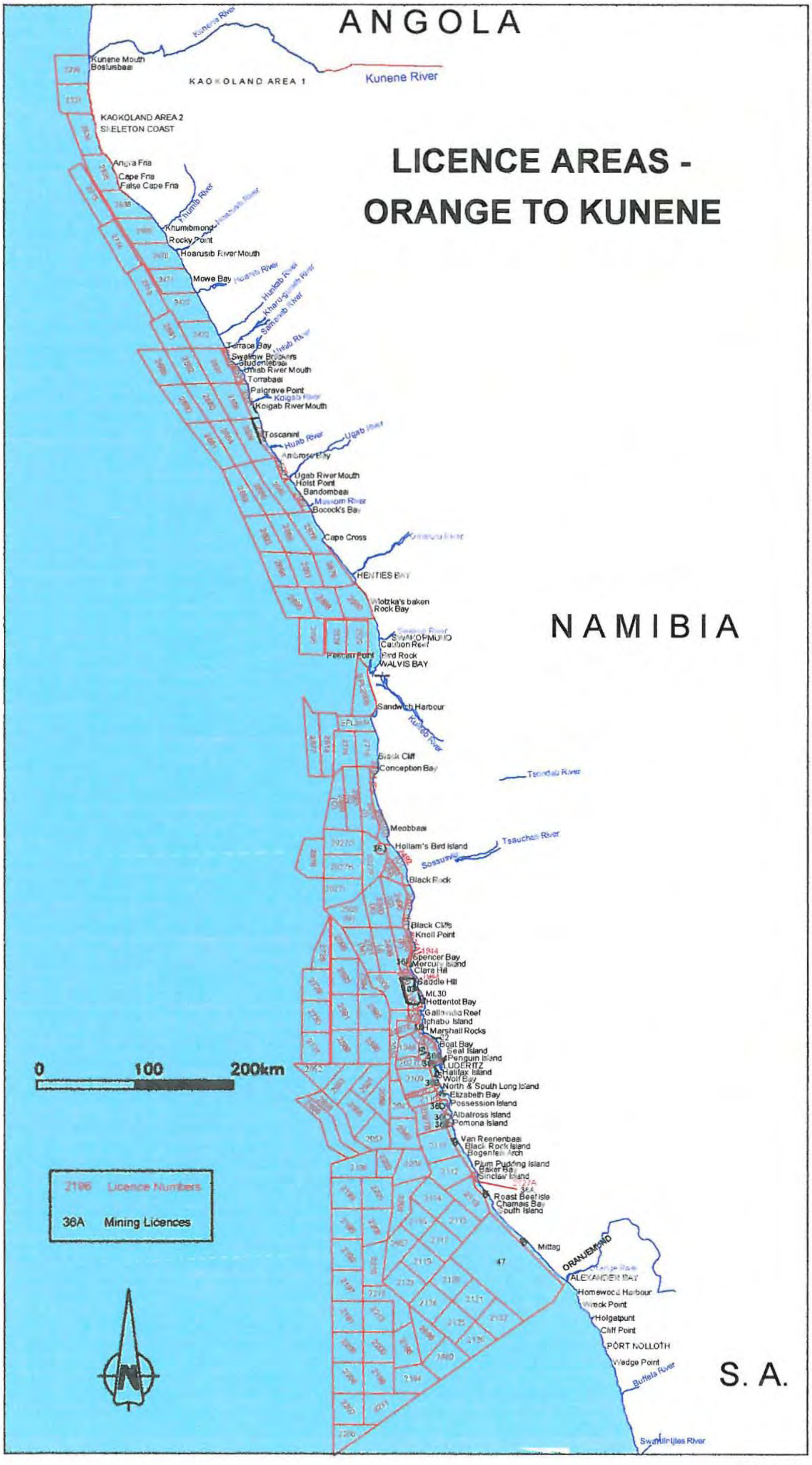

LICENCE AREAS - ORANGE TO KUNENE

Figure 3

Elizabeth Bay, to the south of Lüderitz, is the largest south-facing embayment on the southern Namibian coast. Satellite images show that Elizabeth Bay forms the origin of a significant proportion of the wind-driven sediment plume of the Namib Sand Sea (Figure 4) inland and northward from its beaches. The rocky promontory between Elizabeth Bay and Lüderitz Bay would have been particularly prominent during marine transgressions forming a barrier to northward sediment transport by wave action. There are three headlands between Elizabeth Bay and Spencer Bay that diminish in magnitude toward the north, each flanked by north- and south-facing bays. The most prominent of these is Elizabeth Bay. If one considers that the main supply of diamonds is believed to be the Kalahari River to the south (De Wit, 1999) and that the northward transport of sediment has prevailed since the Cretaceous, then this first large barrier to sediment migration is undoubtably significant in the development of diamond placers in the greater Lüderitz area.

At Diaz Point, the coastline forms a significant re-entrant to create Lüderitz Bay between Diaz Point in the south and Marshall Rocks in the north (Refer: Figure 4). North of Marshall Rocks the coastline is generally rocky, with the south-facing Gallovidia Reef being the most prominent feature. The area between Marshall Rocks and Hottentot Bay has a similar morphology to that of the Elizabeth Bay - Diaz Point area, but is not as prominent.

Hottentot Bay is a north-facing log-spiral sandy bay (Figure 4). Saddle Hill is a small promontory formed by a low north-northwest trending rocky ridge. The coast inflects back gently towards the east before reaching Clara Hill. Spencer Bay is yet another log-spiral bay developed by the hydraulic response of wave refraction of the southwesterly swell to the Clara Hill and Mercury Island headlands.

Oyster Cliffs, Meob and Conception Bays and Sandwich Harbour form small irregularities in the coastline south of the large north-facing Walvis Bay. The coastal plain from Lüderitz to Walvis Bay comprises mainly aeolian sand dunes of the Namib Sand Sea.

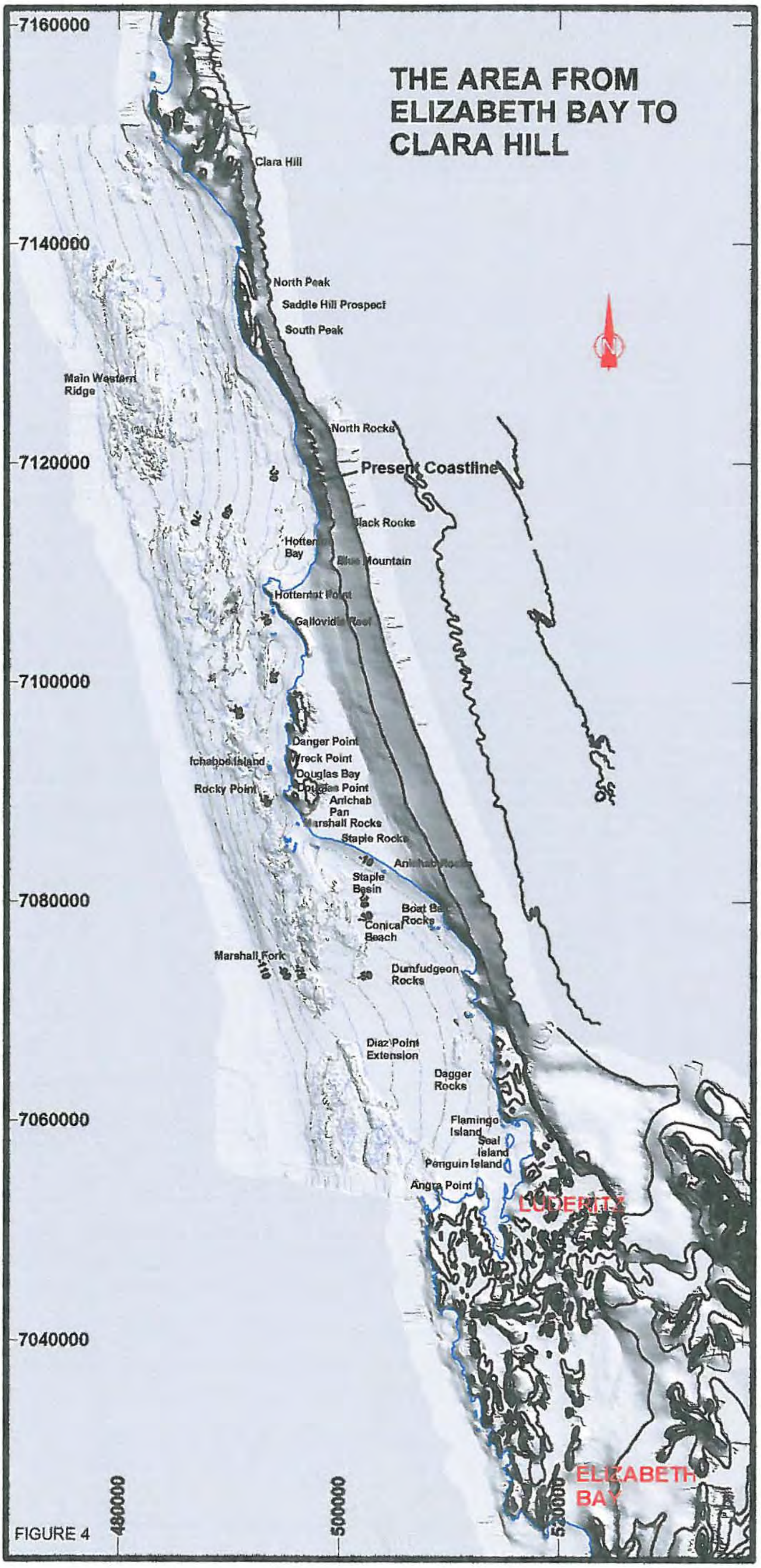


FIGURE 4

THE AREA FROM ELIZABETH BAY TO CLARA HILL

4. LARGE -SCALE PROCESSES AFFECTING THE FORMATION OF MARINE PLACERS

The intertwined roles of both the regional and smaller scale coastal processes is important in comprehending the evolution and grade distribution of marine placer deposits along the west coast of southern Africa. Potential primary diamond sources and the evolution of the southern African drainage systems are fundamental issues in understanding secondary point source distribution along the west coast. This chapter presents an overview of the various theories and models for the source of the west coast diamonds and a review of the drainage evolution of southern Africa.

4.1 INTRODUCTION

There are currently divergent views on the origin of the west coast diamonds. The diamond source is fundamental in understanding the potential size, number and distribution of secondary point sources along the coast.

Kimberlite emplacement ages, sizes, grades and localities are important when assessing potential of secondary sources along the west coast. For example: Are the northern Namibian diamonds derived from the Orange River or have they been introduced by a secondary point source further up the coast? The position of these secondary sources are, in turn, important when assessing the potential of marine placers, as they impact on the grade and average size of the diamonds in the vicinity of the secondary source.

There are differing opinions as to the configuration of the pre-Miocene age drainage evolution in southern Africa (Dingle and Hendey, 1984; Maree, 1987; De Wit, 1993; 1996, 1999 and Partridge and Maud, 1989) owing to the paucity of old alluvial remnants and, until recently, the lack of collaborative and published research from the diamond industry. There is still much to be discovered and learned regarding the evolution of the drainages in southern Africa.

Alluvial and marine mining production results are important in marine diamond placer exploration as they provide information regarding average diamond size, diamond quality and grade at a specific locality. With the marked size reduction, increased sorting and improvement in diamond quality with distance travelled, this knowledge can in turn give an indication of potential point source areas. Secondary point sources along the west coast have direct implications for both average diamond size and grade and are therefore important in identifying potential high priority prospecting areas.

The age of deposition of diamonds along the west coast is particularly important along the Namaqualand coast. If De Wit's, (1999) postulated southern African drainage evolution model is correct, then the Kalahari River captured the Karoo River's headwaters, effectively cutting off further supply to the Namaqualand coast, by the mid-Miocene. Pickford and Senut (1999) using fossil evidence in terrace gravels at Arrisdrift, have postulated that diamonds were being transported through the Lower Orange River gorge by 19 Ma.

4.2 HINTERLAND SOURCE AND TRANSPORT OF DIAMONDS TO THE WEST COAST

There is no unequivocal evidence to support the origin of the west coast marine diamonds being predominantly derived from the erosion of Dwyka tillite (Du Toit, 1952, De Villiers and Söhnge, 1959, Maree, 1987, Moore and Moore, in prep.) or from Cretaceous aged kimberlites (Lotz, 1909, Wilson, 1972, Decker, 1986; Woodborne, 1987; De Wit, 1993; 1996; 1999; Corbett, 1996).

From the days of the early discoveries of diamonds along the west coast prospectors and geologist alike speculated as to the source of the vast quantities of diamonds that were being recovered from the mining of the aeolian and raised marine terrace deposits. The excitement of the chase for the elusive diamond source would have been the sole motivation for many of the early prospectors in the exceptionally harsh desert conditions along the west coast. Large concerns sent the foremost geologists of the day, such as Messrs. Merensky, Reuning and Wagner, to investigate and report back on their findings. As geological knowledge has progressed many of the models proposed during these early years have been disproved and subsequently fallen by the wayside. Three models remain: 1) The diamonds are derived from the erosion of the Dwyka tillites; 2) The diamonds are derived from erosion of Cretaceous kimberlites; and 3) a combination of both, but the relative contribution from each source is unknown.

4.2.1 ORIGIN OF THE WEST COAST DIAMONDS - EARLY MODELS

In the early nineteen hundreds, soon after the diamond placer deposits along the southern African west coast had been discovered, many theories were proposed for the origin of the diamonds. The various models are reviewed in this section.

A summary of the dominant early models for the origin of the marine diamonds is given below:

- Wagner (1914) suggested that the diamonds were derived from kimberlite pipes or other unknown sources in the sea.

- Merensky (1909) proposed the younger littoral deposits were derived from erosion of marine beds of Cretaceous to Eocene age along the coastal plain. Remnants of these older marine terraces are still to be found at about 160 m above present sea-level at Eisenkiesselklippenbanke and Buntfeldschuh.

- Before the discovery of the rich Oranjemund and Alexander Bay deposits, Lotz (1909) had already suggested that the diamonds were derived from the erosion of kimberlites in the interior, transported by the Vaal and Orange Rivers and spread northwards by the Benguela current. His theory was subsequently supported by, amongst others, the general decrease in diamond size north of the Orange and Buffels Rivers noted by Sutherland (1982) along the west coast.

- Beetz (1938), who had prospected extensively in the Lüderitz area, found a limited number of diamonds in the "dry river" gravels underlying and overlying deposits of Miocene age. He proposed that the diamonds had been derived by largely unknown Tertiary river systems tapping unknown kimberlite sources in the interior. He emphasised the fact that the tapering off in diamond size northwards was not well constrained with several anomalies occurring, such as the larger average diamond size at Meob and Conception Bay relative to that found at Hottentot Bay to the south.

- Gevers (1953) favoured the derivation of the diamonds from kimberlites in the immediate hinterland. Even though these kimberlites had been sampled and shown to be barren, he argued that the grade decreases with depth and the previously eroded higher grade crater facies portion of the kimberlite diatreme was the source of the west coast diamonds.

- When diamonds were discovered along the Namaqualand coast at the mouth of the Groen River, it was postulated that these diamonds were transported from the mouth of the Orange River southward by longshore drift. This was based on driftwood and debris exiting from the Orange River mouth that had been found as far south as Port Nolloth. Gevers (1953) correctly noted that surface currents are unlikely to have had any effect on diamond transport and that the angle at which the incident waves approach the shore and set up the littoral drift is the main driving force responsible for the northward movement of gravel and diamonds on the west coast.

Clifford's (1966) recognition that diamondiferous kimberlites were restricted to thick cratonic areas, ruled out a proximal source as proposed by Wagner (1904) and Gevers (1953) for the marine diamonds because the edge of the Kaapvaal craton lies about 600 km east of the Atlantic seaboard.

4.2.2 ORIGIN OF THE WEST COAST DIAMONDS - RECENT MODELS

Two main schools of thought regarding the origin of the west coast diamonds remain, namely: alluvial transportation of diamonds eroded from either: 1) Carboniferous aged Dwyka tillite, or 2) Cretaceous aged kimberlites in the interior. These can be regarded as the end-points of the spectrum and while most scientific views lie between these two models, it is difficult to assess, based on the literature reviewed, what percentage of the diamonds are allocate to each model.

The two models can be summarised as follows:

- **MODEL 1**: The majority of the diamonds are derived from Karoo and pre-Karoo aged sediments, but mainly from the Dwyka tillites (Du Toit, 1952, De Villiers and Söhnge, 1959; Van Wyk and Pienaar, 1986; Maree; 1987 and Moore and Moore, in prep.) and transported by westward flowing drainages to the coast during the Tertiary.

Du Toit, 1952, De Villiers and Söhnge, (1959), Van Wyk and Pienaar (1986) and Maree (1987), Moore and Moore, (in prep) suggest that the diamonds found alongside the inland rivers within the interior of southern

Africa may have originated from pre-Karoo kimberlites. They postulate that the gravel and diamonds were eroded by glacial action and deposited on the Karoo floor, after the thaw of the ice. These diamondiferous basal Karoo sediments and Dwyka tillites were subsequently exposed by the removal of the Karoo cover and consequently eroded and transported to the coast by westward flowing drainages during the Tertiary and reconcentrated by alluvial and marine processes.

- **MODEL 2**: The diamonds are derived from the known Cretaceous aged kimberlites and transported to the coast by two large westward flowing drainages, namely; 1) the Karoo River in the south, exiting via the current Olifants River mouth, and 2) Kalahari River, exiting via the Buffels and current Orange River mouths (De Wit, 1996). There are a few permutations with regard the number, configuration and evolutionary order of these drainages through geological time (Du Toit, 1910; Dingle and Hendey, 1984; Malherbe, *et al.*, 1986; Partridge and Maud, 1987; Partridge, 1998).

De Wit's, (1996) model has two main components, namely: 1) the diamonds were largely derived from Cretaceous aged kimberlites, and 2) the diamonds eroded from these kimberlites during the Late Cretaceous and Tertiary, were predominantly transported to the west coast by the westward flowing Karoo and Kalahari Rivers (Figure 5).

The literature has been reviewed and a summary of the most pertinent factors is presented in the following sections. Although it is unlikely that the concluding discussion will satisfy all views, it is hoped that this topic is covered in sufficient detail to highlight a number of the currently contentious issues inherent in these models.

4.2.2.1 ARGUMENTS FOR MODEL 1

Maree (1987) states that: "the diamonds originated essentially from older kimberlites, were transported primarily on the Karoo floor by glacial action and deposition after the thaw of the ice and thereafter exposed by the removal of the cover of the Karoo strata". He postulates that subsequent erosion of these gravels has resulted in the alluvial and marine placer deposits in southern Africa.

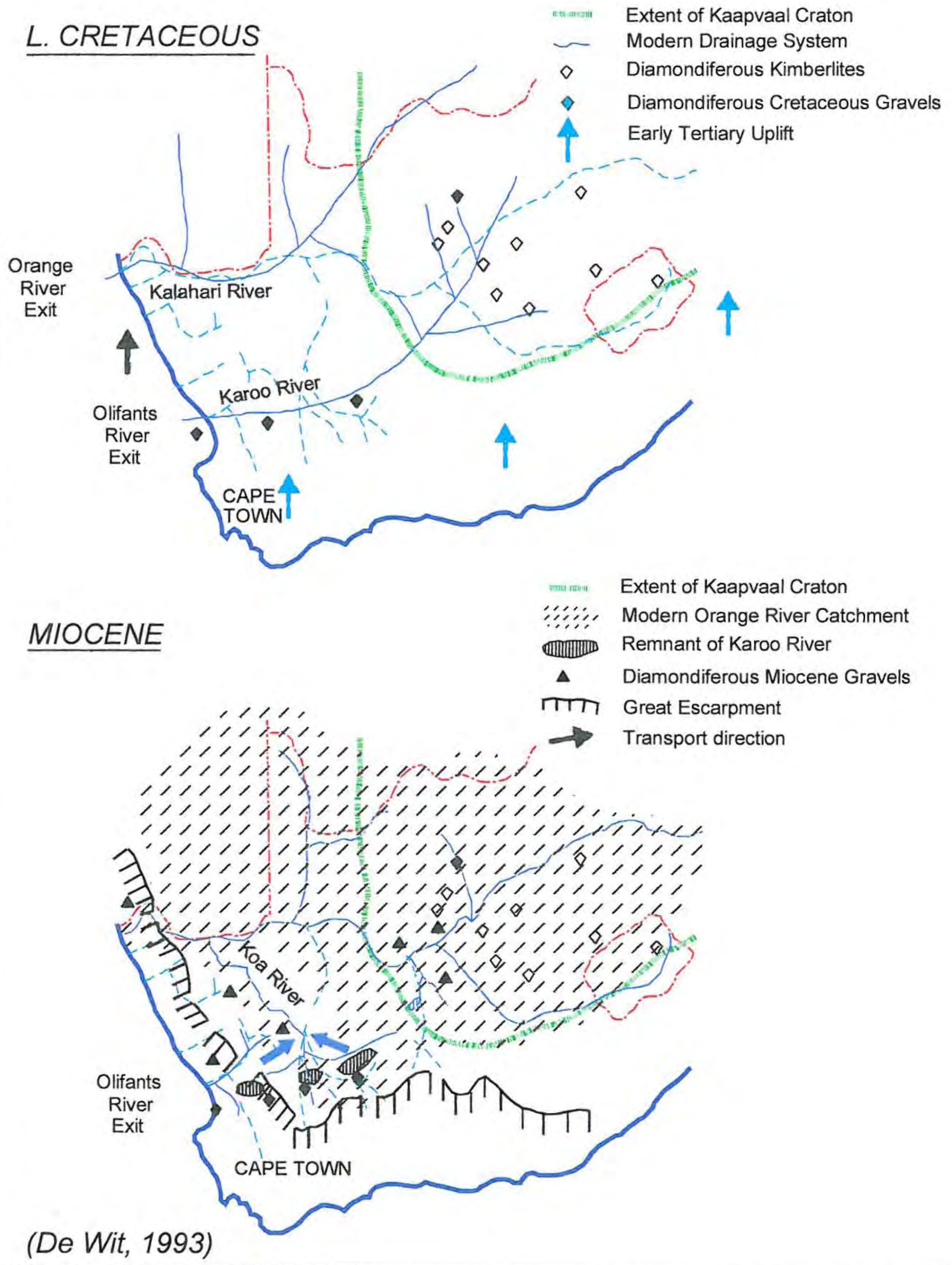
The main issues raised by Maree (1987) in support of his model are:

- Hallam's (1964) statement that: "the source of the Orange River gravels is puzzling, that they appear to contain a significant percentage of Dwyka tillite-derived gravel and that the diamonds are often found within trapsite features in the gravels rather than on the bedrock sediment interface";

- De Villiers and Söhnge (1959) observation that the terraces bordering the Orange River typically consist of allochthonous rounded pebbles and boulders of older Karoo-aged rocks;

- Du Toit's (1952) description of the gravels of the Schweizer-Reneke alluvial diamond fields as, "poorly sorted, angular clasts typical of moraine deposits".

MODEL 2: DRAINAGE EVOLUTION IN SW AFRICA



(De Wit, 1993)

Figure 5

Maree (1987) proposed that the Dwyka tillites eroded off the richest, crater-facies portion of Pre-Cretaceous-aged kimberlites and these were deposited as moraines in glacial valleys. Subsequent erosion, during the African and Post-African I landscape cycles, exposed these tillites which resulted in the diamonds being released into the alluvial systems and concentrated as alluvial placer deposits. He attributes the occurrence of the majority of diamonds in rivers like the Olifants, Swartlintjies, Buffels, Kamma, Holgat and Orange River, in South Africa, and the Ugab River, in northern Namibia, to this process. These drainages show an increase or "kick" in average diamond size at their mouths, which would support a multiple source model. In further support of this model, the diamond recoveries registered from the largely Dwyka-derived river gravels at Nabaskom, Aussenkehrdrif and Rooiwal are cited.

Moore and Moore (in prep) suggest that the diamonds in the west coast deposits are partly derived from erosion of Dwyka sources in both the Karoo and Kalahari Basins, as well as from other pre-Cretaceous glacial and fluvial source rocks, like those of the Gariep Complex, Nama and Table Mountain Groups. This by processes that involve the back-stripping of the western escarpment and Karoo cover and concentration of diamonds in tillite-derived cobble and boulder beds on the pre-Karoo surfaces at the base of the escarpment, during extended periods of crustal stability. Flushing of these low grade, wide-spread lags during discrete periods of uplift and high precipitation, via a few main drainages, transported these gravels and diamonds into the marine and near-coastal fluvial and aeolian environment, where concentration and placer development occurred.

In order to test the validity of a pre-Karoo diamond origin model, the following points need to be critically reviewed:

- Are there sufficient pre-Cretaceous primary diamond sources to account for the diamonds found in the alluvial and marine placer deposits?

- Where have all the diamonds eroded from the Cretaceous kimberlites gone?

- Are there any diamonds in un-eroded pre-Cretaceous age sedimentary units?

- Could the number of diamonds eroded and re-concentrated from these low grade Dwyka sources and other pre-Jurassic glacial and fluvial source rocks (Gariep Complex, Nama and Table Mountain Groups) adequately account for the grade and distribution of the coastal placer deposits?

- Are the sizes, sorting, abrasion and quality of diamonds consistent with what would be expected from glacially transported kimberlitic material deposited in end-moraines and subsequently eroded and transported over relatively short distances, concentrated and deposited in coastal alluvial and marine placers?

4.2.2.1.1 Pre-Cretaceous Aged Primary Diamond Sources

Kimberlites of Cambro-Ordivician age are the most likely source of pre-Dwyka age diamonds (Moore and Moore, in prep). The credibility of Model 1 rests largely on the following: 1) can the eroded portions of these primary sources account for the number of diamonds in the alluvial and marine placer deposits in southwestern Africa, and 2) was the erosion and concentration of sedimentary units, derived from these primary sources, appropriate to explain characteristics noted in west coast marine placer deposits.

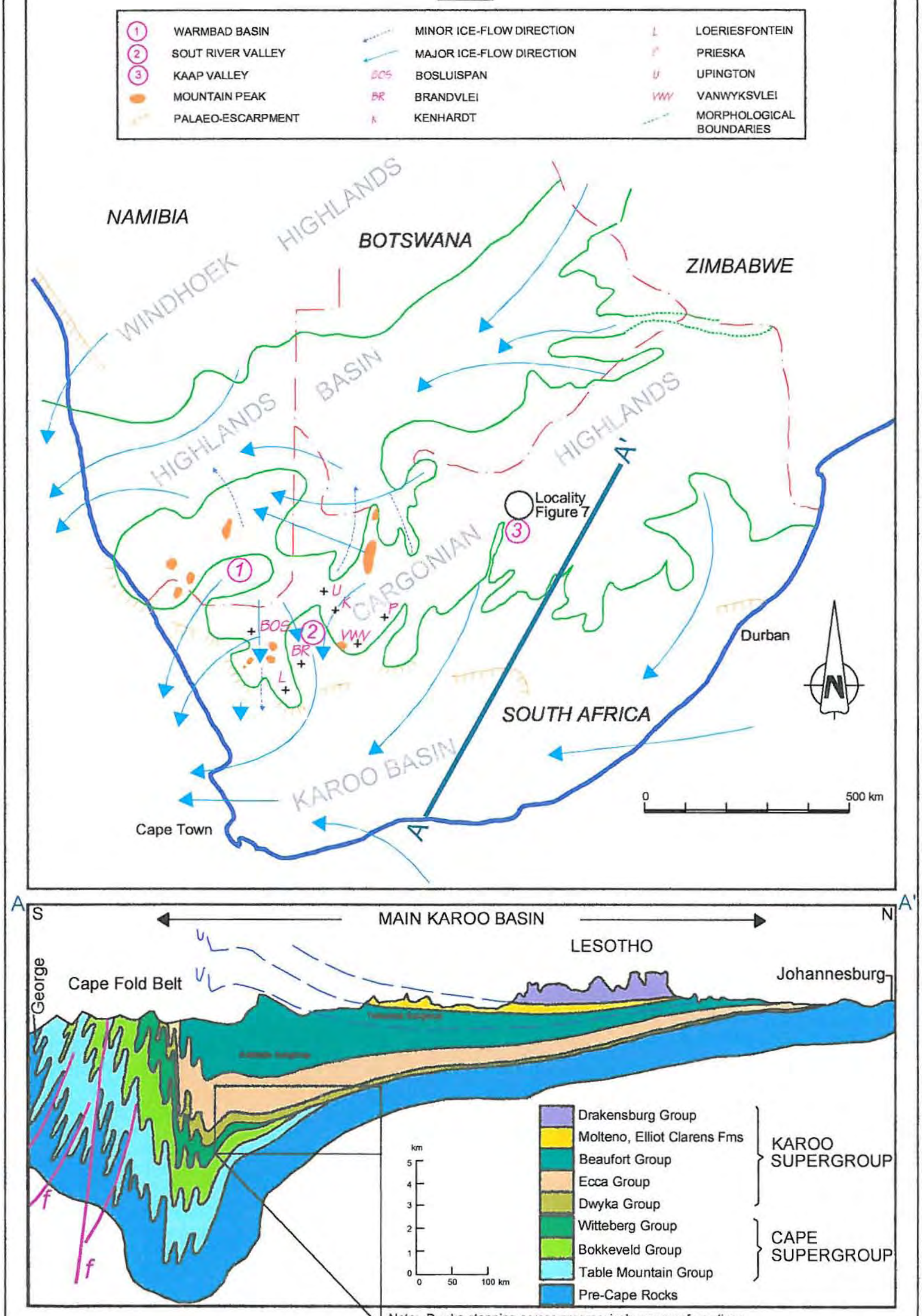
Approximately 50 kimberlites, that pre-date the Karoo sedimentation, have been discovered. The oldest of these are at Kuruman (1640 Ma) and are barren (Lynn, 1998). The presence of diamonds in the Witwatersrand conglomerates (± 2.7 Ga) suggests that there are even older kimberlites (Lynn, 1998), but these are unlikely to have contributed many diamonds to the alluvial and marine placer deposits currently being prospected and mined along the west coast.

A summary of the potential pre-Karoo kimberlite sources, as presented by Moore and Moore (in prep), is paraphrased as follows: Many of the pre-Karoo kimberlites (535-505 Ma) are of Cambro-Ordovician age, including the Venetia cluster (Seggie *et al.*, 1999) and the Marnitz cluster in South Africa (Phillips *et al.*, 1999) and Colossus, River Ranch (Allsopp *et al.*, 1985) and Mwenezi (Williams and Robey, 1999) in Zimbabwe. The Colossus pipe currently comprises hypabyssal-facies kimberlite (Allsopp *et al.*, 1985) and the Mwenezi pipe both hypabyssal- and -crator facies (Williams and Robey, 1999). Premier (1200 Ma - Allsopp *et al.*, 1985) and Venetia are the best mineralised of the pre-Karoo kimberlites (De Beers, 1998). Premier produced 27 million carats at 31 cpht up to 1927 (Gever, 1953), while in 1995, Venetia produced 136,4 cpht (Lynn, 1998). The crator facies of these pipes is likely to have been even richer than the hypabyssal facies that was mined. These pipes are estimated to have been eroded by about 1 to 1.5 km since their emplacement, similar to those in the Kimberley area (Field and Scott Smith, 1999). The syn-Karoo aged Jwaneng, in southern Botswana (240 Ma - Allsopp *et al.*, 1986), is one of the richest pipes in southern Africa. The Dokolwayo kimberlite in eastern Swaziland (Turner and Minter, 1985) could also have contributed to the postulated diamond population in the Karoo sedimentary sequence (Moore and Moore, in prep). The Pre-Cambrian kimberlites are likely to be extensively eroded and their small diameter roots will not be easily be discovered during prospecting programmes.

Glacial transport indicators show that sediments were eroded predominantly from the highland areas of the Cargonian Highlands on the Kaapvaal and Zimbabwe Cratons, moved from the north and east and deposited in the Karoo and Kalahari Basins toward the west (Visser *et al.*, 1997). A palaeo-reconstruction of the late Carboniferous glacial maximum is shown in Figure 6 with the present outcrop positions of the Dwyka Group superimposed. Based on assumptions that the inland erosion of 350 km of escarpment, over a length of 850 km, containing a 100 m thick unit of Dwyka tillite, at a specific gravity of 2.5, Moore and Moore (in prep) calculated that 7 X 10^{13} tons of material would have accumulated. They then calculate that the grade of the Dwyka would only need to be about 20 carats per million tons (i.e. 0.002 cpht) in order to account for the 1.5 billion carats estimated for the west coast placers by Levinson *et al.*, (1992).

PALAEO GEOGRAPHICAL RECONSTRUCTION DURING MAXIMUM GLACIATION AT THE END OF THE CARBONIFEROUS

(AFTER VISSER 1997)



Note: Dwyka stepping across progressively younger formations.

Figure 6

4.2.2.1.2 Discussion

Although Model 1 has merit and cannot be discounted in its entirety, the following factors make it improbable, in its current form, as the dominant diamond source for the west coast placers.

- Maree's (1987) motivation for the Dwyka tillites as a primary diamond source may be groundless because:
  - Hallam's (1964) observation that the diamonds are regularly situated within the gravel package rather than within trapsites on the bedrock surface, most likely stems from the predominant recovery of diamonds from the chemically enriched, surface "Rooikoppie" gravels by the early prospectors.
  - The predominance of Karoo gravel clasts does not automatically imply that the diamonds are also from the Dwyka tillites. The correlation of diamonds and these boulder beds may simply reflect that they are well suited for diamond entrapment. The Fish River drains along the western edge of the Dwyka tillites in Namibia for a significant distance (Refer: Figure 5) and yet all the prospecting on the Fish River gravels has only delivered a few diamonds, of dubious origin, with little to no "kick" in grade at the Orange/Fish River confluence.
  - Recent prospecting and mining in the Schweizer-Reneke alluvial diamond fields (Figure 7) suggests that the gravels are braided alluvial deposits (Marshall, pers comm., 2002) and not moraines as postulated by Du Toit (1952).
- The "diamond gap" between Prieska and Noordoewer may simply reflect the better diamond trapsite environment offered by the boulders, cobbles and pebbles eroded from the tillites (Figure 8), as suggested by De Wit (1999), than that provided by other smoother lithologies occurring elsewhere along the river course.
- Although erosion during the African landscape denudation was concentrated during the Cretaceous (Partridge and Maud, 1987), in all likelihood a large portion, including the large diameter, rich crator facies of these early kimberlites (535-505 Ma) of Cambro-Ordovician age, would have been eroded by the time the Permo-Carboniferous Dwyka glaciation (300 - 270 Ma) occurred, some 200 Ma later. During this significant time span not only would the kimberlites have been eroded, but also many of the associated conglomeratic deposits. There have been no reports of significant diamond recovery from any of pre-Cretaceous aged conglomerates.
- The Kalahari Basin development, through the uplift of surrounding areas and sedimentation, is thought only to have begun in the Late Cretaceous (Partridge and Maud, 1987). This large volume of diamonds would most likely have been eroded by early drainage systems and therefore should not be factored into mass balance calculations presented in support of Model 1.

POSITION OF PRIMARY ALLUVIAL GRAVELS

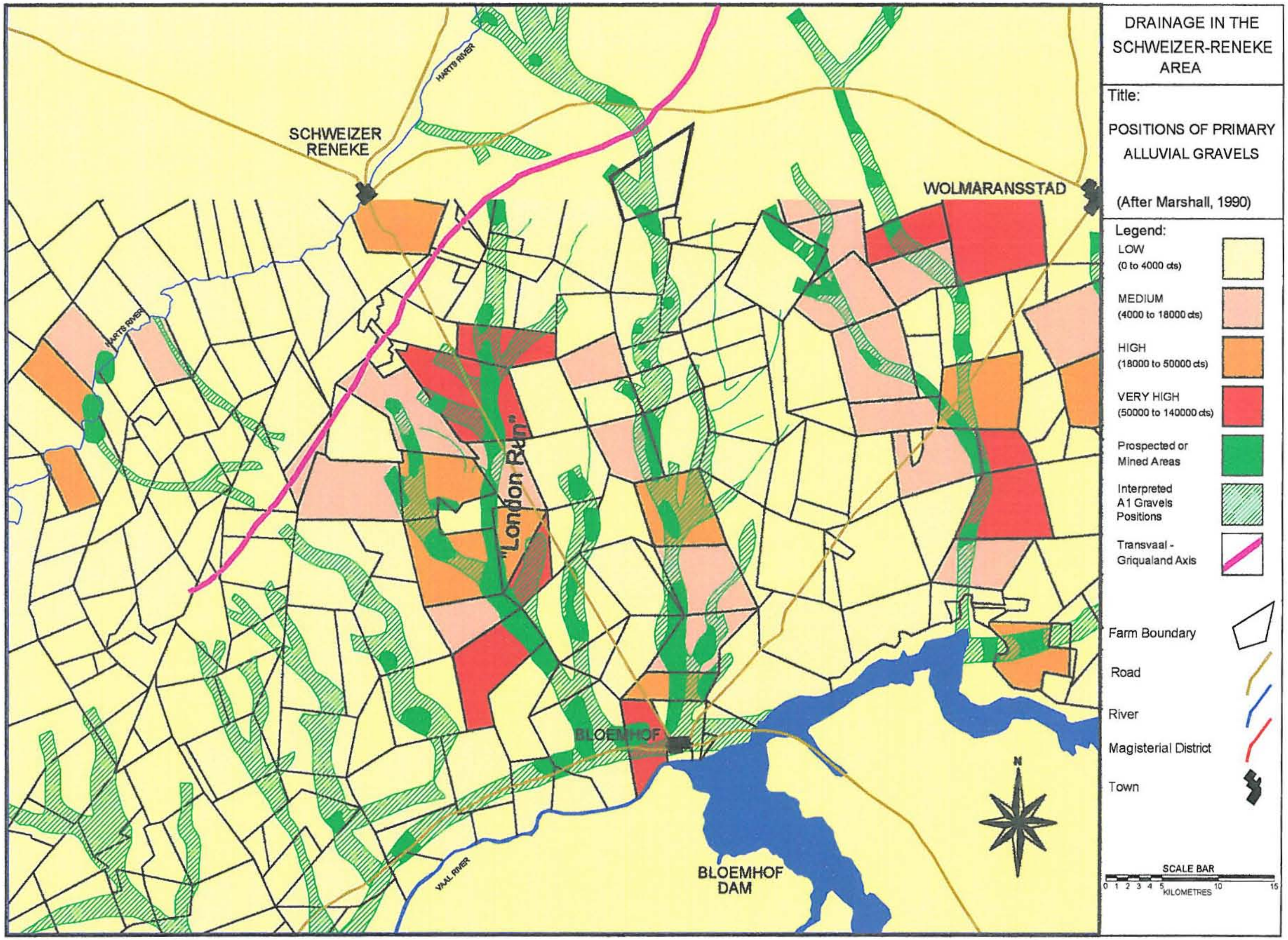


Figure 7

Figure 8. The large volumes of pebble, cobble and boulder material well suited to the entrapment and preservation of diamonds in a prospecting trench on the Lower Orange River near the Fish River confluence.

- It is probable that diamondiferous kimberlites in the interior of southern Africa, where intersected, were eroded and deposited in the Karoo and Kalahari basins as terminal moraines. In light of the known morphology of the Kalahari Basin and the introduction of sediments from the east and southeast, it is unlikely that either proximal or secondary halo diamonds would have been deposited far enough westward to have been eroded by escarpment retreat. These diamondiferous gravels are most likely still deeply buried beneath younger Kalahari and Karoo sediments. In their study of the fluvial transport of Kalahari sands, Moore and Dingle (1998) suggest that the heavy minerals, would most probably have been deposited first in the east of the basin. It is predominantly the western edge of the Kalahari basin, that most likely has the lowest diamond concentration, that has been eroded during the back-wasting of the Great Escarpment. Furthermore, these diamondiferous halos would be in specific localities along the coast and only where erosion of these diamondiferous sediments occurred would they act as secondary point sources for coastal drainages. Also, it is difficult to conceptualise a model with climatic conditions that allow for escarpment retreat, but then postulate (Moore and Moore, in prep) that the diamonds and gravels eroded from these Karoo sediments remain as stone lines or lags at the base of the escarpment. Even in the most arid times there are occasional flood events which would result in a release of these diamonds into the marine system, negating their build-up by denudation of the coastal plain.

- If the erosion of the Dwyka strata were a main source, then one would expect to see a more varied, lower quality and bigger average stone size, diamond population present along the west coast. The distinct drop-off in diamond quality and increase in diamond size at certain localities like within the old, basal, quartz-clast-rich, kaolinitised channel deposits at Hondeklip Bay and Koingnaas that certainly support an alternate diamond source, like the Dwyka tillites as suggested by Moore and Moore (in prep.). However, these poorer quality populations make up the minority of the total marine diamond population which comprises about 90% to 95% well sorted, gem quality stones (Figure 9);

It is likely that only a small proportion of the diamonds on the west coast are derived from the erosion of pre-Karoo sedimentary units. The pre-Cretaceous sources can account for anomalous diamond populations in deposits along the Namaqualand coast like those in the kaolinitised basal gravels at Koingnaas and at Hondeklip Bay.

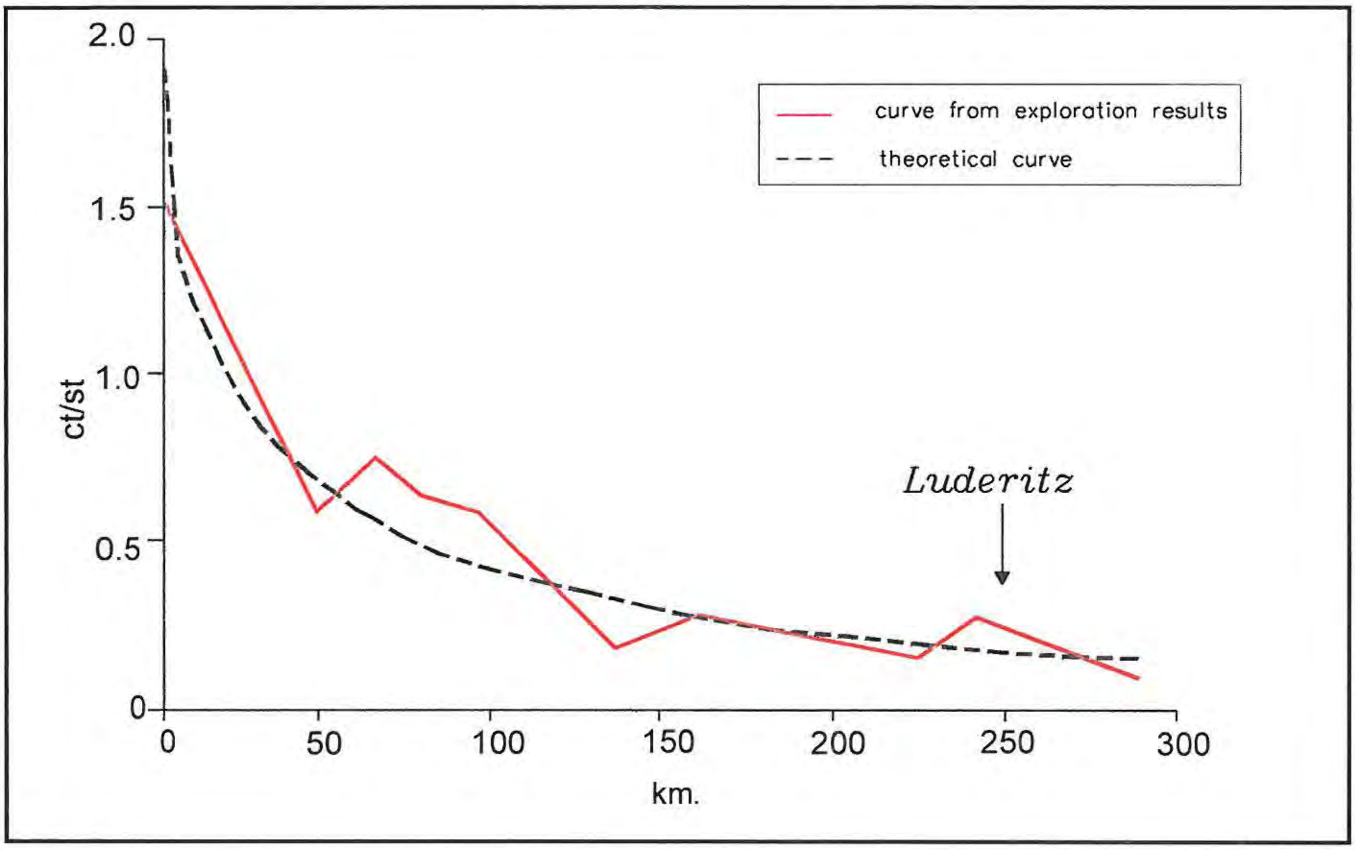
4.2.2.2 ARGUMENTS FOR MODEL 2

The southern African drainage evolution and alluvial system termination positions are integral in assessing the regional diamond placer potential along the west coast. A doctoral thesis by De Wit (1993), and many publications (Malherbe, *et al.*, 1986; Van Wyk and Pienaar, 1986; Partridge and Maud, 1987; Maree; 1987, 1988; De Wit, 1993, 1999; Partridge, 1998 and Jacobs, *et al.*, 1999) have been written about Cretaceous age alluvial gravels, but as a result of the paucity of such gravels, owing to the high degree of erosion of the African surface, geological understanding of their evolution is poor. A summary of this model, based on the literature reviewed, is presented below.

DIAMOND SIZE DISTRIBUTION NORTH & SOUTH OF THE BUFFELS AND ORANGE RIVERS

a) Orange River

(From Sutherland, 1982)



b) Buffels River

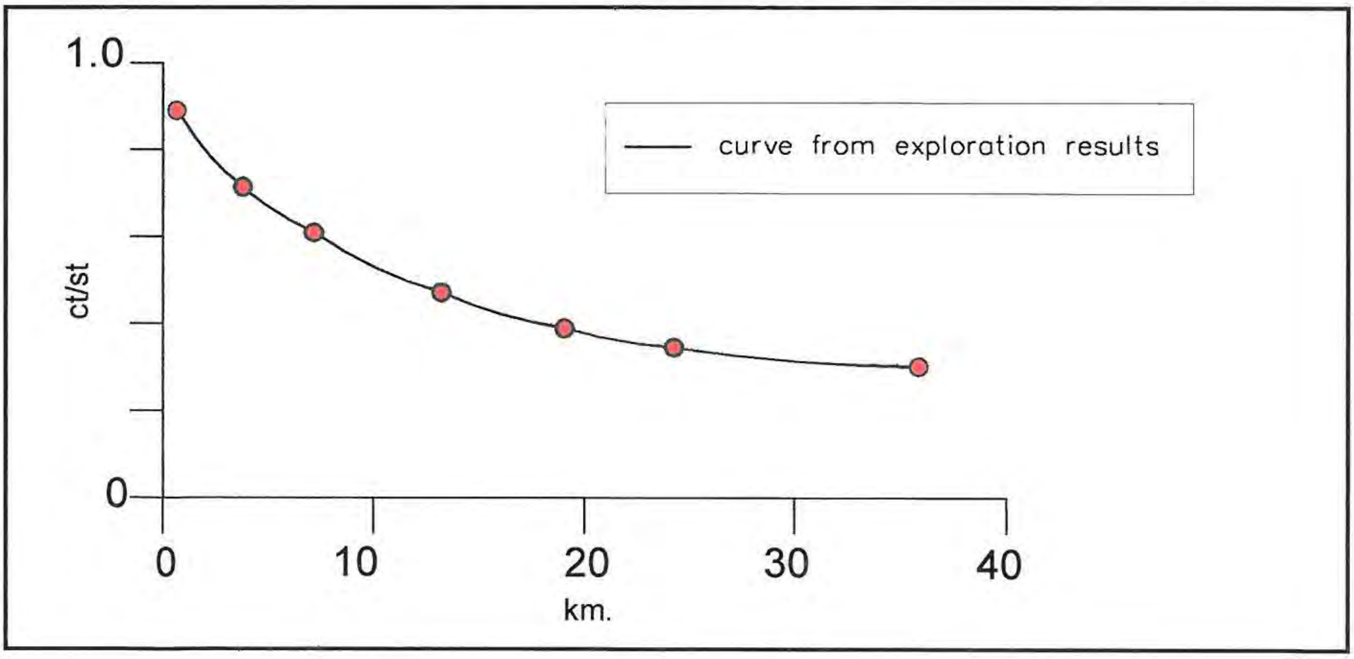


Figure 9

4.2.2.2.1 Cretaceous Aged Primary Diamond Sources

The age, distribution, grade and position of primary sources relative to the major westward drainages is integral to exploration for alluvial and marine diamond placers. Kirkley *et al.* (1991), estimate that there are over 3000 kimberlite occurrences in Southern Africa, the majority of which are Cretaceous in age.

Table 1 summarises some of the key elements of the southern African kimberlites. Figure 10 graphically summarises the age distribution of the various southern African diamondiferous kimberlite occurrences (from Table 2.2 - Allsopp *et al.*, 1989).

TABLE 1: Summary of kimberlite occurrences in southern Africa (after Venter, 1998).

Country	Known Kimberlites	Diamondiferous Occurrences	Comments	References
Angola	638	300	Grades generally vary between 11 and 50 cpht. Almost all production comes from alluvials. There are 18 kimberlites dated Early Cretaceous with limited erosion. The pipes that feed the alluvial Luanda deposits are Late Jurassic in age.	Janse and Sheanan, 1995. Allsopp *et al.*, 1989. Cole, 1998.
Botswana	140 in 11 clusters	56	Orapa (90Ma) and Lethlakane are Cretaceous in age and Jwaneng Early Triassic. Most have crater or diatreme facies preserved, indicating minor erosion prior to deposition of Kalahari Group sediments.	Allsopp et al. 1989. Zweistra, *et al.* 1998.
Lesotho	180	8	Two of the 8 kimberlites are Cretaceous in age.	Nixon, 1973. Allsopp, *et al.*, 1989.
South Africa	935	145	No crater facies, most diatreme and hypabyssal therefore many diamonds eroded and in the secondary system. Premier is 1180 Ma, but most are Cretaceous in age (80 - 100 Ma). Venetia is Cambrian (550 Ma). At Wesselton both Cretaceous kimberlites and Precambrian dykes are present.	Allsopp, *et al.*, 1989. Janse, 1985.
Swaziland	1	1	Late Triassic in age. Generally only diatreme facies preserved.	Turner & Minter, 1985.
Tanzania	400	54	Diatreme facies predominate except for Mwadui (45 - 52 Ma) which has crater facies. Nzega is 53 Ma while a pipe near Bubiki is 1097 Ma.	Janse and Sheahan, 1995. Edwards and Howkins, 1966. Gobba, 1989. Kashabano, 1989.
Zimbabwe	About 65	7	Extensive erosion with preservation of only diatreme and hypabyssal facies. Collosus pipe is of Cambrian age, River Ranch of Silurian and Sebungwe of post-Triassic age.	Allsopp, *et. al.*, 1985. Stocklemayer, 1981.

Based on the worldwide average rate of erosion of about 1 m per 30 000 years, Kirkley *et al.* (1991) calculated that a kimberlite pipe would erode down to its root zone in about 69 Ma. Venter (1998) calculated that the erosion levels of southern African Cretaceous pipes suggest denudation rates of between 3 m and 12 m per million years if those that were protected by younger sequences are ignored. Partridge and Maude (1987) believe stripping rates of 15 m per million years are possible while the author, using their figures, re-calculated a rate of 20 m or 30 m depending on whether 1000 m or 1500 m is stripped in 50 Ma. The age is extrapolated from Stormberg lavas 138 Ma to 140 Ma (Burger and Coertze, 1973) xenoliths included in the 90 Ma pipes at Kimberley (Hawthorne, 1975; Clement *et al.*, 1986). Evidence for high erosion rates during the Late Cretaceous

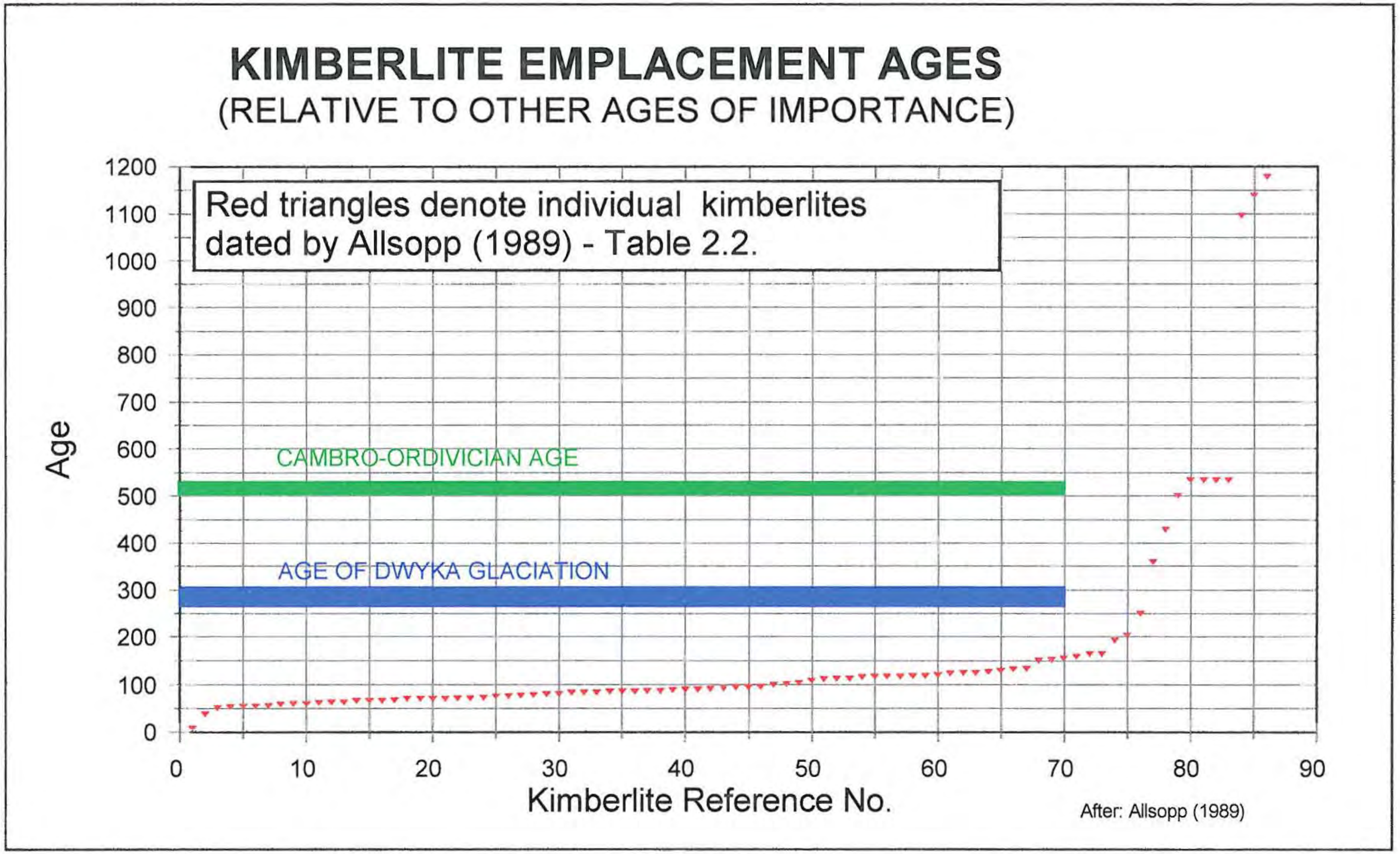


Figure 10: Graph illustrating southern African kimberlite emplacement ages. Ages extracted from Table 2.2 prepared by Allsopp (1989).

is supported by the sedimentary stratigraphy on the middle shelf along the west coast (Dingle & Hendey, 1984). If sidewalls are extrapolated up at the same angle as the preserved portion of the diatreme (average of 82^0) the crator could have had an original surface diameter of up to 1 kilometre (Venter, 1998). Hawthorne (1975) estimated that erosion removed about 1400 m of the pipes in the Kimberley area. Based on mass balance equations, Gurney *et al.*, (1991) estimate that 1.5 billion carats have been eroded from Cretaceous aged kimberlites, transported and deposited in secondary diamond placer deposits along the west coast of southern Africa. Evidence for high erosion rates during the Late Cretaceous is seen in the sedimentary stratigraphy on the middle shelf along the west coast (Dingle and Hendey, 1984).

4.2.2.2.2 Drainage Evolution in Southern Africa

The Orange and Olifants Rivers are recognised as the two major source points through which diamonds were introduced into the marine environment from their origin in the hinterland. Other rivers that are also considered to have acted as significant secondary source points are the Holgat, Buffels, Swartlintjies, Spoeg, Groen and Ugab Rivers.

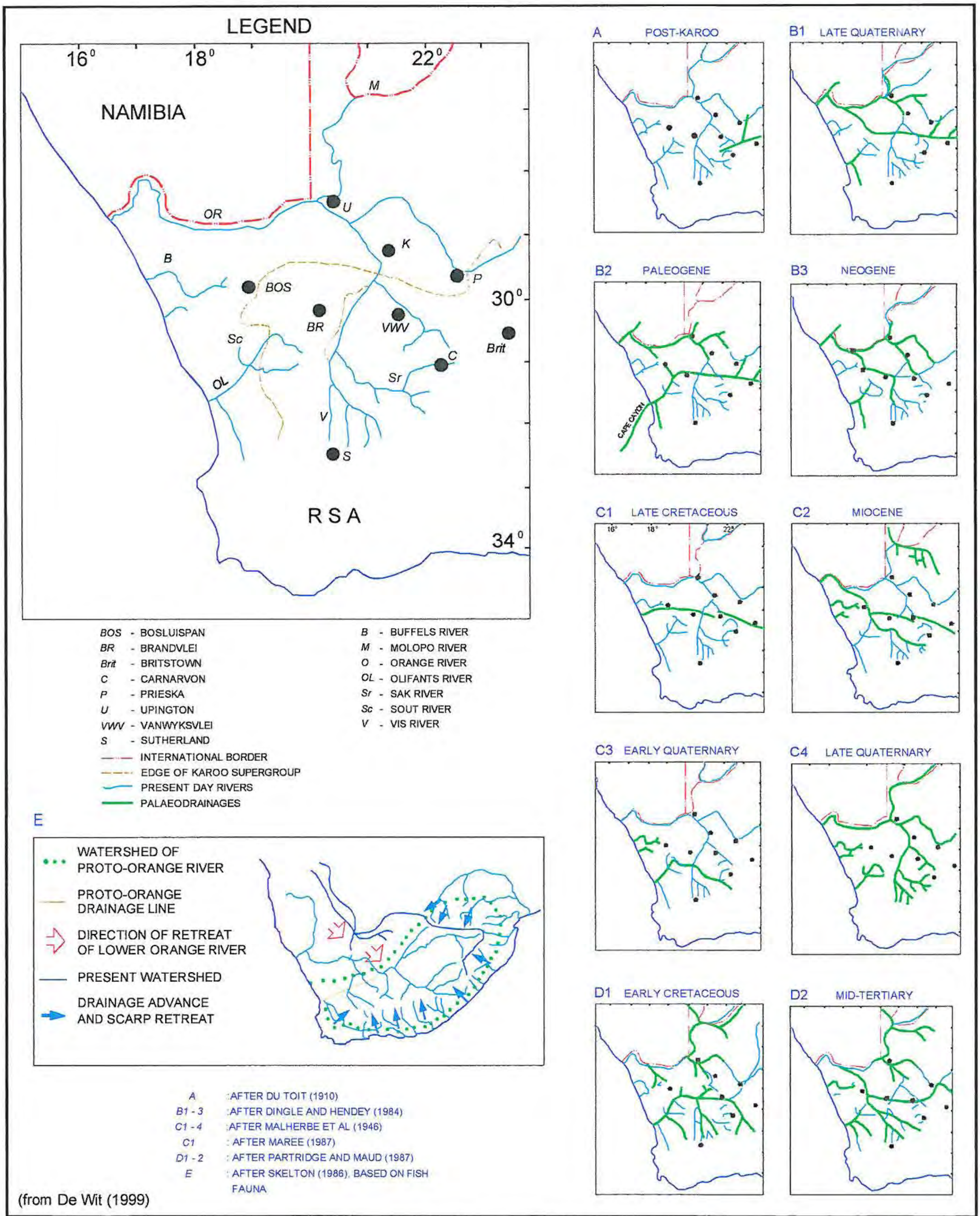
Wagner (1914), Dingle and Hendey (1984), McCarthy *et al.*, (1985), Malherbe *et al.* (1986), Partridge and Maud (1987, 2000), Maree (1987), Marshall (1986, 1994), De Wit (1993, 1996, 1999), De Wit *et al.* (2000) and Moore (2001) have worked extensively in trying to unravel the drainage evolution of southern Africa. De Wit (1999) succinctly summarises the previous models of drainage evolution in southwestern Africa (Figure 11) paraphrased as follows:

- Dingle and Hendey (1984) suggested that in the Late Cretaceous the main westward drainage flowed through the Koa Valley exiting through the Orange River mouth, switched to the Olifants River mouth during the Palaeogene and then back to the Orange River mouth again during the Neogene;

- McCarthy *et al.*, (1985), suggest that the Orange River was captured through Van Wyksvlei-Hartebees River in the post-Oligocene;

- Partridge and Maud (1987) hypothesise an early Cretaceous Olifants River mouth exit point, switching and draining via the Koa River Valley during the Tertiary;

- Malherbe *et al.* (1986) and Maree (1987) favour the Late Cretaceous "oer-Oranje" River that drained the catchment area west of Britztown via Van Wyksvlei and Brandvlei and exited at Kleinzee. They propose that the "oer-Orange" River was then captured by the Koa River during the Miocene and exited via the present Orange River mouth. The mouth of this drainage then moved southward, exiting via the Olifants River Mouth in the Early Quaternary, before finally establishing its present course from the Late Quaternary.



A	:AFTER DU TOIT (1910)
B1 - 3	:AFTER DINGLE AND HENDEY (1984)
C1 - 4	:AFTER MALHERBE ET AL (1946)
C1	: AFTER MAREE (1987)
D1 - 2	: AFTER PARTRIDGE AND MAUD (1987)
E	: AFTER SKELTON (1986), BASED ON FISH FAUNA

(from De Wit (1999)

SUMMARY OF PREVIOUS MODELS
OF DRAINAGE EVOLUTION IN SOUTHWESTERN AFRICA

Figure 11

Maree's (1987) suggests the following drainage evolution sequence for southwestern Africa:

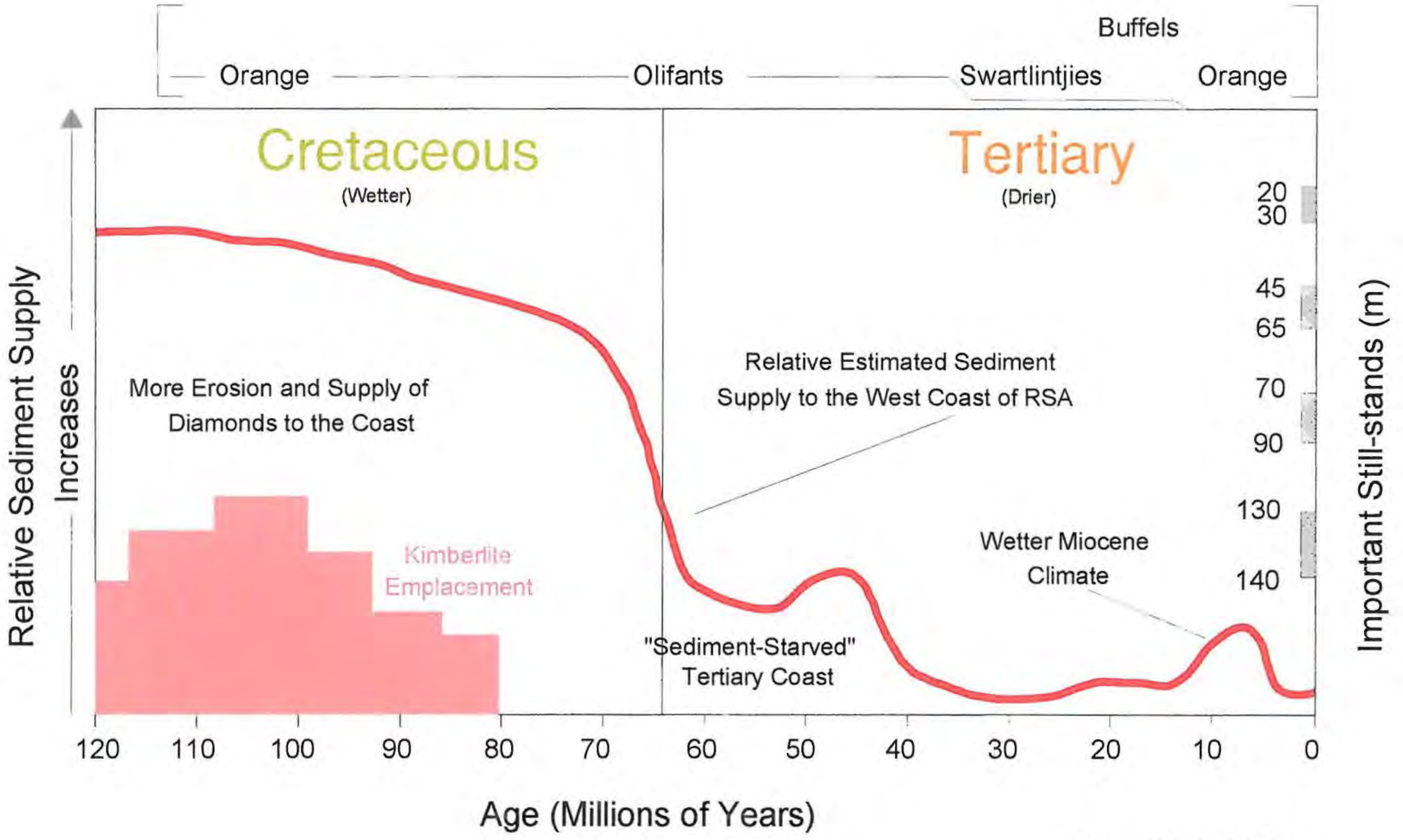
- The Buffels River captured the Swartlintjies River thereby creating a point source at Kleinsee;
- As the break-up of Gondwana proceeded northwards, the Olifants River cut back, capturing the palaeo-Orange River headwaters and depositing diamonds at the mouth of the Olifants River;
- The further northward opening of the Adamaster Ocean resulted in the northward migration of the mouth of palaeo-Olifants River, possibly through the Kamma River at Port Nolloth. The palaeo-Fish River captured the palaeo-Orange River, at the elbow-joint bend below Modderdrif, moving the mouth and the source point of diamonds to the coast, further northwards;
- Much later, the present Orange River captured the palaeo-Orange River near Prieska, resulting in the diamonds found along the flanking terrace gravels and at Oranjemund.

Maree's (1987), postulation that the Holgat, Buffels, Swartlintjies, Spoeg, Groen and Olifants Rivers may have tapped the upper reaches of the palaeo-Orange River at various stages during the Cainozoic implies that there are numerous secondary point sources that supplied diamonds to the west coast. As more exploration companies prospect further inland along the Buffels and Groen Rivers and along the Namaqualand coast, so the understanding of the drainage evolution along the west coast will improve.

Model 2 is based largely on De Wit's (1993, 1999) research of Post-Gondwana drainage evolution in southwestern Africa. His main findings and conclusions can be summarised as follows:

- The post-Gondwana drainages in southern Africa can be viewed in three time periods; 1) Mid to Late Cretaceous; 2) Early to Mid Cenozoic and 3) Late Cenozoic;
- The oldest are of Mid to Late Cretaceous age and have been subjected to a deep chemical weathering process. At that time there were two main rivers draining the interior; 1) the Karoo River which had its catchment in the present upper Vaal/Orange River area, flowed out via the present Olifants River mouth; and 2) the Kalahari River drained southern Botswana and Namibia and entered the Atlantic via the lower Orange River. The Karoo River is thought to have transported the majority of the diamonds eroded from the Cretaceous age kimberlites in the interior, to the coast. By the end of the Cretaceous, denudation rates decreased in response to a climate change to semi- to arid conditions and the supply of diamonds to the coast decreased dramatically (Figure 12);
- By the early Cenozoic the headwaters of the Karoo River had been captured by the Kalahari River and the broad configuration of the Orange River drainage system, as it is today, was established. This northerly shift of the drainage pattern is postulated to be largely a result of asymmetric uplift of the southern and eastern continental margins, as well as continued uplift along the Transvaal/Griqualand axis, in response to the break-up of Gondwana. The Miocene to Plio-Pleistocene wet period resulted in diamonds being reworked

SCHEMATIC REPRESENTATION OF THE WEST COAST DIAMOND PLACER DEPOSITS



(from Kuhns,1995)

Figure 12

out of older Tertiary fluvial deposits. The Koa and Sak Valleys formed a major tributary to the Orange River during the Miocene, eroding diamonds from Cretaceous Karoo River deposits or terraces. The younger Carnarvon Leegte was never part of the Koa system. By the Late Pliocene, the Sak River captured the upper Koa River and by Plio-Pleistocene times the lower terraces in the Sak River and the palaeo-Carnarvon joined the Orange River as a major tributary referred to as the palaeo-Hartbees River;

- Most economic alluvial deposits are located in close proximity to, but off, the horizontally bedded Karoo Supergroup sediments. The close positional correlation can be explained by the preferred trapsite environment created by bedrock competence off the Karoo sediments and the abundance of pebble, cobble and boulder gravels, eroded largely from the basal Karoo tillites and exfoliated Ventersdorp lavas. However, based on mass balance calculations, less than 1% of diamonds eroded from known kimberlitic sources have been captured within these alluvial placers. By implication, 99% have been deposited off the Atlantic seaboard.

4.2.2.2.3 Discussion

The numerous Cretaceous kimberlites in the interior of southern Africa are the most likely source of west coast diamonds. However, diamond population distribution along the coast would suggest that drainage evolution proposed in Model 2 may be a bit simplistic and that some river mouth migration, of both the Karoo and Kalahari Rivers, may have occurred, possibly in response to asymmetric uplift of the southern and eastern continental margins, as well as continued uplift along the Transvaal/Griqualand axis.

Mass balance calculations based on mined grade, size and degree of erosion on the numerous Cretaceous aged kimberlites in the interior of southern Africa, show that there are more than sufficient diamonds in the secondary systems, from this source, to explain the diamonds found along the west coast. The large number of known, diamondiferous, Cretaceous kimberlite sources obviates the need to try to find other, less likely diamond origins. However, the Namaqualand diamond population has a different signature to that typical of the Orange River diamonds mined at Alexkor (A. Thamm - pers. comm., 2002). The Orange River diamond population comprises a high percentage of white stones, while the Namaqualand diamonds have a greater range of colours with many brown stones. The predominate shapes also differ, with the Namaqualand population containing many "stressed" stones that splinter when being cut (J. Moore - pers. comm., 2003). If the diamonds are all derived from the same primary source area, whether it be via the Karoo or Kalahari River system, then there should be no difference in their signatures. It may be argued that the discrepancies can be explained by the preferential erosion of different pipes over different periods, but this seems unlikely considering the Kalahari captured the headwaters of the Karoo and was not a separate river draining a different catchment area. Considering the large diamond populations that have been mined and compared, one would expect them to be similar had they been derived from the same source area. Anomalies like these are more easily explained if a different source, like the pre-Karoo kimberlites, is postulated.

Moore and Moore (in prep.) state that despite all the proponents supporting the idea of the Karoo River, due to the paucity of remnants, there is no unequivocal scientific evidence to support its existence at all. Based on close examination of the literature regarding the drainage and landscape evolution of the interior of southern Africa, it is evident, that while progress has been made in the understanding of the drainage evolution in southwestern Africa since the Cretaceous, many pieces of the puzzle are still missing. The relatively simplistic Karoo-Kalahari-Cretaceous drainage system postulated by De Wit (1999), does not adequately account for the "kicks" in average stone size at localities like the Groen, Swartlintjies (Hondeklip Bay), Buffels (and Somnaas Channel), Holgat, Kaukausib, Koichab and Ugab Rivers. Some drilling and prospecting is currently being undertaken along the eastern extensions of the Groen and Buffels River palaeo-channels, on the coastal plain, while at Koingnaas, a gravel body comprising sub-rounded vein quartz resistate in a kaolinitic matrix is being mined. The chemical alteration of these channels suggest that they are of early Tertiary age (i.e. African Surface). De Wit's (1993, 1996, 1999) studies do not explain how these palaeo-channels fit into the drainage evolution of southern Africa.

Understanding the post-Cretaceous drainage evolution in southern Africa, is paramount to understanding the point sources of west coast diamonds. Currently, there is not conclusive evidence to support a multiple or dual (Karoo and Kalahari Rivers) exit onto the west coast. However, based on average diamond size distribution curves and offshore sediment accumulation, it is clear that the Karoo and Kalahari Rivers were the main fluvial systems draining the interior of southwestern Africa.

4.2.2.3 OTHER POTENTIAL DIAMOND SOURCES

Possible, though unlikely primary sources for the west coast diamonds include the off-craton Bushmanland, Keetmanshoop, Gibeon, Silicon, Maltahöhe, and Barby (near Helmeringhausen 150 km NW of Keetmanshoop) kimberlite pipes and a ilmenite rich rock at Banke. The erosion of the early Tertiary sediments on the coastal plain, though not primary, may have contributed to the marine placer deposits at lower elevations.

The Barby pipe, from which a few diamonds have allegedly been recovered (Gevers, 1953), is particularly relevant to this study in that it is located immediately west of the Koichab River catchment area directly inland from the study area.

Gevers (1953) states that he was shown a piece of kimberlite from the Bushmanland kimberlites that had an estimated 2 carat diamond protruding from it by a government official. The official claimed to have acquired the rock from a prospecting pit on one of the pipes. Gevers (1953) observed that the rock looked identical to those lying in the trench tailings. Subsequent prospecting and sampling failed to recover diamonds from this off-craton kimberlite cluster. At that time diamonds had been recovered as far as 40 km upstream at Wolfsberg. There is currently a renewed exploration drive to locate palaeo-drainages in the Buffels River area by De Beers and by Firestone Diamonds in the Groen River area. Gevers (1953) observed that at Banke a shaft has been sunk into a ilmenite rich kimberlite at the headwaters of the Groen River. He postulates that the crator facies may have contained sufficient diamonds to result in the increase in grades and account for the different diamond population noted at Koingnaas. To illustrate this point, Gevers (1953) quotes surface and grades at depth for various De Beers mines. Gevers's (1953) tabulated results have been converted from carats per load to carats per hundred cubic metres by the author and are presented graphically in Figure 13.

Merensky's (1909) statement that the reworking of older Tertiary sediments along the coastal plains was the source of the diamonds found in the marine placers should be re-considered as a potential source, particularly in Namibia. Merensky (1909) was most likely referring to these sediments as having tapped a primary source directly. However, if they are taken to include early Tertiary raised terraces as well, then this potential secondary source does have merit. The paucity of emerged terraces above 30 m along the Namibian coastline would indicate that they have been eroded and re-worked into younger terraces. This includes the high grade +50 m and +90 m terraces that presently are being mined south of the Orange River. The "kick" in diamond size and grade in areas like Rooiwal Bay and at Koingnaas may be from the erosion of early Tertiary emerged marine terraces, that subsequently reconcentrated diamonds at lower sea levels during regressive phases. This would imply that the average diamond sizes within these older terraces are larger than the more recent deposits. An along-coast decrease in average diamond size has been noted by Sutherland (1982) north of the Buffels and Orange Rivers (Refer: Figure 9) and the author south of the Orange River and from Geelwal Karoo to Klipvley Karoo Kop, located north of the Olifants River, can easily be explained by bottom currents set up by waves impinging obliquely to the shoreline (De Decker, 1986). However, a coast-perpendicular average diamond size variation (i.e. at different sea-levels) noted at Alexkor, Geelwal Karoo/Klipvley Karoo Kop and in the study area (Figure 14), at similar distances from the secondary source, are difficult to explain using wave-action processes. This particularly considering the significant, subsequent re-working of older placer deposits during the numerous transgression/regression cycles that have occurred.

4.2.2.3.1 Discussion

Given the current knowledge on diamondiferous kimberlite occurrence with respect to cratons, it is highly unlikely that the west coast diamonds originated from localised primary sources.

The geological knowledge on the occurrence and control on diamondiferous kimberlites in the early 1950's made Gevers's (1953) ideas plausible at that time. However, current models on the criteria controlling diamondiferous kimberlite occurrence are well constrained and the fact that the Barby, Bushmanland and Banke kimberlites are located off craton make the occurrence of diamonds in these pipes highly improbable, thereby discounting them as possible sources for the west coast diamonds.

Merensky's (1909) model certainly does have merit in light of the current geological knowledge of the coastal plain. If the Tertiary placer deposits have been eroded then it is probable that they have acted as a secondary diamond source to subsequent marine terraces at lower elevations. This particularly given the large volumes of Tertiary sediments located on the middle shelf (Corbett, 1996). The paucity of Tertiary sediments at shallower depths may indicate that they do not constitute the dominant source of diamonds on the inner shelf.

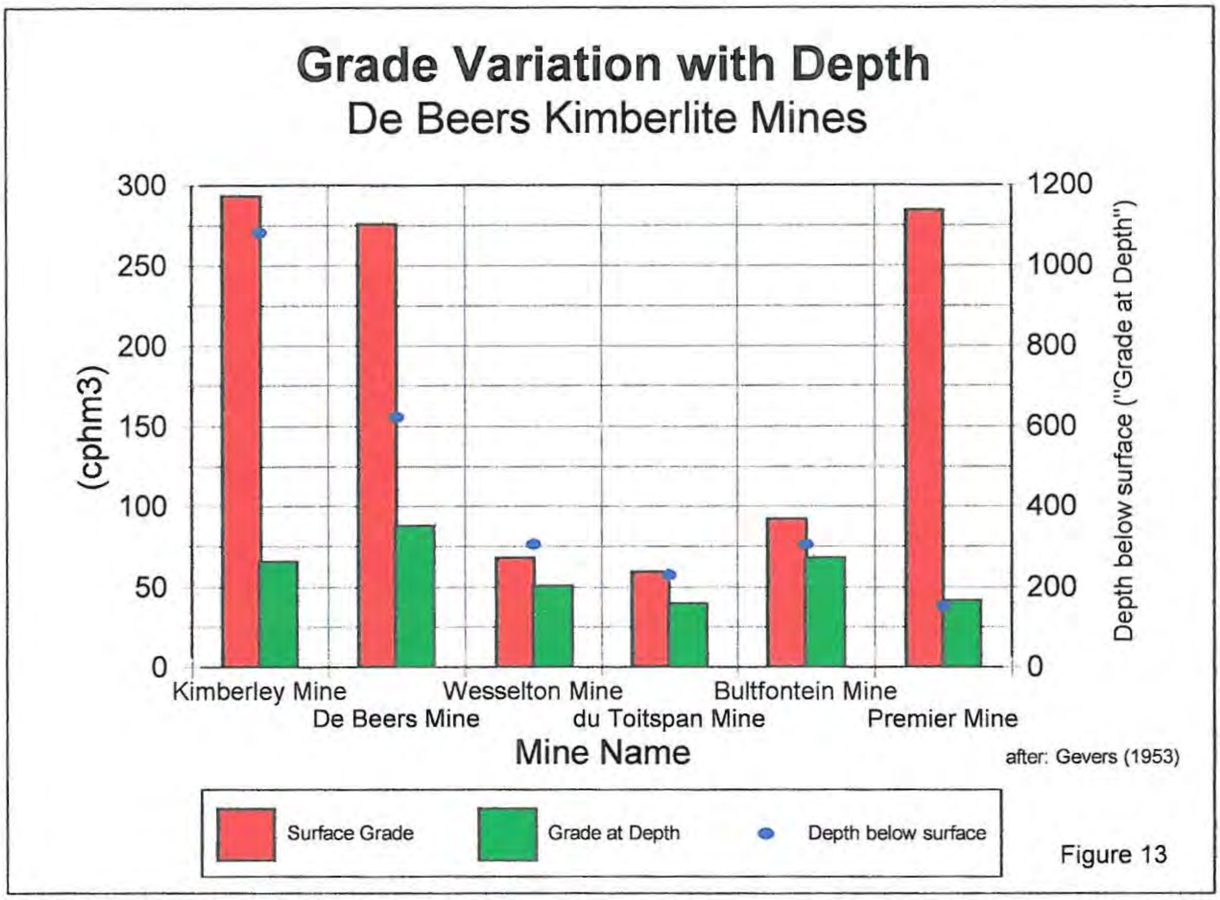


Figure 13

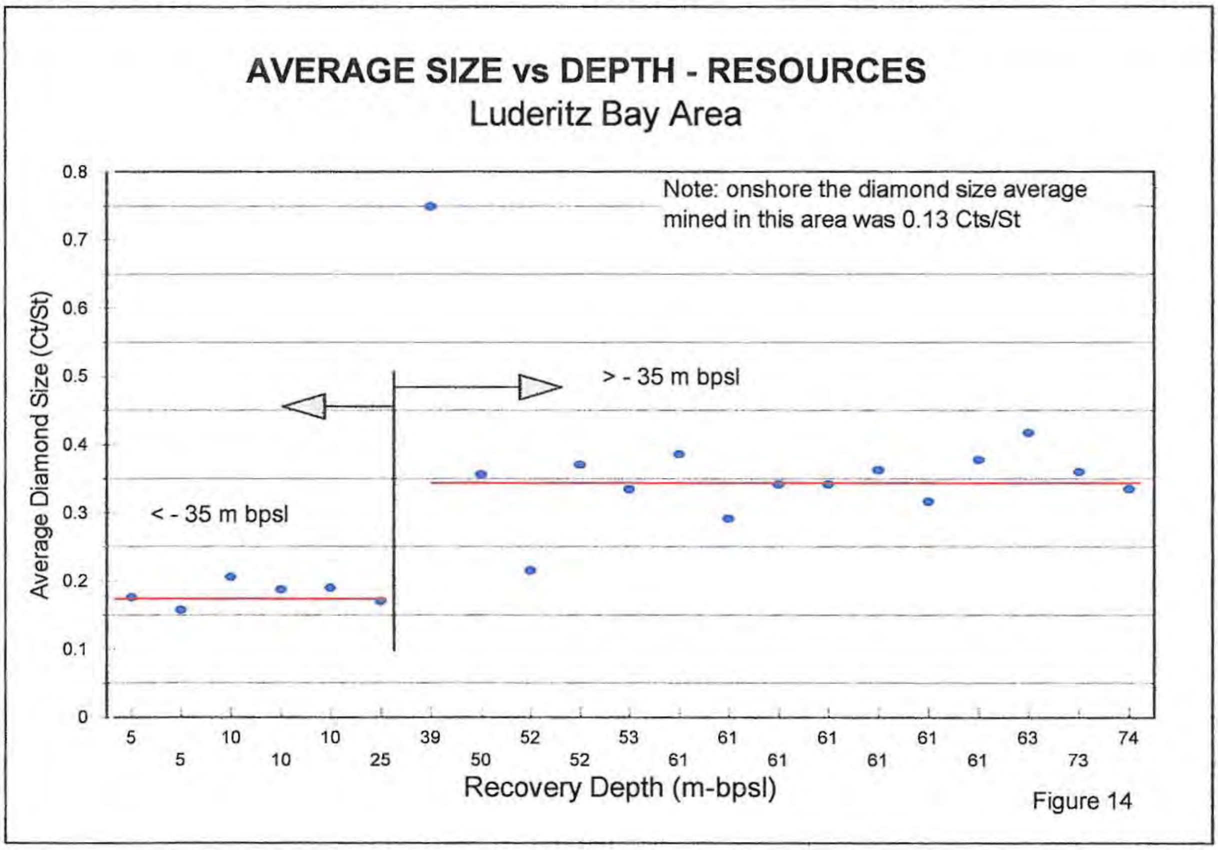


Figure 14

5. LANDSCAPE EVOLUTION IN SOUTHWESTERN AFRICA

The attempted unravelling of the post-Cretaceous landscape evolution in southern Africa is not an easy task due to the age of the deposits, the extensive erosion that has occurred and the resultant paucity of contiguous land surfaces. However, this study is not aimed at unravelling the landscape evolution of southern Africa. The pertinent literature is reviewed and summarised and factors relevant to the current study are discussed in the concluding paragraphs of this chapter.

5.1 INTRODUCTION

5.1.1 LANDSCAPE EVOLUTION IN SOUTHERN AFRICA

The most recent, comprehensive papers on the landscape evolution of South Africa have been published by Partridge and Maud (1987, 2000), and Partridge (1998). Partridge and Maud (1987), analysed a number of sections linking coastal deposits to planation remnants in the interior in order to reconstruct the geomorphic evolution in southern Africa since the Mesozoic.

Their sections and field observations, which extended over regional scale land surfaces, were used to contour plans of elevations of erosion surfaces using the oldest, African surface with its diagnostic deep weathering profiles and duricrust cappings, as a datum. Partridge and Maud (1987) built on the earlier models of Dixey (1938) and King (1944-1951). Partridge and Maud (1987), postulate the following landscape evolution for southern Africa:

- The Great Escarpment formed after continental rifting, and separate base-levels for the plateau and coastal areas were already in existence during the evolution of the alluvial and marine diamond placers in southwestern Africa.

- Based on correlation of onshore and offshore sedimentation, a single cycle of erosion prevailed from the time of rifting to the early Miocene. By the end of this cycle of erosion the gentle African surface extended across most of southern Africa at elevations of 500 - 600 m. Most erosion and scarp recession occurred during the late Jurassic and Cretaceous, producing thick sedimentary units offshore. Shelf sedimentation declined during the Tertiary and had virtually ceased by the Oligocene, when interior planation was in its advanced stages and alluvial erosion was minimal.

- A second smaller (Post-African I) cycle of landscape erosion and concurrent offshore sedimentation followed the modest uplift of 150 - 300 m and westward tilt of the continent in the Miocene to produce the Post-African I surface. This cycle, that terminated near the end of the Pliocene, resulted in the imperfect planation in most areas to levels of no more than 100 - 300 m below the African surface.

- A major uplift at the end of the Pliocene raised the eastern portions of the interior by up to 900 m, with minor uplift in the west and along the Transvaal-Griqualand axis in the interior.

- The Post-African II cycle is characterised by deep incision of the hinterland and downcutting along major rivers in the interior. Planation was limited to coastal areas with the resulting sedimentation evident mainly in the offshore deltas and deeper ocean basins.

- The successive uplifts to which the continent was subjected produced major changes in drainage patterns, but these are not well constrained for the pre-Miocene in many areas.

- The dominance of back-wearing over down-wearing of the interior is ascribed to mechanisms associated with passive continental margins.

A summary of the principal geomorphic events in southern Africa since the Mesozoic is given in Table 2 below, and a diagrammatic summary of the Late Mesozoic-Cenozoic model for major events in the development of the northwest Cape is shown in Figure 15 (De Wit, 1999):

TABLE 2: Geomorphic events in southern Africa since the Mesozoic (From: Partridge and Maud, 1987).

EVENT	GEOMORPHIC MANIFESTATION	OFFSHORE SEDIMENTATION	AGE
Climatic oscillations and glacio-eustatic sea-level changes (most pronounced during middle and late Pleistocene)	Low-level marine benches, coastal dune deposits, river terraces, Kalahari sands	Accumulation of cones off mouths of major rivers. Widespread erosion elsewhere following development of nearshore current circulations. Renewed sedimentation in deep ocean basins	Late Pliocene to Holocene
Post African II cycle of major valley incision, especially in southeastern coastal hinterland	Incision of coastal gorges, downcutting and formation of higher terraces along interior rivers, formation of Post-African II erosion surface (with planation restricted to eastern Lowveld region).		
Major uplift (up to 900 m in eastern marginal areas).	Asymmetrical uplift of the subcontinent and major westward tilting of previous landsurfaces of the interior, with monoclinal warping along the southern and eastern coastal margins		Late Pliocene (~2.5 Ma)
Post-African I cycle of erosion	Development of imperfectly planed Post-African I erosion surface. Major deposition in Kalahari Basin	Renewed sedimentation giving rise to Uloa Fm (southeastern coast), upper Alexandria Fm. (Southern coast), Bredasdorp Fm. (Southern and western coasts) and Elandsfontyn and Varswater Fms. (Western coast). Major resurgence of sedimentation in deep ocean basins.	Early mid-Miocene to late Pliocene
Moderate uplift of 150 - 300 m	Slight westward tilting of African surface with limited coastal monoclinal warping. Subsidence of Bushveld Basin		End of early-Miocene (~18 Ma)
African cycle of erosion (polycyclic)	Advanced planation throughout subcontinent. Surface at two levels above and below Great Escarpment. Development of deep-weatherd laterite and silcrete profiles. Development of Kalahari basin with concomitant onset of sedimentation towards the end of the Cretaceous	Widespread epeirogenic sedimentation in several pulses, as exemplified by offshore Alphard Fm., Mzinene and St Lucia Fms. of the southeastern coast and lower Alexandria Fm. Of the southern coast. General slowing of shelf sedimentation from end-Cretaceous, culminating in major Oligocene unconformity	Late Jurassic/ early Cretaceous to end of early Miocene
Breakup of Gondwanaland through rift faulting	Initiation of Great Escarpment owing to high absolute elevation of southern African portion of Gondwanaland. Deposition of Enon Conglomerate Fm.	Rapid, localised taphrogenic sedimentation producing inter alia Uitenhage Group of the southern coast	Late Jurassic early Cretaceous

LATE MESOZOIC-CENOZOIC MODEL FOR MAJOR EVENTS IN THE DEVELOPMENT OF THE NORTH-WEST CAPE

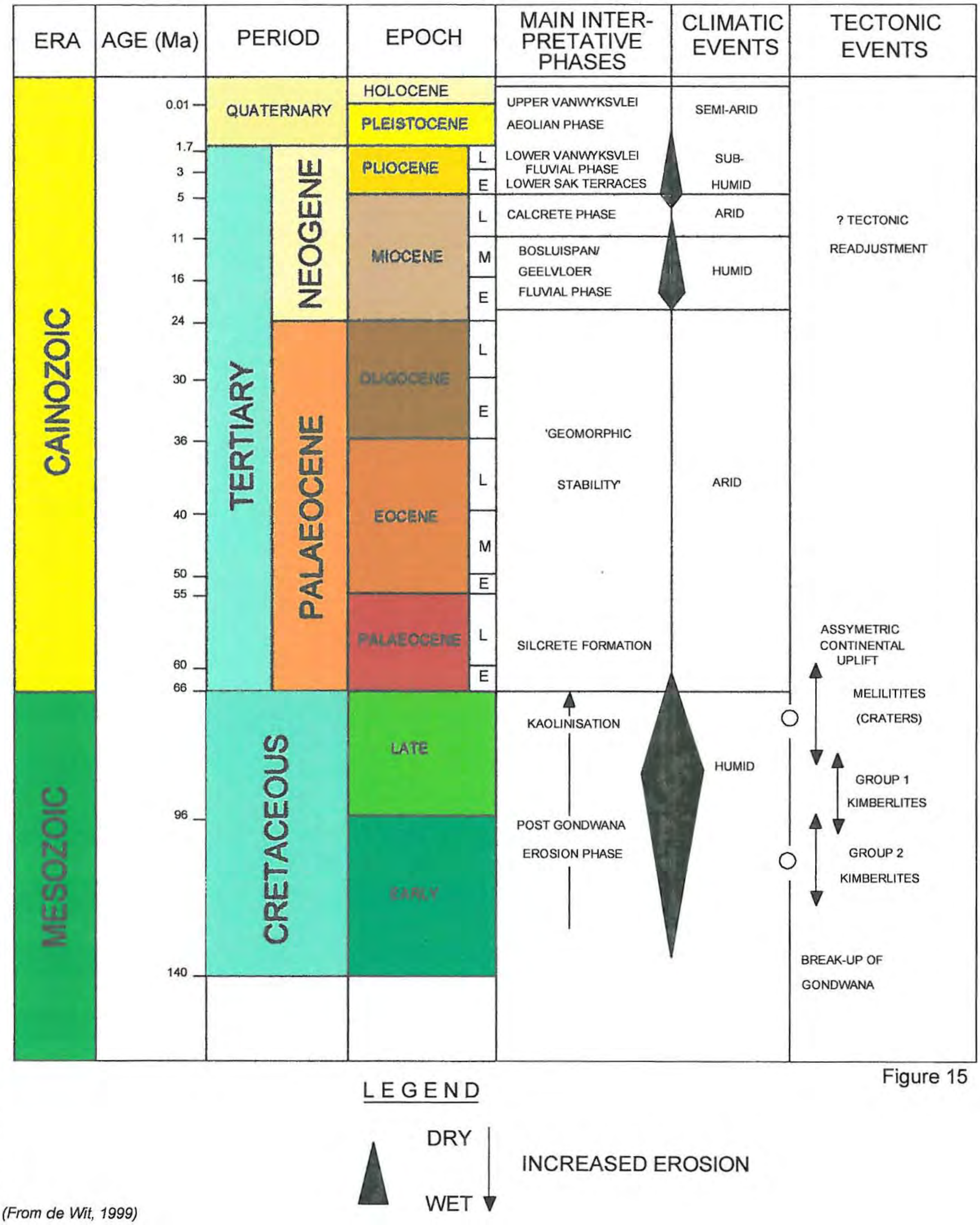


Figure 15

(From de Wit, 1999)

5.2 COASTAL AND CONTINENTAL SHELF EVOLUTION

An understanding of post-Cretaceous, west coast and continental shelf evolution, provides the relevant time-frames and insight into processes and potential controls on grade distribution within coastal diamond placer deposits.

Coastal diamond placer development has occurred within the following broad framework:

- During the Cretaceous the dominant drainage was westward and, due to asymmetrical uplift, has been so throughout most of the denudation of South Africa (Partridge and Maud, 1987).

- It is difficult to establish an accurate age for the introduction of diamonds onto the Namibian coastal margin. The recovery of diamonds from the beaches 160 m amsl at Eisenkiesselklippenbake and at Buntfeldschuh (Corbett, 1996), dated as Early Palaeogene (Siesser and Salmon, 1979), suggest a minimum age of Early Eocene for diamond introduction. Based on diamonds recovered during sampling from Cretaceous units in Concession 6C, Kuhns (1995) believes that diamonds could have been introduced to the Namaqualand coast, via the Karoo River, as early as the Late Cretaceous. Palaeontological research at Auchas Mine has shown the floor of the Orange River palaeo-valley was incised at least 19 Ma ago (Pickford, 1995), making it a Middle Miocene feature.

- The Cretaceous erosion and pediplanation of the coastal zone following the breakup of west Gondwana (Martin, 1973, 1975) resulted in the formation of the Great Escarpment with bevelled Late Precambrian bedrock and isolated inselbergs at its base (Dingle and Scrutton, 1974). This coastal pediplain is referred to as the Namib Unconformity Surface (Ollier, 1977, 1978). This relatively flat, well-planed surface, with relatively little weathering, forms the platform onto which the Namib Sand Sea has been deposited (Ward, 1987). The onset of desert conditions in the Namib have been constrained to the Early to Middle Miocene period by Pickford and Senut (1999) who used biostratigraphic and geochronological controls to determine the age of the Namib Unconformity Surface.

- The early onset of geomorphic stability and west coast aridity by the start of the Tertiary (De Wit, 1999) followed the establishment of the cold Benguela Current and upwelling in the Late Miocene (Siesser, 1980; Diester-Haas *et al.*, 1990). Long duration aridity, following high sedimentation in the Cretaceous and Miocene periods, has given the coastal processes time in which to winnow and concentrate the low grade diluted sediments which had been deposited, into numerous high grade placer deposits. Pickford and Senut, (1999) calculate erosion rates of as high as 15 m of vertical down-wasting, per million years, in the Chalcedon/Tafelberg area. They state that these high rates of erosion, believed to be predominantly by aeolian deflation processes, are restricted to specific coastal zones with high intensity winds. Corbett (1989) believes that these aeolian deflation processes played the most important role, in recent times, in the concentration of the diamond placer deposits within the northern Sperrgebiet.

Pickford and Senut, 1999 give succinct summaries of the main geological events along the Namib (Table 3) plains since continental break-up in the Hautervian and their revised summary of the main geological events in the southern Namib is shown in Figure 16.

TABLE 3: Summary of the Main Geological Events - Namib Coastal Plain (from: Pickford and Senut, 1999).

SUMMARY OF THE MAIN GEOLOGICAL EVENTS IN THE NAMIB COASTAL PLAIN, NAMIBIA SINCE THE SEPARATION OF SOUTH AMERICA FROM AFRICA DURING THE HAUTERVIAN (* = diamondiferous strata)
Sossus Sand Sea Russel's Perch aeolianite formed (Annental) Sandstone Modern beaches of the Sperrgebiet. Cold water fauna*
Deposition of the 2 m raised beach* Marine transgression to 2 m amsl. Cold water fauna
Deposition of 5 m raised beach* Marine transgression to 5 m amsl. Cold water fauna
Deposition of 8 m raised beach* Marine transgression to 8 m amsl, installation of cold water molluscan faunas
Widespread calcrete genesis in Namib Coastal Plain Obib Aeolianites accumulated
Travertnes and grits of the northern Sperrgebiet (Kaukausib, Grillental, Gamachab) ca 2 Ma Fiskus Aeolianites deposited
Deposition of regressive marine *Donax rogersi* package ca 3-2.5 Ma* ?Deposition of Meso-Orange Terrace III? Marine transgression to ca 30 m amsl ca 3-2.5 Ma. Warm water fauna Arrival of Equus in the Namib
Deposition of regressive marine *Donax haughtoni* package ca 7-5 Ma* ?Deposition of Meso-Orange Terrace II? Marine transgression to ca 50 m amsl ca 7 Ma. Warm water fauna
Onset of phosporite genesis (Rooikop)
?Pomona silicified regoliths? Chalcedon Tafelberg siliceous/dolomitic strata accumulate in crater Pedogenesis and weathering of monochiquite Chalcedon Tafelberg crator formed at 15 Ma
Onset of arid to hyperarid conditions in the Central Namib (Rooilepel and Tsondab Aeolianites)
Proto-Orange Terrace I deposited (Auchas, Arridrift, Baken) ca 19-17.5 Ma* Backponding of valleys in northern Sperrgebiet (Fiskus, Grillental, Elisabeth Bay, Elisabethfeld, Langental faunas) ca 20 - 19 Ma Marine transgression to ca 90 m amsl ca 20-17.5 Ma.
Deep incision of the Orange river Valley (to 40 m bmsl) ca Oligocene 27-22.5 Ma
Cessation of kaolinitisation in the Namib ca basal Miocene (ca 23 Ma) ?Skilpadberg Silcrete genesis? Kaolinitisation of bedrock cropping out at the Namib Unconformity Surface (ca Oligocene 31-27 Ma)
Langental Eocene marine deposits ca 34 Ma Klinghardt Phonolite eruptions ca 37 Ma Swartkop fluvial sediments (later silicified after being buried by the phonolite flow)
?Buntfeldschuh marine levels? (Bartonian ca 43 Ma)*
Wanderfeld IV marine deposits in northern Sperrgebiet ca 95 Ma
Onset of backwearing of the Great Escarpment and formation of the Namib Coastal Plain Separation of South America from Africa during the Hauterivian ca 120 Ma

The submarine shelf morphology discussed below, shows that the inner shelf and raised terrace deposits are similar in many respects, while the middle shelf deposits formed in a different environment.

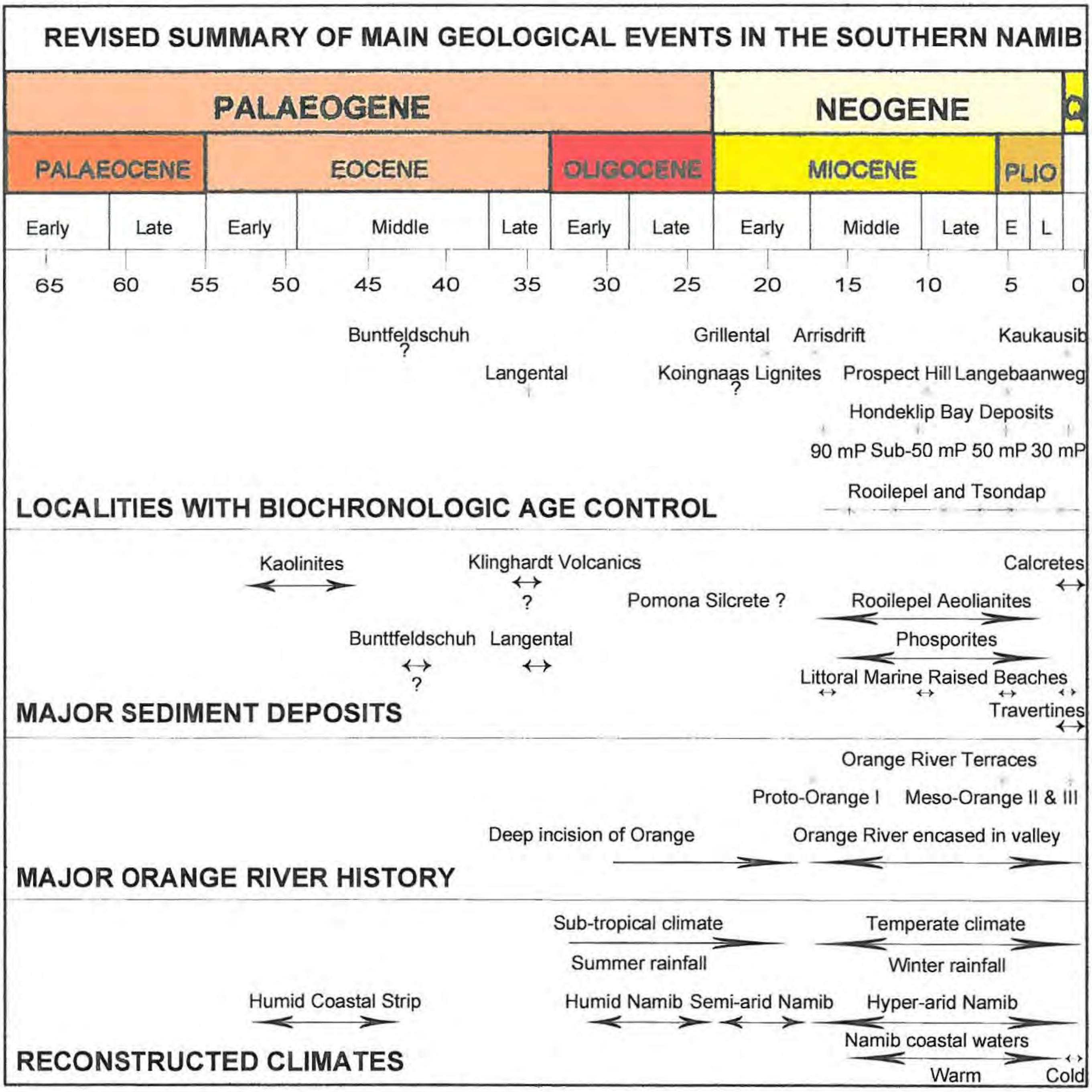


Figure 16: Summary of the main geological events along the west coast (from: Pickford and Senut, 1999)

5.2.1 THE MIDDLE SHELF

Thin, condensed, discontinuous sedimentary units resulting from the erosive nature of the cyclic marine and aeolian processes (Beetz, 1926; Corbett, 1989) make continental shelf, sequence stratigraphy difficult. Detailed micropalaeontological (McMillan, 1987, 1993; Kleinhans *et al.*, 1995) and isotope studies (Lavelle and Armstrong, 1993; Lavelle, 1995) have confirmed a number of unconformities on the continental shelf and have improved the resolution of the chronostratigraphy considerably (Figure 17).

The middle shelf has very low seafloor gradients and low relief (Rogers, 1977; De Decker and Woodborne, 1996). With such low gradients tidal action would have been far more active during periods of sea-level regression to -120 m bsl in the development of the placer deposits and overall shelf morphology than the current tidal processes along the west coast. The Middle and Upper Cretaceous sediments unconformally onlap the Precambrian basement at a well developed, coastally extensive, "knick point" at about 110 m bmsl (Rogers, 1977; De Decker and Woodborne, 1996). This "knick point" marks the contact between the Cretaceous sediments on the middle shelf and the Precambrian basement exposure that forms the reef along the inner shelf. An approximately 10 - 20 m thick Holocene mud wedge is deposited in the natural recess formed at this inflection point (Rogers, 1977; De Decker and Woodborne, 1996). A large number of the marine diamonds produced on the middle shelf, have been recovered from the mining of well winnowed basal lags, often situated against subtle topographical highs formed by resistant ridges in the gently westward dipping Cretaceous strata (Kuhns, 1995).

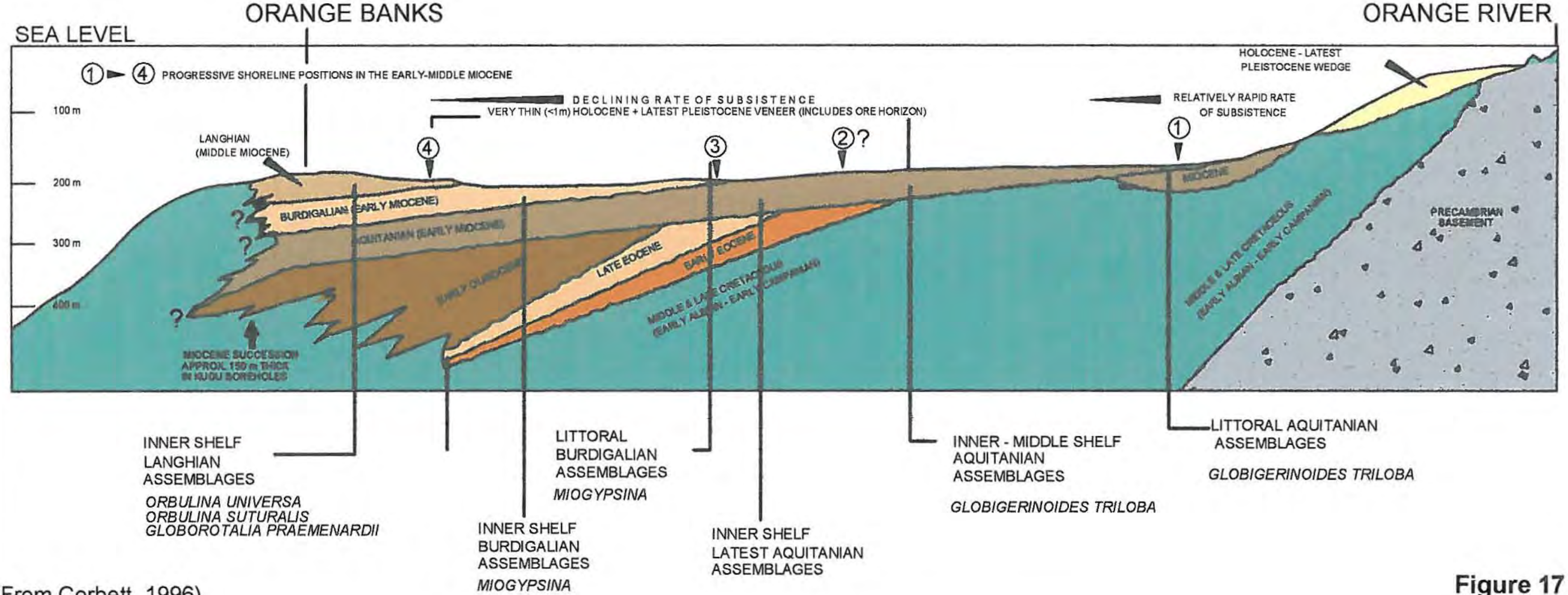
5.2.2 THE INNER SHELF

Of greater importance to the current study is the inner shelf area, which extends from approximately 110 m bmsl to present sea-level (Rogers, 1977). With numerous transgressions and regressions having repeatedly reworked the entire shelf and coastal plain area, from 160 m amsl to 120 m bmsl, the raised terraces, inner and middle shelf deposits can all be considered as contiguous marine placer deposits.

The Precambrian bedrock that forms the inner shelf topography is different to that of the middle shelf, in that it is generally more rugged with well developed gullies, linear depressions, basins, potholes and embayments similar to the current shoreline and onshore diamond deposits (Rogers, 1977; De Decker and Woodborne, 1996). Where placer development has occurred on the inner shelf the bedrock trapsites are filled with variable amounts of terrigenous gravel comprising, quartz, quartzite, epidote, riebeckite, chalcedony, banded ironstone, jasper, agate and varieties of mudstones, siltstones, igneous rocks (predominantly amagdaloidal Ventersdorp Group andesites) and local, bedrock rubble (Corbett, 1996).

STRATIGRAPHY OF THE MIDDLE SHELF OFF NAMIBIA

Chronostratigraphy and major unconformities present on the sediment-starved continental shelf off Namibia, based on detailed micropalaeontological and isotope studies



(From Corbett, 1996)

Figure 17

5.2.3 RAISED MARINE TERRACE DEPOSITS

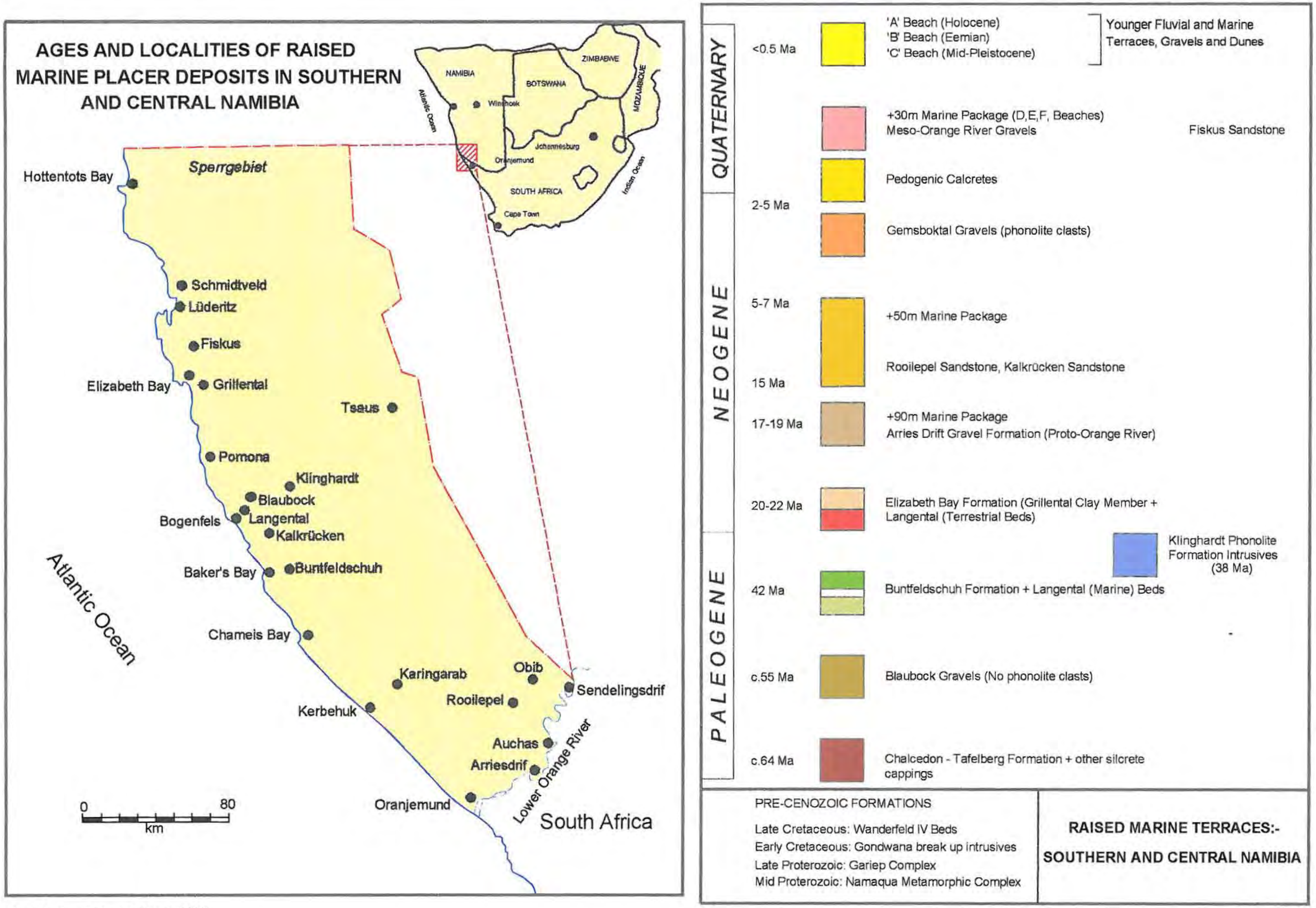
The environment in which the inner shelf deposits were formed is similar to that responsible for the deposition of the raised marine placers. Erosion by transgressive landward retreat of the high energy shoreface produces a diachronous ravinement surface (Nummedal and Swift, 1987) as seen at 30 m and 50 m amsl terrace packages (Corbett, 1996).

Pether (1994a) states that the 30 m amsl package is transgressed by younger raised littoral deposits at 8 m - 12 m, 4 m - 6 m and 2 m - 3 m containing cold water fauna. Each comprises a package of marine sediments deposited during regressive progradation seawards from the maximum elevation reached during the transgressive phase (Pether, 1994a). These packages are deposited en echelon down the bedrock gradient, each truncating the preceding one at a lower elevation. The basal gravels of each of these packages contain economical diamond deposits (Pether, 1994a). The raised 90 m, 50 m and 30 m marine packages, containing warm-water fauna, are relatively extensive formations along the Namaqualand coast (Pether, 1994a). At Alexander Bay immediately south of the Orange River the 90 m, 50 m, 30 m and younger, lower terraces are all evident (Keyser, 1972, De Decker, 1986), whilst immediately north of the river there is little to no evidence of these gravel units (Hallam, 1964). Pether *et al.* (2000), summarise the ages and localities of raised marine placer deposits in southern and central Namibia in Figure 18.

5.2.4 DISCUSSION

The ages and locality of diamond source points onto the littoral placer concentration are of greatest significance to the evolution of the diamond placer deposits along the west coast of southern Africa.

Current literature regarding the landscape evolution along the west coast assigns an age of at least 19 Ma to the incision of the Lower Orange River (Pickford, 1995). Diamondiferous gravels within the Early Palaeogene deposits at Eisenkiesselklippenbake and Buntfeldschuh at about 160 m amsl (Stöken, 1978), suggest that diamond introduction onto the coast had probably occurred by the Early Eocene (Corbett, 1996). The source of these diamonds is not clear as De Wit's (1999) postulated Kalahari River significantly post-dates these Palaeogene deposits. Diamonds on the land-surface in the interior would have been plentiful, with the high rates of erosion of diamonds from the crator facies of the Cretaceous kimberlites during the Late Cretaceous period. The literature reviewed does not address the potential diamond source for the Eisenkiesselklippenbake and Buntfeldschuh deposits. The diamonds could be derived from: 1) the back-wasting of the Great Escarpment - erosion of the Dwyka tillites (Model 1), 2) transported to the coast by a river in the north that has been completely eroded or totally reworked by the Kalahari River, or 3) have been transported northward by littoral processes from the Karoo River mouth. Given that the Albian to Turonian deposits, found in channel remnants along the Namaqualand coast, are generally well mineralised (Pether, 1994b), the paucity of diamonds within the Eocene placer deposits at Buntfeldschuh, is surprising. Pether (1994b) suggests that the stratigraphy of these kaolinitised, oligomictic, subangular clast-filled Namaqualand alluvial channels, is more complex than originally interpreted and that they may have been active over a considerable time-span.



(from Pether, Roberts & Ward - 2000)

Figure 18

The rapid decrease in diamond concentration following the onset of a wet period in geological time, is noteworthy. For example, in the wet Miocene period, gravels in the 90 m amsl are rich when remnants are found, those of the 50 m amsl are of moderate grade while the 30 m amsl package only has viable deposits in limited areas, where extensive reworking has occurred. This rapid grade reduction could be indicative of the following: 1) a fixed quantity of diamonds on the coastal plain, that is being progressively reworked, reducing the overall grade in subsequent younger deposits, 2) down-wasting of kimberlites and alluvial gravels in the interior and at the base of the Great Escarpment, forming stone lines and deflation pavements which are then flushed within a relatively short time following the onset of the wet period (i.e. a single, short-lived, large influx of diamonds to the coast), 3) differences in the coastal processes actively concentrating or diluting the diamond deposits at the specific elevations, or 4) a combination of the aforementioned.

It is evident, based on almost a century of prospecting and mining, that a large proportion of the diamonds eroded from the interior of southern Africa are no longer on the coastal plain or inner shelf. These diamonds are most likely within the Cretaceous strata of the middle shelf or have been moved off the continental shelf entirely, by alluvial and gravitational processes. The majority of diamond deposits currently being mined on the middle and inner shelf, as well as, those in the littoral zone have been concentrated during relatively recent geological times (i.e. Plio-Pleistocene) though the diamonds may be derived by the reworking of older units (Corbett, 1996). However, the dating of reworked marine placer deposits is always tenuous and prone to error. Reworking by high-energy aeolian, alluvial and marine action has destroyed the majority of the older deposits and reconcentrated them in relatively young deposits. Only in those deposits that have been anomalously rich are there remnants of older units. For example, in Marshall Fork, north of Lüderitz, an older basal gravel horizon was intersected beneath a clay layer, which in turn was overlain by gravel and then sand and mud. The top gravel was economical, but the basal gravel was of exceptionally high grade. Nonetheless, these high grades may also be partly attributed to aeolian and alluvial processes active in this area during periods of marine regression. In many cases deposits on the adjacent onshore area can be used as an indication of the potential of the offshore marine placers.

5.3 DIAMOND RE-DISTRIBUTION AND CONCENTRATION ON THE COASTAL PLAIN

The west coast diamond placers represents low grade deposits of approximately 216 214 km^2 which are un-economical over large areas. An understanding of the mechanisms and environments conducive to diamond concentration are important in considered target selection and delineation of economic placers, particularly in light of the high bulk sampling costs associated with marine prospecting. In order to examine the formation and evolution of the marine placers holistically, and understand grade distribution within these deposits, the roles and significance of the aeolian, alluvial and marine processes on the coastal plain must be considered.

Once the diamonds are deposited within the confines of the coastal plain there are a number of aeolian, alluvial, and marine processes that winnow these low-grade deposits into more discrete, higher grade marine placers. The role and significance of each one of these processes, in this poly-cyclic enrichment, needs to be understood, in order to enable considered identification and prioritisation of target areas. On a localised scale, an understanding of bedrock micro-structure and -topography, and the role of aeolian, fluvial and wave action (terrace formation and sediment dynamics) in the concentration and preservation of placer deposits are critical in marine diamond placer evaluation. Aeolian, local alluvial and wave-action processes are responsible for the creation of relatively small, high grade diamond placers within this large low grade deposit.

The preceding sections outlined the broad foundation of the southwestern African and coastal plain evolution. The timing, rates and sequence of the detailed processes, responsible for localised enrichment and placer formation, must fall within this broad framework. Based on the literature it is not possible to determine conclusively whether there were two or multiple secondary diamond sources, but based on mine production it is apparent that the Olifants and Orange Rivers have certainly contributed a significant proportion of the west coast diamonds. The largest diamonds can be expected at or near to the mouths of these rivers. Offset against the advantage of a source point, is the increased sediment cover associated with these depositories. Once the diamonds have been deposited at the coast, wave, aeolian and fluvial processes must redistribute and concentrate them. Understanding the grade distribution within the coastal placers requires the comprehension of the dynamics of these concentration processes. Literature on the aeolian, alluvial and marine processes are reviewed and factors pertinent to the understanding of grade enrichment highlighted. These processes work interactively and therefore should not be viewed as operating in isolation. However, for the purposes of clarity, they are examined individually in the following sections.

5.3.1 EVOLUTION OF THE NAMIB DESERT

Ward and Corbett (1990) propose a five phase model for the evolution of the Namib Desert.

This model stems largely from Ward's (1987) study of the Kuiseb River valley, immediately south of Walvis Bay and slightly to the north of the study area. Their model is a follows:

- **Post-Gondwana erosion phase** (120 Ma - 65 Ma): pediplanation processes bevelled a Late Precambrian bedrock (or exhumed pre-Karoo) surface to form the Namib Unconformity Surface on which the Cenozoic sediments accumulated;

- **Proto-Namib Desert phase** (55 Ma - 20 Ma): the predominantly southerly wind regime during much of the Palaeogene arid periods resulted in the deposition of the Tsondab Sandstone Formation that is thicker and more extensive than its modern counterpart, the Sossus Sand Formation;

- **Karpfenkliff fluvial phase** (22 Ma - 14 Ma): A pluvial phase that reflected a change from arid to mesic, semi-arid conditions. This change in the Miocene to more humid, but nevertheless arid, conditions resulted in the relatively shallow incision of the Kuiseb-Gaub drainage, west of the Great Escarpment, and the deposition of the Karpfenkliff Conglomerate Formation. A 20 m - 40 m amsl high-stand is inferred from the Rooikop gravels which are interpreted to be fluvio-marine deposits (Miller and Seely, 1976). They believe these to be sheet-wash gravels deposited by the proto-Swakop River into a sheltered coastal embayment or tidal lagoon and reworked by marine and aeolian processes. The bedrock scarp demarcation of the eastern edge of the Kuiseb Delta could be the wave-cut cliff associated with this high stand;

- **Pedogenic phase** (14 Ma - 11 Ma): The onset of arid conditions in response to the establishment of the Benguela Current in the Late Miocene. A semi-arid climate and landform stability resulted in the development of the pedogenic Kamberg Calcrete Formation that caps the Tsondab and Karpfenkliff Formations;

- **Namib Desert phase** (10 Ma/7 Ma to present): following the full establishment of the Benguela current, conditions became progressively arid, interrupted only by minor humid fluctuations in response to the glacial/interglacial cycles in the Pliocene/Pleistocene, that are well documented in the northern hemisphere. These resulted in the deep incision of westward-directed drainage systems. The accumulation of the Sossus Sand Formation most likely occurred in the Pliocene while the deep incision of the Kuiseb Valley probably happened in response to epeirogenic uplift at the end of the Tertiary.

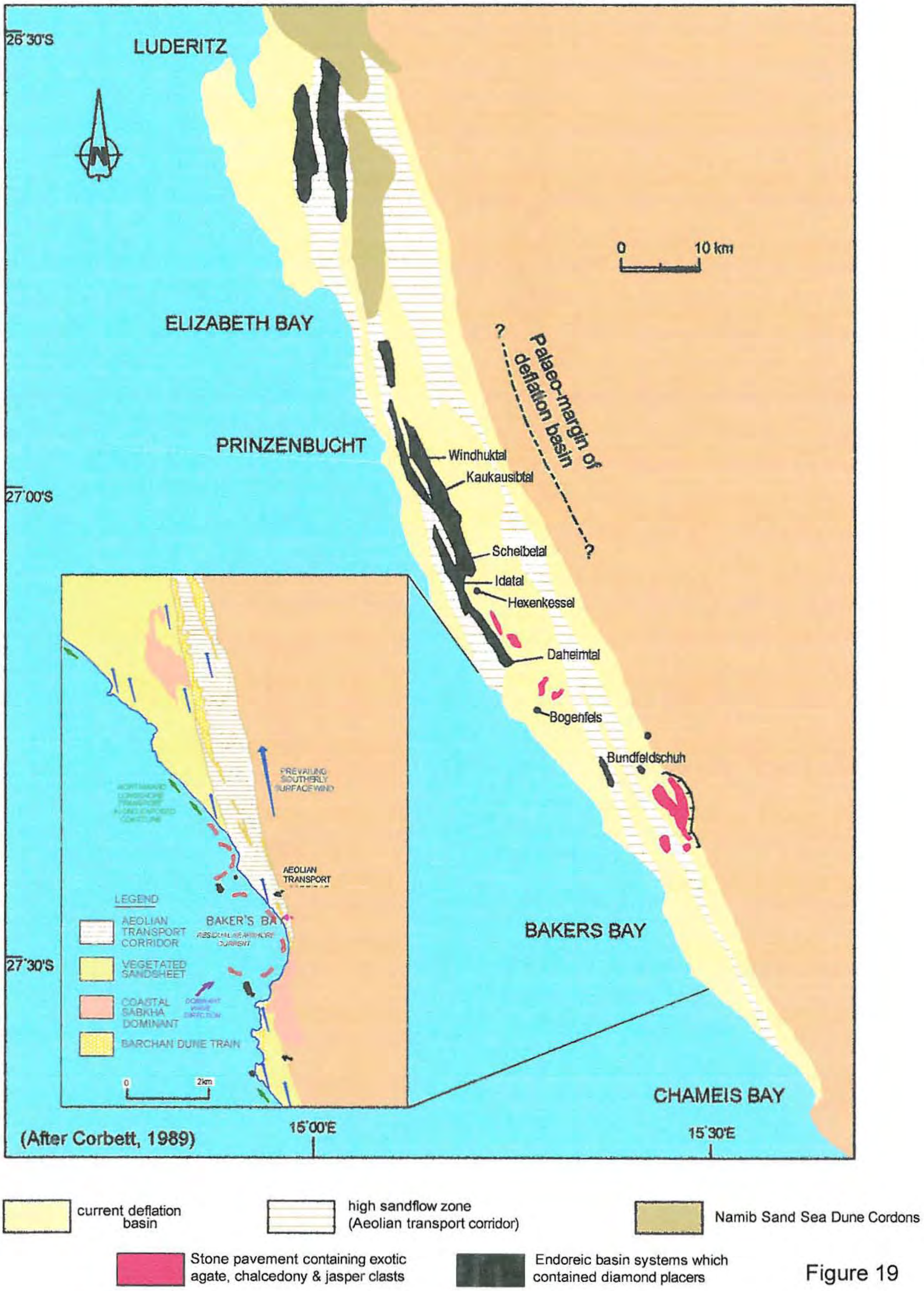
5.3.2 AEOLIAN PROCESSES

Kaiser (1926) noted that diamond concentration in the deposits being mined at that time, increased significantly in the vicinity of barchan dunes. Subsequently numerous studies of aeolian processes have been completed. However, studies by Corbett (1989, 1990, 1993, 1996), Ward (1987), Bestler (1996) and Kocurek *et al.* (1999) that deal quantitatively with aeolian processes, specifically within the arid southern Namibian coastal strip, are most appropriate for the evaluation of the study area.

Corbett (1989) examined the formation of aeolian placers deposits in the southern Namibian "Sperrgebied" in detail. He attributes the formation of the diamond placer deposits on the west coast to the complex interaction between fluvial, marine and aeolian processes that have operated on the west coast since at least the Oligocene (Figure 19). Marine transgressions/regressions, log-spiral bays, aeolian transport corridors, creep, saltation, sheetwash and heavy mineral concentration within micro-topographical bedrock irregularities and by kinematic shock waves, introduced by bottle-necks of various scales, are accepted as central concepts in the formation of aeolian diamond placers. The following summary, paraphrased from Corbett (1989, 1990, 1993, 1996), unless otherwise stated, encapsulates key concepts integral to the understanding of aeolian placer formation:

- The position of these aeolian transport corridors within the deflation basin is a function of the location of log-spiral and/or south-facing embayments along the coast, which in turn varies depending on sea-level movement. Modelling of a marine transgression in the south-facing Bogenfels re-entrant shows that this locality would have been suitable for the generation of major aeolian transport corridors. Geomorphic evidence suggests the presence of an aeolian transport corridor along the western margin of the embayment, which would have formed during marine regression(s). Sea-level fluctuation studies are integral in determining the position of these corridors. Aeolian corridors would have formed during marine

SPATIAL DISTRIBUTION OF AEOLIAN TRANSPORT CORRIDORS FROM CHAMEIS BAY TO LUDERITZ



(After Corbett, 1989)

Figure 19

transgressions and regressions, both above and below the present sea-level. Changes in sea-level and resultant periodical shifts in the positions of the dominant aeolian transport corridor would result in pulses of diamond transport within the corridors, by saltation and creep, at various elevations. Corbett (1989) suggests the mining of the aeolian, Fiskus Sandstone Beds at Elizabeth Bay and, previously, at Kolmanskop provide confirmation that this processes has taken place. Cooper (1990), during the prospecting and re-evaluation of the placer potential of Meob and Conception Bay areas, found that these deposits also had an aeolian origin.

- Weathering by salt and aeolian abrasion is able to alter and destroy raised beach deposits. The long time periods and the consistency of this weathering process is able to break down even the coarsest clastics rendering them available to be transported northwards by aeolian processes. The resultant surface lowering and destruction of these raised marine placer deposits enables diamonds situated within these gravels to be incorporated into the bedload creep population and moved northwards by the prevailing southerly winds. The sand supply and salt weathering is most concentrated in the foreshore and immediate backshore and therefore these processes are concentrated in these environments.

- The concept of aeolian transport corridors, independently maintained by secondary helical vortices in the planetary boundary layer, is central to aeolian diamond dispersal patterns. Corbett (1989) used sand traps and velocity metres to demonstrate that the position of barchan dune trains define the maximum aerial concentration of sandflow within these corridors. Consequently, the creep transport rate which is largely a function of collision of saltating grains with the bed, is the greatest within these corridors. Corbett (1989) demonstrated that the transport along the wind-aligned corridors is very fast in comparison within other parts of the deflation basin and suggests that diamonds may even have been moved onto the stoss slope of the barchan dunes which have been measured to move at between 35 to 60 m per year. This rapid and continuous transport of the resistant heavy mineral component through the endoreic basin system is highly conducive to placer formation. During phases of creep, the bedload would be size- and shape-sorted by the incorporation of different populations into kinematic waves travelling at different speeds. In turn, sandflow rate along the length of the basin would be controlled by coastal and basement morphology.

- Present creep transport measured within these deflation basins is low because current coastal morphology is not conducive for the development of high-energy aeolian transport corridors. However, a minor corridor currently generated at Van Reenen Bay does influence the sediment dispersal within Idatal. The aeolian transport potentially removed many of the diamonds from these basins, and transported them northwards. In response to aeolian size-, density- and shape-sorting, the smaller diamonds were preferentially removed by more rapid transport while the coarser material, forming part of the dynamic creep bedload, followed at a slower transport rate. Therefore, only the diamonds that were too large to be transported by aeolian creep can be interpreted to be residual lag deposits resulting from deflation and aeolian removal processes.

- Kinematic shock waves are introduced by bottle-necks of various scales, influencing sediment and heavy mineral dispersion patterns within the endoreic basin. Bedrock roughness plays an important role in sediment distribution, and provided there is continuous throughput of sediment, heavy mineral clusters will form by bedload segregation and winnowing in response to these micro-topographical features. Granule ripples also provide sites for heavy mineral segregation by subtle variation in the heavy mineral creep transport rate along the stoss slope relative to the bedform itself. South-facing slopes at the northern closure of endoreic basin act as large-scale bottlenecks. The advance of the bedload reaching these terminations appears to decrease, resulting in encroachment deposits which display an imbricate fabric within the surficial units. Continued saltation impacts on the bedload, resulting in a gradual change in particle pivot angles and imbrication. This culminates in increased bedform stability and reduced entrainment potential for diamonds once trapped within these imbricated particles and the formation of aeolian placers. The extent to which these aeolian deposits were modified by subsequent alluvial activity following palaeoclimatic changes and periods of increased rainfall could not be ascertained. This is mainly because the point at which the endoreic basins were fully developed cannot be accurately determined.

- Sheetwash, during infrequent thunderstorms, results in the formation of numerous localised drainages and run-off towards the west into the salt pans or shallow depressions in the rocky coastal plain in the Meob and Conception Bay areas (Cooper, 1990). Corbett (1989) notes that ephemeral fluvial activity operating within the Lüderitzfelder area did rework deposits within the basins located along the eastern edge of the main deflation basin. He suggests that these local fluvial systems transported diamonds, and most likely introduced material derived from raised shorelines further to the east into the southern end of Idatal (Refer: Figure 19). These old shorelines have been completely eroded away. The material deposited on the channel floor by these ephemeral drainages was subsequently reworked by aeolian processes and heavy minerals were incorporated into the placers within Idatal, Hexenkessel, Schiebetal and Kaukausibtal. A corridor has been located within Daheimtal, from which it entered Idatal and then Pomona (Refer: Figure 19). Diamond concentrations were exceptionally high within these corridors.

- Day *et al.* (1992) identified northward trending, coast-parallel depressions from boomer and airgun seismic records to the south of the study area, off the southern Namibia coast, which they interpreted as palaeochannels. This palaeochannel complex, that extends for about 50 km, is 15 to 20 m deep and several hundred metres wide and cuts into the Upper Cretaceous strata at depths of up to 90 to 105 m bpsl (Day *et al.*, 1992). They infer a fluvial origin for these palaeochannels based on their onshore extension, under fluviatile cover (Murray *et al.*, 1970). The palaeochannels are described as being infilled with acoustically structureless sediment and capped by a shallowly pitted upper surface that is at a similar elevation to the adjacent basement. Day *et al.* (1992) interpret the palaeochannels to be formed no earlier than the Late Pleistocene and most likely during the late Eemian and Wurm IIb regression to 130 m bpsl.

5.3.3 TSONDAB SANDSTONE FORMATION AND EVOLUTION OF THE NAMIB SAND SEA

Beneath the modern Namib Sand Sea lies the Tertiary aged, Tsondab Sandstone Formation that represents one of the largest preserved palaeo-ergs in the world (Bestler, 1996). Though the inclusion of this section may appear extraneous, it is a fundamental component in the construction of the revised model proposed for the formation of the marine placer deposits in Central Namibia (Chapter 9).

Bestler (1980) notes, based on the Gemini V satellite image of central Namibia, that the Namib Sand Sea comprises transverse dunes in the coastal part, longitudinal dunes or draa in the middle part and complex pattern dunes in the east. Bestler (1996) and Kocurek *et al.* (1999) concentrated their studies largely on the Tsondab Sandstone Formation and the evolution of the Namib Sand Sea. Bestler, (1996) notes that beneath the modern Namib Sand Sea lies the Tsondab Sandstone Formation, one of the largest preserved palaeo-ergs in the world. Based on biostratigraphy determined from giant avian eggshells (Pickford *et al.*, 1995), Kocurek *et al.* (1999) suggest that the Tsondab sandstones, which are up to 220 m thick, accumulated from the pre-Miocene to the Quaternary, with the bulk of the deposition occurring in the Miocene. This deposit sourced its sand mainly from the marine littoral and the alluvial deposits of rivers draining off the Great Escarpment and forms an important sand source for the modern Namib Sand Sea (Bestler, 1996). Kocurek *et al.* (1999) mapped the foresets of preserved aeolian Tsondab Sandstone dunes at Elim and Diep River along the eastern edge of the Namib Sand Sea. By computer simulations they tried to reconstruct these features and in so doing unravel the Cenozoic evolution of the Namib Desert. They conclude that the morphology is best satisfied by north trending, east migrating main bedforms, which had relatively large and slow-moving dunes superimposed on their eastern flanks that migrated to the north. Kocurek *et al* (1999) note that although there are a number of similarities in the mode of formation and basic configuration of the palaeo-dunes when compared to their modern counterparts, there are also subtle differences, the most significant of which is the stronger eastward migration component of the palaeo-dunes. Furthermore, their evidence suggests that the Tsondab dunes formed in conditions that were more humid than at present, with active dunes vegetated to some significant degree, and not under the same hyperarid climate that characterises the Namib today (Kocurek *et al.*, 1999). They conclude, based on the gross dune morphology, that the wind regime during the time of formation of the Tsondab Sandstone Formation must have been similar to that which formed the modern linear dunes. The onshore area east of the study area, located about a third of the way up from the southern edge of the Namib Sand Sea, would have been effected by the aeolian processes occurring in the Namib Desert at that time. Although a more easterly migration component is suggested by these studies, it is apparent that the southerly wind regime resulted in a net northward migration of sediment along the coastal plain adjacent to the study area.

5.3.4 INTERACTION BETWEEN MARINE AND AEOLIAN COASTAL PROCESSES

The correlation and interpretation of the interaction and chronostratigraphy of the palaeoshorelines, fluvial and palaeodune systems has improved considerably following the discovery and dating of avian shells in six different aeolianites (Dauphin *et al.*, 1993; Pickford *et al.*, 1993; Senut *et al.*, 1994; Senut *et al.*, 1995 and Pickford *et al.*, 1995). This has lead to a clearer understanding of the link between the preserved Namib palaeo-dune systems and behavioural changes in the Orange River, driven by sea-level change (Corbett *et al.*, 1995).

Eustatic sea-level changes in the Plio-Pleistocene exposed the continental shelf to sub-aerial processes and resultant geomorphic modification has resulted in a series of south-north trending endoreic basins (Corbett, 1996). The transgressive flooding of the main deflation basin of the Namib Desert culminated in the present day coastal morphology (Corbett, 1996). The flooding of these south-north linear depressions produced a headland configuration at the southern end, which was modified by wave-action to a log-spiral embayment, whilst a south-facing re-entrant bay formed at the northern end (Corbett, 1996). It is within these endoreic basins that the rich aeolian deposits formed by the interaction of ephemeral stream and aeolian processes (Beetz, 1926; Hallam, 1959; Corbett, 1989, 1993), aided by salt weathering and ablation that condensed the clast essemblage and left the diamond rich resistate behind as placer deposits (Corbett, 1989, 1993, 1996). The genesis of the placer deposits currently being worked at Elizabeth Bay have been attributed to the application of this model to now submerged palaeoshorelines situated to the south of this mine (Corbett, 1996). Ventifacts have also been recovered from the middle shelf (Corbett, 1996), suggesting that these processes may have also been active at depths greater than 100 m bmsl. Alternatively, the ventifacts could have been relocated to the middle shelf by erosion of coastal aeolian deposits during the Pleistocene regression.

The Anichab Salt Pan is a coast-parallel orientated deflation corridor that extends from Marshall Rocks/Gallovidia Reef to Hottentot Bay (Figure 20). Aeolian processes would most likely have transported diamonds deposited in the Marshall Fork/Gallovidia area, as well as beach gravels at the +3 m, +5 m and +9 m levels, down the corridor and deposited them into Hottentot Bay (De Decker, 1993). This aeolian process that occurs at other localities to the south (Corbett, 1989) may, in part, account for Sammy Collins's jackpot find in Hottentot Bay in the sixties.

5.3.5 DISCUSSION

It is evident from the studies that have been completed, that aeolian processes have played a significant role in the evolution of the coastline and diamond placer development along the Namibian coast.

The coast-parallel palaeochannels described by Day *et al.* (1992) as fluvial, could alternately be palaeo-aeolian corridors that have been in-filled subsequent to their erosion. Corbett (1989) mapped a number of coast-parallel aeolian corridors onshore, so given the numerous regressions that have occurred, similar linear depressions are likely to also occur offshore. The structureless nature of the in-fill sediment described by Day *et al.* (1992),

AEOLIAN TRANSPORT CORRIDOR - MARSHALL FORK/GALLOVIDIA REEF TO HOTTENTOT BAY

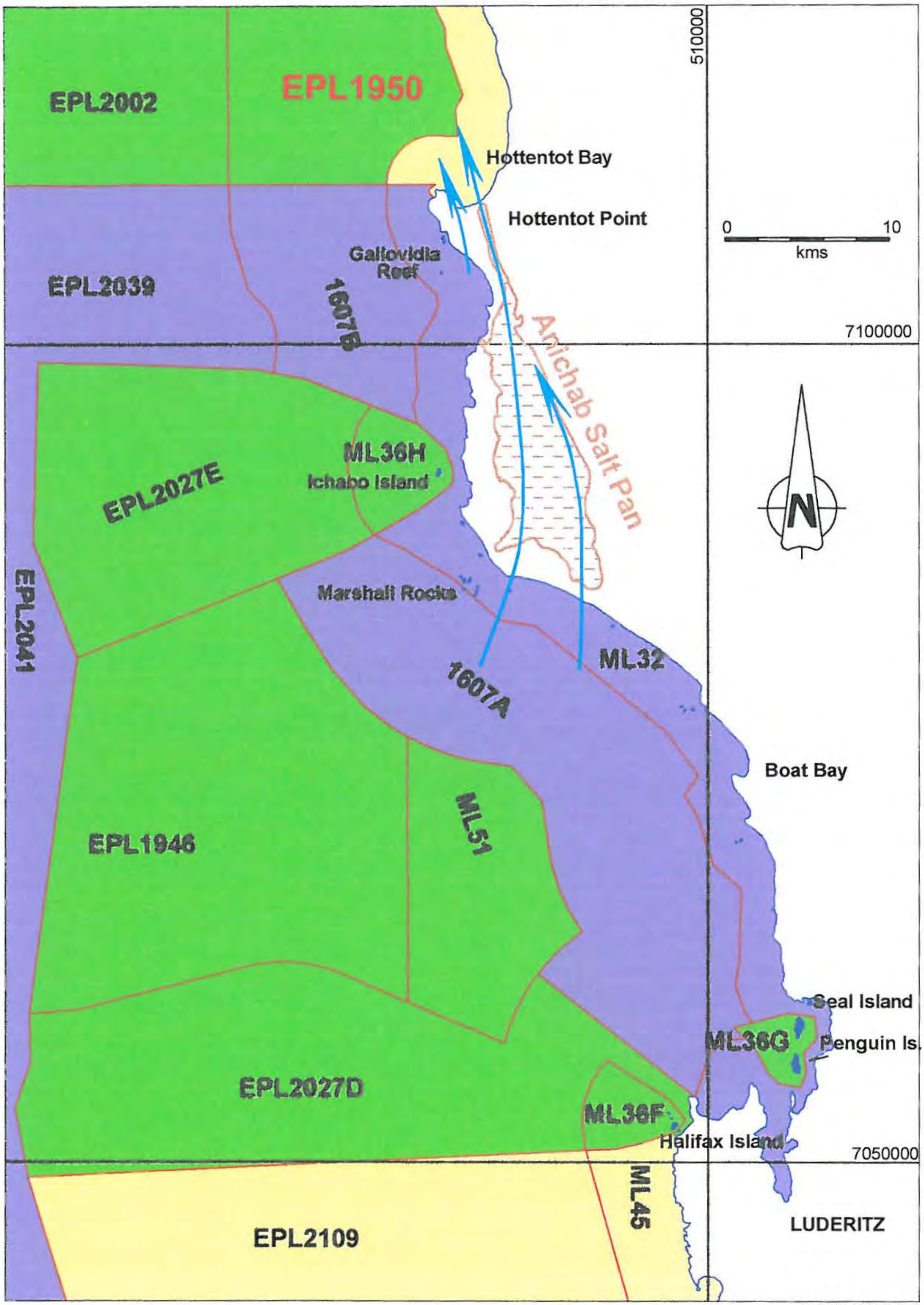


FIGURE 20

🟨 De Beers Consolidated Mines Ltd (NAMDEB)

🟪 Diamond Fields International (DFI)

🟩 Namibian Minerals Corp. Ltd (NAMCO)

↖ Aeolian Transport Direction

may be windblown sand, which has been shown to reach far offshore (Stuut, 2002) and fine sediment and biogenetic material which has settled out the water column, that fills many of the depressions on the inner shelf and forms the bulk of Holocene mud wedge at about 120 m bpsl.

It is important to note that as a result of the numerous transgressions/regressions during the Plio-Pleistocene period, the inner shelf both above and below present sea-level would have been extensively exposed to aeolian and coastal fluvial processes. Of particular importance to the genesis of aeolian corridors is the general geometry of the southern Namibian coastline (Refer: Section 3.2), particularly the inflection of the coastline toward the northwest north of the Orange River mouth with Elizabeth Bay being at the apex of this convex profile. The large volumes of sediment being deposited by the Orange River, combined with the bulge in the coastline in a region of prevailing southerly winds, makes the area between Chameis and Elizabeth Bays the ideal locality for the genesis of aeolian corridors and the inception of the Namib Sand Sea.

5.4 COASTAL ALLUVIAL PROCESSES

The Cenozoic succession in the Kuiseb Valley forms the northern boundary of the Namib Sand Sea. Though north of the area under review, the evolution of the Kuiseb River gives insight into the processes that are likely to have occurred in the Koichab River, adjacent to the study area.

Ward (1987; 1988), Ward and von Brunn (1985) studied the Cenozoic succession in the Kuiseb Valley in detail. Ward (1987) suggests that the Kuiseb River Valley formed the northern boundary of the Namib Sand Sea since the Early to Middle Pleistocene. Climatic conditions throughout most of the Quaternary are interpreted by Ward (1987) as being arid, with the run-off most likely coming from summer rainfall on the interior plateau. Ward (1987) believes that the lowermost 40 km of the Kuiseb River course to have been displaced about 30 km to the north, from Sandwich Harbour to its present position. The northwesterly alignment and northward displacement are most likely in response to progressive dune encroachment from the south. Bagguley (1996) recognised incised submarine canyons off the Kuiseb, Tsuachab and Koichab Rivers in a seismic and sequence stratigraphy study of the post-rift megasequence offshore Namibia, indicating that these were once large rivers.

Ward (1987) suggests that the Namib Unconformity Surface represents a pre-Cretaceous erosion surface, onto which the Cenozoic succession within the Kuiseb valley has been deposited. However, Partridge (1987) favours a Miocene age because of the lack of deep weathering, characteristic of the African Surface elsewhere in southern Africa. Ward (1987) states that the bedrock surface in southern Namib is not always deeply leached and kaolinitised and adds that the 4 km thick succession of Albian-Maastrichtian sediments (112 Ma to 65 Ma) in the Walvis Basin noted by (Dingle *et al.*, 1983) lends credence to a Late Cretaceous age for this unconformity. Considering the high erosion rates of up to 15 m per million years noted by Corbett (1989), the lack of a deeply weathered profile can easily be attributed to erosion by aeolian processes on the coastal plain, particularly in light of the well-bevelled, flat nature of the unconformity surface, indicative of significant ablation.

West of the escarpment, the reddish Tsondab Sandstone overlies the older basement rocks and is in turn covered by Sossus Sand Formation (SACS, 1980) of the main Namib Sand Sea, which began to accumulate toward the end of the Pliocene (Ward, *et al*, 1983; Lancaster, 1984). The Tsondab Sandstone unit was deposited as both dune and sand sheet structures with large northwest and northeast dipping cross-bedding foresets indicating prevailing southerly wind directions (Besler and Marker, 1979; and Ward *et al.*, 1983). Lancaster (1984) suggests they represent an accumulation of a major sand sea in the central and southern Namib over a period of some 20 to 30 million years before the Mid to Late Miocene.

Ward (1987) divides the Cenozoic succession within the Kuiseb Valley into two main categories, namely: 1) Pre-incision deposits that accumulated on the Namib Unconformity Surface, and 2) Post-incision deposits preserved mainly as terrace remnants within the entrenched Kuiseb drainage system. During the proto-Namib palaeo-desert phase in the Palaeogene, the Tsondap Sandstone Formation was deposited (Ward, 1987). His study shows that the overlying Miocene fluvial gravels of the Karpfenkliff Conglomerate Formation, were deposited by seasonal or ephemeral streams during a more humid period that occurred concurrently with a sea-level high stand responsible for the deposition of the Rooikop gravels. The Kamberg Calcrete Formation formed as a result of pedogenic processes induced by the semi-arid climate and landform stability toward the end of the Miocene (Ward, 1987). Ward (1987) suggests that the Oswater Conglomerate Formation was deposited in an ephemeral braided-fluvial system in a more effective hydraulogical regime than that experienced by the Kuiseb during the latter stages of its evolution. The Homeb Silt Formation and the Awa-gamteb muds were deposited during a second aggradational phase and the Gobabeb Gravel Formation incised these older deposited during the latter stages of the Pleistocene (Ward, 1987).

The predominantly hyper-arid desert conditions during the Quaternary were interrupted by short-lived humid periods during which the Khommabes Carbonate Member of the Sossus Formation and the calcareous Hudaob Tufa Formation pan deposits were precipitated at localised spring/seep sites (Ward, 1987). Ward (1987) suggests that the flood events responsible for these post-Pleistocene erosional and depositional cycles could have been caused by a base level change or in response to climatic changes in the rivers catchment area. As this is interpreted as being an arid period in southern Africa (Tankard and Rogers, 1978) higher rainfall seems improbable, but similar high run-off noted at the Swakop, Omaruru, Huab and Hoanib Rivers draining westward suggest that a climatic anomaly may have existed at that time along the western escarpment (Ward, 1987). Vogel (1983) obtained an age of 33 000 ka from ^{14}C analysis of terrestrial snail shells, suggesting that the Hoarusib River deposits in northern Namibia, sedimentologically similar to the Homeb Silt Formation, accumulated prior to the Last Glacial Maximum.

Being far to the north of the study area, the detailed description of these units are not critical to the current study, however, the examination of the environmental conditions responsible for their formation offers insight into the conditions and processes occurring along this coastal plain throughout the Cenozoic. These can be extrapolated southward to gain insight into the processes active in the formation of the landscape adjacent to the study area.

5.4.1 DISCUSSION

The combined role of aeolian processes and the westward flowing coastal drainages, between the Kaukausib and the Kuiseb, is central to the revised model for placer formation in central Namibia.

Ward (1987) highlights the fact that the Kuiseb River forms the northern boundary of the Namib Sand Sea, but does not go into specific detail as to the processes responsible for curtailing the northward migration. The existence of the Kuiseb River valley indicates that this river was able to transport sediment westward into the Atlantic at the same rate as it was being deposited into the valley by the wind. This "flushing" may have occurred during sporadic flood events, following extended periods of aeolian deposition, clearing the unconsolidated, braided sediments clogging the waterways within the valley. Ward (1987) suggests the generation of pans and precipitation of the Khommabes Carbonate Member can be linked to total clogging of the drainage, as aridity increased in the late Quaternary, that finally choked the Kuiseb River. The Koichab, Tsauchab and Tsondab Rivers, to the south, are likely to have experienced a similar fate, where aeolian sand deposition exceeded fluvial erosion and the western extent of the rivers was cut off from the sea. The Koichab River is of particular importance because, after the Kaukausib River that reaches the Atlantic seaboard at Elizabeth Bay, it was the first westward draining river which slowed the northward migration of the Namib Sand Sea. This coastal process is important not only in the formation of aeolian placer deposits, but is also fundamental in the revised model for marine placers evolution in central Namibia, presented later in this thesis (Chapter 9).

6. EARLY INVESTIGATIONS UNDERTAKEN IN HOTTENTOT BAY GRANT

No marine diamond placers are currently forming within the case study area, nevertheless minor modifications may occur along the shallower eastern edge of the existing deposits. Evidence required to support a model for placer formation, must be sought using all the geological and geophysical data available from the area. A sound understanding of the mechanisms involved in placer formation and controls on grade distribution form the foundation for subsequent target delineation and prioritisation. This chapter reviews geological and geophysical data from the coastal plain and shallow marine zone, east of the study area and summarises the principal findings of the publically available, placer-related study of the onshore area adjacent to the HBG study area, as well as incorporating additional important factors from various studies regarding the diamond potential of the onshore area south, adjacent and north of the study area.

6.1 INTRODUCTION

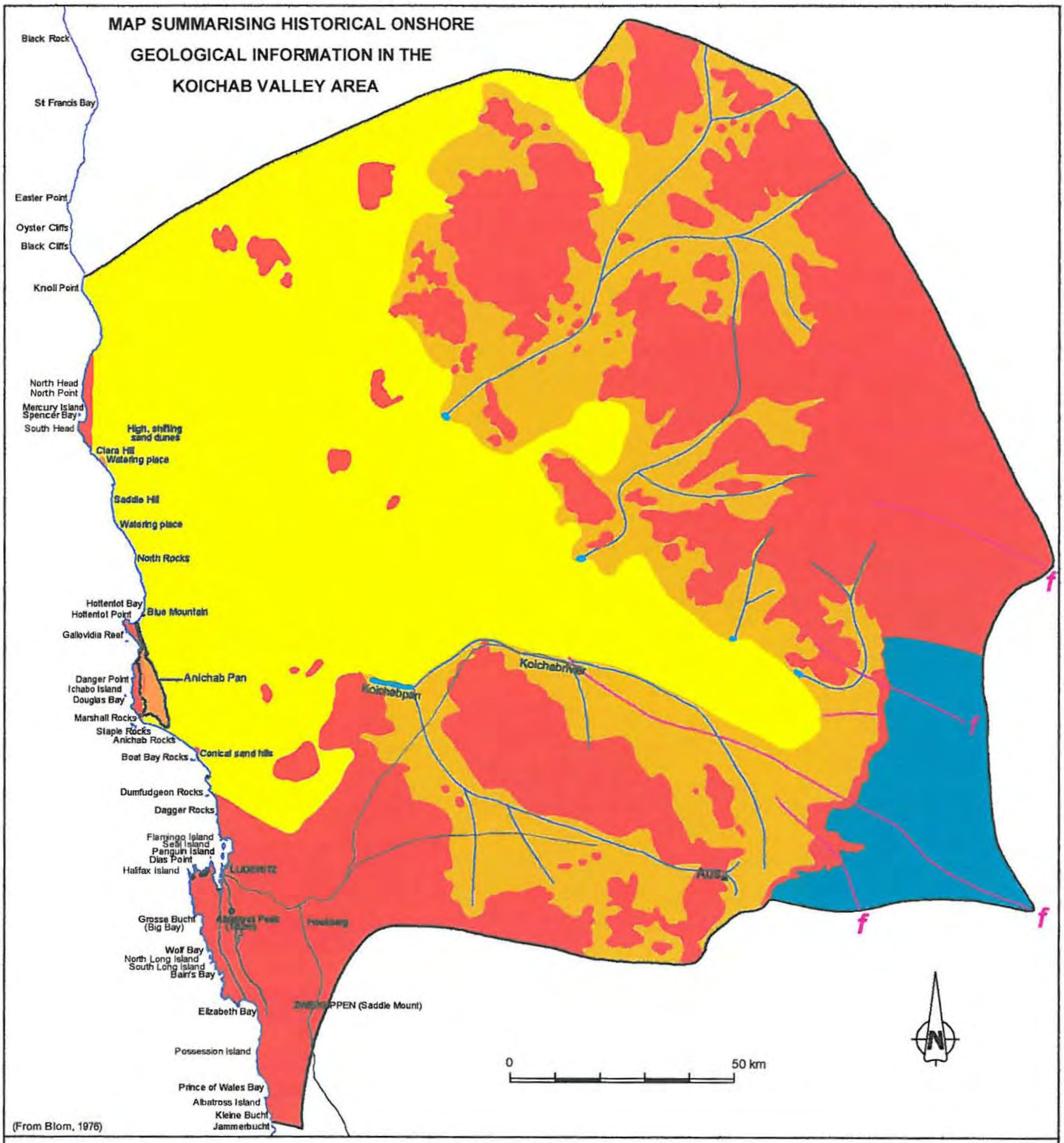
Early geophysical investigations undertaken on the coastal plain and in shallow marine zone, east of HBG study area, were examined and collated and interpretations have been drawn. Some of these studies, particularly the hydrological investigation for the supply of water to Lüderitz (Blom, 1976; De Beer *et al.*, 1986), are not specifically related to the current study, but do contain relevant geological data. In some instances, re-interpretation of these data were required to present it in a more case-specific format, although the original integrity of the data has been kept intact. Furthermore, all the pertinent data from these unrelated, historical geological studies were digitally collated and incorporated into the map of the case study area. Figure 21 was compiled using all the available historical data for the area and should be used as a reference for this chapter. This information is integral to the comprehensive examination of the poly-cyclic processes hypothesised to be responsible for the formation of marine placers in central Namibia (Chapter 9), particularly in light of the paucity of other conclusive supporting evidence.

6.2 EXAMINATION OF GEOLOGICAL AND GEOPHYSICAL DATA AVAILABLE FOR THE ADJACENT ONSHORE AREA

6.2.1 LITHOLOGY

The adjacent coastal strip is predominantly sand-covered, with little exposed bedrock (Kroner and Jackson, 1974). Onshore, geological mapping at Saddle Hill Prospect and the region to the north of Clara Hill Prospect (Refer: Figure 21) shows that the bedrock comprises feldspathic orthoquartzite and laminated micaceous quartzite with occasional mafic dykes (Kroner and Jackson, 1974). Kroner and Jackson (1974) indicate that the main shear orientation plane direction trends north-south, while fractures and joints are orientated in a northwest-southeast direction with another fairly prominent set trending northeast-southwest. Hottentot Point

MAP SUMMARISING HISTORICAL ONSHORE GEOLOGICAL INFORMATION IN THE KOICHAB VALLEY AREA



(From Blom, 1976)

🟨	Dune Sand		Recent to Tertiary
🟧	Alluvium		
🟦	Quartzite	Kuibis Formation	Nama System
🟥	Metasediments - different varieties of gneiss, diorite, granodiorite, acidic lavas and amphibolite		Namakwa & Maltahohe Provinces
— f —	Fault		
●	Pan		
～	Rivers		
～	Roads		

Figure 21

in the south (Refer: Figure 21) is formed of Late-Precambrian metagabbroids and amphibolites (Kroner and Jackson, 1974). This differs from that noted offshore in ML103a where sampling log sheets, completed by Namco's onboard geologists, indicate that excavations in SHP generally terminated on melanocratic gneisses and quartz/chlorite schists (Reference: Namco daily log sheets, 1996). However, in some instances a "false" footwall of sandstone, calcarenite, metaquartzite and various clay horizons was intersected.

6.2.2 DESCRIPTION OF THE DIAMOND OCCURRENCE IN DIAMOND AREA II

Gevers (1953) conducted a detailed investigation in Diamond Area II for Industrial Diamonds of S.A. Ltd. Gevers's (1953) study for the area adjacent to the HBG, though dated, is the most comprehensive diamond-placer-related study presently available. His report offers invaluable insight into the historical mining and prospecting activities conducted by Industrial Diamonds of S.A. Ltd., as well as processes active in the formation of diamond placers on the coastal plain, east of the study area. A summary of key information paraphrased mainly from Gevers's (1953) report is presented below:

Range (1912) noted a kimberlite pipe situated on the farm Barby (Kunjas), near Helmeringhausen, in the upper drainage area of the Konkip River that currently joins the southward draining Fish River. Gevers (1953) points out that only a few kilometres to the west of Kunjas the catchment drains westward terminating in the Koichab Pan, implying that the Konkip River may have flowed westward at some stage in the past, having tapped diamonds from this kimberlitic source. In the area south of Lüderitz, diamonds have been recovered from alluvials, but no economic deposits have yet been discovered in Tertiary River gravels at Hottentot Bay (Gevers, 1953). Gevers (1953) states that the Miocene period must have been relatively wet, as evidenced by hoof prints of rhinoceros, giraffe and antelope that have been found in the clayey Pleistocene deposits near Kolmanskop. Gevers (1953) suggests that during these wetter periods the Koichab River, now buried beneath the sand dunes, must have continued westward to reach the sea near Anichab, or Hottentot Bay, or south of Saddle Hill. Gevers (1953) states that prior to the 1st World War, specimens of concentrate from Bogenfels to Conception Bay were sent for analysis and not a single pyrope garnet was found in all the samples submitted. This included concentrated material from the washing plant at Saddle Hill and from Spencer Bay. Furthermore, no pyrope garnets had been recovered from any of the Tertiary alluvial deposits on the coastal littoral. The fact that this kimberlite pipe is situated off craton, together with the results of the garnet analysis, indicate that it is highly unlikely that the diamonds found in the study area originated from this source.

Gevers (1953) describes the marine diamond placer mine at Saddle Hill as follows:

The diamondiferous terrace lies beneath a modern aeolian and/or marine sand cover. The overburden is about 12 m thick. The underlying terrace extends inland in an arcuate crescent, measuring about 1100 m, from the current relatively straight shoreline. The thickness of the gravel terrace is variable, but reaches a maximum thickness of about 1.8 m, with sorting and roundness of clasts improving towards the base. In the west, where the old shoreline is backed by quartzites, the terrace comprises angular quartzite rubble and grades are low. While diamond concentration was only high in bedrock irregularities on the western edge of the terrace, along the outermost northeastern rim of the terrace in the palaeo-embayment the richest concentrations were deposited on the relatively smooth, gently sloping sandstone of the "False Bed[1]". The main terrace mined south of Saddle Hill ridge is situated about 2.5 m bmsl and is overlain by a yellowish clayey sand about 1 m thick, but reaching a maximum thickness of 3 m in an area referred to as the "Anomaly" excavation and is interpreted to be deposited in a lagoonal environment identical to that seen at Spencer Bay (Gevers, 1953). The water pumped that seeps into the excavations from above the "False Bed" and below the impermeable clayey lagoonal sediments is "fresh", though somewhat brackish, indicating an easterly terrestrial origin (Gevers, 1953).

Gevers (1953) describes the "False Bed" to comprise layers of lime-cemented lighter layers alternating with softer, reddish brown, more ferrugenous beds increases rapidly, to over 65 m in thickness, to the southwest. About 5 km to the south, in the Dune Valley, near "Gibraltar Rock", it is absent, suggesting that this sandstone unit is in-fill within a deep valley. Gevers (1953) notes that this reddish sandstone, with intercalated well rounded coarse grains and smallish angular grains, has been found beneath the marine terraces or more recent aeolian sands at Spencer Bay, Oyster Cliffs and Meob and Conception Bay and as inselbergs east of Spencer Bay and at Uri-Hauchab at 25 km east of Oyster Cliffs. Gevers (1953) interprets this sandstone unit to be an older infilling of topographical lows within the old land-surface similar to the aeolian units deposited during periods of aridity in the Miocene stream courses south of Lüderitz

The significant magnetic "Anomaly" at Saddle Hill was interpreted as either a placer deposit at 45 m depth or a ultrabasic intrusion at 140 m depth, such as the hornblende peridotite stock, opposite Ichabo Island, 40 km south of Saddle Hill (Gevers, 1953). The "Anomaly" was drilled and logged by Gevers (1953), from top to bottom, as follows:

Top - 12 m of loose aeolian sand; 3 m of yellowish clayey lagoonal sand; about 1 m of marine terrace gravel; followed by reddish-brown grading to yellowish-grey sandstone of the "False Bed" down to a depth of 73 m; then a angular quartz in a sandy matrix; a solid glassy quartz in core marked 80 m; grading into slightly brownish quartz with small mica flakes and some feldspar at 90 m; soon after which at a depth of 91.5 m the hole was terminated. The final conclusion was that the anomaly was caused by the significant proportion of magnetite in the thick "False Bed" sandstone which fills the deep valley incised in this area to a depth of approximately 95 m. The general axis of the elongate zone of higher magnetic values, parallels, but is located slightly seaward of the subcrop of the main diamondiferous marine terrace at Saddle Hill.

Gevers (1953) states that the two richest deposits at Saddle Hill were in two depressions, about 100 m to 200 m long, separated by a low sandstone ridge, westward of a high marginal dune. Gevers (1953) noted the largest diamonds were recovered on the upper slopes of a broad south-facing depression and that sheet-wash was most likely responsible for the small patch of diamonds within a linear depression west of the main workings and in a small fan at the mouth of the valley. Gevers (1953) states that where the old shoreline straightens towards the north to follow the present shoreline more closely, the diamond content falls off significantly.

---

[1] The "False Bed" is most likely the Tsondab Sandstone (SACS, 1980), that represents an accumulation of a major sand sea in the central and southern Namib over a period of some 20 to 30 million years before the mid to Late Miocene (Lancaster, 1984).

Gevers (1953) states that the diamonds produced over a six year period (1948 - 1953) by Industrial Diamonds of South Africa Ltd., just south of Saddle Hill, averaged 0.05 to 0.08 carats per stone (cts/st). However, some larger diamonds had been recovered from a small area on the northern slopes of Saddle Hill. Beetz (1938) noted that there was not a steady decrease in average diamond size from Pomona to Conception Bay, but rather variations, particularly in the northern section of the diamondiferous coastal belt. Beetz's (1938) study also mentions that in the former Lüderitz diamondfields, stones of up to 35 cts in weight were recovered, but these were a rare occurrence in a population that averaged 0.125 to 0.17 cts/st . Gevers (1953) notes that to the north of the main workings at Saddle Hill, toward Spencer Bay, some larger average diamond sizes were recovered from gravels deposited on the well developed wave-cut bench at +3 m amsl.

Gevers (1953) notes that the diamonds were recovered from an area several hundred acres in extent on the southwest slope of Saddle Hill Ridge. Production information indicates that grades reduced southwards toward the low-lying shoreward portion of the gradually rising slope and again eastwards towards the high marginal dune. The highest grades are said to have been recovered from typically aeolian concentrate overlying less windswept material in a broad shallow depression.

Other relevant diamond-related information for the onshore deposits is the production figures for the Saddle Hill area (as supplied by the Directorate of Mines, Namibia) shown in Table 4(Schneider and Miller, 1993).

TABLE 4: Production figures: Saddle Hill Area- from: Directorate of Mines, Namibia (Schneider and Miller,1993).

Year	**Production (Carats)**	**Year**	**Production (Carats)**
1944	19	1954	1095
1946	1521	1955	15579.6
1947	8812	1956	17716
1948	11270	1957	13434.6
1949	36682.75	1958	6431
1950	127009	1959	2878.15
1951	24907.5	1960	315
1952	24745	1962	62
1953	19797.25	1963	2.75
		TOTAL	**312277.6**

Tidal Diamonds recovered another 585 diamonds weighing 35 carats during prospecting operations in the area in 1965. Because part of this operation included the treatment of tailings dumps the average diamond size may not be representative of the total diamond size population(Schneider and Miller, 1993). In order to fulfill their licencing requirements, Tidal Diamonds South West Africa (Pty) Ltd had Sullivan (1966) draw up a report on their prospecting operations carried out during the twelve months ending 31 December 1965. A summary of the most important points extracted from Sullivan's (1966) report with regard the diamond placer deposits are presented below:

Wide diameter drilling, churn drilling, 195 m of trenching, dump sampling and beach sampling above the high water mark were carried out at Saddle Hill. One hundred and four, 1.2 m diameter holes, of which 100 were acceptable (1042 m total depth), were drilled on a 152 m grid. Results are summarised in Table 5 below:

TABLE 5: Drilling Results - Saddle Hill area, Tidal Diamonds South West Africa (Pty) Ltd. (From Sullivan, 1966).

Method	**No.**	**Bulked m^3**	**screened m^3 (-10 to +1 mm)**	**No. of Diamonds**	**Cts**	**Grade (Cts/100m^3)**	**Av. Stone size**
Large diameter drill	100	313.2	33.325	71	7.225	2.31	0.1
Large diameter drill	4			10	0.9		0.09
Trenching		69.75	10.9	29	2	2.87	0.07
Tailings Dumps		1326.6*	141.15	378	18.5	1.39*	0.05
Old Mine Dumps		326	5.615	86	5.49	1.68	0.06
Beach Sampling		51.7	6.12	11	0.85	1.64	0.08
TOTAL/AVERAGE		**2087.25**	**197.11**	**585**	**34.965**	**1.68**	**0.06**

* Bulked cubic metres and grade calculated using the ratio of screened material to bulked material obtained from the large diameter drill results.

Wide diameter drilling, churn drilling and dump sampling were carried out at Saddle Hill North. Sixty, 1.2 m diameter holes, of the planned 100 were completed and a total of 1367.8 m drilled on a 152 m grid, by the time the report was submitted. Results are summarised in Table 6 below:

TABLE 6: Drilling Results-Saddle Hill North, Tidal Diamonds South West Africa (Pty) Ltd. (From Sullivan, 1966).

Method	**No.**	**Bulked m^3**	**screened m^3 (-10 to +1 mm)**	**No. of Diamonds**	**Cts**	**Grade (Cts/100m^3)**	**Av. Stone size**
Large diameter drill	60	143.4	16.055	26	2.2	1.53	0.08
Dump Sampling			0.92	16	1		0.06
TOTAL/AVERAGE		**143.4**	**16.975**	**42**	**3.2**	**1.53**	**0.07**

Gevers (1953) states that all the diamonds deposited at Saddle Hill Prospect come from the sea, even those 1.5 km up the slope southeast of Saddle Hill ridge, though redistributing by the rain-wash and wind are considered to play an important role in the final configuration and concentration of the deposit. The latter is said to account for the concentration of diamonds predominately on the northern termination of south-facing embayments (Gevers, 1953), as noted by Corbett (1989) in his study in southern Namibia. Gevers (1953) states that no deflation diamonds have ever been recovered beyond the neck on the northwards facing slopes of the Saddle Hill ridge. Gevers (1953) notes that the angular quartz rubble at the base of the sandstone of the "False Bed" is different from the Tertiary alluvial gravels south of Lüderitz from which diamonds have been recovered. Nevertheless, this horizon is considered by Gevers (1953) as being the possible source of the diamonds, despite having been tested on a limited scale and found to be barren. Gevers (1953) suggests that the sporadic nature of these drainages would not have allowed for the concentration of diamonds resulting in poorly-sorted, diluted deposits requiring further processing by aeolian or wave action to winnow the deposits and increase the grade to economical levels. Gevers (1953) emphasises the importance of wind concentration of the diamonds and formation of the thin, diamondiferous deflation residues in the Lüderitz fields and along coastal plains, stretching as far north as Conception Bay.

Gevers (1953) investigations at Saddle Hill revealed no relics of terraces higher up at 30 m amsl, though at Sylvia Hill, numerous smallish round pebbles were found on a promontory at about 40 m and a well rounded marine shingle in a little depression on its northern side below 30 m. However, 2300 m south of the embayment, thin discontinuous diamondiferous gravels were found within the overburden of sea sand (Gevers, 1953). Gevers (1953) notes that many boreholes and two excavations have been used to test the potential of viable marine terrace gravels, along the narrow coastal strip, down to the 26th Parallel of Latitude. Diamonds were found in a gravel of limited extent lying above the main terrace horizon. Gevers (1953) conclusion from his assessment of the Saddle Hill prospect can be summarised as follows: It is not surprising, owing to the thick wind-blown sand cover and little potential of any other economically exploitable deposits, that after the aeolian diamond deposits at Saddle Hill, Spencer Bay and Conception Bay had been mined out in the early 1920's, interest in this area waned.

6.2.3 HYDROLOGICAL AND GEOPHYSICAL STUDY - KOICHAB VALLEY

Although it may not be immediately apparent what these studies have to do with marine placer deposits, bedrock elevations derived from the borehole logs and geophysical sections, transposed onto plan, provide an indication of the buried Koichab palaeo-channel beneath the blanketing Namib Sand Sea. The role of the Koichab River is integral to placer formation within the study area.

Blom (1976) undertook a hydrological study of the Koichab Valley and Anigab areas, aimed at intersecting fresh water to supply Lüderitz town. The water shortage in the area was particularly severe during the Hottentot War (1904 to 1907), during construction of the railway line and after the discovery and diamond rush at Kolmanskop (Blom, 1976). In 1914 Dr Range, a geologist, was contracted to write a report to the Governor assessing the groundwater occurrence potential of the area, based on the drilling and associated geological investigations that had been undertaken. In 1966 and 1986 studies were conducted by the Geological Survey and the Council for Scientific and Industrial Research (CSIR) to delineate the palaeo-Koichab drainage aquifer beneath the northward migrating sand dunes of the Namib Sand Sea. These studies were aimed at the geo-hydrology of the area, but offer insight into the topography and characteristics of the sediments beneath the aeolian dunes that currently blanket the area between Lüderitz and Walvis Bay. The following paraphrased points, relevant to the understanding the formation of the marine placer deposits in the study area, were extracted from Blom's (1976) report:

- The Koichab River headwaters are presently on the farm *Kubub 15* at 1 555 m above sea-level. The headwaters follows a 25 km wide westward trending valley. The non-perennial river heads northwards from its source, then northwestwards before terminating against a series of north-south orientated sand dunes which block the valley. The dry river valley ends in a series of pans, at an elevation of about 350 m, bounded to the north and west by high sand dunes. A number of dry river beds join the valley from the south which only run during heavy downpours and then drain away into the pans.

- The stratigraphic column of the Koichab Valley area is described in Table 7.

TABLE 7: Stratigraphy of the Koichab Valley area (From: Blom, 1976).

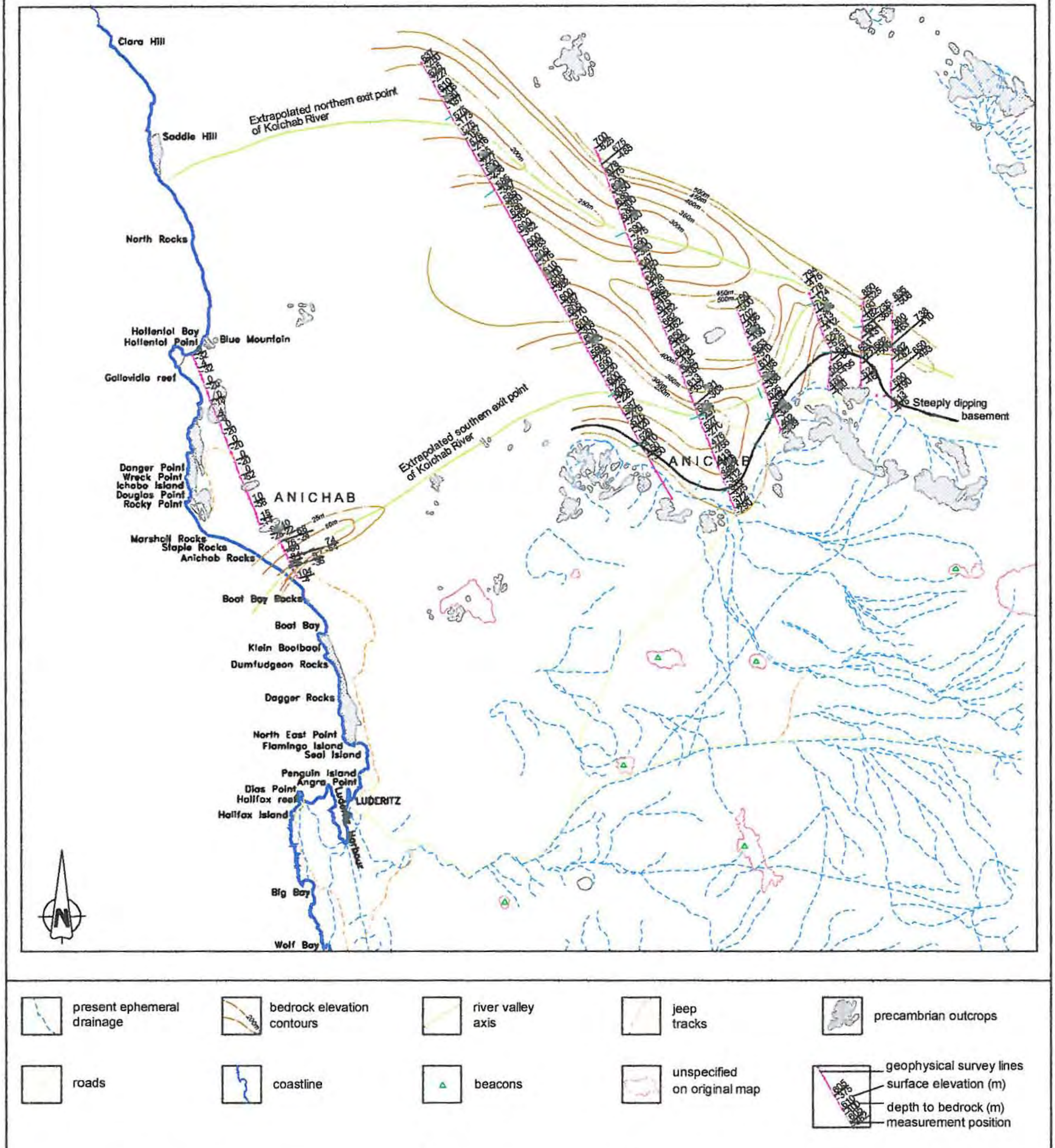
Tertiary to recent		Red coloured dune cordon up to 15 km wide.
		Alluvium can reach 200 m thickness.
		Calcrete mainly on the high lying areas of the valley can reach 6 m thickness.
Nama Group	Kuibis Formation	Shale with overlying quartzite and black limestone are found at the Terrace Plateau on the southeasterly end of the Koichab Valley.
Namakwa Province	Garub	Highly metamorphosed metasediments like marble, calc-granofels, skarn, granofels, meta-quartzite, sillimanite-cordierite-granite-gneiss.
	Horab River granulite	pre-tectonic mafic suite metamorphosed to granulite during the intrusion of syn-tectonic charnockites.
	Tsirub gneiss	The Tsirub gneiss is an intrusive within the Horab River granulite. This augen gneiss has been subjected to a number of phases of re-foliation.
	Biotite gneiss	Mainly in the Aus area. A pre-tectonic biotite layered gneiss with the same structure and characteristics as the adjoining Garub rocks.
Maltahöhe Province		Found north of Koichab Valley. Highly sheared and foliated diorite-granodiorite, metamorphosed amphibolites and mylonites are found.

- The area has seen numerous phases of structural deformation resulting in southeasterly trending isoclinal and open folds, shears and mylonitic zones. One of the shearing events appears to be pre-Nama, while the other two observed appear to be of Tertiary age or, are in fact older, but have been reactivated during more recent times.

- A percussion drilling programme was approved and 24 holes were drilled, most of which were situated in the lower reaches of the Koichab Valley. The stratigraphy varied from hole to hole with some holes containing thick clay units while others contained more gravel-rich sediments. An accurate stratigraphic sequence could not be determined due to contamination commonly associated with percussion drilling. Based on the 10 holes drilled, the alternating clay-, sand and pebble- and cobble-filled river channel intersected in the Anichab area (Figure 22), was interpreted as the easterly extension of the buried Koichab channel. However, due to the dune cover and wide spacing of the drill lines this could not be confirmed. The most unconsolidated gravel was intersected in drillholes 8677, 8684 and 8690 (Refer: Figure 22). Underground water flow measurements indicate a west-northwest direction under the dunes (Blom, 1976). Drill-hole bedrock intersections in the centre of the channel in the Anichab area are at 60 m below sea-level. Based on the drilling results Blom (1976) interprets the following geomorphological phases for the Koichab Valley:

1) The rainfall in pre-Tertiary times in this area was significantly higher than at present and, together with the uplift of the coastal plain (or lowering of base-level), resulted in increased run-off and erosion of up to

MAP SUMMARISING HISTORICAL GEOLOGICAL AND GEOPHYSICAL INTEPRETATIONS - KOICHAB VALLEY AREA



(after De Beer, Blume, Coetsee, 1986)

Figure 22

250 m below the current land surface.

2) During the Tertiary degradation resulted in an overall lowering of the surface, lowering stream gradients and resulting in a braided channel environment. Ultimately, this caused stream aggradation, congestion and a significant reduction in water flow.

3) The fluvial sequence was subsequently covered by northward migrating sand dunes during a particularly dry period, which most likely corresponded with the Cenozoic deposition of the Kalahari sands elsewhere in southern Africa. The weakly-flowing Koichab, Tsondab and Tsauchab Rivers, with relatively small catchment areas, were not able to erode and transport the aeolian sediments being deposited into them along the western extremities of the coastal plain. They were eventually cut off from the sea during this period. Other drainages, like the Kuiseb, Swakop and Hoarusib Rivers with bigger catchment areas, changed course to accommodate the moving sand and/or were able to flush the sand during high rainfall years.

In a follow-up study, De Beer *et al.* (1986) re-examined the Koichab and Anichab areas in order to establish an accurate estimate of the ground water reserves. They used time-domain electromagnetic and direct current resistivity surveys. Limited success was achieved using these methods due to the depth of the bedrock beneath the dune and alluvium sand cover, as well as the presence of clay horizons and gravel aquifers. The geophysical records were subsequently correlated with the drilling information obtained by Blom (1976), to improve the accuracy of the interpretation. The geophysical profiles were represented as individual traverses in the De Beer *et al.* (1986) report. In order to get a better idea of the relative positions of these channels with respect to the offshore features the author transposed the bedrock intersection elevations onto plan view and contoured these depths (Refer: Figure 22). Even though the lines are widely spaced and the interpretation only indicative of the broad topography, the result shows the two channel features buried beneath the dune cover, one to the south heading toward Anichab and another heading toward HBG. The deep, in-filled channel to the north does not appear to be connected to the southern channel towards the west. The survey does not show conclusive evidence that the Koichab River system enters the sea at Anigab. The channels, as defined at present, show a tendency to swing northwards on approaching the ocean (De Beer *et al.*, 1986). The report states that the relationship between the two channels is not clear, but one interpretation could be that the channel to the south was blocked by aeolian sediment forcing it to migrate northward with time, until the consistent influx of sand blocked this passage to the sea as well and covered up the valley entirely.

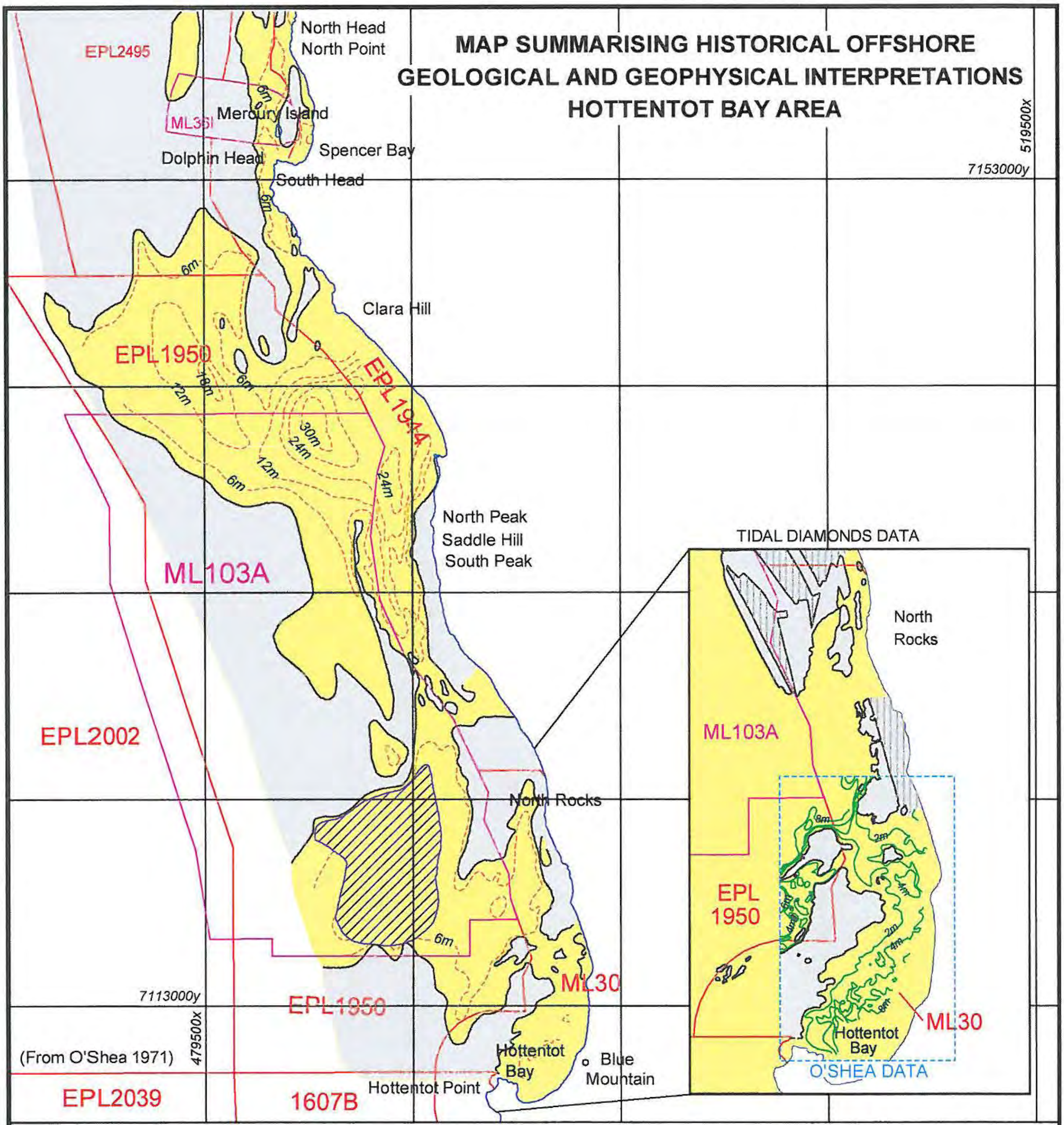
6.3 REVIEW OF HISTORICAL MARINE GEOPHYSICAL DATA

O'Shea (1971) was the first to examine the inner shelf area of the west coast in detail focussing on the inner shelf, between Walvis Bay and the Olifants River mouth. O'Shea's (1971) interpretations and results for the Hottentot Bay area, provide the most detailed marine data available, prior to this study in 1994. They offer a regional insight into the geophysics and geology within the 0 m to 60 m water depth zone.

The regional geophysical and relatively detailed sampling survey that provided the information required for O'Shea's (1971) study was undertaken by various companies including Tidal Diamonds, Ocean Science and Marine Diamond Corporation off the vessels M.V. *Xhosa Coast*, M.V *Rockeater* and S.T. *Bellatrix*. O'Shea (1971) integrated this information with regional sampling information obtained using the *Emerson K* in 1965. Various continuous sub-bottom profiling systems were used namely; Sparker, Lizard and Pinger. Side-scan sonar records were also collected and interpreted in selected areas (O'Shea, 1971). The original sparker survey was run on survey lines 9.6 km long in a coast-perpendicular direction and were spaced 1.6 km apart. These survey lines were adequate to, with some extrapolation, determine the rock and sediment distribution and thickness along the inner portion of the inner shelf up to about the 60 m isobath. A detailed sedimentological study was conducted using sonoprobe samples that were collected on grid with lines 66 m apart and with drill holes spaced at 30 m. All the available geophysical and sedimentological data available at that time were collated and interpreted by O'Shea (1971) and used in the compilation of his thesis. Based on discussions with C. Baltas (pers. comm., 2002 - De Beers - Elizabeth Bay), the geologist responsible for Diamond Area 2, it would appear that the positional accuracy of the Tidal Diamonds marine geophysical data is poor. This may be due to navigational problems with the original geophysical data or may have occurred during subsequent co-ordinate transformations or interpretation and extrapolation of the relatively widely spaced data. Nevertheless, the Tidal Diamond and O'Shea (1971) data have been digitally captured and adjusted wherever possible and is adequate to provide a relatively detailed insight into the geology of the shallow water area inshore of EPL 1950 (Figure 23). Results pertinent to assessing the placer potential of HBG paraphrased from O'Shea's (1971) study and are outlined below.

Hottentot Bay is characterised by large areas of relatively thin sediment and low bedrock relief. The southern shore of the prominent north facing Hottentot embayment is a flat, low lying sandy plain indicative of a tidal pan, while the eastern side of the bay has steep, dune-covered slopes with occasional basement outcrop. The submarine topography is dominated by a northeast striking bedrock ridge with low relief (4 m to 5 m) that is a sub-aerial extension of Hottentot Point headland. To the northeast, it disappears beneath a thin sand cover and then outcrops again west of Black Rock, but is not evident on the beach further to the north. The area as a whole is flat, but the reefs tend to have steeper slopes on the seaward side. The area appears to have been planed off at the -18 m to -24 m level. In the southeastern section of the Hottentot Bay the seismic signal was attenuated, by a sandstone layer that occurs in that area, making accurate identification of the bedrock topography difficult. A third of the distance between the beacon at Hottentot Point at and the one at Black Rock there is a small bedrock rise at -18 m flanked by lows at -22 m filled with thicker sediment. At two thirds the distance from Hottentot Point another minor bedrock rise at similar elevation occurs, that seemingly had a

MAP SUMMARISING HISTORICAL OFFSHORE GEOLOGICAL AND GEOPHYSICAL INTERPRETATIONS HOTTENTOT BAY AREA



⬜	rock
🟨	sediment
▨	acoustic blanking layer
--12m--	sediment isopachs at 6 metre intervals
--2m--	sediment isopachs at 2 metre intervals (O'Shea data)
1607B	Exclusive Prospecting Licence Number
ML103A	Mining Licence
▥	inferred rock (NO DATA)

Figure 23

significant effect on sediment distribution. A northeasterly striking reef forms the western boundary of a 6 km long by 2 km wide sediment body that fills most of the inner bend of Hottentot Bay and extends up to Black Rocks. O'Shea (1971) interprets this sediment as having mainly been deposited by the prevailing southerly winds blowing sediments across the Anichab pan, and strong easterly winds contributing dune sand during the winter months. This sediment body swings northwest off Black Rock to form the main thick, offshore deposit approximately 3.5 km west of the beacon situated there. The sediment in the inner part of the bay thickens to the south and the east, but the relatively flat bedrock results in the water depth being only -12 m some 2 km seaward of the beacon at Blue Mountain. The isopachs strike northeast, resulting in a comparative thinning of the sediments and deepening of the water towards Black Rock. To the northwest of Black Rock, the sediment has filled the flat shallow valley that is flanked by two headlands and reaches a thickness of greater than 8 m in the northwest.

O'Shea (1971) notes that the three main sedimentary facies found are, namely: 1) Dark green to brownish clay (compacted silty sand) which occurs predominantly in the south and east portions of the bay, but also as thinner (<4 m) patches northeast of Hottentot Point; 2) Gravel comprising angular to sub-angular pebble to cobble sized clasts, consisting predominantly of local bedrock rubble, except for one patch located far west off Blue Mountain beacon where well-rounded spherical, terrace gravels were sampled; and 3) Greyish to pale green, coarse-grained, relatively friable, calcareous, sandstone that is conglomeritic in places in a gypsum, dolomite and felspar-rich, shelly sand matrix, particularly in the northern and western sections of Hottentot Bay, occurring at elevations ranging from -12 m to -30 m, beneath the layer of unconsolidated sand. Shells are present in minor quantities with the predominant species comprising *Cultellus cellecidus* in the upper portion of the sediment and *Lutraria capensis* in the basal layers. *Tellina* and *Tapes* were also common.

O'Shea (1971) notes that farther north off beacon Gibralter, the sediment is thick and comprises shell-rich silty sand covering traces of bedrock rubble. At 30 m water depth, the drill holes penetrated 1 m of fine sand and 6 m of olive-green clay, while further inshore as the sediment body narrows, a sandy shell with sub-rounded basal gravel overlying a sandstone "false" bedrock was observed. Just to the south of beacon Saddle Hill South, a shelly gravel is present in thin sediments, but the volume of shell and clay thickens quickly away from the bedrock outcrop. A traverse in a westerly direction off Clara Hill beacon confirmed the persistent shell-clay-bedrock succession. Northwards from the Clara Hill beacon, is a fairly regular inshore sediment lens. Off beacon Pan, little gravel is present, but seaward of Mercury Island the gravelly basal shell bed in the east grades seaward into a closely packed angular rubble containing occasional rounded quartz pebbles. Further westwards, shell and birdseed gravel predominate.

6.4 DISCUSSION

Though somewhat disjointed, having been extracted from a number of unrelated studies, this review of historical data represents the core of the relevant geological information available on the inner shelf and on the coastal plain east of the case study area prior to the current study.

Prior to the recent geophysical surveys of the HBG area and subsequent interpretations these studies represented the majority of the information available from which an assessment of the diamond potential of the study area could be made. It should be noted that only the most relevant data have been extracted and has been presented in a manner that best illustrates and evaluates those aspects important in assessing offshore diamond placer potential having had further insight from years of working with the geological, geophysical, geotechnical and resource/reserve data in the study area. In hindsight, from a diamond exploration point of view the following deductions could have been made:

- The average diamond size for this portion of the coast is small averaging 5 to 10 diamonds per carat.
- A number of marine placer deposits have been mined in the areas adjacent to the study area, with over 650 000 Cts having been produced and therefore potential for further deposits offshore is good.
- Onshore geophysical interpretations show the northern limb of the currently buried Koichab River valley could have traversed the study area but negative results from the limited testing of this palaeo-channel indicates that its presence does not necessarily enhance the diamond potential of the area.
- Geophysical interpretations within the shallows of Hottentot Bay shows the area to be characterised by large areas of relatively thin sediment and low bedrock relief (Low bedrock relief is not conducive to diamond entrapment and placer formation).

The small average diamond size and low bedrock relief would place this regional target in the moderate to low prospect potential category. This is not the case with a mining licence and 73 766 Cts probable reserve, 266 599 Cts indicated and 535 097 Cts inferred resource allocated at a average diamond size of 0.27 Ct/St (De Decker, 2002). How, over such a short distance, directly offshore can the placer characteristics have changed so significantly? This thesis presents a revised model for placer formation in central Namibia which offers an explanation.

7. RECENT GEOPHYSICAL AND OCEANOGRAPHICAL INVESTIGATIONS IN THE STUDY AREA

7.1 AUTHORS ROLE IN THE ACQUISITION, INTERPRETATION AND COLLATION OF GEOLOGICAL DATA IN THE STUDY AREA

The author was involved from the very earliest stages of exploration in the study area. This involvement included data acquisition, geophysical interpretation as well as a number of other geological investigations, including: 1) terrace level studies; 2) sediment dynamic studies; 3) sample planning and programme management; 4) contributions to the feasibility study; 5) resource estimations; and 6) contributions to various listing documents. The author's role and the approximate duration of the various activities are listed below in Table 8.

The author has been registered intermittently at Rhodes University since 1994 as a MSc student. Since the outset of the Economic Masters course, HBG has been considered as a suitable thesis topic, but owing to confidentiality issues, could not be pursued. Nevertheless, large amounts of time and effort were expended completing various studies and compiling numerous internal reports on behalf of Marine and Coastal Geoscience Pty Ltd (MCG) for Namco on HBG. In December 2001 Namco granted permission for the use of the data for this thesis and the author commenced with compilation, in January 2002.

Over 900 working days have been spent by the author completing various studies in HBG over the last 9 years. This thesis assesses the evolution of this marine placer deposit by drawing on many of these detailed studies, assimilating and interpreting all the data accumulated in the study area, neighbouring prospects and adjoining onshore areas collectively, within the context of the literature reviewed in the preceding sections.

TABLE 8: Summary of the authors role in studies conducted within ML 103a and EPL1950.

Project	**Capacity**	**Duration (months)**
1994 - Geophysical survey data	Completed bathymetry, side-scan and seismic data interpretation	6
1995 - Terrace level study	Completed a regional terrace level study in ML 103A	2
1996 - Namrod Prospecting programme	Selected target features, sample sites and assisted in programme management - EPL 1950 and EPL 1946 for the Namrod sampling.	3 + 18
1996 - Terrace level study	Completed a detailed terrace level study in ML 103A	1
1996 - Namibian, Toronto and Vancouver stock exchange reports	Assisted in the drafting of the bankable documents for Namco's listing	2
1996 - Geophysical survey	Client representative aboard the *Kommador Theresa* for the survey of Features 19 & 20 of ML 51 and Feature 22 of ML 103A	0.75
1996 - Feasibility report	Contributed toward Namco's feasibility report/mine development	3
1996 - Resource estimates	Resource estimates made in ML 103A and ML 51	1
1996 - Resource estimates	Estimated resources in Feature 22 of ML 103A	1
1998 - Resource estimate revisions	Revised the resource estimates made in ML 103A and ML 51 based on additional sampling and mining information	0.5
1999 - Resource estimate revisions	Reviewed resources and resource potential in ML 103A and ML 51	0.5
1999 - Sediment dynamics study	Conducted a sediment dynamics study in ML 103A and selected additional high priority prospecting features	1
1999 - Geophysical survey of Clara Hill and Blue Mountain Prospects - EPL 1950	Party chief and client representative aboard the *mv "Cape Infanta"* for the geophysical survey.	1
1999 - Operations report	Compiled the operations report for the geophysical survey in ML 103A	1
1999/2000 - Data interpretation and geological report	Completed bathymetry, side-scan and seismic data interpretation and wrote the geological report for EPL 1950	4
2000 - Geophysical survey	Party chief for the survey of many of Namco's areas including Feature 12 and Feature 22 of ML 103A. Geophysical data interpreted by Namco's geologists and not available to the author or included in this thesis.	1
2000 - Review of prospecting programme	Reviewed and modified the sampling programme devised by Namco's geologists	0.1
2001 - Annual information form	Assisted in the compilation of Namco's annual Information form	0.2
2002 - Re-process ISIS 100 - Swath Bathymetry Data	Re-process the 30 Gb of raw swath bathymetry data within BMP to improve on the existing interpretation	1

7.2 GEOPHYSICAL SURVEY COVERAGE

Geophysical surveys undertaken in the study area since 1993 are reviewed in this Section. The various system used in these surveys are briefly described. Table 9 below gives a summary of the surveys completed in the study area on an annual basis since exploration started in 1993.

TABLE 9: Surveys Conducted Per Year in ML 103 a and EPL 1950 in Namibia.

Survey Date	Vessel	Lease Id	Line Spacing(m)	Equipment	Line-km's
Dec. 1993	*Fox*	ML 103A	150	ES,B,CH,SS	2191
May 1996	*Kommador Theresa*	ML 103A	150	ES,CH,AG,SS	286
Sep. 1999	*Cape Infanta*	EPL 1950	150	ES,SB,AG,P,SS	1424
April 2000	*Zacharias*	ML 103A	50	SB,T,SP/P,SS	226
				Total	**4127**

Note: ES = Echo-sounder, SB = Swath bathymetry, AG = Airgun, P = Pinger, SS = Side-scan sonar, CH = Chirp, B = Boomer, SP/P Sparker and/or Pinger and T = Topas.

In December 1993, Namco contracted a British Survey Company, Wimpol UK Ltd, to conduct its first geophysical surveys and geological sampling. A total of 2 191 line-kilometres of detailed geophysical survey data were collected in Saddle Hill Prospect (SHP roughly equivalent to ML103a) in 1993/1994. While Mr R. H. De Decker and Mr. M. W Woodborne of MCG were on board during the survey as client representatives, and completed the initial, regional interpretations, the majority of the detailed geophysical interpretation was completed by the author. The digitising was completed by Mrs S. Smith of MCG and GIS and ArcView file compilation was completed by Mr R Herbert of Interactive Graphics CC, under instruction from MCG.

In May 1996 RACAL were commissioned to do a regional survey of EPL 2002 and, based on a onboard interpretation of the geophysical data by Mr R. H. De Decker of MCG, a detailed survey along the southwestern edge of SHP was recommended and approved. The proposed area measured approximately 39.8 km^2 , and adjoins the area surveyed by Wimpol in 1994. Lines at 150 m spacing were run in a north-south direction. Two hundred and eighty six line kilometres of side-scan sonar, chirp, airgun (10 cubic inch - 4 NS lines only) and echo-sounder data were collected in this area. The seismic and SSS data were interpreted by Namco and the Council for Geoscience, respectively. The Council for Geoscience also digitally captured the seismic data interpreted by Namco. During the last quarter of 1999, MCG was commissioned to take the digital data into the GIS and create ArcViewshape files.

A detailed survey amounting to 1 424 line-kilometres was undertaken by MCG in EPL 1950 and ML 103A in September 1999. This survey covered the bedrock outcrops in Clara Hill and Blue Mountain Prospects in the north and south of the EPL 1950 area, respectively. These high potential areas were identified originally in the regional survey lines of the December 1993 survey, but were not surveyed due to budgetary constraints at that time. The author completed the geophysical interpretation and GIS and ArcView file compilation were completed by Mr R Herbert of Interactive Graphics CC.

The December 1993 and May 1996 surveys, though recorded digitally were interpreted predominantly from hard-copy continuous thermal prints, due to budgetary constraints. The September 1999 survey's single-beam echo-sounder, side-scan sonar mosaic and seismic processing were completed using digital processing software.

7.3 GEOPHYSICAL SURVEY EQUIPMENT USED TO SURVEY THE STUDY AREA

This section, lists the instruments used in surveying the study area. Information regarding the equipment specifications and potential problems associated with geophysical survey and data interpretation are briefly addressed.

7.3.1 NAVIGATION

Positioning of the vessel and the various fixed and towed instruments in relation to the navigation datum is an important aspect of any survey. Modern Differential Global Positioning Systems (DGPS) have an accuracy of better than 3 m. Should the positioning be incorrect, the subsequent interpretation of geophysical data can be severely compromised and in extreme cases, worthless. Typically, the absolute positional error introduced on a successful survey does not exceed 10 m, in water depths of < 150 m. The navigation specifications for the various surveys undertaken in the study area are listed in Table 10.

TABLE 10: Navigational systems used during the survey of the study area.

Survey - Year	Positional System	Navigation Software	Geodetic Information
December 1993	RACAL SkyFix	Direct from Trimble 4000DL	WGS 84, UTM Zone 33 S, Datum 15^{0}E
May 1996	SkyFix & DeltaFix	RACAL Navigation System	WGS 84, UTM Zone 33 S, Datum 15^{0}E
September 1999	Seastar DGPS	HydroMAT	WGS 84, UTM Zone 33 S, Datum 15^{0}E
April 2000	Landstar	HYDROpro	WGS 84, UTM Zone 33 S, Datum 15^{0}E

7.3.2 ECHO-SOUNDER

A 200kHz or 210 kHz, single-beam echo-sounder is a standard geophysical survey item used to measure depth in marine diamond exploration work. The echo-sounder is interfaced with a heave/swell compensator which corrects for the up and down motion of the vessel. The velocity and draft corrected depth is recorded by the navigation computer together with an offset corrected positional string. A tide-gauge can be deployed on site but usually the tidal correction is obtained using predicted tide tables. The single-beam echo-sounder systems deployed for the various surveys undertaken in the study area are specified in Table 11.

TABLE 11: Bathymetry instrumentation used during the survey of the study area.

Survey - Year	Echo-Sounder	Heave/Swell Unit	Echo-sounder Accuracy
December 1993	Atlas Deso 20	TSS 320	> of 5 cm or 0.5% of the water depth
May 1996	Atlas Deso 25	TSS 320	> of 5 cm or 0.5% of the water depth
September 1999	Odom Hydrotrac	TSS HS50	> of 5 cm or 0.5% of the water depth
April 2000	Odom Echotrac DK3200/Mk2	Seatex MRU 5	> of 5 cm or 0.5% of the water depth

7.3.3 SWATH BATHYMETRY

"Multi-beam" and/or interferometry swath bathymetry systems, capable of recording very accurate depth soundings with 100 % seafloor coverage are succeeding from single-beam systems. Swath bathymetry systems are considerably more costly to operate than single-beam echo-sounders, but collect exceptionally higher quality data. The effects of vessel motion are reduced using motion reference units (MRU) which compensate for heave, pitch and roll and feed the soundings to on-board processing units which produce a corrected data set. Tidal, sound velocity profiles, transducer plate angle and draft corrections, and spike removal filters are applied to the raw data during post-processing to produce the final bathymetry map. A side-scan sonar image can be collected simultaneously using the amplitude signal received by the transducer. Results from recent surveys along the west coast using the interferometry system have produced outstanding results (Figure 24). It is likely that in future many surveys will be undertaken using only a swath bathymetry and sub-bottom profiler system. The swath bathymetry system deployed for the various surveys undertaken in the study area are specified in Table 12.

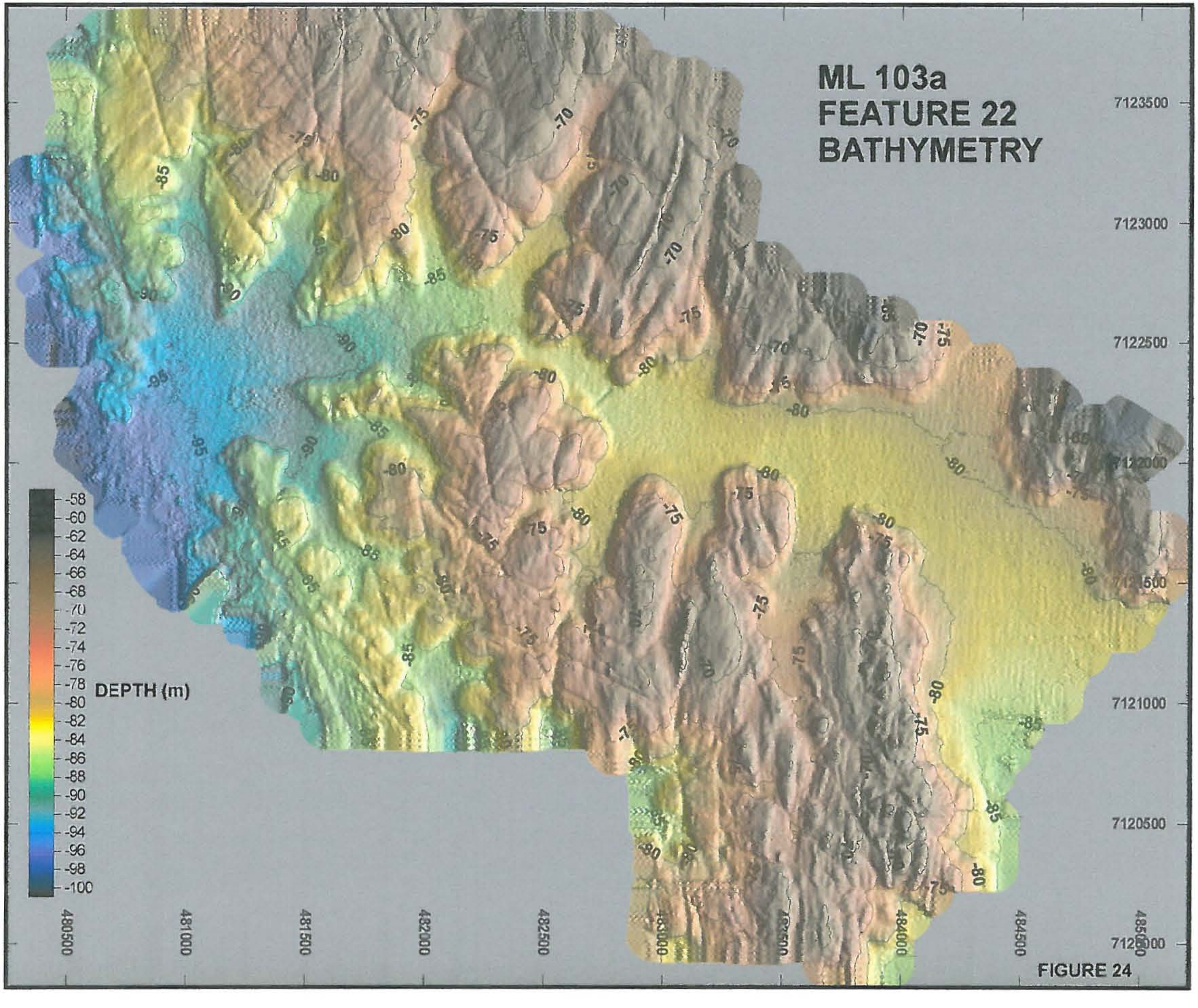
TABLE 12: Swath Bathymetry systems used during the survey of the study area.

Survey - Year	Swath-Bathymetry System	MRU Unit	Accuracy
December 1993	Not Used	Not Used	Not Relevant
May 1996	Not Used	Not Used	Not Relevant
September 1999	ISIS 100 (Interferometry)	Octans MRU	> of 30 cm or 1% of the water depth
April 2000	RTS 2000 (Interferometry)	Octans MRU	> of 30 cm or 1% of the water depth

7.3.4 SIDE-SCAN SONAR SYSTEMS

For all the surveys undertaken in the study area a side scan sonar system was used (Table 13). It receives and processes data, producing an image that is fully corrected for slant range, ship speed and amplitude, giving an accurate 1:1 ratio plan view of the sea floor topography. Tow-fish layback, was measured by an electronic cable counter and the offset corrected position recorded by the side-scan unit.

For the 1996 survey side-scan sonar interpretation was completed off photo-reduced, "cut-and-paste" mosaics. Subsequent interpretations were completed digitally, using post-processing software that enables the user to



correct bottom-tracking (where necessary), balance the contrast of the channels individually, adjust the time varied gain (TVG) and produce a slant corrected, digital side-scan sonar mosaic.

TABLE 13: Sonographic instrumentation used during the survey of the study area.

Survey - Year	Side-scan System	Interpretation
December 1993	EG&G Model 260TH	Photo-reduced "cut and paste" mosaics, -interpretation on film, -digitised
May 1996	EG&G DF 1000	Delph-Map processing software
September 1999	EG&G Model 260TH	ETX SONAR side-scan processing software
April 2000	GeoAcoustics SS941	Triton ISIS side-scan processing software

7.3.5 SUB-BOTTOM PROFILERS

Numerous geophysical sub-bottom profilers are available, each with their own merits and problems. The correct system to use is dependant on the aim of the survey, the geological characteristics of the sediment in the survey area and the correct operation of the seismic system. Diamond exploration requires a relatively shallow penetration, high resolution seismic system. As mining rate is inversely proportional to sediment depth, which in turn is integrally linked to mining cost, the deepest deposits that can be mined offshore have about 8 m sediment cover. Even with improved technology in the future it is unlikely that these mining overburden depths will exceed 12 - 15 m. Generally the pinger and locally developed chirp systems which have a maximum penetration of 15 m and 0.5 m resolution in un-consolidated sediment, have been used. The seismic signal of these high resolution systems can easily be attenuated by rippled coarse sediment (scattered), clay, shell, or semi-indurated horizons. If used alone it is often difficult to determine if bedrock has been intersected so these systems are usually used in conjunction with a slightly coarser resolution system (1 - 2 m) such as a sparker, boomer or mini-airgun (1 cubic inch) which can penetrate 20 m and 60 m into the seafloor, respectively. The systems described above are usually towed using a fixed deck cable. The seismic signal beam has a footprint, which is larger in deeper water, that "wanders" around on the seabed depending on the motion of the tow-fish. This tends to "smudge" the record reducing the vertical resolution and positional accuracy of the interpretation. More recently directional source systems have been developed that transmit the seismic pulse directly downward resulting in a more focussed footprint. One such system is the Topas sub-bottom profiler developed by Kongsberg Simrad, that was used on the April 2000 survey. Sub-bottom profilers used in ML 103a and EPL 1950 are shown in Table 14.

TABLE 14: Sub-bottom profilers used during the survey of the study area.

Survey-Year	High Resolution System	Medium Resolution System	Interpretation
Dec. 1993	Datasonics CHIRP	EG&G Boomer	Author-from hard-copy thermal records
May 1996	EG&G X-Star CHIRP	Mini Airgun (6 inch)	By MCG and Namco geologists
Sept. 1999	Pinger	Mini Airgun (1 inch)	Digital processing by the author
April 2000	Topas/Pinger	Sparker	Digital processing - Namco geologists

7.3.6 GEOPHYSICAL SURVEYING IN THE FUTURE

Autonomous Underwater Vehicle (AUV) technology has improved considerably over the last 3 years. When applied to geophysical survey these systems are normally fitted with a side-scan sonar, high resolution sub-bottom profiler, a swath bathymetry system and a video camera. As they operate independently from the support vessel and beneath the sea surface they are not affected by sea-state (swell) and therefore can collect exceptionally good quality records. As all the geophysical systems are housed in the same vehicle, which is accurately positioned, records can be directly correlated, facilitating easy comparison and interpretation. However, these AUV systems are currently very expensive to purchase or rent and bottom-time is limited. Therefore their use is presently restricted to small, highly detailed surveys like mine block evaluation, mine support, site and wreck surveys and it will still be some time before they take over the regional geophysical survey role. As AUV bottom-times improve and their operating costs are reduced, they will eventually take over from the conventional ship borne geophysical methods.

8. RESULTS FROM GEOPHYSICAL AND OCEANOGRAPHICAL INVESTIGATIONS IN THE STUDY AREA

The results from the detailed interpretation of bathymetry, side-scan sonar and seismic data are presented in this section. Furthermore, studies derived from further examination of the base data are used to investigate the terrace levels and sediment dynamics of SHP. All the data are used to identify and prioritise high potential marine diamond placer targets within the study area.

The data in the study area were collected during three separate geophysical surveys. Saddle Hill Prospect was surveyed in 1994, EPL 2002 in 1998 and the remainder of the EPL 1950 areas in 1999. Detailed evaluation surveys were conducted in two small portions of Saddle Hill Prospect in 2000. In order to facilitate easier referencing and be able to present diagrams at a legible scale, the large HBG has been subdivided into 6 areas. These areas, that roughly correspond with the survey boundaries, split the area into a number of coherent bedrock outcrops separated by large sediment filled areas (Figure 25), namely:

- **Blue Mountain Prospect** (**BMP**) - this outcrop has been subdivided into Blue Mountain West, Blue Mountain Central, Blue Mountain East and Sammy's Ridge North and Sammy's Ridge South along the eastern edge of the area.

- **HB Prospect** (**HBP**) - coast-parallel reefs along the eastern edge of HBG.

- **Clara Hill Prospect** (**CHP**) - in the northeast corner of the study area.

- **HD Prospect** (**HDP**) - a small bedrock outcrop surrounded by a large expanse of sediment situated in the northwestern corner of the prospect. The SE corner of the area covered by the HDP survey is contiguous with the NW corner of the Main Western Ridge (**MWR**).

- **Saddle Hill Prospect** (**SHP**) - The large central portion of the study area which has the MWR and Main Eastern Ridge (MER) separated by a large NNW trending sediment filled basin.

- **EPL 2002 Detailed** - this prospecting licence adjoins the southwestern edge of the study area and is included for completeness. Morphologically, it forms part of the MWR and is forthwith incorporated into SHP for this study.

Names have been allocated to each of the larger basins and ridges, and letters to potential target features to simplify referencing within the study area (Refer: Figure 25). The thick sediment areas between SHP and HDP/CHP and that separates SHP and BMP have not been included as the excessive overburden precludes economical extraction of diamond placers using current mining technology. The order of presentation has been kept consistent throughout the geophysical data interpretation sections in this thesis to improve coherency. The reference names, shown in Figure 25, can be used as a locality guide when reviewing this chapter.

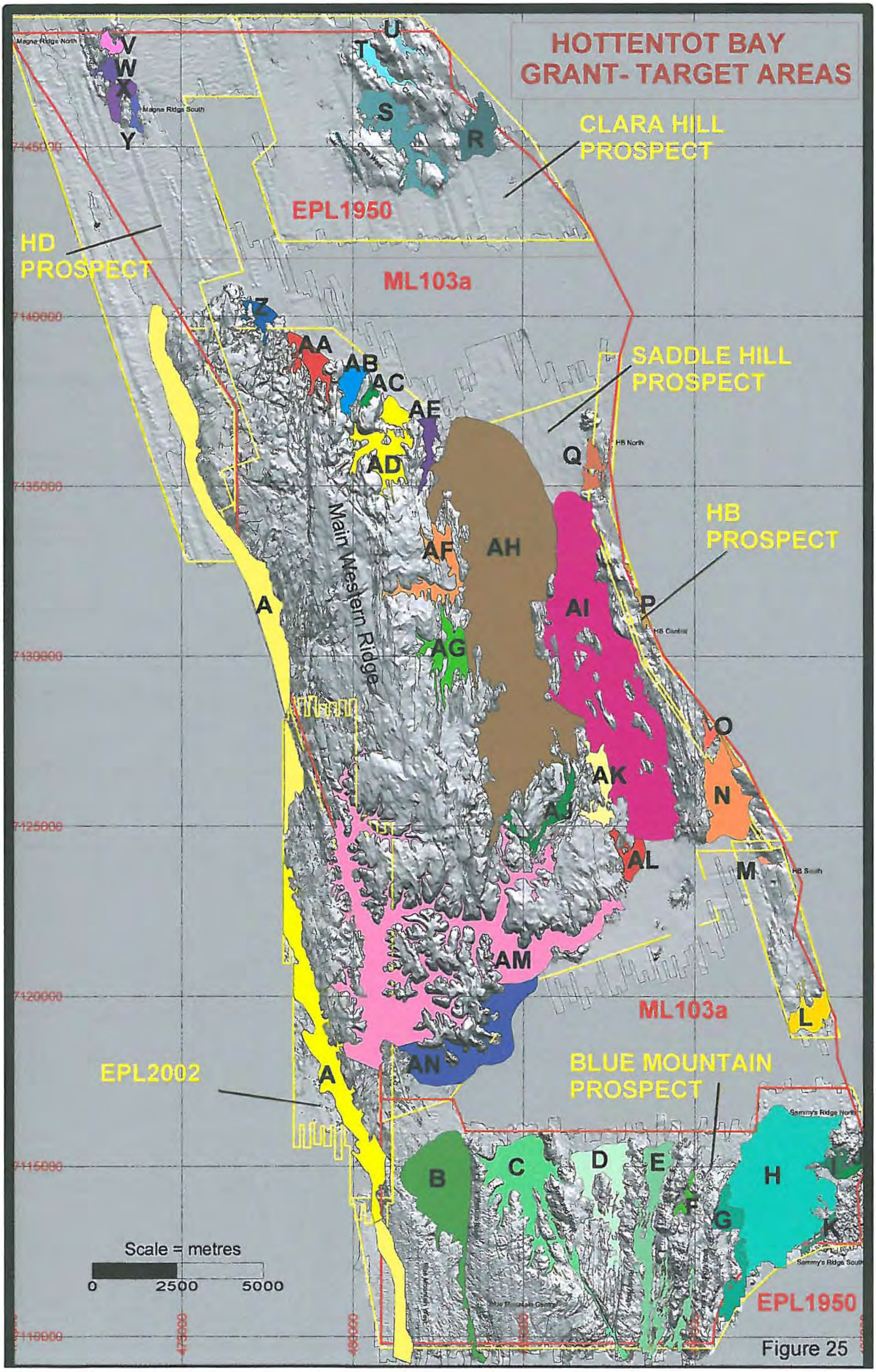

HOTTENTOT BAY
GRANT- TARGET AREAS
CLARA HILL
PROSPECT
HD
PROSPECT
SADDLE HILL
PROSPECT
HB
PROSPECT
BLUE MOUNTAIN
PROSPECT
EPL1950
ML103a
ML103a
EPL2002
EPL1950
Main Western Ridge
Magna Ridge North
Magna Ridge South
HB North
HB Central
HB South
Sammy's Ridge North
Sammy's Ridge South
A
B
C
D
E
F
G
H
I
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
AA
AB
AC
AD
AE
AF
AG
AH
AI
AJ
AK
AL
AM
AN
7145000
7140000
7135000
7130000
7125000
7120000
7115000
7110000
475000
480000
Scale = metres
0
2500
5000

Figure 25

8.1 BATHYMETRY

8.1.1 INTERPRETATION METHODOLOGY

The majority of the bathymetry interpretation was completed on 1:5000 scale faircharts at 1 m intervals using the side-scan sonar as a base. ISIS 100 swath bathymetry data were processed and interpreted for BMP, CHP, HD and HB.

The heave corrected depths collected by the single beam echosounder in SHP (1994 survey) were tide corrected to chart datum using predicted tide tables for the area as supplied by the SA Navy. From the spot depths, faircharts were compiled and plotted at 1:5 000 scale on transparent film. The resultant 24 AO faircharts, were hand contoured at 1 m intervals, by the author, using the side-scan sonar mosaic as a base. Because there is 100% coverage of the seafloor with the side-scan sonar data, hand contoured isobaths can be geologically biassed to more accurately reflect the seafloor morphology by recognising the continuity and orientation of seafloor features, where no bathymetry data are available. The interpreted isobaths were then edge-matched, digitised and compiled into a single bathymetry contour map for the SHP area. The bathymetry for the remainder of the EPL 1950 area was digitally contoured using ISIS 100 swath bathymetry data. During processing, the ISIS 100 raw data are first filtered for navigation errors and swath files produced. In the swath file various filters are applied to remove spikes and spurious data. These corrected files are gridded and digitally contoured at 1 m intervals. The swath bathymetry interpretation for the southern, Blue Mountain portion of EPL 1950 was subsequently re-processed for this study, by the author, to improve the quality of the original interpretation completed by Marine Data Solutions (MDS).

8.1.2 BATHYMETRY OF THE INNER SHELF - LÜDERITZ TO SPENCER BAY

The bathymetry of the area from Lüderitz Bay to Clara Hill that covers 1 440 km^2 of the inner shelf was compiled largely by the author. This compilation, the most detailed available over this large section of the inner shelf on the central Namibian coast, provides a foundation for the detailed bathymetry, terrace level and sediment dynamic studies presented in this thesis.

The area between Lüderitz and Clara Hill comprises a number of licence areas, owned by different companies. Within each licence area a number of surveys of varying detail and accuracy have been conducted by the different companies and interpreted by their geologists or consultants over the last decade. Over 100 A0 hand contoured faircharts form the core of the information from which this detailed bathymetry map is constructed. The majority of these bathymetry interpretations were completed by geologists working at Marine and Coastal (MCG), namely Mr R. H. De Decker, Mr M.W. Woodborne, Dr A. J. Rau and the author, at that time. In plan view the combined, original bathymetry interpretations resemble a patchwork blanket, with regional interpretations overlain by detailed patches which in turn are covered by other information from neighbouring licence areas. In order to compile a coherent bathymetry map all these bathymetry sheets had to be edge-matched and conflicting elevations resolved. This compilation was completed, for this study, by the author with

CAD assistance from Mrs S. Smith. The more accurate, detailed bathymetry data were used to adjust the more regional data where necessary. The difficultly comes in trying to present these large volumes (original interpretations laid side by side, would cover a rugby field) of detailed data in a legible format for this thesis. While most marine data are examined using GIS software a hard-copy map is required for this study. While the full detail cannot be reflected, current software allows one to present maps that show most of the inherent definition. The relative detail of the resultant bathymetry interpretation can be visually assessed by examining the bedrock micro-topography on the shaded relief map (Figure 26). The resultant bathymetry map is the most detailed yet produced for this large portion of the west coast and forms the core of the process modelling diagrams presented forthwith. For the cover of Benguela Concessions Annual Report in 1995, the BENCO geologists rendered a digital terrain model (DTM) map of the Lüderitz Bay area (with their sediment dynamic data overlaid) using bathymetry data interpreted predominantly by the geologists at MCG. The current map is considerably more detailed, and covers a far larger area, than that used for this report cover.

The following points, pertinent to the evaluation of the marine diamond potential of the greater Lüderitz region, can be interpreted from this bathymetry map:

- The edge of the Precambrian basement is relatively straight for 100 km, trending NNW at a water depth of about 110 m bsl and correlates well with depths for the inner shelf break, noted during previous studies (O'Shea, 1971; Dingle, 1973a; Rogers, 1977). The inflection back to -70 m water depth at the mouth of Lüderitz Bay (7070000 N) would have resulted in a significant embayment in the area during marine regressions to those elevations. Maree (1966) also suggested a presence of an embayment at Lüderitz but had the water depths at -35 m to -40 m at the mouth of the embayment.

- There are 3 breaches in the large, NNW trending, submarine ridge that extends for almost 100 km. The first is at Lüderitz Bay (7070000 N) and the other two are within EPL 1950. Based on the lobate shape of a phosphate encrusted lobate shaped, relict sediment wedge (Rau, 1996), the first is interpreted to be eroded by a river (Refer: Figure 26 - 7068000) exiting at that locality. The possibility of the Koichab River exiting via Luderitz Bay has been suggested earlier (Maree, 1966; De Decker, 1993), but could not be scientifically supported at that time, as no marine geophysical data existed in that area. The second between BMP and the MWR of SHP is most likely a sub-marine extension of the Koichab River. De Decker (1993) suggested that the palaeo Koichab River may cross SHP but placed the traverse further to the north and discounted the possibility due to a shallowing of the isopachs interpreted by O'Shea (1971) toward the west, in that area. Interestingly, the channel traversed the southern end of the SHP at some time rather than taking the currently more obvious route, between the two ridges (Refer: Figure 25 - **AM**). This may indicate that originally this extensive offshore reef was continuous, but was subsequently breached by the Koichab River creating the more direct westward route.

- Marshall Fork does not appear to be fluvially eroded as it has no obvious eastward extension.

- During marine regressions of shallower than 70 m the large rugged, submarine ridges would have significantly curbed the northward transport of diamonds by wave action. Northward diamond migration is

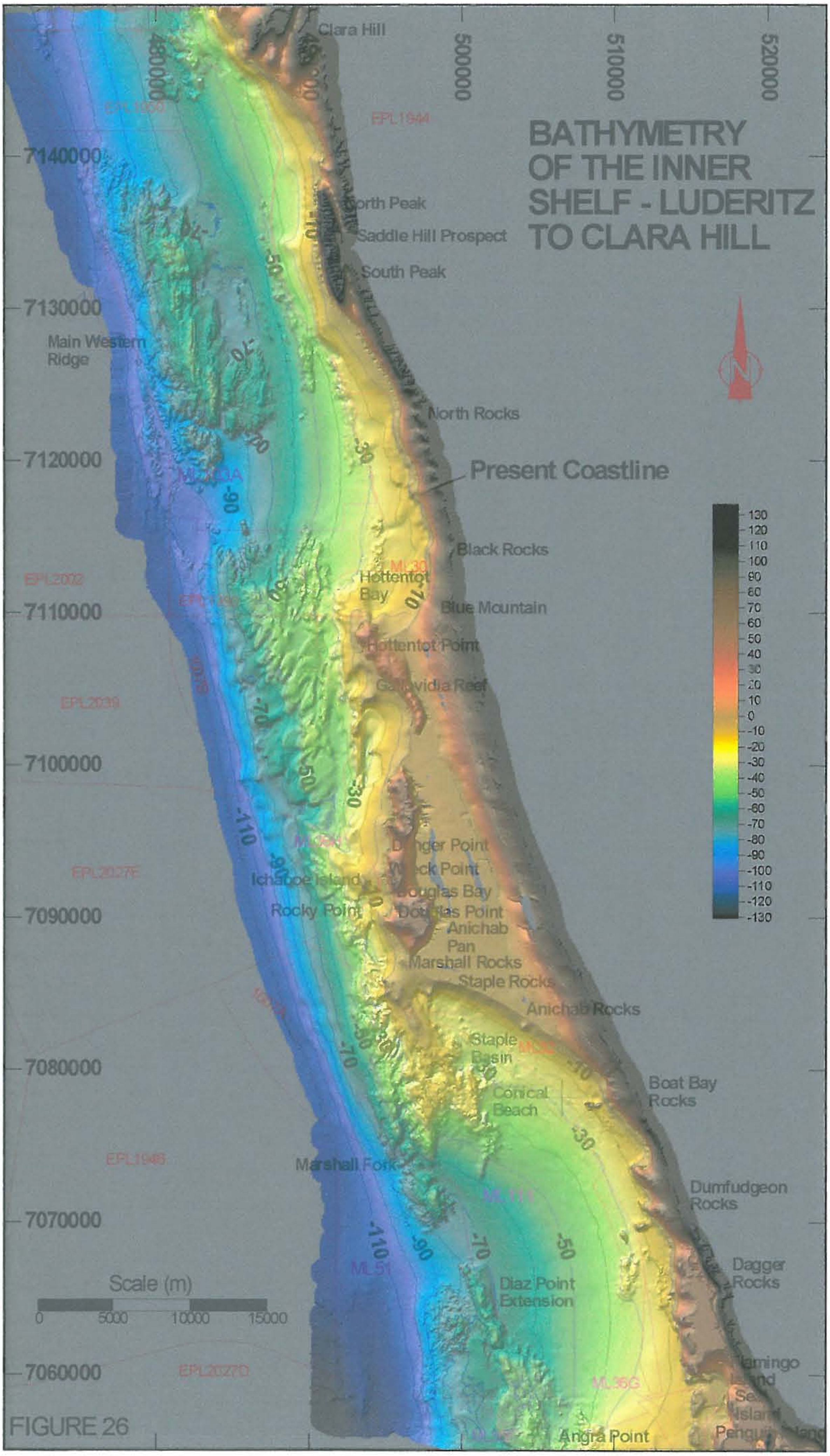

BATHYMETRY OF THE INNER SHELF - LUDERITZ TO CLARA HILL
Clara Hill
480000
490000
500000
510000
520000
7140000
7130000
7120000
7110000
7100000
7090000
7080000
7070000
7060000
EPL1944
North Peak
Saddle Hill Prospect
South Peak
Main Western Ridge
North Rocks
Present Coastline
Black Rocks
ML30
Hottentot Bay
Blue Mountain
EPL2002
Hottentot Point
Gallovidia Reef
EPL2039
Danger Point
Wreck Point
Ichaboe Island
Douglas Bay
Rocky Point
Douglas Point
EPL2027E
Anichab Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
Staple Basin
ML32
Conical Beach
Boat Bay Rocks
EPL1946
Marshall Fork
Dumfudgeon Rocks
ML111
ML51
Diaz Point Extension
Dagger Rocks
Scale (m)
0
5000
10000
15000
EPL2027D
ML36G
Flamingo Island
Seal Island
Penguin Island
Angra Point
-10
-30
-50
-70
-90
-110
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
N

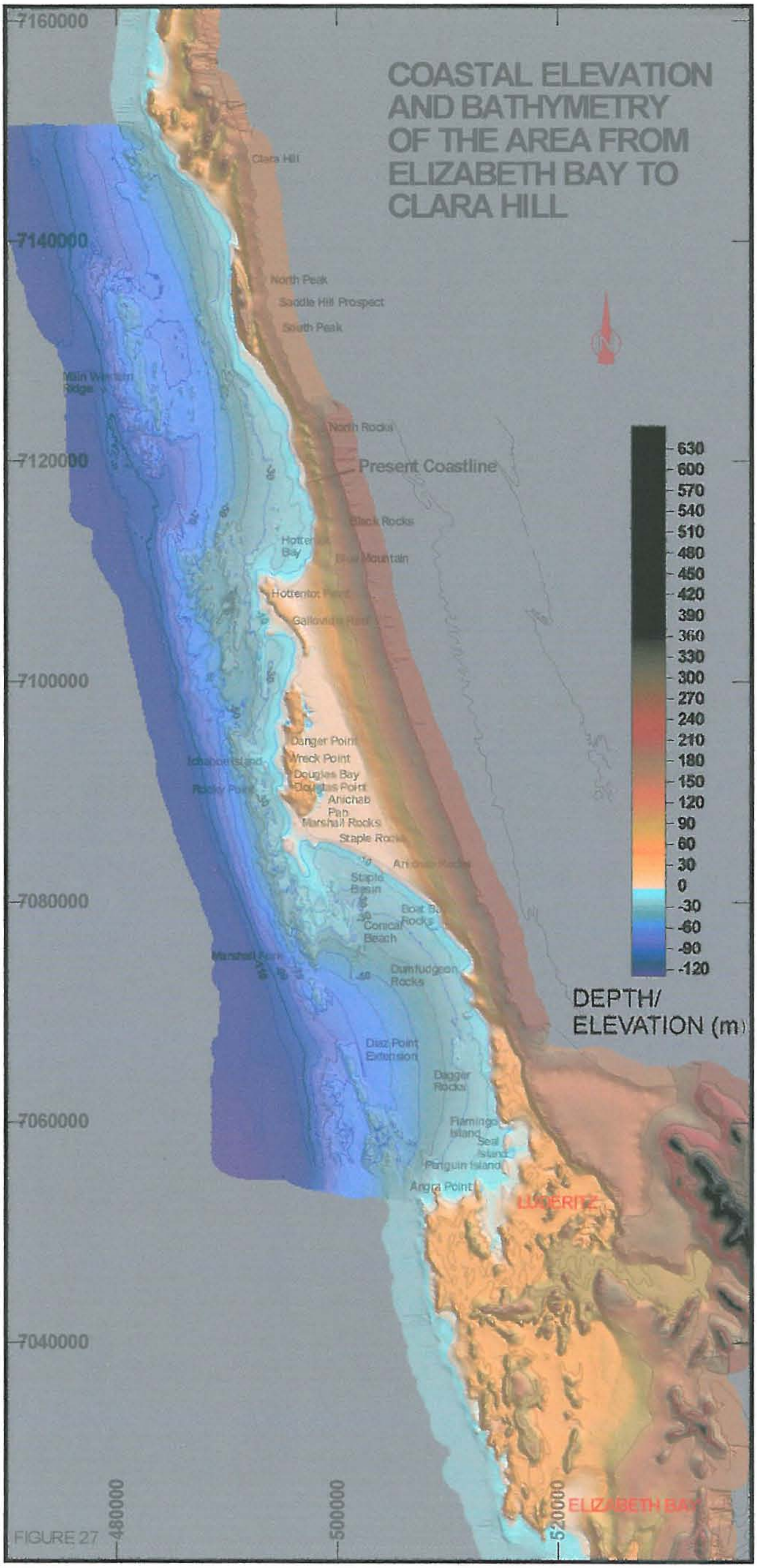
FIGURE 26

likely to have occurred predominantly along the front of the ridge (-90 m to -110 m) and behind the back of the ridge (+1 m to + 10 m). The onshore elevation contours from the SA Navy 110 chart (SAN 110 - Spencer Bay to Elizabeth Bay) were digitised by Mrs S. Smith and Mrs J. Jones and added to the offshore bathymetry data set (Figure 27). This map that covers an area of 5 337 km^2, is used as a base map to illustrate the process modelling for diamond placer formation in central Namibia (Chapter 9). The topography behind Rocky Point through the Anichab Pan is conducive to diamond transport by aeolian processes (headland bypassing), similar to that proposed by Corbett (1989) at Bakers Bay and by De Decker (1993) at Hottentot Bay. The regional morphology of the area from Lüderitz Bay northward to Saddle Hill is similar to that from Possession Island to Marshall Rocks (Refer: Figure 27). Of particular significance is the similarity in the south facing Elizabeth Bay and Anichab Pan morphology(Refer: Figure 27). The one difference being that there is an active mine at Elizabeth Bay with large reserves, which produced 93 891 carats from 1 976 000 tons at 4.75 cpht in 2001 (Namdeb Annual Report, 2001) while the limited historical sampling of the Anichab Pan area yielded poor results. Possible reasons for this difference are addressed in Chapter 9.

- Elizabeth Bay is separated from Lüderitz Harbour by numerous high ridges (Refer: Figure 27). The depression running up from Elizabeth Bay passes well to the east of Lüderitz through the Kolmanskop area as indicated by the southern extents of the Namib Sand Sea. Based on the topography digitised from the SA Navy 110 chart headland bypassing, if any, to Griffith Bay would have come from the Wolf Bay area (adjacent to North and South Long Island). Similarly, Shearwater Bay would have been linked to Grosse Bucht.

- The main lineament trend is approximately N-S and corresponds to the shear plane orientation which, with differential erosion, form N-S ridges. These N-S ridges form the bounding hills that contain the aeolian corridors (Corbett, 1989). Cross-cutting the shear plane are a dominant joint set trending NNW to NW and a less obvious joint set to the NE. The NNW to NW joint set have been more extensively eroded than the NE set, forming mega-gullies and linear depressions. Subsequent deformation resulted in a large scale open folding and sinuosity within the NS bedrock ridges most clearly visible in the Hottentot Point area. A detailed examination of the structural features and relative movements along faults is possible, given the high resolution bathymetry in certain localities, but is beyond the scope of this study.

- The difference in the topography of the onshore ridges in comparison with their offshore equivalents is noteworthy. For example, Saddle Hill (7130000) rises about 200 m above the surrounding land-surface while the larger sub-marine MWR only has a maximum elevation of about 60 m. The uniform nature of this difference over the entire area would suggest that it is indicative of higher rates of erosion by marine mechanisms than by the predominant aeolian erosion onshore. However, with no knowledge of the original height of each feature, a quantitative estimate would be highly speculative.



COASTAL ELEVATION AND BATHYMETRY OF THE AREA FROM ELIZABETH BAY TO CLARA HILL

FIGURE 27

8.1.3 DETAILED BATHYMETRY OF THE STUDY AREA

The water depths in HBG areas range from -20 m on the southeastern landward side (BMP) to -119 m along the seaward boundary (Figure 28). The bathymetry of the study area highlights two prominent, fine sediment-filled coast-perpendicular depressions that divide the large coast-parallel ridges into segments. The shaded relief map of the bathymetry shows that the morphology of the area is strongly controlled by the structure (Figure 29).

The shaded relief bathymetry map clearly illustrates a number of prominent coast-parallel ridges that have formed in response to differential erosion of the north-south trending regional shear fabric. These ridges rise tens of metres above the surrounding sediment covered seafloor. This coast-parallel shearing formed largely in response to tensional forces that arose during the splitting of the African and South American continental plates (Dingle, 1983). The sheared bedrock now comprises coast-parallel bands of gneiss, schist and mylonite depending on the degree of shearing. The gneiss, being more resistant to weathering, forms large coast-parallel ridges while the schist and mylonite, more susceptible to weathering, are eroded to form coast-parallel depressions. The shear fabric is cross-cut by a conjugate joint set with a dominant northwest and subordinate northeast orientation. Differential erosion of these structural features has culminated in the ridge and gully morphology which form the depositories for the marine placer deposits. The submarine expression of Hottentot Point and Saddle Hill can be easily distinguished. A dendritic feature typical of fluvial erosion, is evident in the southwest corner of SHP. Straight, extensive, coast-parallel bedrock outcrops edges are often indicative of wave eroded sea-cliffs and the bathymetry map compiled for this study is of sufficient resolution to model these palaeo strandlines and interpret sea-level stillstands. The most prominent of these terraces are at -112 m, -100 m, -87 m, -75 m, -52 m and -38 m bsl, while the -81 m, -65 m, -29 m and -20 m bsl levels are also clearly evident. This terrace level modelling is addressed in detail in Section 8.4.

A summary of the bathymetry of the prominent geological features in each area is listed in a table presented at the end of the appropriate section. The average of the shallowest depths along the top of each ridge and the average of the deepest depths along the base of the ridge is listed. Likewise the averages of the deepest and shallowest portions of the main basins are tabulated.

8.1.3.1 BLUE MOUNTAIN PROSPECT

The eastern edge of this area are in the -17 m to -29 m water depth range while the isobaths to the west reach a maximum depth of -119 m. Blue Mountain Prospect (Figures 30) is characterised by prominent submarine northerly trending ridges separated by sediment filled basins.

The inshore portion of BMP (Sammy's Ridge North and Sammy's Ridge South) is in the -17 m to -29 m water depth range while the isobaths to the west of Blue Mountain West reach a maximum depth of -119 m. BMP is characterised by prominent submarine ridges that trend in a northerly direction. The sediment filled basins separating these ridges form the highest potential target features in this area. A number of large northwest-

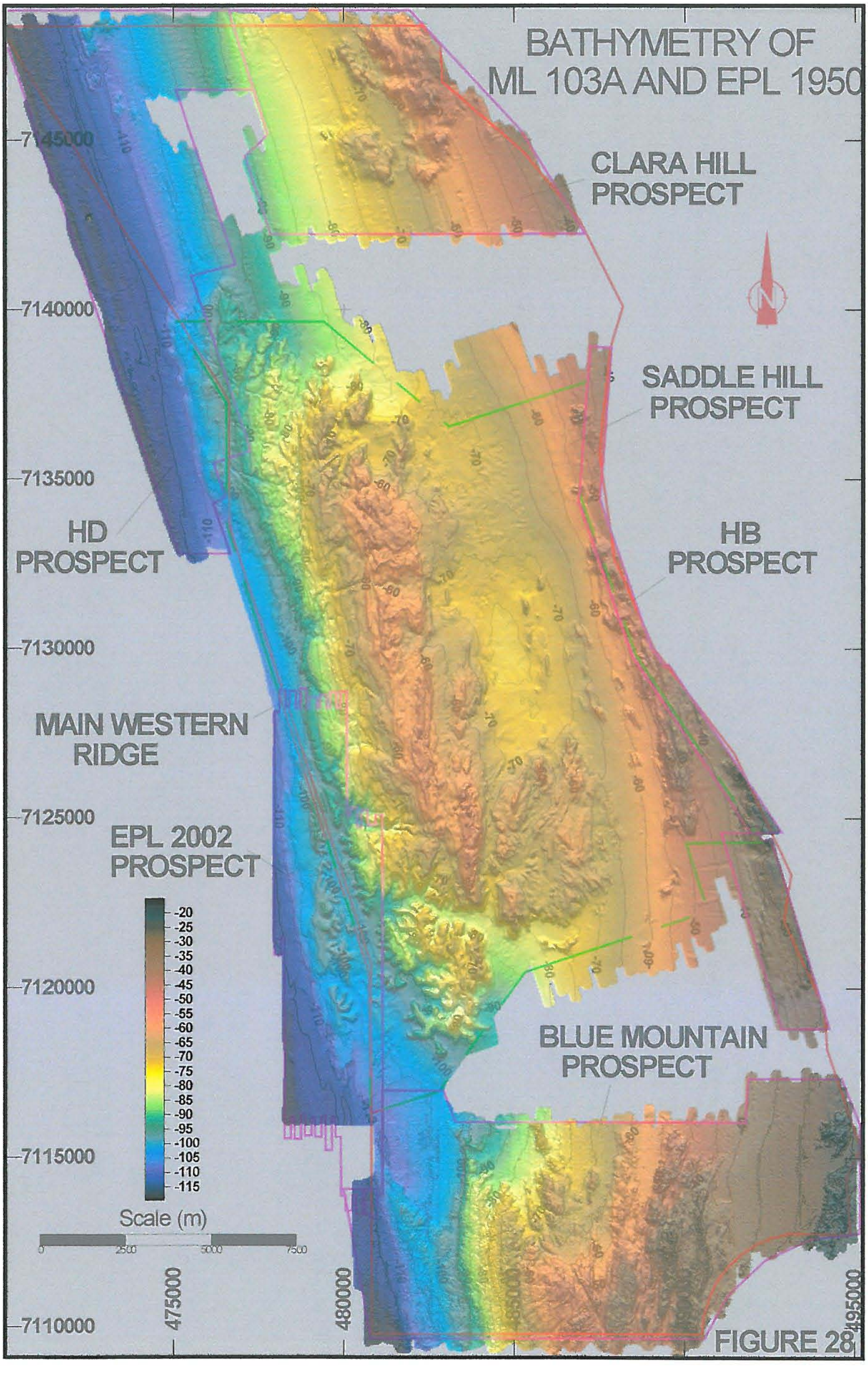

BATHYMETRY OF
ML 103A AND EPL 1950
CLARA HILL
PROSPECT
SADDLE HILL
PROSPECT
HD
PROSPECT
HB
PROSPECT
MAIN WESTERN
RIDGE
EPL 2002
PROSPECT
BLUE MOUNTAIN
PROSPECT
N
-7145000
-7140000
-7135000
-7130000
-7125000
-7120000
-7115000
-7110000
475000
480000
495000
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
-95
-100
-105
-110
-115
Scale (m)
0
2500
5000
7500

FIGURE 28

BATHYMETRY OF ML 103A AND EPL 1950

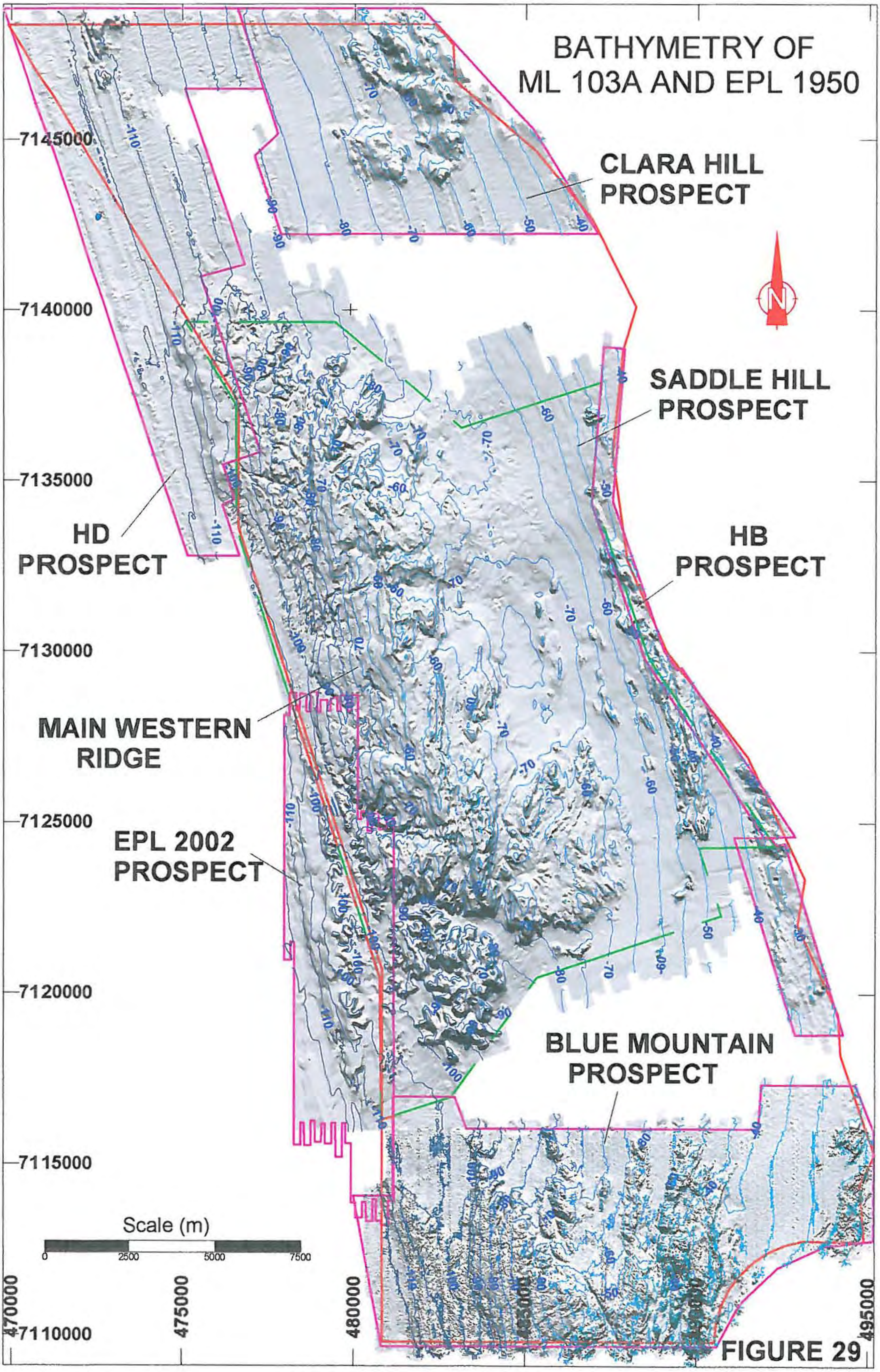


FIGURE 29

BLUE MOUNTAIN PROSPECT - BATHYMETRY

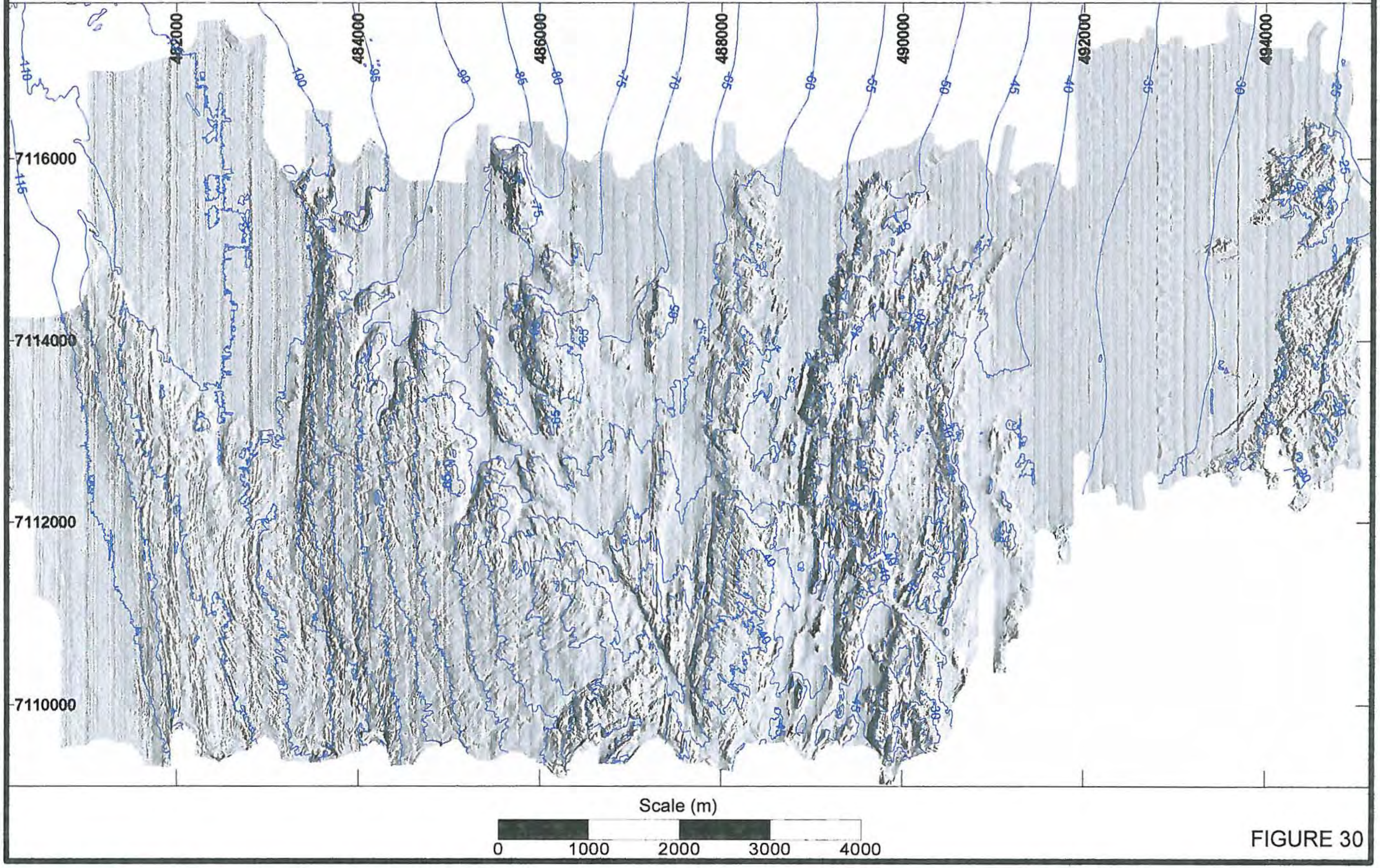


FIGURE 30

trending joints are evident, the most noteworthy being the one that cross-cuts Blue Mountain Central **(C)**. The high resolution swath bathymetry interpretation for this area is able to show the structural features in the bedrock. The shear fabric has been folded giving it a sinuosity when viewed in plan and the NW and NE trending joint sets can be easily distinguished **(Blue Mountain West)**. No offsets can be distinguished and the orientation of this conjugate joint pair suggests that it is associated with the tensional forces responsible for the shearing. Sinuosity evident within the joints suggests that they predate the folding. These finer (<1 m) structural features, though geologically interesting, are too small to be economically exploited by large mining tools and are located too deep to be of interest to diver operators and are therefore are not considered as high potential targets. The ridge, depression and gully type terrain in BMP is well suited to diamond entrapment and concentration. A summary of the bathymetric features in BMP is presented in Table 15.

TABLE 15: Summary of bathymetry in Blue Mountain Prospect.

Feature	Shallowest Depth (m)	Deepest Depth (m)
A	-111	-116
Blue Mountain West	-106	-119
B	-95	-109
Perruzzi Ridge	-85	-104
Blue Mountain Central	-65	-93
C	-45	-97
Fractured Ridge	-55	-78
D	-45	-80
Royal Ridge	-36	-45
E	-46	-60
Blue Mountain East	-28	-46
G	-39	-41
H	-29	-41
Sammy's Ridge South	-19	-29
I	-25	-28
J	-24	-26
Sammy's Ridge North	-17	-27

8.1.3.2 HB PROSPECT

A 14 m to 18 m high, northerly trending reef in the -23 m to -56 m bsl water depth range along the eastern edge of ML103A (Refer: Figures 29).

The shallowest isobath at -23 m bsl in this area is in the southeast corner while the seaward edge is at about -35 m bsl along HB South and -56 m bsl in HB Central and HB North. The reef has an elevation of about -14 m in HB South, while in HB Central and North the bedrock rises about 18 m above the sediment and is more rugged with a number of west-facing embayments along the seaward edge of this bedrock ridge. These reefs would have formed prominent cliffs during sea-level regressions. It is evident from the bathymetry that they were eroded by the -60 m to -65 m bsl and -35 m to -38 m bsl sea-levels, widely recognised along the inner shelf of the west coast (Murray, *et al.*, 1970, De Decker, 1986). In some places these embayments have been eroded toward the east and have broken through, segmenting the reef (**L, N** and **Q**). In these instances wave action may have been transported diamonds eastwards towards the current shoreline at Saddle Hill. The NE trending depression **(N)** between HB South and HB Central is postulated to be a potential position where the Koichab River could have bisected this coast-parallel reef. Alternately, the area between BMP and HBP could have been utilised **(L)**. A summary of the bathymetric depths of the sediments in the target features in HB Prospect is presented in Table 16.

TABLE 16: Summary of bathymetry in HB Prospect.

Feature	Shallowest Depth (m)	Deepest Depth (m)
L	-30	-36
HB South	-20	-43
M	-27	-38
N	-35	-47
O	-38	-45
HB Central	-22	-55
P	-45	-46
Q	-43	-56
HB North	-38	-58

8.1.3.3 CLARA HILL PROSPECT

The water depth in this area ranges from -40 m in the east to -91 m in the southwest. The bathymetry in Clara Hill Prospect shows this area to be at similar depths to Blue Mountain East (Refer: Figure 29).

The shaded relief map clearly shows a large north-northwest-facing depression **(T)** and a deep depression **(S)** between Clara East and Clara West. Two eastward-trending mega-gullies branching off the central portion of this depression **(S)** cutting back into Clara East. Introduction of gravel and heavy minerals into **(T)** could take place through the bathymetric low point on the reef to the northeast of Clara West. Once gravels and heavy minerals have been deposited in this depression it would be difficult for them to be transported out by wave action because the reef is up to 20 m high, along its eastern edge. This could result in the concentration of gravels and heavy minerals during regressions in the – 55 m to –65 m range. The depression **(U)** and southerly extensions thereof are similar to **(T)**, but are not as well developed. The bathymetry highlights a subtle north-south-trending depression through which diamonds deposited in the vicinity of **(R)** could be introduced into this basin. A summary of the bathymetric features in Clara Hill Prospect is presented in Table 17.

TABLE 17: Summary of bathymetry in Clara Hill Prospect.

Feature	Shallowest Depth (m)	Deepest Depth (m)
R	-47	-55
Clara East	-40	-68
S	-57	-73
T	-52	-67
U	-46	-66
Clara West	-61	-78

8.1.3.4 HD PROSPECT

A small bedrock outcrop, most likely a westerly remnant of the Precambrian basement and the northerly extension of the MWR, is present in the NW corner of the study area. The water depth in the HD area ranges from -84 m in the east to -119 m in the west (Refer: Figure 29).

The large north-south-trending ridge in the southeastern corner of HDP is contiguous with the MWR and is included in the assessment of that area. The bedrock outcrops in the northern portion of HD Prospect have been called Magna Ridge North and Magna Ridge South. The isobaths on this reef show Magna Ridge South has a low relief topography rising only about 3 m above the surrounding sediment-covered sea-floor. The relief along the southwestern edge of Magna Ridge North is more prominent with a height of about 5 m to 6 m. The isobaths for the western portion of the area reflects the gently westward dipping surface of the mudbelt at water depths of between -114 m and -119 m. This Holocene aged mudbelt abuts the crystalline Precambrian bedrock (De Decker and Woodborne, 1996) at about -112 m bsl. A summary of the bathymetrical features in HDP is presented in Table 18.

TABLE 18: Summary of bathymetry in HD Prospect.

Feature	Shallowest Depth (m)	Deepest Depth (m)
V	-105	-109
Magna Ridge North	-100	-114
W	-109	-112
Magna Ridge South	-105	-112
X	-107	-112
Y	-107	-109

8.1.3.5 SADDLE HILL PROSPECT

The MWR, the most prominent feature in the study area reaches a minimum depth of -50 m bsl. Sediment/rock contact depth averages -68 m and -112 m bsl along the eastern and western edges of this reef, respectively. Between the MWR and HB Prospect there is a sediment filled basin that reaches a maximum water depth of -76 m (Refer: Figure 29).

The linear sediment filled depression in the lee of the MWR slopes gently toward the south and would have formed a sheltered, north facing embayment during regressions in the -68 m water depth range **(AH** and **AI)**. Some small reefs at average water depths, along their seaward edges, of -59 m, -64 m and -74 m, remain as bedrock remnants within this basin. Structural features within the MWR have been eroded to form a number of dendritic shaped features, well suited for diamond entrapment. These features are predominantly along the southern, eastern and northern edges of the MWR with only a few present on the seaward edge. The most striking of these is **(AM)** which is postulated to have been used by the Koichab River to breach the MWR at some time. The sediment filled base of **(AM)** is at an average water depth of -82 m. A N-S trending fault transects the northern portion of the reef and forms the western edge of the southern half of the MWR (extends through **AA**), is evident on Figure 29. Another striking feature is the NNW trending portion of the structural feature that forms **(AM)** that may be an extension of the 330^0 trending fault in **(C)**. This structural feature appears to control the western limits of the Precambrian bedrock in the northern half of the concession. A summary of the bathymetrical features in SHP is presented in Table 19.

TABLE 19: Summary of bathymetry in Saddle Hill Prospect.

Feature	Shallowest Depth (m)	Deepest Depth (m)
MWR	-50	-112
A	-102	-113
Z	-94	-96
AA	-87	-92
AB	-74	-84
AC	-70	-82
AD	-56	-81
AE	-68	-72
AF	-59	-71
AG	-60	-69
AH	-64	-76
AI	-53	-73
AJ	-62	-67
AK	-64	-68
AL	-62	-66
AM	-64	-108
AN	-84	-104

8.1.3.6 DISCUSSION

The seafloor depths for all the potential target features in the study area have been defined above and are used for target delineation and prioritisation in Chapter 9.

The detailed examination of the bathymetry forms an integral part of marine diamond placer exploration. Not only does it give the geologist the depths of the various target features to compare to sea-level still-stand elevations, and depths of known mineralisation in adjacent areas, but also provides a digital elevation model (DEM) which aids in the visualisation of the seabed. Swath bathymetry systems are now reaching a level where they offer such good quality data that they are taking over the primary seafloor mapping role, previously held by side-scan sonar systems. Bedrock sediment contacts can be accurately defined using statistical algorithms such as horizontal derivatives. The main benefit of the side-scan sonar is that, once correlated with grab samples and type areas defined the interpretations can be used to map surficial sediment types present within the area.

8.2 SIDE-SCAN SONAR

8.2.1 INTERPRETATION METHODOLOGY

Various methods were required to create the side-scan mosaics essential for interpretation. "Cut-and-paste" mosaics were made from photo-reduced thermal records for the early geophysical data while later mosaics were digitally compiled. A sonographic facies discrimination system using seafloor micro-topography, developed by MCG specifically to suite the needs of the west coast diamond exploration industry, was used for all interpretations.

Only thermal hard-copy records are available for interpretation for the survey completed in 1994 for the SHP area. These 1:1000 scale sonargraph roles were photo-reduced to 1:5000 scale and cut-and-paste mosaics produced by MCG. A detailed 1:5000 scale side-scan sonar interpretation was undertaken, predominantly by the author onto these mosaics using the original 1:1000 scale thermal records as a reference. The 24 A0, 1:5000 scale interpretations were edge-matched and digitised by Mrs S. Smith.

The raw side-scan sonar data for the 1999 survey were post-processed using specialised in-house application processing software (ET-X MiniMap - now supported by CodaOctopus). During post-processing the records were bottom-track and slant-range-corrected and individually contrast balanced. Where necessary, a TVG gain was applied to the slant-range correction and toward the outer edge of the record. The overall quality of the processed data set is good. Mosaic tiles at a 0.4 m per pixel ground resolution were created, merged and mosaics were plotted at 1:5 000 scale. The side-scan records were interpreted, on transparent film, using the original 1:1 000 as a guide for interpretation of the 1:5 000 mosaic. The interpretation delineated the sediment/bedrock distribution, characterised the exposed bedrock in terms of relief and structure, and identified sediment textures in terms of fine and coarse sediment. The hand-drawn interpretation was digitised and line drawings were produced at a 1:5 000 scale. The sonograph interpretation formed the basis for the interpretation of the seismic data. The sedimentary and bedrock textural divisions used during the interpretation are defined in Section 8.2.1.1 and 8.2.1.2 below.

Semi-automatic seafloor recognition software options are available, but have not been used in this study. They enable the discrimination of various textural facies based on defined amplitude ranges of the acoustic return. This software requires very high quality data in order to distinguish textural facies consistently and effectively and cannot differentiate seafloor micro-topography in as much detail as is possible from a manual interpretation.

8.2.1.1 SEDIMENTARY FACIES

A side-scan sonar interpretation methodology was initially proposed by De Decker (1986) and subsequently developed by MCG specifically for diamond prospecting purposes. This system, that focusses on the qualitative assessment and characterisation of the seafloor micro-topography, has proven to be a consistent parameter by which potentially diamondiferous environments can be delineated (De Decker and Woodborne, 1996). Depending on the micro-topography the seafloor sediments being washed around by wave action, diamonds are either transported or impeded, culminating in diamond re-distribution or concentration, respectively along the palaeoshoreline. Therefore, this seafloor characterisation gives a qualitative indication of areas conducive to placer formation and preservation. On the inner shelf the texture of the surficial sediment can give an indication of the hydrological environment during deposition. Patches of coarse sediment, pebbles, cobbles or boulders are indicative of high energy environments. Owing to their high specific gravity (3.52) diamonds are generally associated with these sedimentary facies and thus the classification of these facies is important in marine diamond exploration. However, the subsequent burial of these coarser units by finer sediments settling out the water column during periods of transgression when water depths are deeper and sediment are located below wave-base, often precludes the recognition of the coarser units by these acoustic systems designed for seafloor surface characterisation. The classification divides the side-scan textural facies into those predominantly comprised of sediment (soft acoustic return) and those mainly consisting of rock (hard acoustic return). These two main categories are further sub-divided into classes as defined below.

The subdivisions within the sedimentary facies are fine sediment (fs), coarse sediment (cs), rippled coarse sediment (rcs) and areas of intermittently exposed bedrock covered with a veneer of coarse sediment (csv).

fs Fine sediment - generally consisting of silt and sand, is acoustically non-reflective and is the most prevalent of the sedimentary facies.

cs Coarse sediment - usually comprises coarse sand, pebbles, cobbles and sometimes boulders up to 0.5 m in diameter. Cs generally occurs as small isolated deposits within bedrock hollows and in linear depressions (joints, faults, bedding and shear planes or along the base of reefs) in the rock outcrops and is often associated with coarse sediment veneer. Phosphorite and glauconite have a similar sonographic textural appearance to terrigenous pebbles of a similar size. They can often be distinguished from the latter based on their depositional environment and depth of occurrence. Grab samples and/or cores are required for definitive identification[2]. Seafloor samples collected in the area indicate that phosphorite deposits are regularly situated immediately seaward of the western edge of the Precambrian outcrop at an average depth of about -120 m bsl.

rcs Rippled coarse sediment - identified by the occurrence of bedforms. The occurrence of sedimentary bedforms is usually indicative of cs that is in dynamic equilibrium with wave-induced bottom currents. This facies regularly comprises bioclastic and coarse grained bedrock material and gravel in the vicinity of rock outcrops.

csv Coarse sediment veneer - discontinuous cs to boulder deposits, generally less than 1 m thick covering more than 50% of the bedrock. Csv occurs frequently within the joints, gullies, bedrock depressions or fringing rock outcrops particularly where the topography is rugged. This facies often has gradational boundaries with subdued rock (SR), cs and rcs making its precise location on the seafloor difficult to interpret.

8.2.1.2 BEDROCK FACIES

Bedrock sonograph facies divisions are based on micro-relief interpreted from the third channel on the 1:1 000 side-scan sonar records that gives a profile of the seafloor beneath the towfish. In EPL 1950 the micro-topography (i.e. topography over <10 m) of the majority of the rock outcrops are generally in the 0-1 m range. It should be noted that a large smooth reef with little micro-topography would be classified as low rock (LR) according to this system that is aimed at assessing the bedrock's diamond trapping potential. This classification system developed by De Decker (1986) is similar to that described for alluvial systems by De Wit (1999), where increased diamond concentration is directly related to the Sak River flowing from the relatively smooth Karoo Sequence onto the more rugged basement rocks. In the marine environment, relatively flat bedrock surfaces with steep drop-offs into well confined basins/depressions are considered to have good diamond entrapment potential, similar to the enrichment within potholes described by Jacob *et al.,* (1999) for alluvial systems along the Lower Orange River. Many of the gullies interpreted during this study are too small to be of economic significance to a large scale mining operation. However, where a number of these small gullies lead into a larger, well confined basin the potential for diamond deposition and concentration increases. Each of the well developed basins, linear depressions, mega-gullies and gullies are assessed on its own merits. Based on this classification system, most of the outcrops in HBG fall into the low relief category.

SR Subdued relief rock - bedrock with less than 1 m micro-relief with a sediment veneer covering 25 % to 50 % of the bedrock surface. Sediment veneer occurs in linear depressions in the bedrock as well as in patches on the bedrock surface.

---

[2] During the EPL 2002 survey this material was sampled and the acoustic facies was confirmed to be of a phosphatic nature. The dredge could not recover any sample in some areas, suggesting that certain areas are indurated. It collected cemented conglomeritic phosphatic rubble in other areas indicating that reworking has occurred as described by Corbett (1996) for the deposits on the middle shelf. These precipitated, cemented surficial layers are prevalent in the northwest of SHP and along the western edge of HD and BMP.

LR Low relief rock - bedrock with up to 1 m micro-relief and sediment veneer covering less than 25 % of the bedrock surface. Low relief bedrock predominates in the area.

MR Moderate relief rock - bedrock with between 1 and 3 m micro-relief. This facies usually comprises ridges and reefs and is commonly associated with steeper than average seafloor gradients. Moderate rock was present in Blue Mountain, Clara Hill and HD Prospects. MR types identified are indicated in the legend of the ArcView coverages

RR Rugged relief rock - bedrock with a relief greater than 3 m micro-relief. Rugged relief generally occurs as small outcrops, usually associated with MR.

The detailed, 1:5 000 scale, side-scan interpretation of the study area was completed on approximately 50 A0 sheets. These sheets were digitised and subsequently incorporated into a GIS by Mr R. Herbert of Interactive Graphics. These original 1:5 000 scale interpretations, together with the similar number of interpreted bathymetry and seismic sheets, cannot be included in this thesis as they are too voluminous.

8.2.2 SURFICIAL SEDIMENTS OF THE INNER SHELF - LÜDERITZ TO SPENCER BAY

The bedrock sediment contact for the area between Lüderitz and Clara Hill Prospect is shown as an overlay on a shaded relief map of the bathymetry (Refer: Figure 31). The relative differences in the detail of the interpreted interface gives an indication of the quality data available for compilation within each area and are not necessarily indicative of lower lineament frequency. This interpretation is not able to show much more than that which is obvious through careful examination of the sun shaded relief map of the bathymetry. The extent of the Precambrian bedrock along the outer edge of the inner shelf is clearly visible. The relationship between the onshore headlands and their submarine expression can also be clearly seen. The open folding and structural features and their regional relationships are in places more apparent than what was demonstrated by the bathymetry alone.

8.2.3 SURFICIAL SEDIMENTS OF THE STUDY AREA

Figure 32 shows the sonographic interpretation, extracted from the GIS database, superimposed on a shaded relief map of the bathymetry. This map illustrates the side-scan interpretation clearly and should be used as a reference throughout this section. The clear, three-dimensional representation of the multifaceted, detailed interpretation of this remote sub-marine deposit, is such that one can mistakenly believe that this deposit is situated onshore. The sonograph interpretation shows that there is a relationship between the surficial sediments and the facies divisions described above. Changes in these sonographic facies are often gradational, particularly between cs, csv, rcs and SR, making these boundaries difficult to define precisely. It is evident that fs and LR are the dominant facies present in the area. Facies associated with coarser sediments (cs, rcs and csv) are located predominantly in the lee of the MWR and between the ridges in BMP. Sample log-sheets recorded by Namco's on-board geologists show that much of this coarser fraction comprises bedrock rubble. Bedrock fragments are likely to be washed over these reefs during regressional periods when water depths were

FIGURE 31

SEDIMENT/ROCK BOUNDARIES OF THE INNER SHELF - LUDERITZ TO CLARA HILL

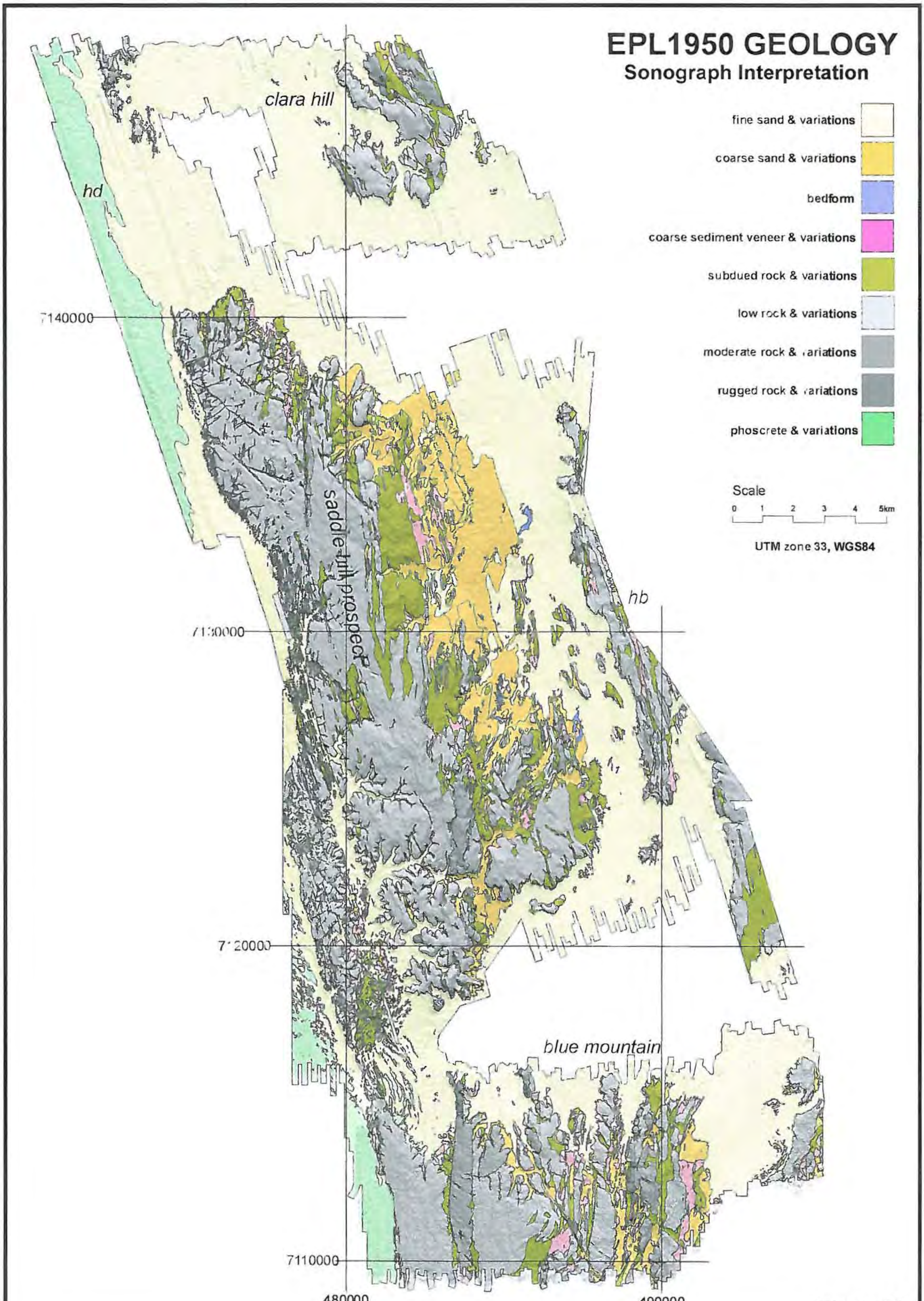

EPL1950 GEOLOGY
Sonograph Interpretation
fine sand & variations
coarse sand & variations
bedform
coarse sediment veneer & variations
subdued rock & variations
low rock & variations
moderate rock & variations
rugged rock & variations
phoscrete & variations
Scale
0 1 2 3 4 5km
UTM zone 33, WGS84
clara hill
hd
saddle hill prospect
hb
blue mountain
7140000
7130000
7120000
7110000
480000
490000

Figure 32

such that the orbital velocities on the seafloor created by the waves were able to move weathered bedrock located upon the outcrop. Gravitational processes could also contribute to this material but the predominance of this coarser fraction to the northeast of most of the prominent ridges suggests that wave action from the southwest was the dominant factor. The distribution of the phoscrete between the inner edge of this deposit and the -112 m to -114 m isobaths suggests that formation of these deposits is closely related to depth. The reason for the prominent band of SR along the eastern edge of the MWR is not clear. Correlation between the facies map and the bedrock lithology intersected at the termination of bulk sample sites suggests that it may be related to the more gneissic, rather than schistose nature of the bedrock, in this area.

8.2.3.1 BLUE MOUNTAIN PROSPECT

This area comprises of a number of north-south-trending ridges separated by large sediment filled depressions (Figure 33). Approximately 30% of the area is sediment covered, of which 20% comprises fs and the remaining 10% cs, csv, and rcs.

The ridges comprise predominantly LR with isolated MR ridges and rare RR outcrops. SR is closely associated with, and occurs along the edges and at the terminations of the larger structural features. The depressions are filled with cs, csv and fs. Most of the fs-filled basins are located along the northern edge of Blue Mountain Prospect. The basins are relatively wide toward the north and taper in toward the south. The sediment within the basins tends to get coarser toward the south. This may be indicative of a dominantly northward transport of weathered bedrock situated within these NS trending linear features. Coarser material near the source fining northwards toward the tail, as seen in BMP is commonly associated with sorting within most marine, fluvial and aeolian processes. In **(C)** there is one very prominent, cs filled, northwest-trending mega-gully, eroded along a joint or fault. Descriptions of the sonographic facies within this area are listed from west to east in Table 20.

GEOLOGY OF BLUE MOUNTAIN -
SONOGRAPH INTERPRETATION

Figure 33

TABLE 20: Summary of sonographic features in Blue Mountain Prospect.

Feature	Comment
A	Phosphatic material occurs along the edge of the reef in Blue Mountain West.
Blue Mountain West	A large LR outcrop along the western edge of this area with only minor sediment cover. Based on the examination of lineaments it is evident that deformation and folding has taken place. Phosphatic sediments occur as gully infill.
B	A fs-filled "wine glass-shaped" basin with a southward-trending "stem". From the side-scan sonar texture it appears as if the sediments in the "stem" area and around the western rim are phosphatic. Phosphatic ridges occur within the NW portion of the basin suggesting induration of these sediments.
Perruzzi Ridge	This MR ridge has a very straight, steep, well defined seaward face 12 m to 14 m high. This ridge is almost featureless with only a few NW-trending fractures dissecting it.
C	This basin is "wine glass-shaped" with a long cs-, csv-filled "stem" that extends toward the SE with a number of dendritic extensions along its periphery similar to **(B)** and **(D)**. **(C)** is orientated differently to **(B)** and **(D)**. A large outcrop at its "stem" creates two mega-gullies partially filled by cs. This prominent SE-NW-trending joint and the dendritic features associated with are similar to those evident within **(AM)**
Blue Mountain Central	The crest of this reef is relatively featureless comprising mostly LR and SR facies. Some subtle csv-filled depressions are present in the SE corner of the area. Folding and faulting are clearly evident.
Fractured Ridge	MR occurs along the western edge while the eastern edge comprises numerous patches of LR, SR, csv and cs reflecting a steep seaward and more gently sloping, topographically low, shoreward ridge profile.
D	A large NS-trending, wine glass-shaped, fs-filled depression tapering toward the south. Sediments coarsen toward the central and southern portions of the basin as it narrows. Sonographic textural changes in this area are gradational and difficult to distinguish. A large rock outcrop is situated in the central part of what would be the bottom of the wine glass, creating a mega-gully on either side of it.
Royal Ridge	A predominantly LR ridge with a number of NW- trending lineaments dissecting it. These lineaments are sub-parallel to the large joint through **(C)**.
E	A long, thin, "champagne flute-shaped", predominantly fs filled depression between Blue Mountain East and Royal Ridge that tapers toward the south. From the central section southward cs, csv and SR are the dominant sonographic facies, respectively.
Blue Mountain East	A complex terrain with a number of NS-trending ridges and depressions. Careful examination of the SSS mosaics shows gradational changes from cs to csv to SR to LR. Large cs/csv patches occur along the eastern edge and within linear depressions down the central axis of this area. Some MR and RR occurs along the western edge.
H	A large, fs-filled, north facing embayment separating Sammy's Ridges from Blue Mountain East.
Sammy's Ridge North	Predominantly LR with some cs and csv along the eastern edge. A SW-facing fs-filled embayment is situated along its southern edge. A SW-trending depression separates Sammy's Ridge North and South. A small LR outcrop is situated to the SW of Sammy's Ridge North.
Sammy's Ridge South	The western portion comprises LR with csv patches. The eastern portion has some fs-, cs- and csv-filled depressions. Along the western edge there is a mega-gully to the SE of a segmented ridge comprising a number of smaller LR and SR outcrops.

8.2.3.2 HB PROSPECT

This area that lies along the eastern margin of SHP, has three predominantly LR to SR outcrops named HB North (HB-N), HB Central (HB-C) and HB South (HB-S) separated by fs (Figure 34).

There is a sediment covered area to the south and west of HB-S. A NS-trending sediment-filled depression separates HB-S and HB-C. Some fs-filled depressions are seen along the eastern edge of the study toward the northeast of HB-C. The regional sediment bedrock interpretation indicates that HB-C and HB-N form a segmented, NNW trending reef with sediment on either side (Refer: Figure 31). HB-N is the most northerly segment of this reef before it outcrops again onshore at Clara Hill. The reef that forms HB-North is more disseminated than that of HB-C and HB-S indicative of increased erosion associated with waves refracting around the northern edge of the MWR (Refer: Section 8.5). Two westward-facing embayments are located along the western margin of this rock outcrop. Sonographic features of interest in this area are listed from south to north in Table 21.

TABLE 21: Summary of sonographic features in HB Prospect.

Feature	Comment
L	The southern half of HB Prospect comprises a flat, featureless surface covered with some thin patches of cs/csv, placing it in the SR category.
M	A small fs-filled west facing gully along the western edge of HB-S.
N	A sediment-filled depression separating HB-C and HB-S. Based on the regional bedrock/sediment interpretation incorporated into this data set it appears as if this 800 m wide depression continues towards the east, south of Saddle Hill (onshore) and may be the northern entry point of the Koichab River palaeo-channel (Refer: Sections 6.2.3).
O	A small fs-filled basin along the southeasterly edge of HB-C formed along a northerly trending joint.
P	A NS orientated deposit of fs and csv is along the eastern edge of this ridge. The csv could be bedrock rubble in the lee of this reef.
HB-S / HB-C	A fs-filled coast-perpendicular break between HB-N and HB-C that links **(AI)** to a sediment filled basin of similar size, shape and orientation, that separates this reef from one along the shoreline.
Q	Two fs-filled westward-facing embayments are located along the western edge of HB-N. Their eastern edges are linked by a long thin, NS-trending fs-filled depression.
E of HB-N	A NS orientated deposit of fs is present. This sediment extends toward the shore.
NE of HB-N	A large fs-filled depression that extends 15 km northward where the CHP reef outcrops.

GEOLOGY OF HB AREA
SONOGRAPH INTERPRETATION

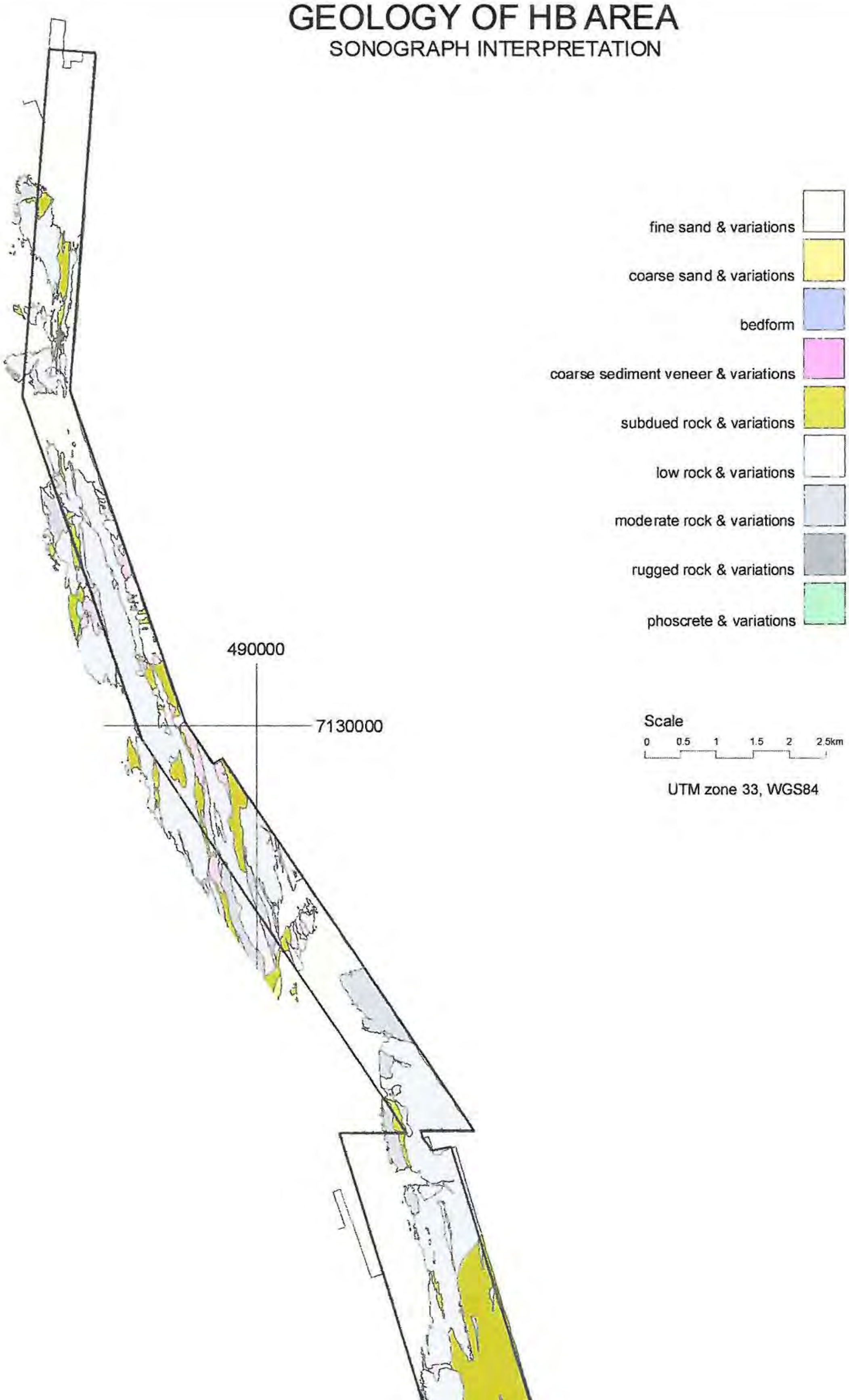


Figure 34

8.2.3.3 CLARA HILL PROSPECT

A number of hillocks, abutting the shoreline, form a headland at Clara Hill. These topographically positive features may be indicative of a lithological change or less deformation in that area. The large reef, comprising mainly LR surrounded by fs, forms the offshore extension of the headland (Figure 35).

The area has been divided into Clara East and Clara West, separated by a wide NNW trending fs-filled basin. Examination of the side-scan sonar records of the bedrock in CHP shows it to be less deformed than that encountered in HB-N, HB-C and Blue Mountain East which are at the same water depth and most likely form part of the same north trending reef. The rock in CHP appears to be more competent with less micro-topography upon the reef itself. Onshore, at Clara Hill, there are a number of hillocks which form a headland in that area. It is not known whether this topographically positive feature is a function of a lithological change or indicative of less deformation in that area. Nevertheless, the reef at CHP seems to correspond with the onshore geology forming an offshore extension of the headland. The reef itself has little micro-topography, comprising mainly gradational changes between LR, SR, csv and cs. Sediment/rock contacts are well defined, indicative of steep gradients along the bedrock edges noted in the bathymetry interpretation of this area. The smooth, bulborous nature of the outcrop is consistent with that typical of core stones in gneissic or granitic lithologies. Sonographic features of interest in this area are listed in Table 22.

TABLE 22: Summary of sonographic features in Clara Hill Prospect.

Feature	Comment
R	A fs-filled large, south-facing embayment. Based on the regional interpretation of the sediment/bedrock interface it appears as if this linear depression extends in a northerly direction all the way to the shore, north of Clara Hill. A LR/ SR outcrop forms the SE rim of the basin.
Clara East	This large, predominantly LR outcrop is most likely a continuation of the ridge that runs through HB-C and HB-N. To the SE of Clara East there is a small SR outcrop within a large area of fs.
S	A large fs-filled channel/depression separating Clara East from Clara West. The southern half of the channel is NS-trending while the northern half thickens and bends toward the NE. Again this is a typical, structurally controlled morphology. Two, smaller fs-filled, west-facing basins are located along the eastern edge of the southern portion of Star Basin.
T	Similar in shape and orientation to Trapese Basin but much larger. Predominantly fs infill, coarsening in the SE extremities. This basin's "zig-zag" shape is indicative of strong structural control. The eastern part of the basin is flanked by a MR ridge.
U	A small SE-facing basin tapering toward the NW. The basin has fs infill toward the north with coarser sediments in the south. Like **(T)** this basin's shape also reflects a strong structural control.
Clara West	Comprises predominantly LR with MR along the western edge. Isolated csv patches occur particularly within long, thin, linear depressions shoreward of the MR sector along the west of the ridge. Based on the isobaths this reef is most likely the northern extension of the reef along the eastern edge of the MWR that contains **(AJ)**, **(AK)** and **(AL)** and sub-divides **(AH)** and **(AI)**. Some isolated LR and MR outcrops occur as isolated outcrops north of Clara West as well as toward the NW extremities of CHP. Fs is the only facies present toward the southwest.

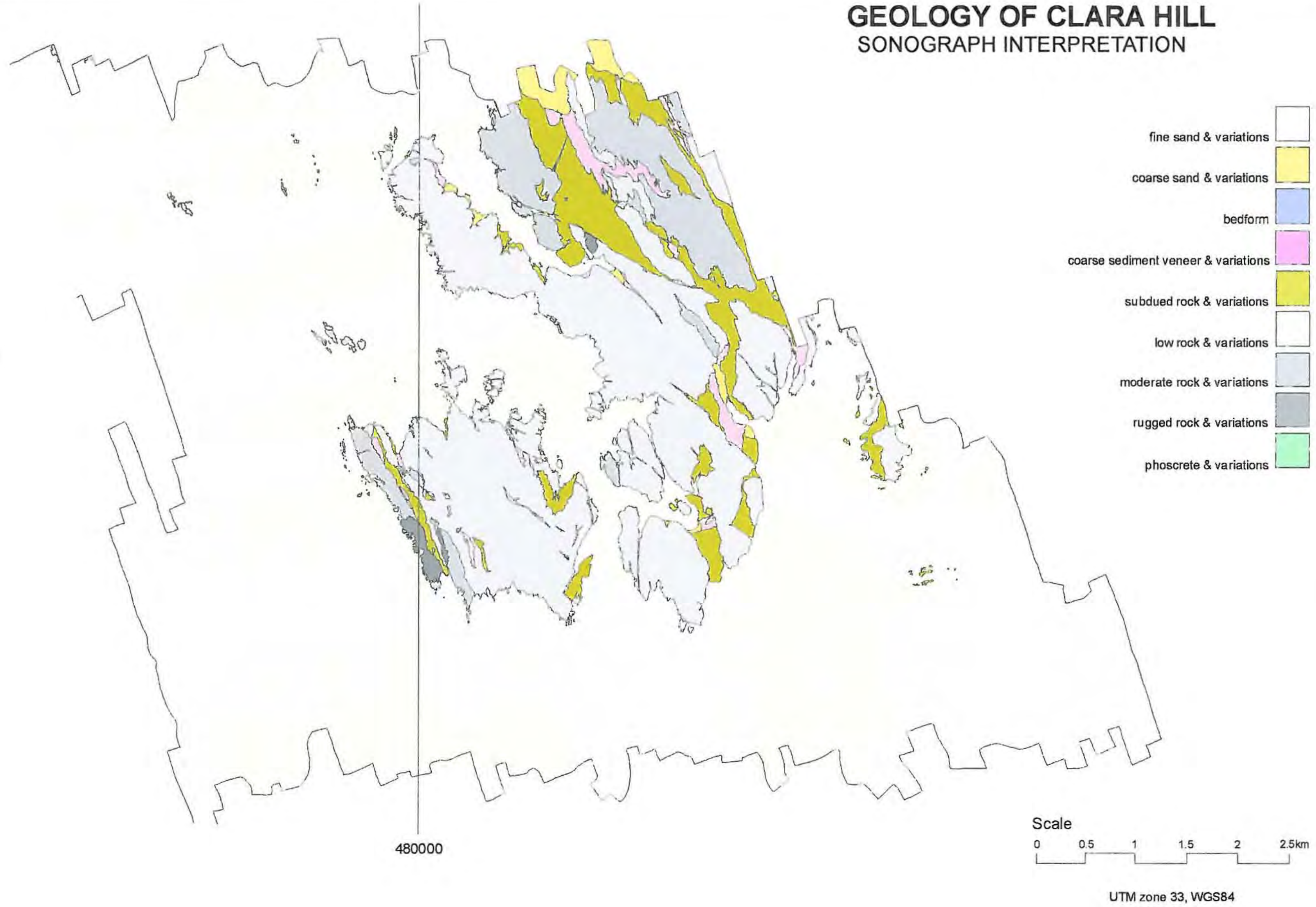

GEOLOGY OF CLARA HILL
SONOGRAPH INTERPRETATION
fine sand & variations
coarse sand & variations
bedform
coarse sediment veneer & variations
subdued rock & variations
low rock & variations
moderate rock & variations
rugged rock & variations
phoscrete & variations
480000
Scale
0
0.5
1
1.5
2
2.5km
UTM zone 33, WGS84

Figure 35

8.2.3.4 HD PROSPECT

Three small LR to MR reefs occur just within the northwestern extents of the study area. They are surrounded by fs with phosphatic sediments evident along the western edge of the area, in water depths exceeding -112 m bsl (Refer: Figure 32).

The predominantly LR reef visible in the southeast corner coincides with the MWR and is interpreted with SHP. Some small LR and MR outcrops are located near the northern boundary of HD Prospect. They are surrounded by the dominant fs facies that is located throughout the central and eastern portions of the area. The acoustic textural signature along the western edge of the area is similar to what have been interpreted as phosphatic sediments, described along the western edge BMP in the -112 m bsl water depth range. Sonographic features in this area are described from north to south in Table 23.

TABLE 23: Summary of sonographic features in HD Prospect.

Feature	Comment
Magna Ridge North	A disseminated rock outcrop similar in nature to that along the W edge of the MWR in SHP. Within the outcrop area the majority of the linear sediment patches appear to have been phosphatised.
V	A basin that opens toward the SE, situated west of Magna Ridge North. Sediments along the western rim of this basin have a black acoustic texture on the SSS mosaic, consistent with similar acoustic textures, sampled in EPL 2002, identified as being of a phosphatic nature.
W	A fs-filled, east-facing embayment along the SW edge of Magna Ridge North. This embayment cuts through to the fs wedge to the west of Magna Ridge North.
X	This fs-filled channel/depression separates Magna Ridge North and Magna Ridge South.
Y	A fs-filled, linear depression along the eastern edge of Magna Ridge South.
Magna Ridge South	This rock outcrop is even more disseminated than Magna Ridge North. This ridge comprises mainly LR and fs patches some of which appears to consist of phoscrete.

8.2.3.5 SADDLE HILL PROSPECT

The MWR, though bathymetrically significant, is relatively smooth on a micro-topographical scale comprising predominantly LR. The limited number of structural features present have been exploited by erosional forces to form fs, cs and csv filled gullies, mega-gullies and dendritic shaped features.

The structural features upon the MWR are highlighted in Figure 32. Narrow, cs, csv and SR filled joint sets, trending at 310^0, 290^0 and 245^0 toward the NW edge of the MWR are clearly visible but are too small to be of economic interest when utilising large mining tools. The significant proportion of cs, rcs, csv and SR in the lee, to the NE of the reefs in **(AA)**, **(AB)**, **(AC)**, **(AD)**, **(AE)**, **(AF)**, **(AG)**, **(AH)**, **(AK)** and **(AL)**, suggests that they have been deposited in response to the predominant SW swell. Sample log sheets completed by Namco's onboard geologists note an increase of bedrock fragments and biogenic debris within the overburden in these areas, indicating that much of this surficial coarse material is sourced from weathered bedrock and organisms living on the reef, and therefore cannot be directly correlated with diamond placer potential. However, its presence would indicate the dominant transport direction over the reef and the sheltered environment in the lee of the MWR, conducive to placer preservation. By contrast along front edge of the MWR only fs is present. On a broad scale there is a marked difference between the western and eastern edges of the reef with the latter being far more irregular. It is not evident whether this is a function of the lithology or of a difference in the erosion pattern by the wave action. A fs-filled dendritic shaped feature along the central and southern edge along the seaward side of this reef are the most striking features on the MWR. The shape of these features suggests they're structurally controlled. Sonographic features of interest are listed from north to south in Table 24.

TABLE 24: Summary of sonographic features in Saddle Hill Prospect.

Feature	Comment
A	fs together with some phosphatic sediments are present along the seaward edge of the MWR.
Z	A northward facing csv- and fs-filled strike parallel gully eroded into the N edge of the MWR.
AA	A N facing csv- & fs-filled strike gully, with SR around the rim, eroded into the N edge of the MWR
AB	Very similar to (AA) but with a large area of cs in the lee of a large round reef protruding from the northeastern edge of the MWR.
AC	A small NE trending cs- and csv-filled gully along the northeastern edge of the MWR.
AD	A large dendritic shaped cs-filled basin situated in the lee of the MWR.
AE	A relatively poorly morphologically confined cs-filled gully bounded by SR and CSV.
AF	A cs- and csv-filled easterly trending gully formed along a joint that dissects and forms a saddle near the centre, along the shoreward edge of the MWR.
AG	Very similar to **(AF)** but the joint along which it is formed does not extend is not as pervasive terminating near the central axis of the reef.
AH	This large predominantly cs-filled depression in the lee of the MWR has been kept together as a single morphological feature for the geophysical interpretation descriptions. However, the southern portion of this large feature is more conducive to diamond introduction and therefore for target prioritisation it has been sub-divided into a number of target features.
AI	This large predominantly fs-filled depression in the lee of the MWR adjoins the eastern edge of **(AH)**. This north trending linear depression along the seaward edge of HB has a number of small reefs scattered throughout it as well as a dissected ridge separating it from **(AH)**.
AJ	A cs-, csv- and SR-filled linear depression filled with small reef outcrops joining **(AM)** with **(AH)**. The alignment of this feature parallel to the dominant SW swell is conducive to diamond transport into **(AH)** and **(AI)** from **(AM)**.
AK	A relatively poorly formed cs-filled easterly facing gully along the southeasterly edge of the MWR.
AL	A small fs- and csv-filled strike parallel gully along the southeasterly edge of the MWR.
AM	This fs-filled dendritic shaped mega-gully is the most striking feature in the study area. Its eastern extremities are cs-filled while to the southwest small SR and LR patches are littered throughout the fs. For target prioritisation purposes, though clearly one morphologically distinct feature, (AM) has been sub-divided into a number portions corresponding to changes in orientation of the main linear depressions.
AN	A relatively poorly defined fs-filled feature along the southern edge of the MWR.

8.2.3.6 DISCUSSION

In deeper water environments, recent surficial sediment deposits often mask the more relevant textural signatures associated with the period of diamond placer formation. This modification has detracted significantly from the usefulness of the side-scan sonar interpretation for diamond placer delineation and prioritisation in the study area.

Deposition of modern, surficial sediments masked the relict sediment in some localities in the study area. Nevertheless, factors like the predominant transport direction and delineation of areas of preservation, shown by deposition patterns in the more recent sediments, are also likely to apply to the older basal deposits. With marine regressions the orbital velocities on the seafloor would have shifted offshore therefore it is difficult to equate the current deposition patterns with those in the past on a one to one basis. Nevertheless, on a large scale trends are likely to be similar.

8.3 SEISMIC DATA

8.3.1 INTRODUCTION

The interpretation of good quality, high resolution seismic data form an integral part of successful diamond placer target delineation and prioritisation on the inner shelf of the west coast.

Cost limitations currently restrict marine diamond mining to typically less than 5 m, sediment overburden thicknesses. Therefore, subsequent to the seismic interpretation, the area under investigation can be substantially reduced and only the sediment cover suitable for economic diamond extraction focussed on in greater detail. Marine seismic technology has largely been developed by the oil industry. However, the oil industry requires systems capable of penetrating 100's of metres below the seafloor while the marine diamond mining industry requires very high resolution to 10 m penetration. High resolution chirp, pinger, and TOPAS and medium resolution boomer, sparker and mini-airgun seismic systems have been used at various stages during exploration in the study area. Interpretation of these records has shown that the TOPAS, chirp and pinger systems give the resolution required but penetration can be limited when rippled coarse sand, clay, shell or indurated horizons are intersected. The medium resolution systems are not affected by these units but lack the resolution required for accurate interpretation of bedrock micro-topography. These deeper penetrating systems can also penetrate an indurated "false footwall" above the Precambrian bedrock which cannot be excavated by the mining tools currently active on the inner shelf of the west coast. However, these indurated horizons are difficult to distinguish from gravel, boulder, clay, shell and semi-indurated horizons which have a similar acoustic signature. This can lead to erroneous volume calculations and a mis-representation of an area being beyond mining depths (i.e. >8 m) when in fact it should be targeted during further investigations. Seismic resolution is partly a function of the acoustic "footprint" on the seafloor. Most seismic pulses are not corrected for transducer movements resulting in the "footprint" wandering around on the seafloor and adversely affecting the resolution of the acoustic record. The higher the transducer above the seafloor the greater the affect. Motion reference corrected seismic systems like the TOPAS can produce high resolution seismic records.

8.3.2 INTERPRETATION METHODOLOGY

A combination of analog and digital techniques were used to interpret sediment isopachs from a variety of sub-bottom profile records collected during different geophysical surveys.

Only thermal hard-copy records are available for interpretation of the SHP survey area completed in 1994. Spot depths of the sediment thickness to acoustic basement, as well as well defined internal horizons, were transposed from the 1:1000 scale, synchronised chirp and boomer records onto plan, 1:5000 scale, A0 maps. Acoustic basement is the deepest horizon resolved by the chirp and boomer and does not necessarily coincide with Precambrian basement although in most cases these surfaces are analogous. Where weathered bedrock rubble, gravel, massive shell horizons, indurated units and thick clay layers are present, particularly if located directly on bedrock, they are often impenetrable to high resolution seismic systems. This "false bottom" is referred to as acoustic basement. Often it is not possible to distinguish between this "false bottom" and the Precambrian bedrock. The latter in the study area is typically more rugged, being schistose but because the seismic resolution is often poor at the limits of penetration, a clear distinction cannot be consistently made. Therefore, to improve the accuracy, lower resolution seismic systems, capable of penetrating all unconsolidated sedimentary horizons, are interpreted concurrently. The detailed seismic interpretation, of the acoustic basement of SHP, spanning several months was undertaken, by the author, using the side-scan sonar as a guide in areas of extrapolation between survey lines. The 24 A0, 1:5000 scale interpretations were edge-matched, digitised by Mrs S. Smith and incorporated into the GIS by Mr R. Herbert of Interactive Graphics.

The pinger records collected during the 1999 survey were digitally enhanced using various filters available within ET-X seismic processing software (now supported by CodaOctopus) and the acoustic basement reflector digitised. These digitised files were merged and spot depths digitally transposed onto the plan, side-scan sonar mosaics. The high quality 1 cubic-inch airgun seismic records were also enhanced using ET-X software and the Precambrian basement and significant internal reflectors digitised. The spot depths were merged and transposed onto side-scan sonar mosaics along with the pinger depths. The spot-depths were then compared and conflicting lines re-interpreted where necessary. Comparisons show the data to correlate well with less than 1 m difference between the independently digitised pinger and airgun spot depths in areas where sediment thicknesses are in the > 2 m and < 10 m range. This iterative correction methodology culminated in the re-processing of a small number of conflicting lines. The internal horizon spot-depths tended to be discontinuous in many areas. The spot-depths were hand-contoured at 1 m intervals, by the author, using both the pinger and airgun spot-depths and the side-scan sonar mosaics as a guide where extrapolation between lines was necessary. By viewing both sets of spot-depths simultaneously it was possible to ascertain whether the pinger signal had attenuated on an internal horizon or whether the bedrock surface was being interpreted. The higher resolution pinger was used predominantly in the thinner sediment areas (<8 to 10 m) cross-referencing the airgun, while in thicker sediments (>10 m) the airgun was used preferentially. The side-scan interpretation was used to guide the seismic interpretation in areas of extrapolation between survey lines and near bedrock contacts. The independently interpreted seismic results were thereby integrated into a single, coherent interpretation of sediment thickness in the study area. Specific notes on difficulties experienced during the interpretation and how they were resolved, are discussed in greater detail in Sections 8.3.2.1 and 8.3.2.2 below.

These interpretations were digitised by Mrs S. Smith and subsequently incorporated into a GIS by Mr. R. Herbert of Interactive Graphics. The seismic interpretation superimposed on the side-scan facies interpretation was extracted directly from the GIS and is used throughout this section. Four, coast-perpendicular examples of the 1999 survey are included in Appendix 2.

8.3.2.1 1999 SURVEY - PINGER

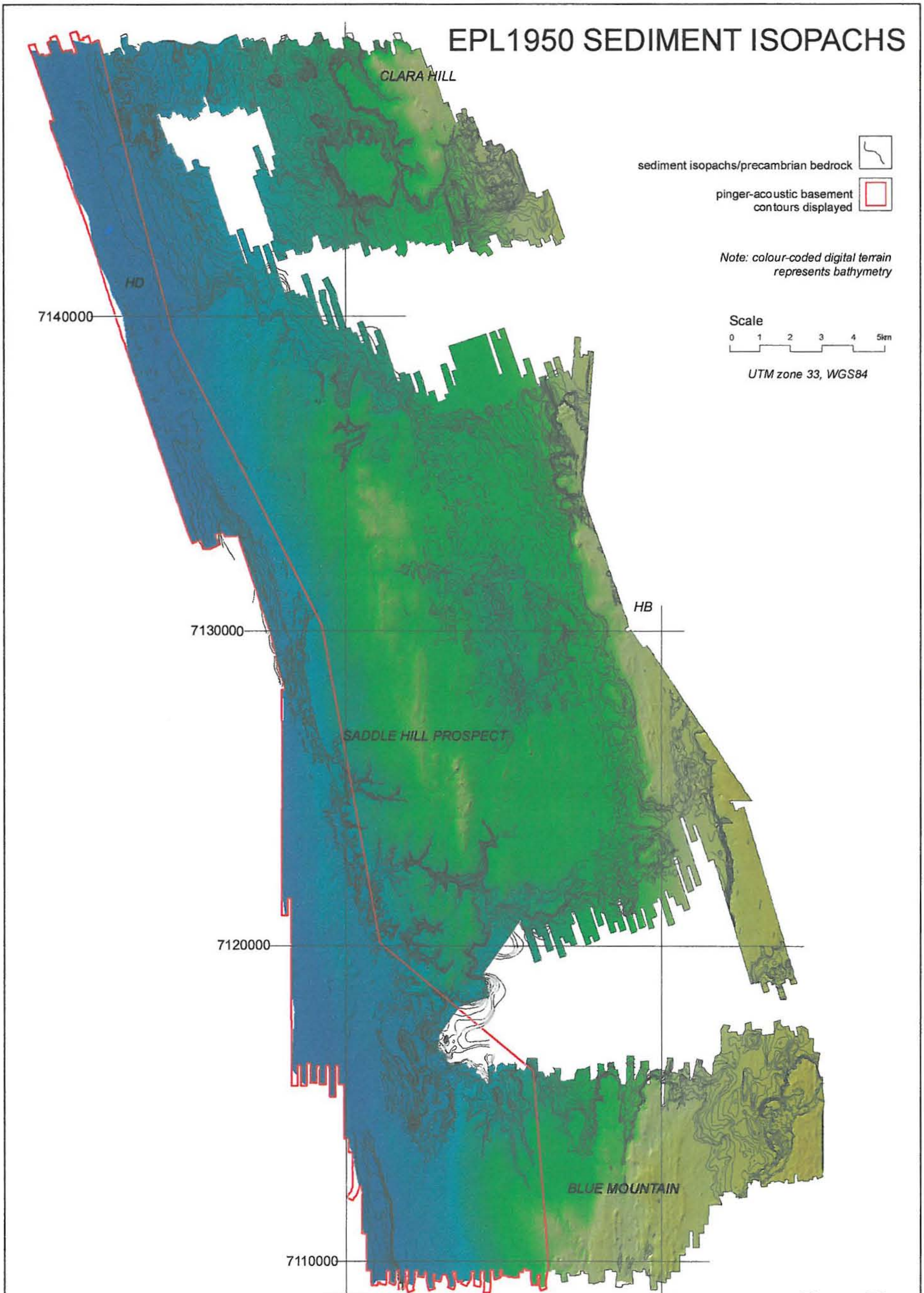
In certain areas the pinger and airgun spot-depths correlated poorly because of the pinger's inability to penetrate surficial indurated horizons that could easily be penetrated by the more powerful airgun. These areas corresponded with the semi- to indurated, surficial phosphatic layers evident on the side-scan sonar interpretation.

Phosphatic horizons are prevalent toward the west and northwest of BMP, south and west of SHP and along the western edge of HD. To the northwest of BMP the seismic interpretation was complicated by edge-matching of two independent surveys using different seismic systems with different penetration and resolution characteristics. The medium resolution boomer used in the 1994 survey of SHP terminated on a strongly reflective internal horizon (most likely indicative of it being semi-indurated or indurated) along the NW and SW edges of the survey area but could not resolve the underlying Precambrian basement that was detected using the mini-airgun during the 1999 survey of BMP and HD. In order to edge-match these data sets the equivalent strongly reflective internal horizon in BMP and HD had to be interpreted and contoured. However, this horizon is not laterally continuous in BMP. Where the horizon pinches out or is not indurated the pinger penetrates through to the next significant layer many metres below this surficial horizon. This highly variable penetration, corresponding to the degree of induration of this internal reflector, gives the appearance of deep, vertical-sided, holes/edges in areas where penetration was achieved. In order to make some sense of these interpretations, spot depths of pinger acoustic basement were contoured and edge-matched to the 1999 data set as a separate coverage for the northwest basin in BMP as well as along the western edge of HD Prospect (Figure 36). It is not possible to tell whether the sediments beneath this surficial, indurated horizon are consolidated/semi-indurated or whether this phosphatic horizon is a hard duri-crust perched upon unconsolidated sediment. Based on the pinger seismic interpretation, the latter seems more probable because the penetration of up to 10 m was achieved within areas where this surficial, indurated horizon pinches out.

8.3.2.2 1999 SURVEY - AIRGUN

The mini-airgun used during the 1999 survey provided high quality sub-bottom records, with a resolution of about 1-2 m, down to bedrock.

Based on the airgun records it is evident that the Precambrian basement in **(B)** and along the western edge **(A)** of BMP, lies in excess of 20 m below the seafloor surface. Furthermore, it is evident from the side-scan sonar and pinger records that in **(B)** there is an indurated horizon that outcrops in places. The pinger sediment isopachs were contoured to show the depth of this surficial indurated horizon beneath seafloor surface in these



EPL1950 SEDIMENT ISOPACHS

Figure 36

areas. In this northwestern sector of BMP the airgun penetrated this surficial indurated unit as well as a number of other strongly reflective horizons easily, before terminating on Precambrian basement. Without ground-truthing with vibrocores/drilling it is not possible to ascertain which of these numerous horizons is indurated. One horizon was particularly well developed, occurring as a relatively continuous, strongly reflective unit at a number of localities along the western edge of the study area. It was called the "1st significant horizon". This "1st significant horizon" was digitised, contoured and a separate ArcView coverage created for the two north-facing basins on the northwestern edge and to the west of BMP, as well as, along the western edge of HD Prospect, where it occurs.

8.3.3 RESULTS OF THE SEISMIC INTERPRETATION

8.3.3.1 BLUE MOUNTAIN PROSPECT

For the eastern two thirds of BMP >90% of the interpreted pinger and airgun bedrock spot depths corresponded to within 1 m of each other. However, in (B) and (C) the seismic stratigraphy is more complex with the pinger's acoustic signal terminating on an internal horizon far shallower than the Precambrian bedrock, shown in Figure 37.

The Precambrian basement interpreted from the airgun in **(B)** dips down to more than 28 m below the present seafloor. Between the internal horizon that attenuated the pinger acoustic signal and the Precambrian bedrock is another strongly reflective horizon, forthwith referred to as the "1st significant horizon" (Figure 38). Based on its strongly reflective acoustic return it appears consolidated but without further quantitative investigation it is not possible to determine the exact nature of this surface. This horizon is present throughout the western part of the study area and most likely represents a major chrono-stratigraphic boundary. The 1st significant horizon reaches a maximum of about 19 m below the present seafloor within this basin (Refer: Figure 38). On and near the present seafloor level, along the southern and western rim of **(B)**, is another strongly reflective acoustic horizon (Figure 39) that corresponds with the phosphatic sediments interpreted from the side-scan sonar records. The strongly reflective nature of the seismic return would suggest that this surficial horizon is semi-indurated or indurated (phoscrete). A reworked phosphatic pavement with similar acoustic properties was described by Namco's onboard geologists during the sampling programme in EPL 1946 and dredged and described by Mr. De Decker (pers. comm) during the EPL 2002 survey. This horizon pinches out toward the east with only a few remnants interpreted in that area. The pinger was not able to penetrate this horizon along the western and southern rim of the basin, but did penetrate down to the "1st significant horizon" toward the east of the basin where the surficial phoscrete horizon is poorly developed. The surficial horizon was the deepest horizon resolved by the seismic systems during the 1994 survey interpretation and therefore in order to produce a coherent surface these corresponding seismic horizons had to be edge-matched and not the Precambrian basement detected by the airgun in the 1999 survey, situated many metres further down. Table 25 summarises the seismic features of interest noted in BMP from east to west.

BLUE MOUNTAIN SEISMIC INTERPRETATION
WITH PRECAMBRIAN BEDROCK SEDIMENT ISOPACHS

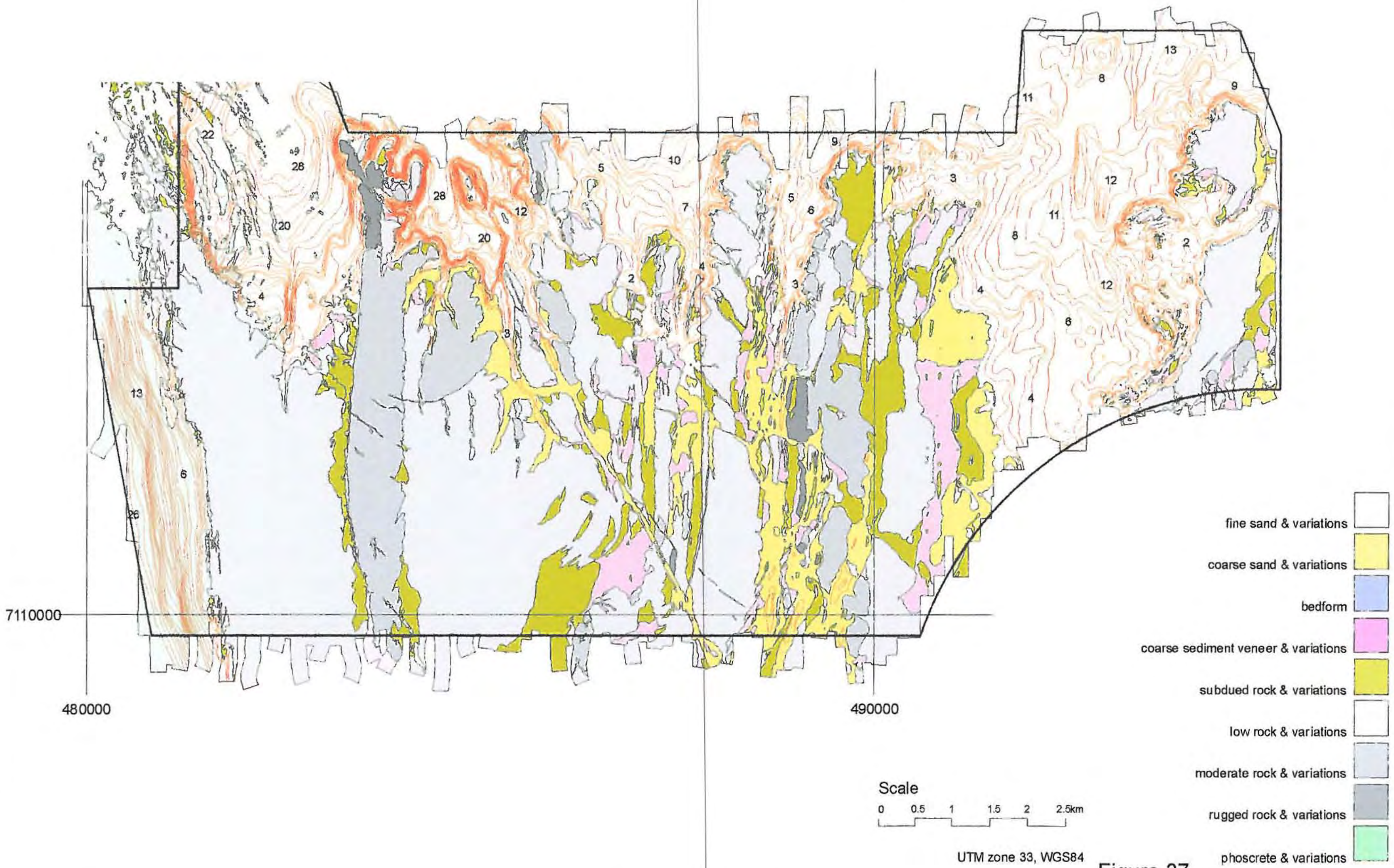


Figure 37

BLUE MOUNTAIN SEISMIC INTERPRETATION

WITH FIRST SIGNIFICANT INTERNAL SEDIMENT HORIZON

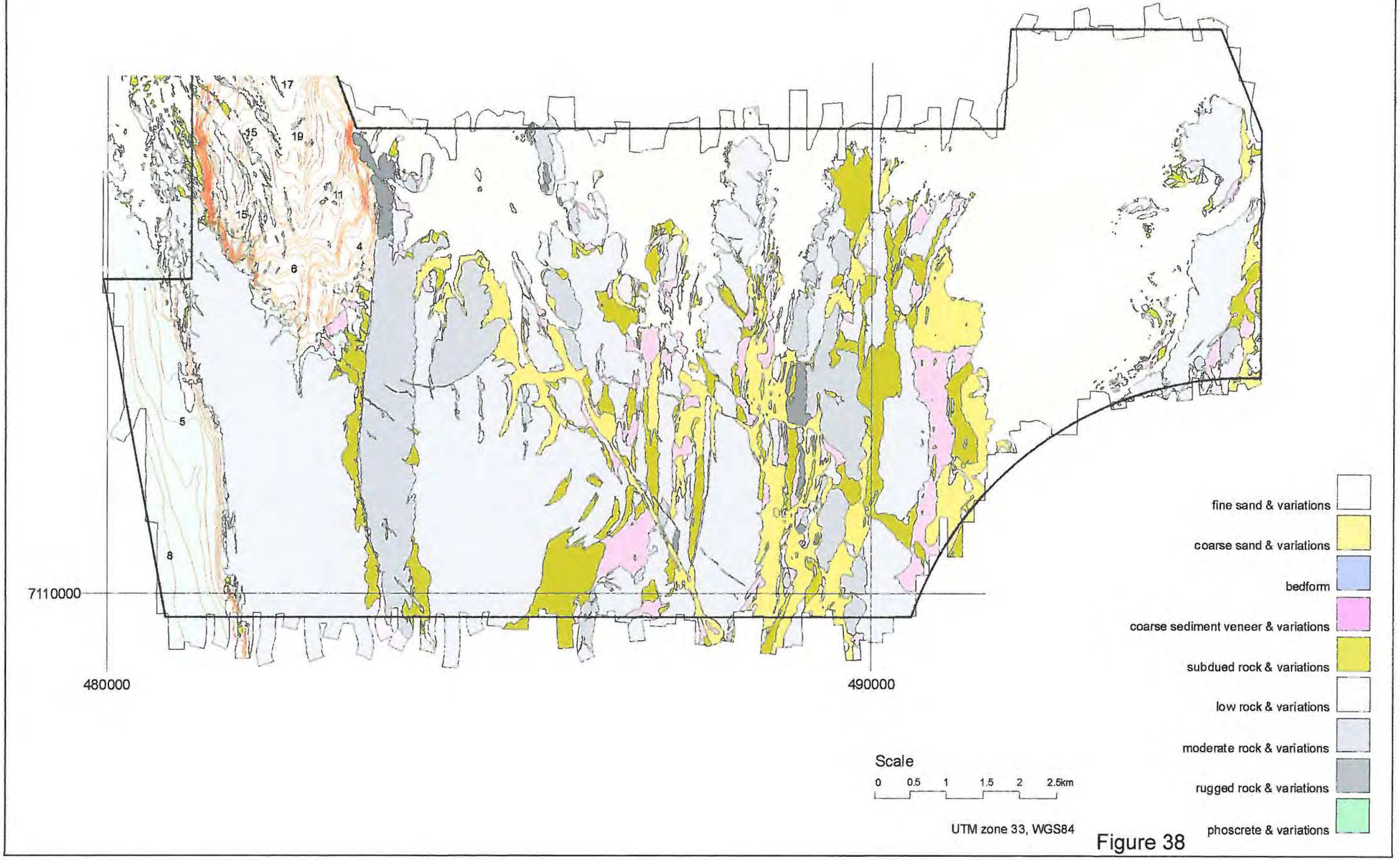


Figure 38

BLUE MOUNTAIN SEISMIC INTERPRETATION

WITH PINGER/BOOMER ACOUSTIC BASEMENT SEDIMENT ISOPACHS

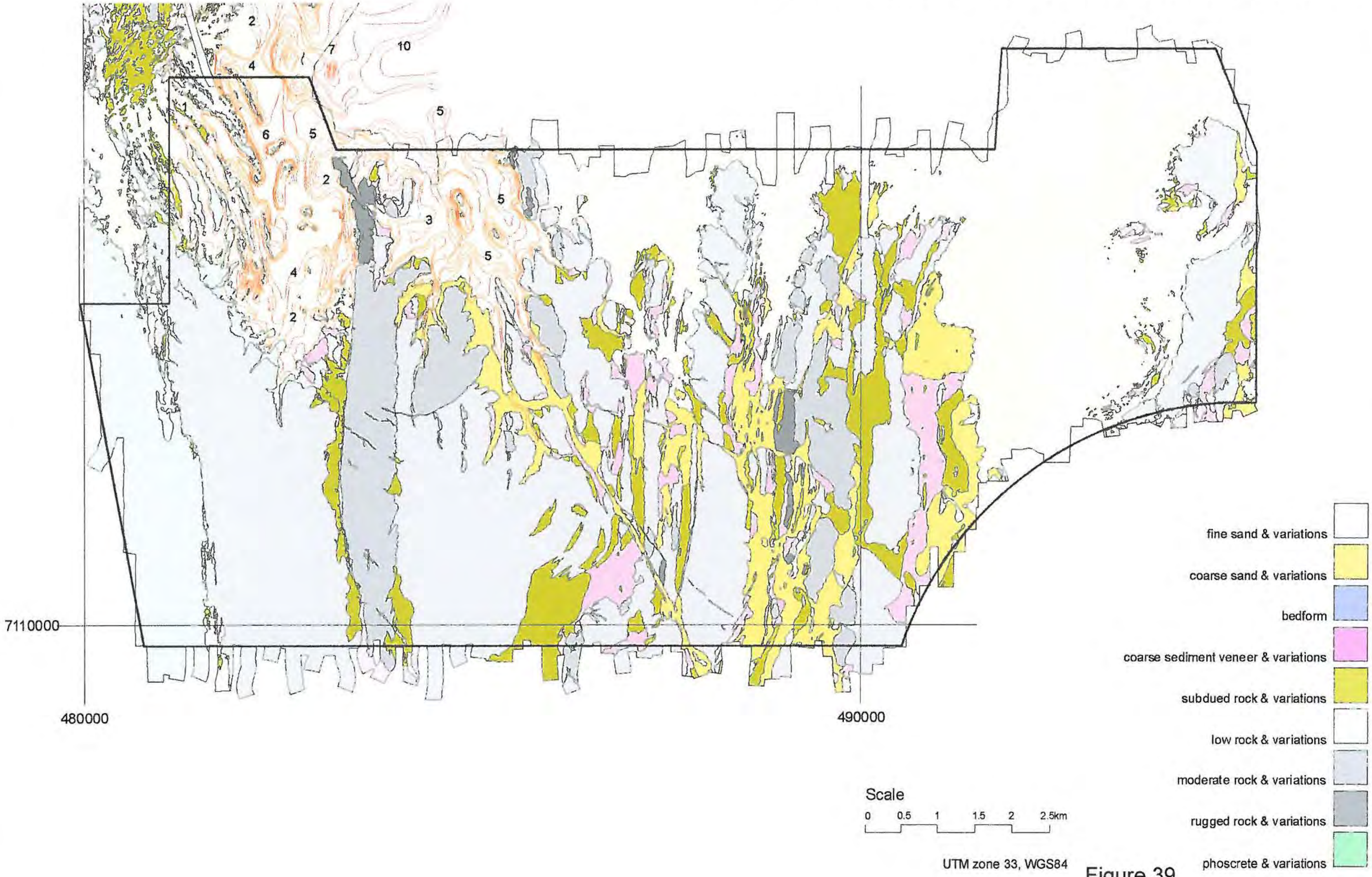


Figure 39

TABLE 25: Summary of seismic features of interest in Blue Mountain Prospect.

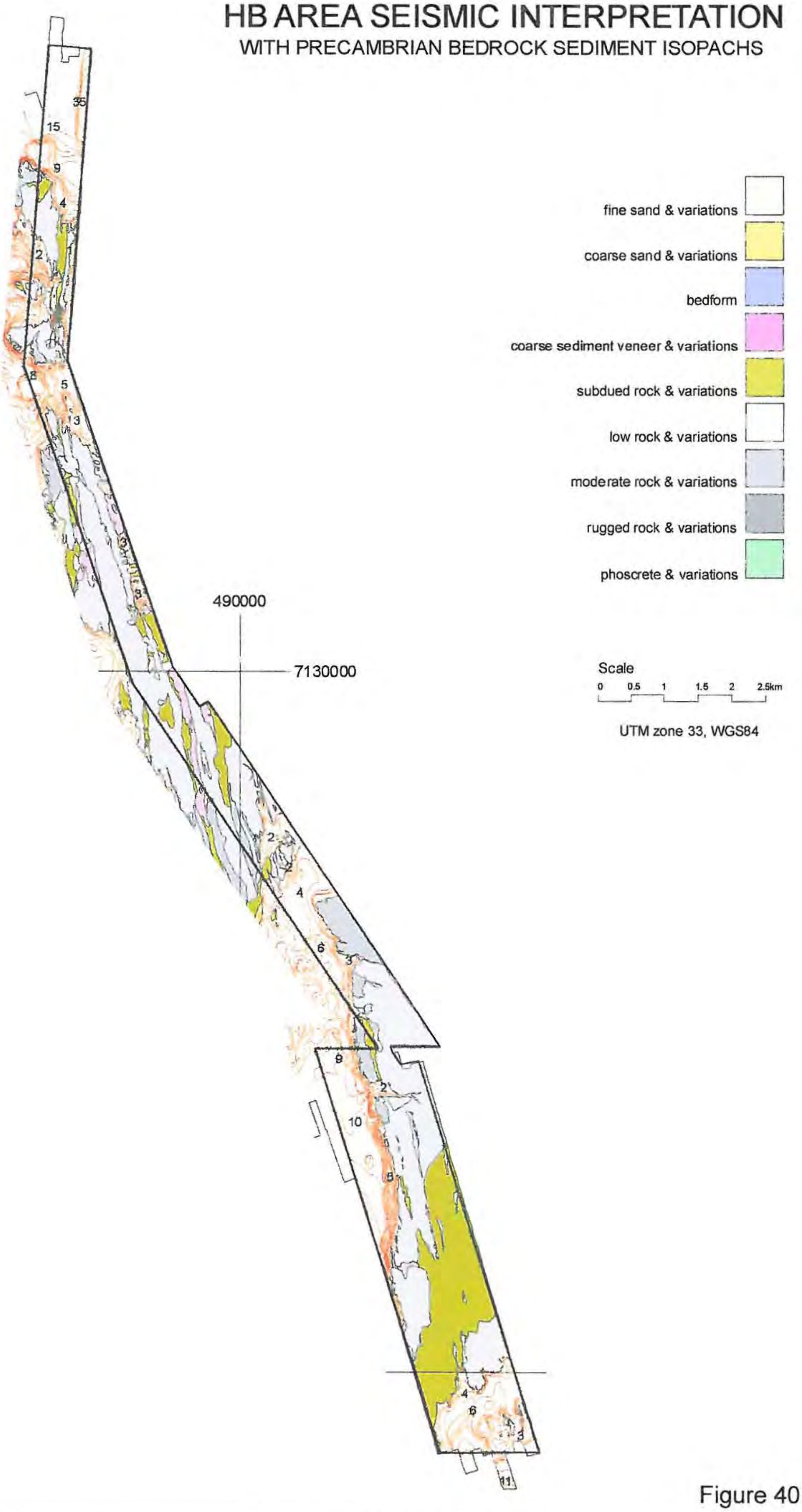
Feature	Seismic summary
J	The sediments in the central portion of this NE trending depression reach a thickness of 2-3 m, but increase along the seaward axis to a maximum of 5 m.
I	Sediment in this broad, flat south facing embayment are on average 2 m thick but reach 4 m towards the SW.
H	Broad flat north facing basin with gently sloping edges levelling out at about 11 m sediment thickness but reaching a maximum of 14 m. Some linear, NS trending depressions reaching up to 14 m sediment thickness are situated near the centre of this basin. Isopachs in the south show that this basin closes off in this direction. This interpretation is supported by the regional sediment/bedrock interpretation though data in that area are sparse. The SE rim of this basin is relatively rocky with the average sediment thickness < 3 m.
G	The cs along the eastern rim of this ridge was not penetrated by the pinger and was too thin to be resolved by the airgun. Typically these cs sediments vary from 0 to 2 m in thickness. Along the southern, central portion of this ridge a NNE-trending cs-filled basin occurs. Penetration of 1 to 2 m was recorded in the central part of this basin.
F	Two small cs-filled basins occur within which sediment thickness could not be resolved.
E	The northern portion of this northerly trending linear depression reach a maximum thickness of 6 to 7 m along the central axis near the mouth (average 4 m). From the central section of the basin southward where the sediments get coarser, sediment thickness was not well resolved by the pinger and was too thin to be resolved by the airgun. Based on intermittent pinger penetration sediment thicknesses appear to be in the 0 to 2 m range.
D	Sediment thickness in this northerly trending linear depression exceed 8 m toward the north. To the south of the rock outcrop in the southern, central part of the depression, sediment thickness averages 1 - 2 m. From the central section of the depression southward where the sediments get coarser, sediment thickness was not well resolved by the pinger and is was too thin to be resolved by the airgun. Based on intermittent pinger penetration sediment thicknesses appear to be in the 0 to 2 m range.
C	The Precambrian basement is located about 30 m below the present seafloor at the mouth of this linear, NNW trending basin. In the centre of the basin there are two basement outcrops with another slightly toward the SE which form a deep seated ridge along the SE rim of the basin. The edges of the basin are steeply dipping along the eastern and western rims, but are more moderate toward the south. The pinger acoustic basement, a strong internal horizon, reaches 7 m below the present seafloor toward the northern extremities of the basin (ave. 4 to 5 m). A number of gullies extend from the SW, S and SE rims of the basin. The depressions from the S and SE, which extends to the S limit of the licence area is particularly noteworththy. Near the top of these linear depressions, where the sediments are relatively coarse, the pinger penetrated 2 to 3 m. Further south and toward the gullies extremities, the pinger was not able to resolve the sediment thickness. Based on limited pinger penetration it is evident that the sediment is roughly in the 0 to 2 m.

Feature	Seismic summary
B	Similar in seismic character to **(C)**. Steeply dipping Precambrian basement (particularly along the western rim) reaches 29 m below the present seafloor. The 1st significant horizon above the basement reaches a maximum of 19 m below the seafloor near the mouth (ave.10 m). Along the eastern and particularly the western rim this internal horizon dips down beneath the present seafloor very steeply. A northerly trending structural feature is reflected in the morphology of the basement as well as this strong internal reflector along the southern edge of the basin. The internal horizon that attenuated the pinger's signal (pinger acoustic basement) in the eastern portion of this feature, is interpreted to be the phoscrete horizon visible along the western rim of the basin. Towards the south the basin it is broader and flatter and the sediment is about 5 m thick along its central axis. The indurated horizon interpreted is not a chrono-stratigraphic boundary. Along the western rim of the basin, where the indurated horizon is present the sediment isopachs seldom exceed 3 m. Towards the south and east the indurated phoscrete horizon only occurs intermittently and the pinger penetrated down to the 1st significant horizon. There is an area where the pinger did not penetrate down to the 1st significant horizon (not contoured) but this horizon will be in the 10 to 15 m thickness range as defined by the contours of the 1st significant horizon.
A	The Precambrian basement dips gently toward the west reaching about 28 m below the seafloor along the SW edge of the survey area. The 1st significant horizon dips down in a similar manner to about 8 m. Based on the strongly reflective nature of this internal horizon it appears to be semi-indurated or indurated.

8.3.3.2 HB PROSPECT

The pinger and airgun depth to bedrock spot depths corresponded well in this portion of the study area. Furthermore, in areas where the 1994 and 1999 surveys overlapped the isopachs also aligned well. The seismic stratigraphy in this area was relatively straightforward with sediment thicknesses increasing rapidly along the western edge of the northerly trending reefs as well as to the north and south of HB (Figure 40).

No deep incision of the bedrock is evident in the two breaks in the reef in this area indicating that if they were utilised by fluvial systems erosion was not pronounced at these points of intersection. Potential explanations for limited erosion may include: 1) relatively short duration of the fluvial erosion occurring during low base-levels stillstands; 2) the ephemeral nature of the river was not conducive to erosion; and/or 3) the lithology of the ridge was resistant to fluvial weathering by a low gradient river system. Table 26 summarises the seismic features of interest from south to north.



HB AREA SEISMIC INTERPRETATION
WITH PRECAMBRIAN BEDROCK SEDIMENT ISOPACHS

Figure 40

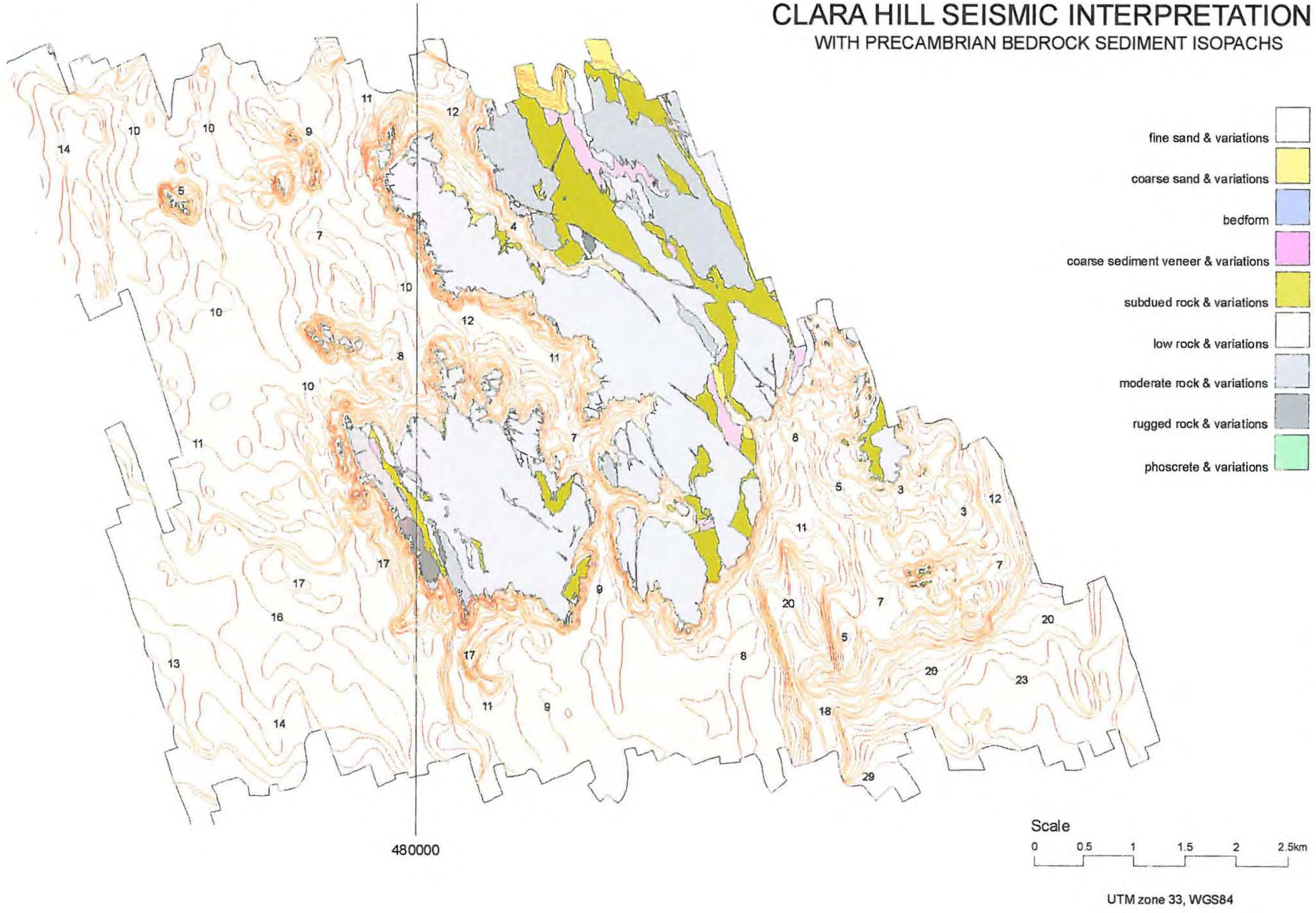
TABLE 26: Summary of seismic features of interest in HB Prospect.

Feature	Seismic summary
L	Toward the S edge of HB-S there is a linear depression which has about 6 m sediment cover (8m max.). This depression is open ended toward the E within the study area but the regional interpretation shows that it closes off toward the NE. Sediment thickness is in the 1 to 2 m range in the vicinity of the patchy rock outcrop that forms the S edge of the feature. A small N-trending gully is located off the N edge of this feature. Isopachs indicate 3 m sediment thickness at the mouth of this small gully. The N extremities of this gully are not crossed by survey lines and no isopach information is available.
M	The Precambrian basement along the NW edge of HB-S dips moderately down to 10 m beneath the fs seafloor surface and then dips gently to a maximum of 12 m along the W edge of the surveyed area. **(M)** a W-facing gully which has 4 m sediment thickness near its mouth branches off the W edge of HB-S.
N	The depression that separates HB-S and HB-C reaches a maximum sediment thickness of 6 m. Sediment thickness in this linear depression reaches a depth 4 m toward the east where it crosses to the remnants of the ridge beneath the sediment. The regional interpretation indicates that this NE trending linear depression swings to the east between the study area and the shoreline intersecting the shore immediately to the south of Saddle Hill.
O	A small sediment-filled basin is located along the S edge of HB-C. Sediment thickness in the central portion of this basin reach 2.5 to 3 m. A north-trending gully branches off the northern rim of this basin. Seismic penetration is erratic but sediment thickness in this N extension does not appear to exceed 1 m.
P	There are a number of small fs-filled depressions along the eastern edge of HB-C. The sediment is up to 3 m thick in these areas.
N edge of HB-C	The depression that separates HB-C and HB-N reaches a maximum thickness of 10 m along the NW edge, but the apex of the ridge beneath the sediment is at about 5 m. Some small rock outcrops are evident immediately to the north of HB-C. This depression links a northerly trending linear depression in the lee of HB-C with **(Al)**.
Q	Two west-facing basins are located along the western edge of HB-N. Sediment thickness in the southernmost of these embayments is about 5 m at the mouth while in the northernmost basin 8 m is reached. The eastern extremities of these two basins are linked by a NS-trending depression which has 1 to 2 m sediment cover.
N of HB-N	Sediment thickness increases offshore in a NE direction to more than 35 m. The Precambrian basement in this area appears to be partly obscured by the occurrence of gas attenuating the acoustic signal.

8.3.3.3 CLARA HILL PROSPECT

The pinger and airgun interpretation for this area is shown in Figure 41. The Precambrian basement dips relatively steeply to 17 m beneath the seafloor, towards the west of Clara West and to 8 to 12 m to the west of Clara East. Sediment thickness in the SE corner below Clara East reach a maximum of 25 m, rise to about 8 m to the south of Clara West, then increase to a maximum thickness of about 18 m before rising to about 12 m along the western edge of this area (7 m in the far SW corner).

The ridge along the southeastern edge of **(R)** outcrops in a number of places. The sediment isopachs show that



CLARA HILL SEISMIC INTERPRETATION

WITH PRECAMBRIAN BEDROCK SEDIMENT ISOPACHS

Figure 41

this ridge extends beneath the sediment to the south for about 2.5 km . Isopachs indicate sediment cover on the ridge is in the 4 to 6 m range, while down the axis of **(R)**, 20 m sediment thickness is reached. The fs filled depression between Clara West and Clara East has a minimum sediment thickness of 4 m at a saddle, increasing toward the northwest and south. There is a deep sediment filled basin (17 m), immediately to the south of Clara West. To the north of Clara West and west of Clara East, there are a few rock outcrops and isopachs are on average 10 m. Table 27 summarises the seismic features of interest from south to north.

TABLE 27: Summary of seismic features of interest in Clara Hill Prospect.

Feature	**Seismic summary**
R	The regional interpretation shows that this linear depression extends to the NE up to the shoreline. Sediment thickness in the central part of the enclosed portion of this basin is in the 5 to 6 m range thinning to 1 to 3 m around the NE rim. Two small linear depressions branch of the northern rim of the basin and sediment thicknesses of up to 2 m are recorded along the central axes of these gullies. A cs-filled extension of the most westerly of these basins is not crossed by a survey line and therefore the sediment thickness is unknown. Along the central axis of **(R)**, isopachs reach 9 m near the mouth of the depression, while further southwestward 20 m sediment thickness is recorded.
S	This large sediment-filled depression/basin separates Clara East and West. At its narrowest point sediment thickness is 4 m. This increases to 12 m toward the NW and 9 m to the south. The southern end of the basin is predominantly in the 5 to 7 m range while the northern half is far deeper at >10 m along most of its central axis. Two west-facing basins branch off the central, eastern margin of this depression. The most northerly of these reaches 6 m near its mouth, while the eastern half has on average <3 m. The more southerly of these basins has a similar morphology and sediment cover to its northern counterpart. However, this basin splits into two depressions toward the east. The most southerly of these branches has 0 to 1 m sediment cover, while sediment isopachs reach 3 m in the northerly arm. Along the western edge of **(S)** there are a couple of northeast-facing basins. The central axes of these basins have about 5 to 6 m sediment cover toward their mouths.
T	Sediment isopachs in this NW-trending depression range from 1 to 2 m in the SE extremities, 3 to 5 m in the central portion and 10 to 13 m at the mouth. During the interpretation it was noted that in the central section and toward the N, the pinger was easily able to penetrate down through the acoustically transparent sediment to bedrock, indicative of thick, soft mud that may complicate sampling.
U	Sediment thicknesses were not resolved in this cs-filled NW-trending depression, but based the numerous rock outcrops noted on the SSS textures, appears to be in the 0 to 2 m range. Towards the mouth of the basin the sediment is finer and up to 8 m penetration was recorded in the north.
N edge of Clara West	There is a WNW-facing basin along the southern rim of Clara West. A ridge 7 m beneath the sediment joins Clara West and the rock outcrop immediately to the north of it. This ridge therefore splits this basin in two. The one portion faces a westerly direction and isopachs reach a depth of 13 m near the mouth. The other, situated more toward the east, has 8 m sediment cover. Strong basal reflectors in the latter suggest coarse material may be present.
W of Clara West	Immediately to the east of the western edge of Clara West there is a long NW-trending depression. The pinger was not able to resolve the sediment thickness but the numerous bedrock outcrops within it noted on the SSS would suggest that sediment within it, is very thin. To the west of Clara West sediment cover is relatively thick (10 to 18 m).

8.3.3.4 HD PROSPECT

Along the central section and western boundary of the licence area an indurated horizon precluded penetration by the pinger, except for those areas where patches of mud were present or where the indurated surface was eroded or pinched out (Figure 42).

This indurated horizon has similar acoustic properties to other horizons interpreted as a phosphatic pavement at similar depths elsewhere in the study area. North-south- orientated acoustically relatively transparent sediments interpreted as a mud wedge has been deposited onto the Precambrian basement toward the east. The airgun was able to penetrate the indurated horizon and resolve the Precambrian bedrock at about 58 m below the seafloor, along the western boundary (Figure 43). Between the indurated horizon and the Precambrian basement there are numerous internal horizons (Figure 44). Based on their strong acoustic signature and lateral continuity, it appears as if some of these horizons and may be semi-consolidated to consolidated. Without a significant number of east/west airgun lines across the area it is not possible to correlate the horizons detected on the north-south lines with certainty between survey lines. Based on similar features noted during the interpretation of the east-west seismic lines in SHP it is likely that these internal horizons represent a number of gently westward-dipping bedding planes situated consistent with the Cretaceous horizons beneath the Holocene mud wedge interpreted by Corbett (1996) using palaeontological and isotope studies at similar depths elsewhere along the Namibian coast. For the HD area the indurated horizon (pinger acoustic basement - Refer: Figure 42), the "1st significant reflector" (Figure 45 - generally based on the airgun) and the Precambrian basement were interpreted in order to be consistent with that completed in BMP.

An acoustically transparent mud wedge is perched on the relatively horizontal phoscrete horizon reaches a maximum thickness of 8 to 9 m where it abuts the MWR and Magna Ridge North and South.

The Precambrian basement can be followed dipping down fairly evenly toward the west to 58 m below the seafloor from the MWR. The channel between Magna North and South has approximately 6 m sediment cover. This sediment thickness remains constant down the panhandle of the HD Prospect for about 2 km towards the east. Immediately east of this there is a gentle depression within the bedrock where sediment thickness reaches about 10 to 12 m. To the east of this there is another ridge where sediment thickness decreases to about 5 m before increasing to 16 m further to the east. To the west of Magna North and South the Precambrian bedrock dips gently westward beneath the sediment cover reaching 50 m along the western extremities. To the south of Magna Ridge North and South the underlying topographical expression of the bedrock that links it to the MWR can be detected. It should be noted that a significant north facing log-spiral bay is present along the edge of the inner shelf at this locality. Also noteworthy is that the bathymetry does not reflect the underlying bedrock morphology in any way. This would most likely suggest that the overlying sediments have settled from the water column filling the topographical lows in a quite, deep water environment below wave base. Table 28 summarises the seismic features of interest from north to south.

HD AREA SEISMIC INTERPRETATION

WITH PINGER/BOOMER ACOUSTIC BASEMENT SEDIMENT ISOPACHS

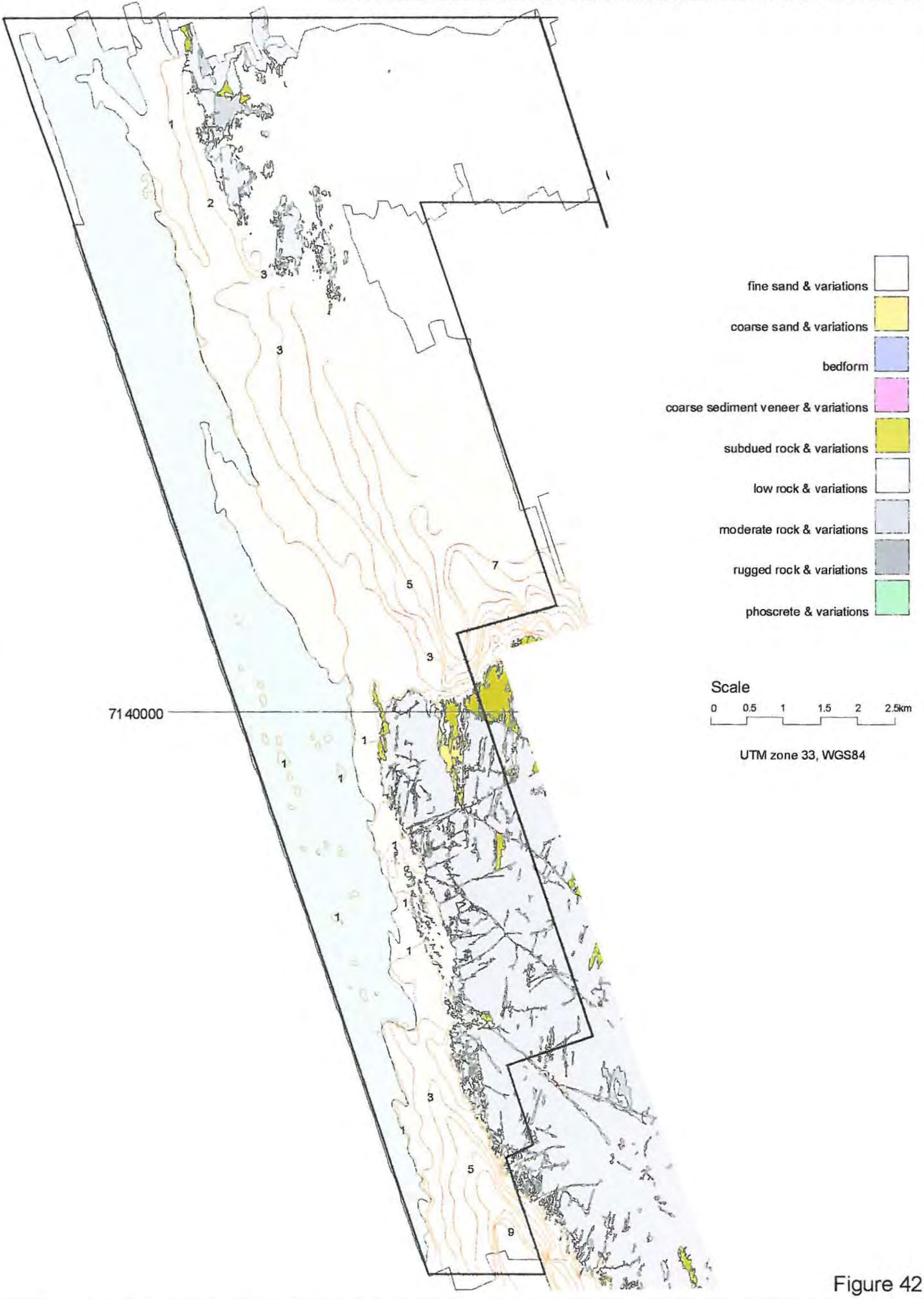


Figure 42

HD AREA SEISMIC INTERPRETATION

WITH PRECAMBRIAN BEDROCK SEDIMENT ISOPACHS

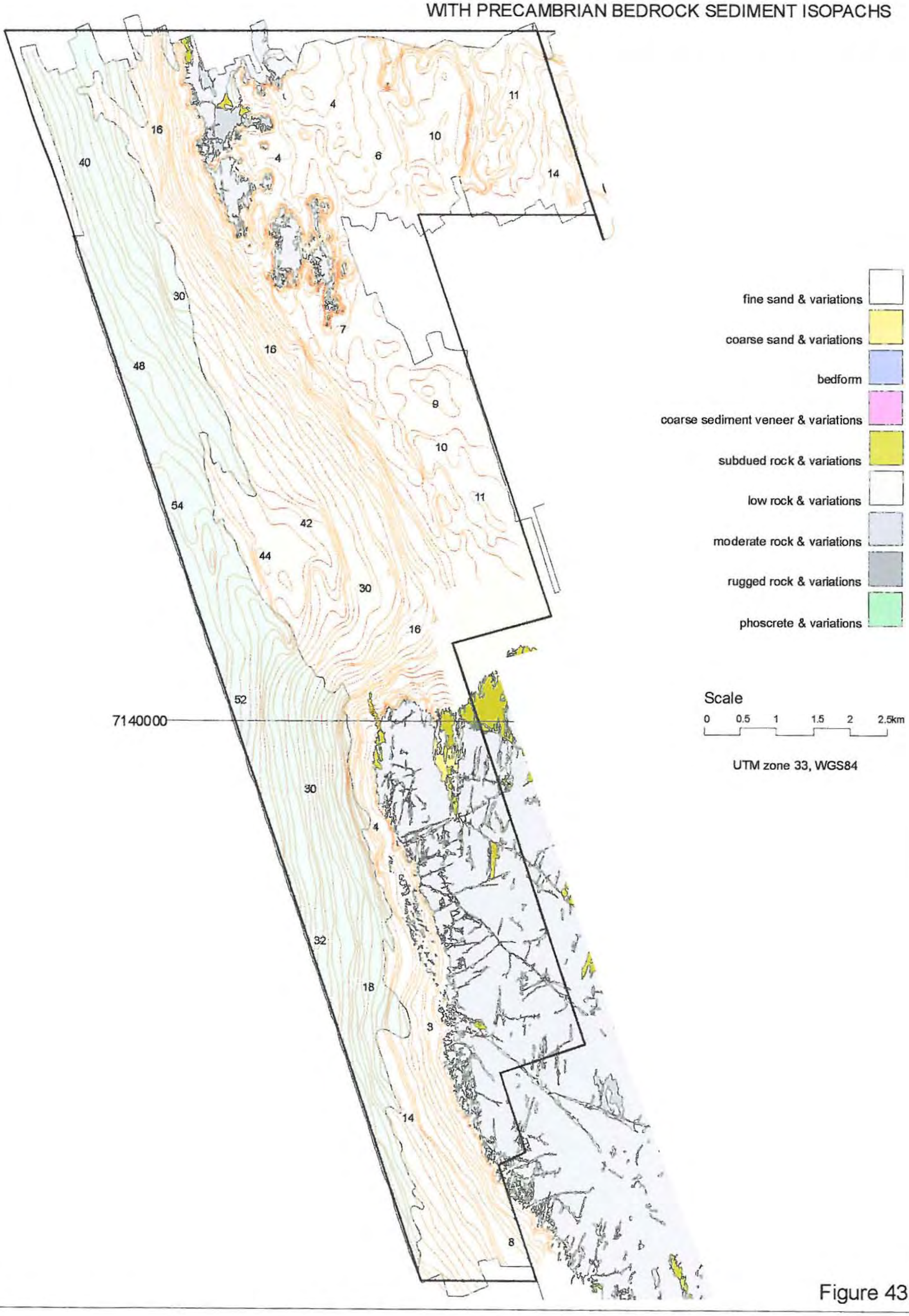
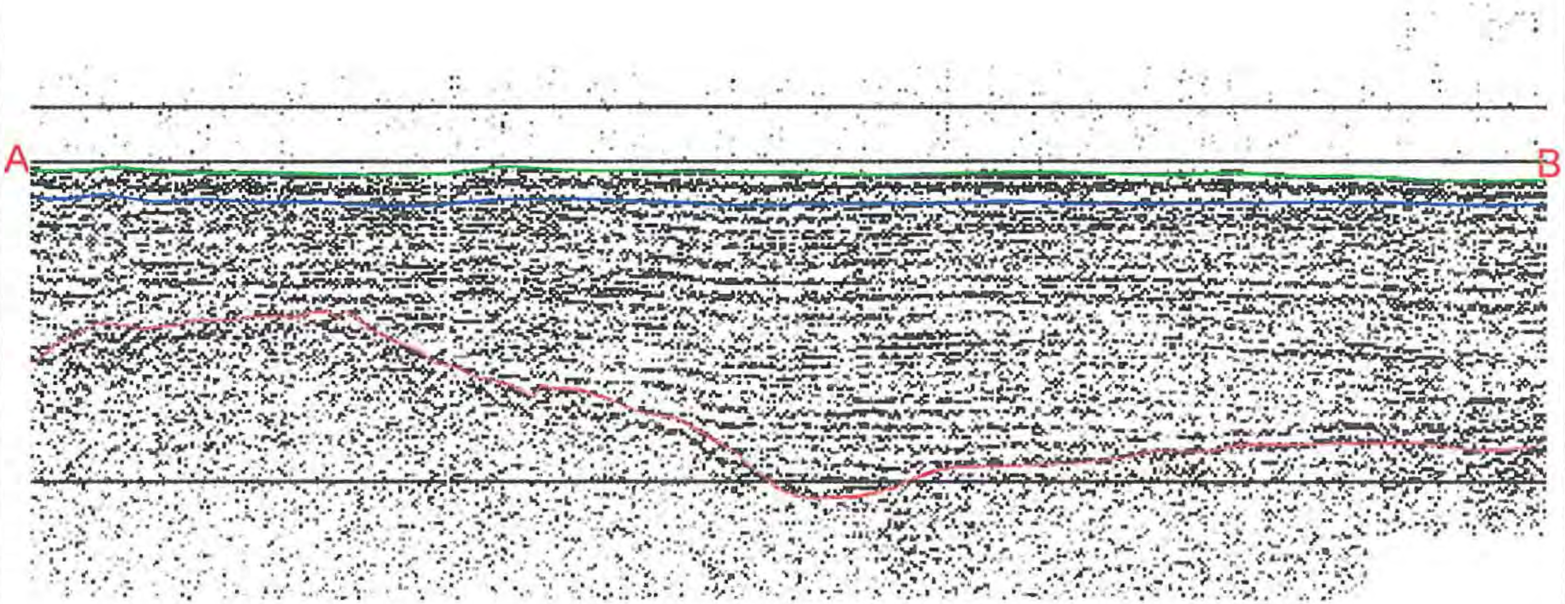


Figure 43

EPL1950
Detailed Survey
HD Prospect
Line 159
Airgun

Vertical Scale

10m



Seismic Stratigraphy Boundaries

🟥 PRECAMBRIAN BEDROCK
🟦 1st SIGNIFICANT HORIZON
🟩 INDURATED HORIZON
🟨 PINGER ACOUSTIC BASEMENT

Distance between A and B = 16.6 km

Figure 44

HD AREA SEISMIC INTERPRETATION

WITH FIRST SIGNIFICANT INTERNAL SEDIMENT HORIZON

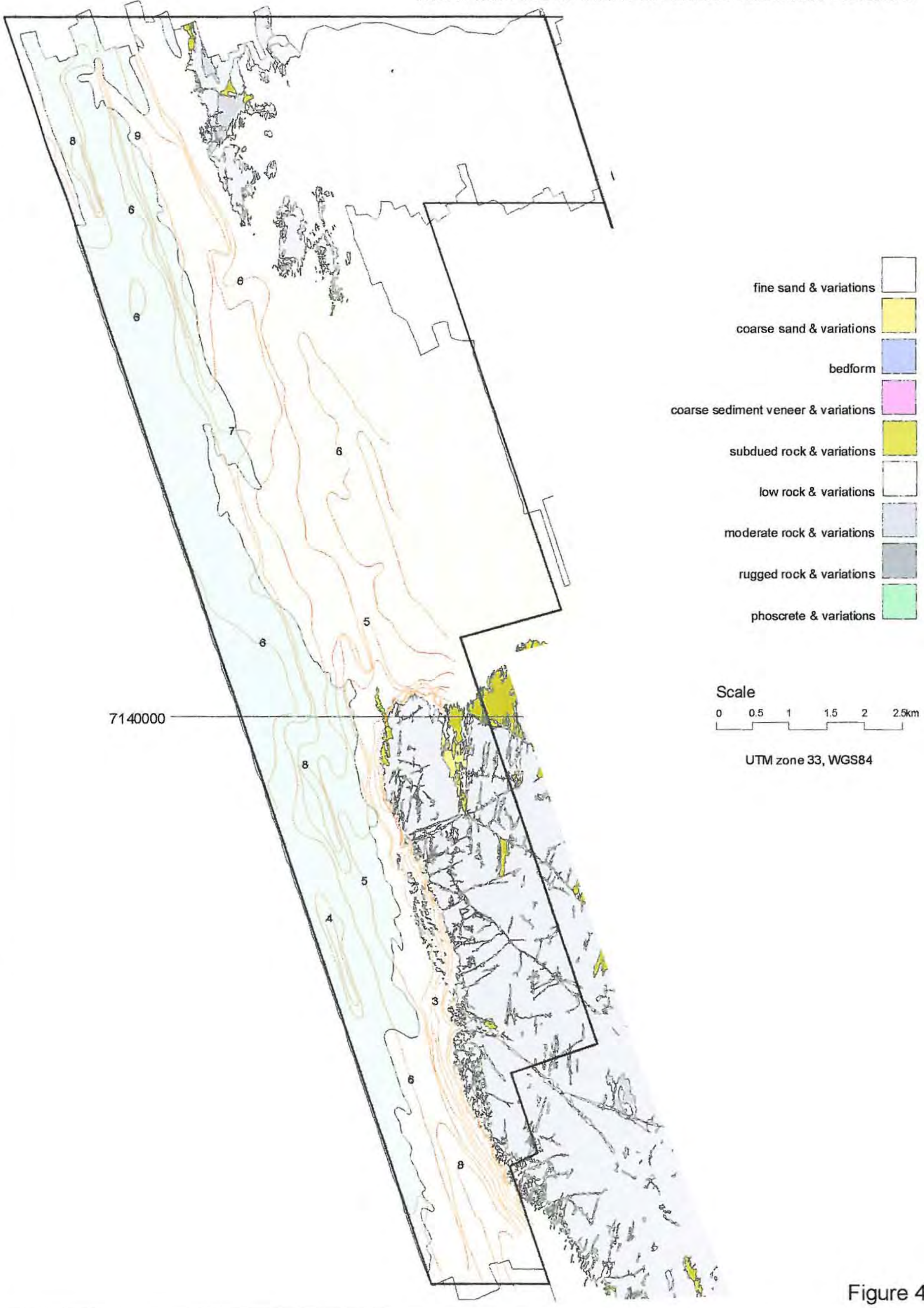


Figure 45

TABLE 28: Summary of seismic features of interest in HD Prospect.

Feature	Seismic summary
V	Sediments along the axis of this SE opening basin reach a maximum thickness of 3 m. The sediment along the western rim of the basin are phosphatised and were not resolved by the pinger, but the overburden is most likely to be in the 0 to 2 m range.
W	Sediment thickness in this basin reaches a maximum thickness of 4 m. On the western edge of the linear extension to the west of the basin there is a small area where sediment cover is 2 m, but through the central part of this linear extension overburden is in the 0 to 1 m range.
X	This depression that separates Magna Ridge North and South has a maximum sediment cover of 6 m in the central section, decreasing to 3 m and then increasing to 5 m toward the NE.
Y	A thin NS-trending depression separates this ridge into an east and west section. Sediment cover in the middle of this depression is thin with many rock outcropping. Toward the north the sediment increases to 3 m at the mouth, while southwards 5 m is reached.

8.3.3.5 SADDLE HILL PROSPECT

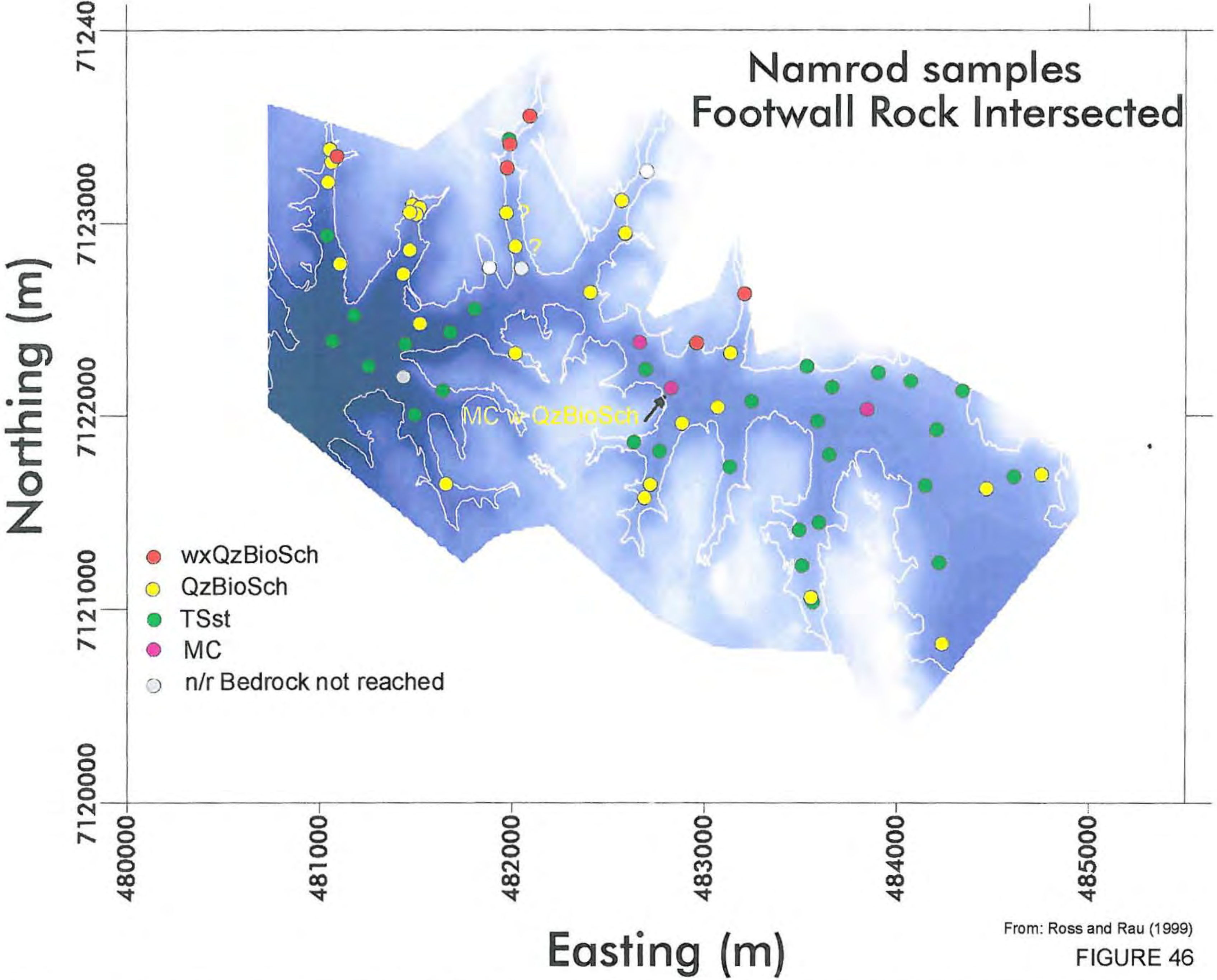
The interpretation of the seismics for SHP was completed off thermal chirp and boomer records and is representative of the acoustic basement. Large coast-perpendicular sediment covered areas are present to the south and north of the MWR separating the bedrock in SHP from that in BMP and CHP and HD respectively.

Interpretations of regional survey lines run in 1994 across these large sediment basins separating the rock outcrops, show sediment thickness are in excess of 5 m, and were therefore excluded from the detailed survey programmes. The sediment in the coast-parallel linear depression that separates the MWR from HB Prospect is on average < 5 m thick making it conducive for marine diamond placer exploration. However, along the western and northwestern edge of HB-N a deep sediment trough is present reaching up to 25 m thicknesses, excluding this area from diamond extraction using present marine mining techniques. The flat lying isopachs in the northwest portion of this linear depression along the landward edge of the MWR are indicative the pinger and boomer acoustic signals terminated on a "false footwall". This is supported by vibrocore and sample logs recorded in this area, by Namco's onboard geologists, have indicated the presence of a "beachrock" horizon lying directly on bedrock in this area. In areas where the sampling excavator was able to penetrate through this horizon it seldom exceeded 1 m. Studies done on the vibrocores by Thompson (1996) and Compton et al., (2001) indicated that the dolomite within the lithified quartz sand is formed by in situ evaporitic processes in a hypersaline environment. In order to present a conclusive analysis of the environmental conditions within this basin more quantitative information needs to be examined. However, based on Thompson's (1996) and Compton's et al., (2001) findings, the reworked burrow casts at the base of the sequence and the overlying marine sands and clays, it is evident, based on the oxygen isotope values that this basin went through phases where a lagoonal environment existed interspersed with higher energy conditions as sea-level transgressed and regressed through the -50 m to -70 m range.

Isopachs show that the bedrock along the northern edge of the MWR dip gentle down, over a distance of about 1 km to 8 m to 9 m below the seafloor. The two basins on top the northern part of this reef reach 5 m to 6 m but the translucent nature of the seismic signal would suggest that they are filled with mud.

Along the southeastern edge of the MWR the convoluted nature of the isopachs suggest that no "false footwall" is present and the Precambrian bedrock is situated a maximum of about 8 m below the seafloor. The sediments thin to 3 m to 4 m in the area to the east of **(AK)** suggesting that the southern edge of HB-C and the southeastern edge of the MWR may have been linked topographically at some stage. Subsequent erosion has deflated the bedrock surface somewhat but a saddle still exists, beneath the sediment, within this linear depression.

The dendritic feature in the southwestern corner of the MWR has the superficial appearance of a fluvially eroded feature. Upon close examination of the seismic records the exact nature of this feature is not as clearly defined. To the entrance to this channel like feature the sediment isopachs reach a maximum of 10 m but rapidly decrease to 3 m once inside the feature itself. The central axis of the main WNW trending arm has a maximum of 9 m sediment within it but thins to 3 m near a 50 m wide restriction near the centre of the feature. The channel then swings toward the WSW and deepens to 8 m before levelling out at an average sediment thickness of 4 m - 5 m. The basal topography along the central axis of this feature, particularly in light of the depth below the present seafloor of the Precambrian bedrock identified in **(B)** and **(C)**, appears too shallow if bedrock topography alone is considered. It is possible that this is an original course and that the larger depression immediately to the south was eroded at a later stage. Furthermore, the different penetration capabilities of the seismic systems used in SHP and BMP complicates the issue further because sample logs show that in **(AM)** the Precambrian bedrock was not consistently analogous with acoustic basement. On the SE side of the feature where sediment isopachs thin to 3 m, a footwall of terrestrial sandstone and occasionally beachrock was recorded on the logs with the quartz-biotite-schist being more prominent in the western extremities of the feature. Figure 46 shows the footwall rock-types intersected during the Namrod sampling programme (Ross and Rau, 1999). Therefore, the uneven central axis indicated by the interpretation of the acoustic basement does not necessarily reflect the true basement lithology which is most probably topographically more consistent. The presence of terrestrial sandstone within this channel does not necessarily indicate that it is *in situ* deposition by the palaeo-Koichab River because the dominant SW storm swell could just as easily have transported these sediments into this feature from deposits immediately to the south. Nevertheless, the presence of large volumes of terrestrial material suggests that the palaeo-Koichab River debouched sediments in the vicinity at some period in time. A description of the target features from north to south is given in Table 29 below.



From: Ross and Rau (1999)

FIGURE 46

TABLE 29: Summary of seismic features of interest in Clara Hill Prospect.

Feature	Seismic summary
A	The phosphatic horizon intersects the MWR 1 m below the seafllor surface. However, the airgun which penetrated this surface shows it to dip in a westerly direction down to 44 m beneath the seafloor surface, 1.5 km to the west of reef. Numerous strongly reflective internal horizons are present between the basement and the phophoritic surface.
Z	Sediment thickness reach a maximum of 3 m within this flat bottomed N-facing embayment.
AA	On the western side of this feature there are a series of shallow basins with an average sedimment thickness in the 1 m range. Sediments in the eastern side of this feature are thicker reaching 4 m within a narrow, well developed gully running along the eastern edge. The sediment thin out towards the mouth of the feature in the north where isopachs of 2 m are present.
AB	Well developed, deeply eroded north trending gully with and average of 7 m of sediment along the central axis but reaching a maximum of 9 m.
AC	The sediments in this NE trending gully were not resolved by the seismic systems. This may be because the sediments were too thin or that an horizon impenetrable to thiese high resolution seismic system was directly overlying bedrock. This frequently occurs when bedrock rubble, gravel or other coarse sediments with a strong acoustic return are perched directly on bedrock. Based on sampling results it is evident that these units seldom exceed 1 m thickness.
AD	Sediments in the northern end of this north facing embayment are in the 1 m - 2 m range but thin over a ridge in the central part of the feature before increasing to 5 m to 6 m in two basins towards the south. The translucent nature of the seismic signal would suggest that the latter are filled with a soft mud present, sampled and described as a surface horizon by Namco's onboard geologists, in several areas but also in (AH) immediately to the east of this feature.
AE	A narrow, north trending gully with an average of 1 m sediment thickness but reaching a maximum of 2 m.
AF	The northernmost and best developed of a pair of east trending gullies in the lee of the MWR. Sediments reach a maximum of 4 m within this feature.
AG	The southernmost of a pair of east trending gullies. The seismic systems were not able to resolve the sediment thickness in the west of this feature while isopachs indicate a maximum of 4 m but an average of 1 m to 2 m in the eastern portions where it intersects **(AH)**.
AH	Sediments in this large linear depression lying in the lee of the MWR are on average in the 2 m to 3 m sediment thickness range. The flat nature of the seafloor indicated by the widely spaced isopachs would suggest that the seismic signal terminated on a "false footwall". Sample logs also indicate the presence of an indurated marine sandstone in this area which would support this deduction. In is not clear whether the deeper holes indicated by the seismics are not windows in this "false footwall" or areas where it is semi-indurated and could be penetrated by the high resolution seismic systems. Toward the northeast the acoustic basement dips down to 13 m suggesting that the truncation in the northern edge of the MWR continues beneath the sediment and that no obvious topographical connection between SHP and CHP exists. In the southern extremities of this basin isolated areas of 4 m - 5 m sediment thickness exist but on average the sediments are 2 m - 3 m thick.

AI	A deep trough extends northwards from the northern tip of HB-C past the western edge of HB-N with > 8 m mostly translucent sediments within it, indicative of soft mud, making this are unsuitable as a marine placer exploration target using present mining technology. Along the western edge of HB-C the acoustic basement dips down to a maximum of about 5 m below the seafloor surface.
AJ	The seismic systems were not able to resolve the thickness of the coarse sediments within this northeasterly trending linear depression. Sample logs recorded by Namco's onboard geologists show that the majority of the coarse sediments, bedrock rubble and gravel are less than 1 m thick in this feature.
AK	The seismic signature in this feature was similar to that in **(AJ)** but in places a thin (<1 m) layer was resolved by the seismic system.
AL	Sediments in this southeasterly facing feature are on average less than 1 m thick increasing marginally in thickness towards the southeast extremities.
AM	To the entrance to this channel like feature the sediment isopachs reach a maximum of 10 m but rapidly decrease to 3 m once inside the feature itself. The central axis of the main WNW trending arm has a maximum of 9 m sediment within it but thins to 3 m near a 50 m wide restriction near the centre of the feature. The channel then swings toward the WSW and deepens to 8 m before levelling out at an average sediment thickness of 4 m - 5 m.
AN	The southern edge of the MWR dips down more steeply than the northern edge. The rapid dip to about 5 m to 7 m sediment thickness followed by an inflection an a gentler dip to 10 m may be indicative that the interpreted acoustic basement may have switched from Precambrian basement to a strongly reflective internal horizon at about 7 m depth. With the maximum penetration of these high resolution seismic systems being in the 10 m range in the west coast environment this is quite possible since 7 m is near the limits of the system and therefore is unlikely to have been well resolved.

8.3.3.6 DISCUSSION

Improvements to high resolution seismic systems available for marine diamond prospecting would certainly improve the accuracy of interpretations and the selection and evaluation of target sites. Dynamically corrected, narrow beam systems like the TOPAS may improve seismic record quality and subsequent interpretations and target delineation in the future.

The interpretation of seismic stratigraphy is subjective and largely dependent on the skill and experience of the interpreter. The author was fortunate to be involved with the first phases of the sampling programme management for the study area. Regular checks could be conducted at specific sample sites where the sample log recorded by the Namco onboard geologist could be compared with the original seismic record and the seismic interpretation. Based on comparisons approximately 80 % of the seismic isopach interpretation is within 1 m of the sediment depth recorded on sample logsheets. Considering that the seismic contours are extrapolated over a distance of 150 m and that not all the samples lie directly on the seismic lines it is apparent that the seismic interpretation is a fairly accurate representation of the sub-bottom stratigraphy within the study area. The internal horizons situated well above the basement (i.e. the surficial indurated horizon and the 1st significant horizon) that could not be penetrated by the high resolution seismic system, are generally situated in thick sediment areas unsuitable for marine diamond placer exploration.

8.4 TERRACE LEVEL STUDY

8.4.1 INTRODUCTION - EUSTATIC SEA-LEVEL FLUCTUATIONS

Marine placers are formed along strandlines that form during periods of marine transgressions and regressions making sea-level fluctuations important components in the exploration and evaluation of these deposits.

The subject of eustatic sea-level change and correlation of marine stillstands is a complex one about which a wealth of information exists, particularly in the northern hemisphere. World-wide sea-level changes are caused by either: 1) uptake or release of water during glacial/interglacial cycles; or 2) large-scale tectonic events or combinations thereof (Pethick, 1984). Correlations of stillstand levels in any particular locality are further complicated by localised factors such as warping and isostacy. Siesser and Dingle (1981) and Hendey (1984) prepared a widely accepted eustatic Tertiary sea-level curve for southern Africa. These larger scale sea-level movements can be summarised as follows:

- The Mesozoic was characterised by worldwide transgressions attributed by Valentine and Moores (1970) to the splitting of Pangea. No placer diamonds deposits of this age have been noted along the west coast.

- The Early Eocene has been interpreted to be a period of sea-level highs (Siesser and Dingle, 1981) during which the Langental Formation was deposited (Dingle, *et al.*, 1983);

- The Late Oligocene was a period of extremely low sea-levels during which a number of canyons were eroded into the continental shelf off southern Africa (Light, *et al.*, 1992).

- A transgression followed in times raising sea-levels to at least 50 m above present levels by Middle Miocene times. Shackelton and Kennet (1975) suggest that the late Miocene fall was due to the rapid build up of the East Antarctic Ice Sheet. Pether (1994a) suggests that the main evidence to support a Early Miocene transgression to 50 m apsl is provided by brackish-water serpulids at Arrisdrift and terrestrial fossils at Ryskop and Hondeklip Bay. An extensive marine package at 90 m at Alexkor, south of the Orange River Mouth, and at Hondeklip Bay (Pether, 1994a) indicate that sea-level may have risen higher. Although, paucity of marine remnants elsewhere on the western seaboard, at this elevation, suggest differential uplift post-deposition. A general reduction in terrace elevation towards northern Namibia and southward towards Cape Town further support a tectonic explanation;

- Numerous raised and submerged beach deposits along the west coast attest to the rapidly fluctuating sea-levels during the Pliocene and Pleistocene periods. Hallam (1964) suggests that these fluctuations are largely due to glacio-eustatic causes. Flemming and Roberts (1973) believe that the Late Miocene to Early Pliocene transgression can be attributed to an acceleration in global spreading rates at about 10 Ma. Shackelton and Kennett (1975) suggest that the Late Pliocene fall was due to further build up of the East Antarctic Ice Sheet and the rapid build up of the West Antarctic Ice Sheet. Tankard *et al.* (1982) inferred a sea-level stillstand at about -70 m during the Late Pleistocene to account for the large dune ridge located south of Durban at Aliwal Shoal and Protea Banks.

- During the Pleistocene at about 19 000 to 18 000 years ago, sea-level regressed to the -123 m to -130 m water depth range (Emery and Garrison, 1967; Tija, 1970) before the post-glacial rise to a few metres above present sea-level during the Flandrian transgression at 5 500 ya, before regressing to its present level (Flemming, 1977; Yates *et al.*, 1986). More recent studies by Yokoyama et al., (2001) place the Pleistocene regression at 22 000 to 19 000 years ago.

Superimposed on this eustatic curve are numerous more localised, minor sea-level fluctuations. The detailed study of the marine terraces in central Namibia and the study area will mainly focus on these high frequency fluctuations.

8.4.2 INVESTIGATION OF REGIONAL TERRACE LEVELS FROM LÜDERITZ TO CLARA HILL

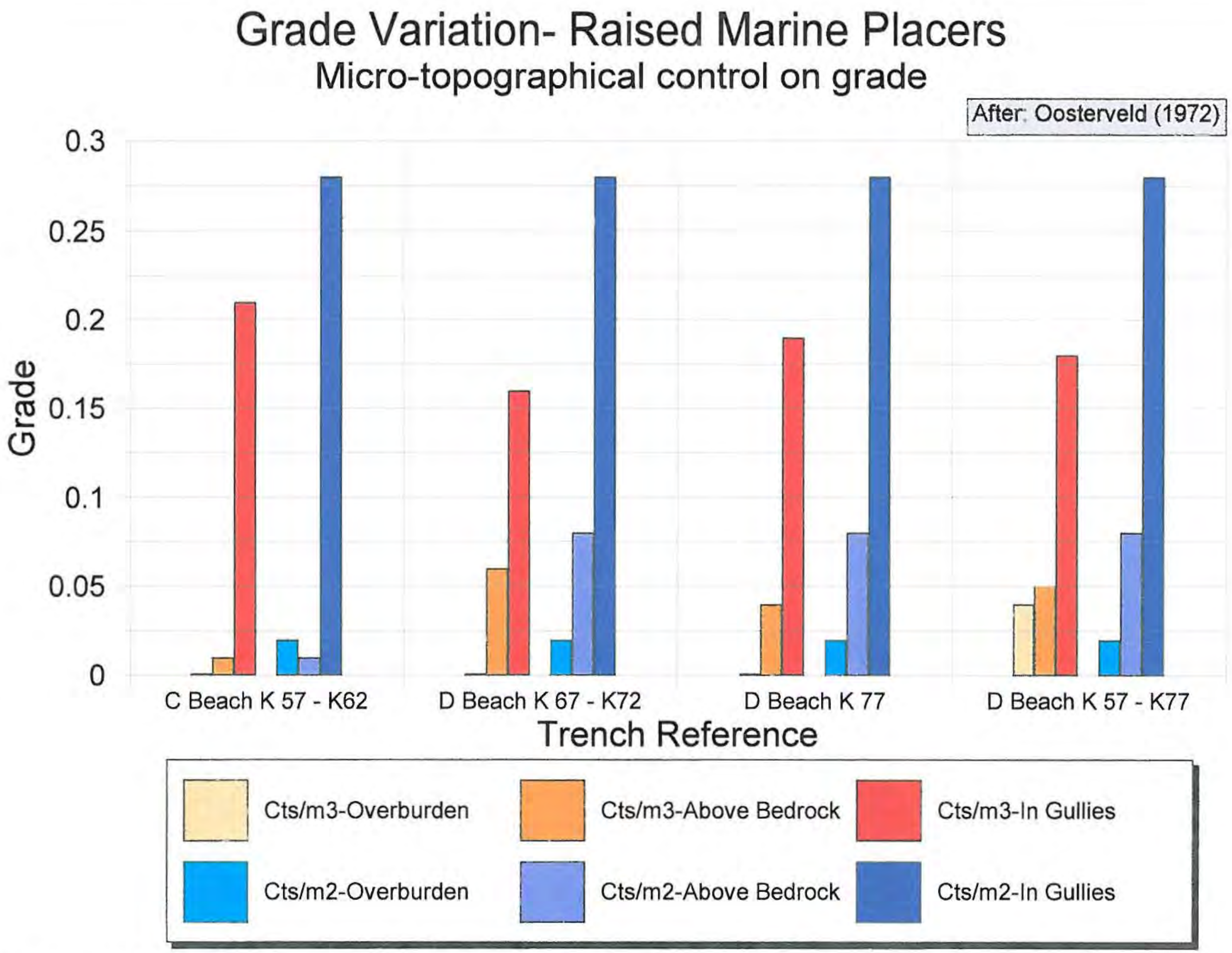
The detailed bathymetry map for the area between Lüderitz and Clara Hill allows for the most thorough investigation of the terrace levels off the central Namibian coast conducted to date. As the results contribute significantly toward the understanding of the inner shelf in central Namibia additional time and effort has been expended in the level of detail presented in this section.

Numerous sea-level transgressive/regressive cycles have occurred along the coast of southern Africa during the Tertiary and Quaternary period. These cycles of sea-level movement have had important implications for the development of coastline morphology and terraces upon which diamond placers have been deposited. A terrace is defined as "Any long, narrow, relatively level or gently inclined surface, generally less broad than a plain, bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope; a large bench or steplike ledge breaking continuity of a slope" in the glossary of Geology (Jackson, 1997).

Pickford and Senut, (1999) believe the main control on transgression and regression along the west coast was eustatic rather than epeirogenic, based on the close correlation of the southern African curve with that of western Australia (Quilty, 1977). However, they suggest some epeirogenic uplift to account for the perfect order of the raised marine placer deposits along the west coast, with the oldest beaches at the highest elevations and the lowest at the youngest. Pickford and Senut, (1999) add that this could also be an artifact of the older ones being reworked by the younger ones transgressing to a higher level. A older unit beneath the 3 m to 5 m asl, Eemian aged terrace located Klipvley Karoo Kop, 35 km north of the Olifants River supports the latter (Rau, 2002). These Eemian aged gravels appear to have derived the majority of their diamonds from the reworking of an underlying, more ancient gravel unit which has not yet been decribed in the literature (Rau, 2002).

The identification and dating of sea-level stillstands along the inner shelf and coastal plain along the west coast is an important component of marine diamond placer exploration. The preferential concentration of diamonds at specific sea-level elevations has been recognised by diamond exploration companies active along the west coast since the early 1900's. The aim of numerous internal terrace level studies has been to accurately define these elevations and ages and correlate them to recovered grades. Historically, the richest portions mined on these terraces have been within topographical lows (depressions, gullies, pot-holes, joints, etc.) and along the base of sea-cliffs eroded by wave action during prolonged sea-level stillstands (Le Roux, 1986). Jacob's (2001) study of the raised marine placer deposits north of the Orange River, suggests that the highest grades are associated within the rugged bedrock topography located between terrace levels. Based on graphs constructed using Oosterveld's (1972) data for the raised marine terraces north of the Orange River it is evident that the highest grades are associated with topographical features eroded into and therefore situated below the average terrace floor elevation. A graph compiled using Oosterveld's (1972) trench sampling data table shows the large percentage of diamonds located within the bottom portion of the gravel profile supporting the strong relationship evident between bedrock micro-topography and diamond concentration (Figure 47). Murray *et al.*, (1970) and Jacob (2001) note that the micro-topography is in turn controlled by many factors including lithology, density and orientation of structural features, bedding or shear plane dip angle, degree of shearing abundance of abrading agents (gravel). The occurrence of the greatest bedrock relief between terrace levels in Jacob's (2001) study area may be coincidental and applicable for that locality only.

The correlation between diamond concentration and terrace levels is cited in almost every marine diamond placer related paper written for the west coast. It follows that the longer the stillstand and the better the development of the terrace the greater the potential for diamond concentration at a specific sea-level, assuming the availability of diamonds is relatively constant. Should a terrace level be occupied a number of times during the cycles of transgression and regression the opportunity for further diamond introduction and concentration is further enhanced. Therefore, identification of specific, well developed terraces is an important factor in marine diamond placer exploration. Having thoroughly reviewed the literature it is clear that this is not straightforward, with the many contradictory models that still exist. For example, the Early Pleistocene terrace complex north of the Orange River mouth has been subjected to down-warping, having an elevation of about 20 m to 25 m at the mouth and 9 m, approximately 100 km to north, at Chameis Bay (Schneider and Miller, 1993). Whereas, the Eemian terraces at 0 m and 2 m to 4 m have not been subjected to the same warping resulting in erosion and reworking of the older beaches to the north by the younger ones (Kilham, 1992). Pickford and Senut (1999) believe that an equally valid alternative is the preferential erosion of the highest elevation gravels toward the north giving an erroneous impression of post-depositional northward tilting. As one progressively goes further back in time so the magnitude of these localized isostatic fluctuations is likely to increase. This makes correlation among the west coast terraces using elevation alone difficult. This particularly where many terraces occur at similar elevations with later events having re-worked earlier strandlines. Further complications are introduced by changes in lithology and structure. Horizontally bedded, soft, or gently dipping bedrock is more conducive to terrace development than hard or steeply dipping bedrock (O'Shea, 1971). Therefore, a long duration sea-level stillstand occurring at the elevation of the latter may only erode a poorly formed terrace, while a few kilometres away, on the former, well developed terraces may form. Individual terraces also do not form at a single elevation but tend to occur over a range of about 2 - 4 m, making accurate definition of specific still-stands difficult. All these factors, combined with vastly different standards of interpretation, have resulted in there being so many contradictions in elevations, that it is difficult to make sense of it all. Geologists and palaeontologists along the west coast have more recently moved to the



Note: These CDM trenches, immediately north of the Orange River, covered a total area of 4,97 square km and contained a total volume of 29 255 000 cubic metres of which 13 211 000 cubic metres was overburden.

Figure 47

examination of faunal assemblages and chrono-stratigraphy to try to improve the accuracy of the interpreted sea-level movements along the west coast. However, this approach is also not conclusive, on the inner shelf, as the terrace deposits have been reworked and mixed during the polycyclic processes of placer formation causing contamination of assemblages and conflicting results. Some studies have correlated the ages, positions and volumes of offshore sediment accumulations and compared those with onshore observations in a more holistic, mass balance approach (Dingle *et al.*, 1983). It is clear, based on seismic surveys, DSDP cores and studies of fossiliferous sedimentary units along the coastal plain, that southern African west coast was subjected to numerous sea-levels stillstands, evidenced by terraces preserved across the entire inner shelf Frans-Odendaal (2002).

Adams (2002) believes that the Quaternary was punctuated by a large number of relatively sudden climatic transitions and corresponding sea-level fluctuations. He suggests these cold periods (stadials) and warm interstadials may have occurred over periods as little as a few centuries and that these changes are likely to have been sudden jumps rather than incremental changes. Adams (2002) suggests that these sudden changes are in response to various mechanisms, involving changes in ocean circulation, dust fluxes from the land surface and changes in snow cover and water vapour content of the atmosphere.

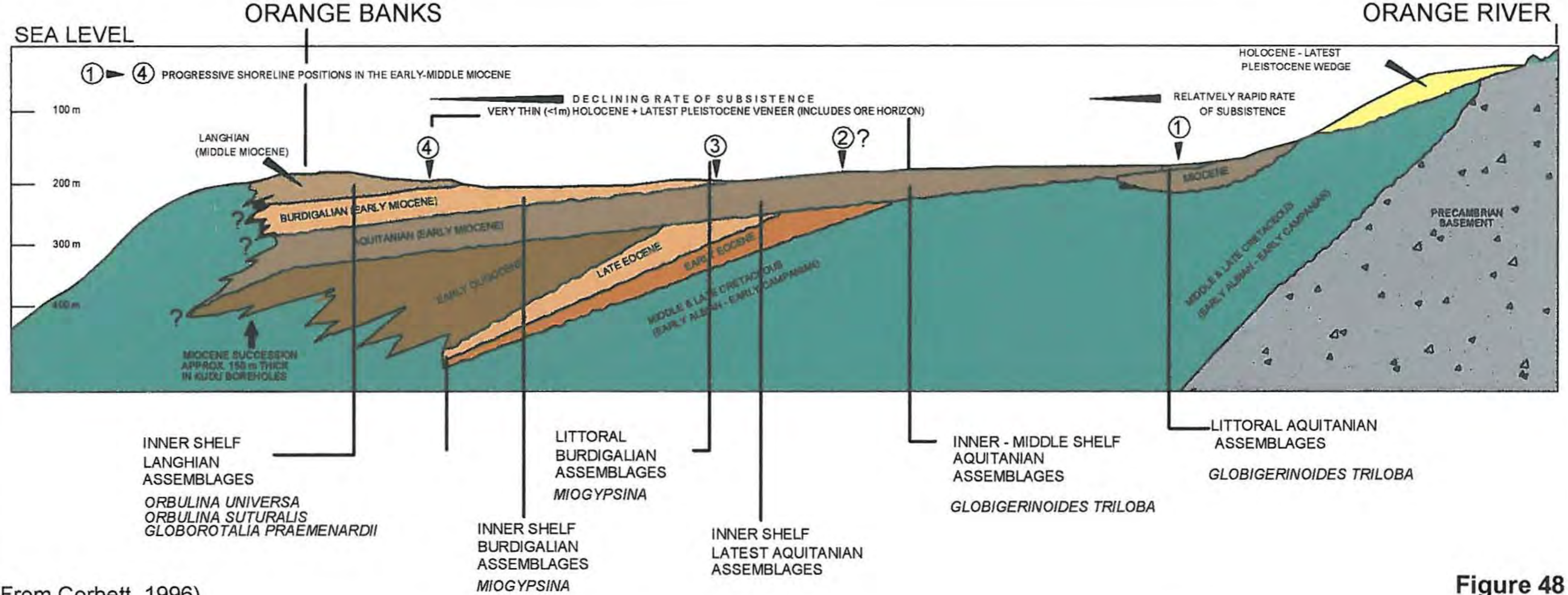
Authors like De Decker (1986) and Woodborne (1987) have identified terraces based on high resolution detailed geophysical survey data covering the areas between the Orange River and Wreck Point and Stompneus Bay to White Point, respectively. Others such as Murray *et al.*, (1970), O'Shea (1971), Flemming (1976), Martin and Flemming (1986) amongst others, have also examined the terrace levels occurring along the inner shelf of the west coast. The most significant sea-level fluctuations and related events, documented along the west coast, are summarised below:

- Work conducted by Nummedal and Swift (1987), Lavelle (1995) Dale and McMillan (1995) and Corbett (1996) and the oil industry based on micropalaeontological and isotope studies have resulted in a relatively well defined model of the chrono-stratigraphy and major unconformities present on the middle shelf. Figure 48 illustrates a section across the middle shelf of southern Namibia (Corbett, 1996).

- The exact ages of the various raised marine terraces is currently poorly constrained. Corbett (1996) and Pether (1994a) are of the opinion that these beaches are of Late Miocene, Pliocene and Pleistocene age, while Stocken (1978) estimated a Middle Miocene age for the highest terraces. Based on mammalian fossils recovered recently along the Namaqualand coast, particularly at Langebaanweg, it would appear as if the beach deposit are older than previously thought (Frans-Odendaal, 2002).. Pickford and Senut (1999) indicate sea-level highstands at the end of the Early Miocene (15 - 17 Ma), the end of the Middle Miocene (11 - 10 Ma), at the end of the Miocene (7 - 5 Ma) and during the Pliocene, Pleistocene and Holocene periods. This Late Miocene/Pliocene 50 m package does not correlate with Haq *et al.* (1987) eustatic sea-level curve that suggests global elevations around 80 m to 90 m at this time. This could indicate subsidence of the coastal plain post deposition or a deviation from the global curve at along the west coast at this time (Pickford and Senut, 1999). Figure 49 shows the high-low elevation of raised marine terraces along the west coast recorded from the literature by the author during this study. The most commonly referred to sea-

STRATIGRAPHY OF THE MIDDLE SHELF OFF NAMIBIA

Chronostratigraphy and major unconformities present on the sediment-starved continental shelf off Namibia, based on detailed micropalaeontological and isotope studies



(From Corbett, 1996)

Figure 48

Ref. No.	Locality	Source
1	Kleinzee	Rogers et al., 1990
2	Hondeklip Bay	Pether, 1994
3	CDM	Schneider and Miller, 1993
4	Namaqualand	Carrington and Kensley, 1969
5	Alexkor	Gresse, 1988
6	CDM	Schneider and Miller, 1993
7	Alexkor	Gresse, 1988
8	Namaqualand	Carrington and Kensley, 1969
9	False Bay	Bowie, 1966
10	CDM	Schneider and Miller, 1993
11	Klipvley Karoo Kop	Rau, 2002
12	Port Nolloth	Krige, 1927
13	Namaqualand	Carrington and Kensley, 1969
14	CDM	Schneider and Miller, 1993
15	CDM	Schneider and Miller, 1993
16	Kleinzee	Rogers et al., 1990
17	Alexkor	Gresse, 1988
18	Van Rhynsdorp	Krige, 1927
19	Alexkor	Gresse, 1988
20	False Bay	Bowie, 1966
21	Hondeklip Bay	Pether, 1994
22	Namaqualand	Carrington and Kensley, 1969
23	CDM	Schneider and Miller, 1993
24	Alexkor	Gresse, 1988
25	Namaqualand	Carrington and Kensley, 1969
26	Kleinzee	Rogers et al., 1990
27	Alexkor	Gresse, 1988
28	Kleinzee	Rogers et al., 1990
29	Namaqualand	Carrington and Kensley, 1969
30	Alexkor	Gresse, 1988
31	Alexkor	Gresse, 1988
32	Hondeklip Bay	Pether, 1994
33	Alexkor	Gresse, 1988
34	Hondeklip Bay	Pether, 1994
35	Kleinzee	Rogers et al., 1990
36	Namaqualand	Carrington and Kensley, 1969
37	Alexkor	Gresse, 1988

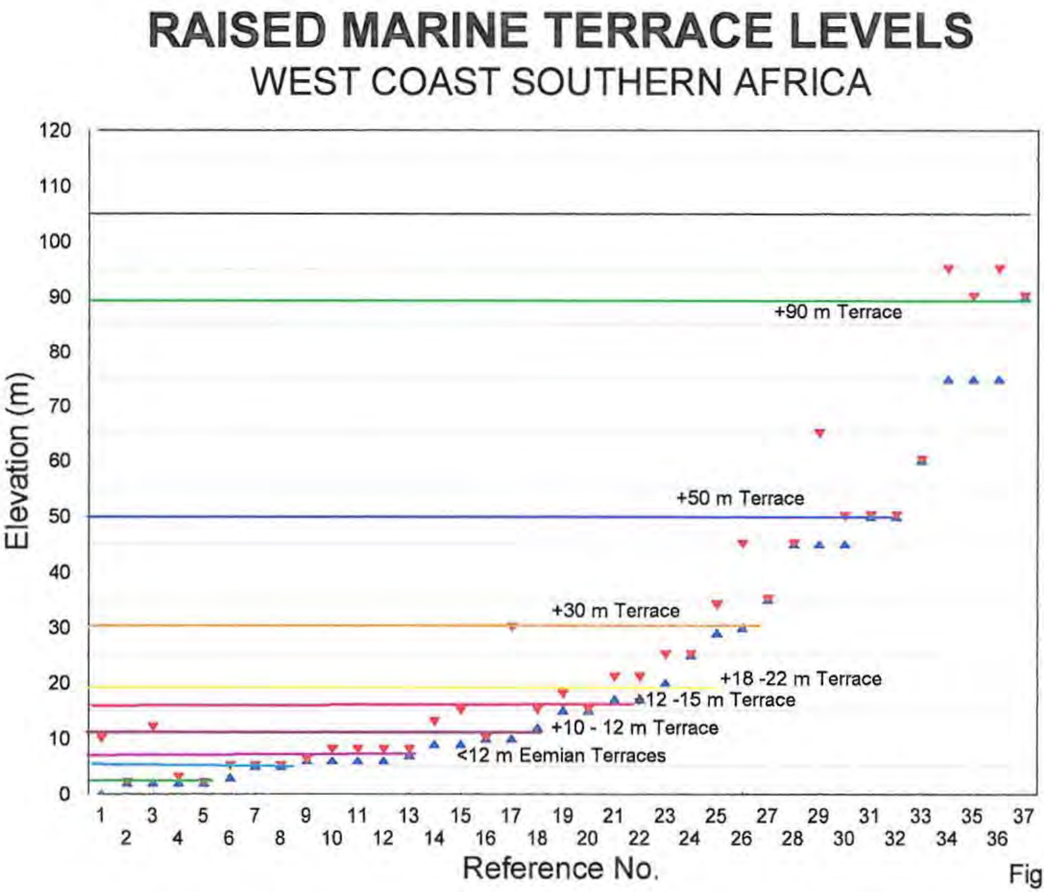


Figure 49

level stillstands have been super-imposed. Though some of the elevation ranges are relatively broad the data correlate well. The reduction in the correlation at higher elevations is most likely indicative of a combination of erosion (gravitational wasting) and local tectonic movements of these isolated gravel remnants.

- The Eemian interglacial that occurred at 135 000 to 125 000 ya saw sea-levels rise to about 4 m - 6 m asl along the west coast (Moore, 1982; Hendey and Volman, 1986). The diamonds at Saddle Hill Prospect adjacent to the study area were recovered at about this elevation.

- Andel and Tzedakis (1996) deduced from the study of pollens in cores that intense cold events at 75 000 and 58 000 ya saw sea-levels drop to 75 m bpsl off the west coast.

- Tankard (1976) suggests, using data collected from the South African coastline, that sea-level stood at about 20 m bsl between 47 000 and 25 000 ya which he correlated with a wave-cut cliff at similar elevation noted by Murray *et al.* (1970) along the west coast. Murray *et al.* (1970), based on bathymetry and seismic data, combined with diver observations, traced a sea-cliff of 1 m to 1.5 m at -18 m to -20 m over a distance of 15 km between Mittag and Kerbehuk. O'Shea (1971) noted a similar feature while examining terraces in the Plumpudding, Hottentot, Meob and Conception Bay areas in the -18 m to -24 m water depth range. This prominent nick-point therefore occurs intermittently over a distance of 550 km along the southern and central Namibian coast. Murray *et al.* (1970) suggest that this cliff could have been eroded as little as 9 000 ya, and note that it runs roughly coast-parallel, although its detailed direction is controlled by joints and the strike of the foliation.

- Sea-levels again dropped to -70 m bpsl during the period from 39 000 to 36 000 ya (Andel and Tzedakis, 1996) which would discount the broad dates noted by Tankard (1976) for the -20 m bsl stillstand.

- During the Pleistocene at about 19 000 to 18 000 years ago, sea-level regressed to the -123 m to -130 m water depth range (Emery and Garrison, 1967; Tija, 1963) before the post-glacial rise to present sea-level. The Orange and Kaukausib River palaeo-channels are eroded into the continental shelf to a depth of -85 m and -120 m to -130 m, respectively (O'Shea, 1971). The Koichab River also has it's base level at -120 m to -130 m (Rau, 1996). This level compares favourably with the global continental shelf break at an average depth of -137 m (Shepard, 1963).

- During the Holocene, cold, dry period (10 800 to 10 200 ya) linear dunes may have re-activated in the area north of the Orange River (Adams, 2002).

- Flemming (1977) proposed that present sea-level was reached 6500 ya, a level that was previously occupied 120 000 to 130 000 ya (Tankard, 1976)

It is evident, based on the literature reviewed, that knowledge of the submerged terraces on the inner shelf is tenuous with little or no age control. Most terrace level studies on the inner shelf have been interpreted from bathymetric and seismic sections from geophysical lines surveyed perpendicular to the coast. Poor control on the absolute positional accuracy of some of the earlier geophysical records, combined with varying standards of interpretation and the smoothed profile produced by the conical acoustic beam, transmitted by geophysical systems, make accurate interpretation and assessment of the validity these results difficult. A number of the submerged resource/reserve levels have been graphically presented in Figure 50 and can be used to give an indication of well mineralised sea-level elevations. A summary of previously published terrace levels compiled by De Decker (1993), on the inner shelf is given in Table 30. Figure 51 shows the most prominent sea-level elevations interpreted during this study superimposed on a bathymetry map of the area from Lüderitz to Clara Hill.

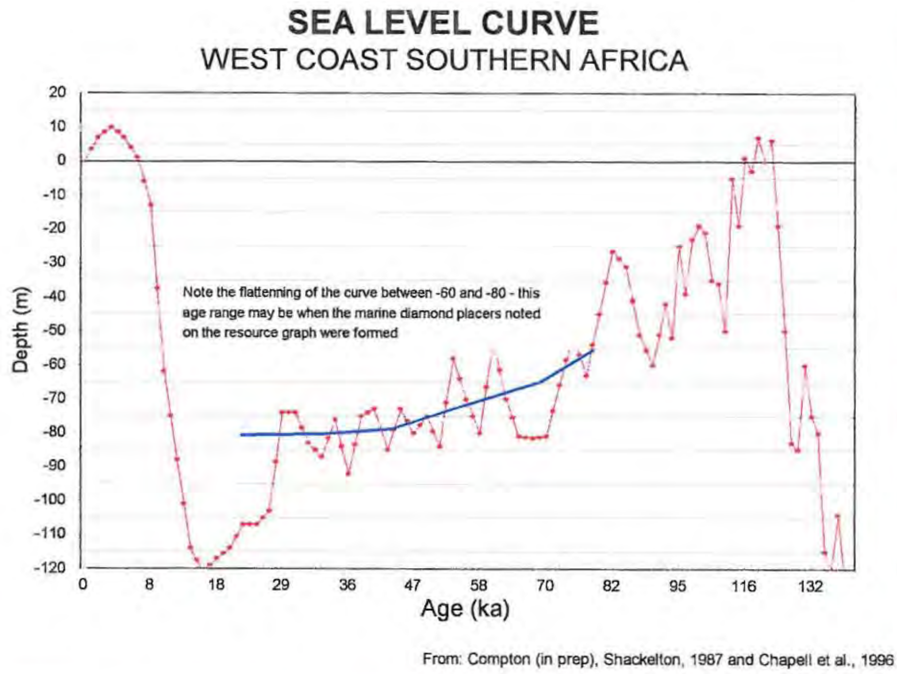
TABLE 30: Comparison of terraces mapped off the southern African coast (from De Decker 1993).

Maud, 1968	**Murray et al., 1970**	**O'Shea, 1971**	**Flemming, 1976**	**De Decker, 1986**	**Woodborne, 1991**	**Martin and Flemming, 1986**
18				10-13 16-19	14-18	
	20	18-24 26-28		22-25	22-28	
36		32-34	35-40	30-35	33-40	
47		40-42		40-45	44-53	40
		52-54 56-59	55-60	50		50-55
				60		65-70
						75-80
						85-90
						90-100
						100-105

This study offers an opportunity to examine terraces on a regional scale based on detailed bathymetry. As seismic data are not available for many of the areas covered by the bathymetry map, it was not possible to take the thickness of recent sediment deposition into account, when determining the "nick-points". Where seismic data are available in the study area, recent sediments were taken into account to improve the accuracy of the interpretation.

Well defined coast-parallel reefs were used as the main criteria to decide the position of the most prominent still-stand elevations in the Lüderitz to Clara Hill area. Detailed modelling has highlighted the -20 m, -29 m, -38 m, -52 m, -65 m, -75 m, -81 m, -87 m, -100 m and -112 m as being the levels that best fit the bedrock morphology of the area. Some of these modelled sea-levels are shown in Figures 51, 52, 53, 54, 55, 56, 57, 58 and 59 have been superimposed on the bathymetry to give a visual indication of where the modelled

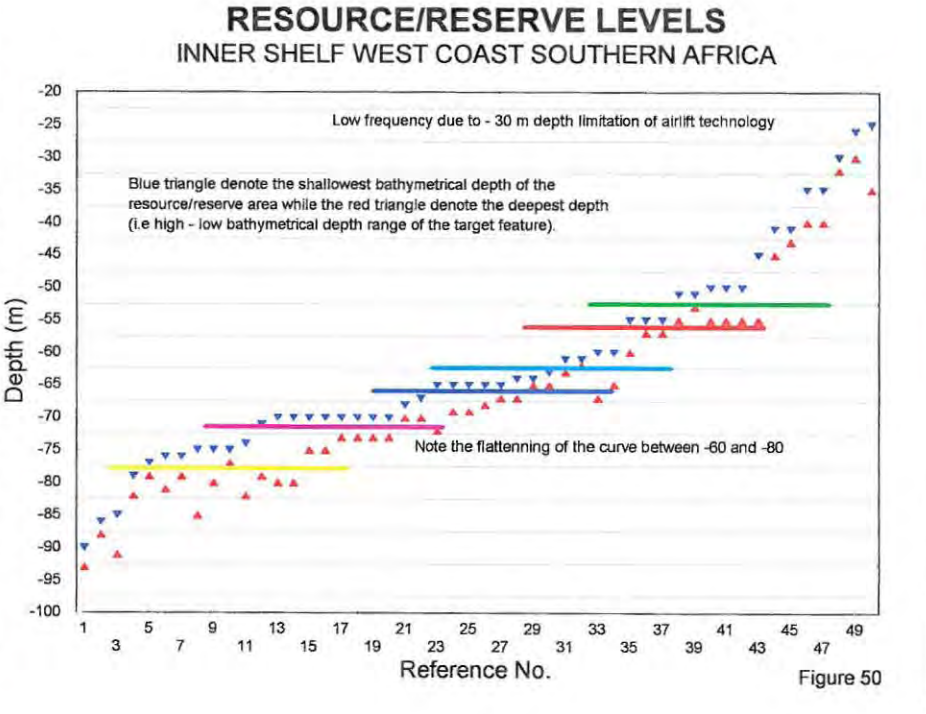
Ref. No.	Area
1	ML36E
2	ML36E
3	ML103A
4	ML36E
5	ML36E
6	ML103A
7	ML51
8	ML103A
9	ML36E
10	ML36E
11	ML103A
12	ML51
13	ML103A
14	ML103A
15	ML36F
16	ML111
17	ML36F
18	ML36F
19	ML36F
20	ML36F
21	ML36F
22	ML111
23	ML36F
24	ML51
25	ML51
26	ML51
27	ML111
28	ML36F
29	ML36F
30	ML111
31	ML111
32	ML36F
33	ML111
34	ML111
35	ML111
36	ML36F
37	ML36D
38	ML36E
39	ML36F
40	ML111
41	ML36D
42	ML111
43	ML111
44	ML36C
45	ML36C
46	ML111
47	ML111
48	ML111
49	ML36A
50	ML111



SEA LEVEL CURVE

WEST COAST SOUTHERN AFRICA

From: Compton (in prep), Shackelton, 1987 and Chapell et al., 1996



RESOURCE/RESERVE LEVELS

INNER SHELF WEST COAST SOUTHERN AFRICA

Figure 50

TERRACE LEVELS OF THE INNER SHELF - LUDERITZ TO CLARA HILL

FIGURE 51

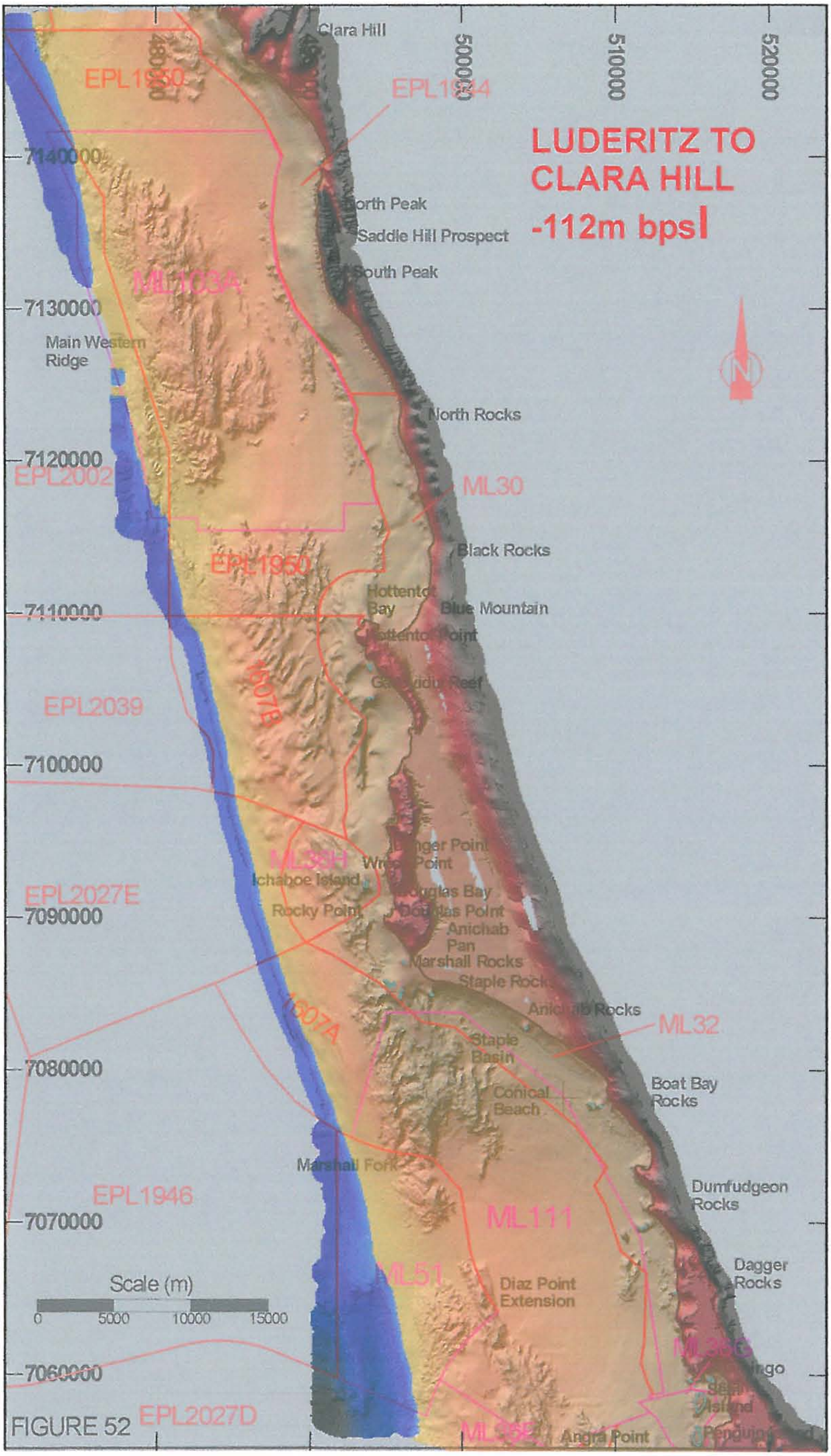

LUDERITZ TO CLARA HILL
-112m bpsl
480000
490000
500000
510000
520000
7140000
7130000
7120000
7110000
7100000
7090000
7080000
7070000
7060000
Clara Hill
EPL1950
EPL1944
North Peak
Saddle Hill Prospect
South Peak
ML103A
Main Western Ridge
N
North Rocks
EPL2002
ML30
EPL1950
Black Rocks
Hottentot Bay
Blue Mountain
Hottentot Point
1607B
EPL2039
Danger Point
ML36H
Wreck Point
Ichaboe Island
Douglas Bay
EPL2027E
Rocky Point
Douglas Point
Anichab Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
ML32
1607A
Staple Basin
Boat Bay Rocks
Conical Beach
Marshall Fork
Dumfudgeon Rocks
EPL1946
ML111
ML51
Dagger Rocks
Scale (m)
0
5000
10000
15000
Diaz Point Extension
ML36G
Ingo
Seal Island
EPL2027D
ML36E
Angra Point
Penguin Island

FIGURE 52

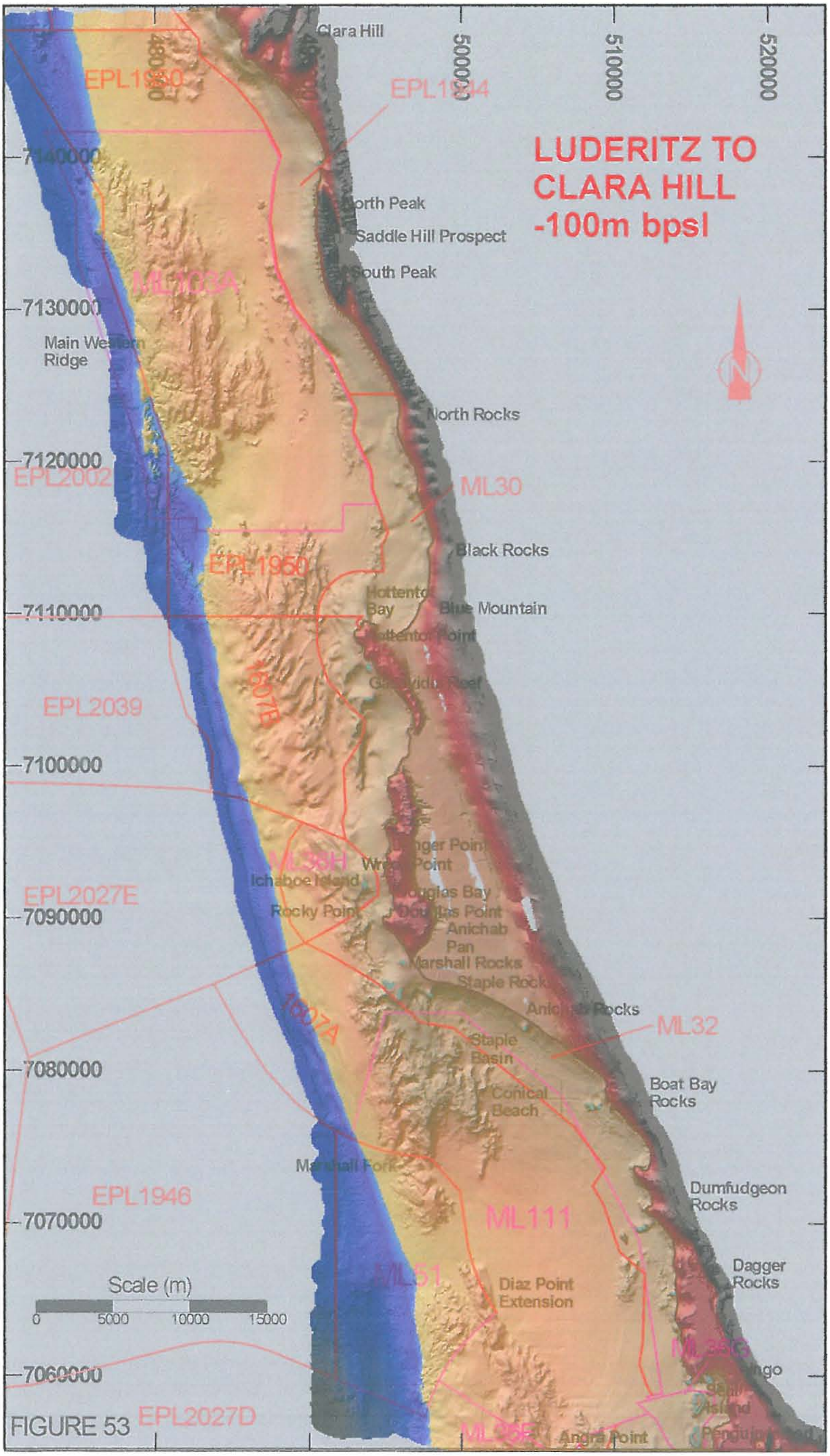

LUDERITZ TO
CLARA HILL
-100m bpsl
Clara Hill
480000
490000
500000
510000
520000
7140000
7130000
7120000
7110000
7100000
7090000
7080000
7070000
7060000
EPL1950
EPL1944
North Peak
Saddle Hill Prospect
South Peak
ML103A
Main Western
Ridge
North Rocks
EPL2002
ML30
Black Rocks
EPL1950
Hottentot
Bay
Blue Mountain
Hottentot Point
Gazavida Reef
EPL2039
1607B
Danger Point
Wreck Point
ML36H
Ichaboe Island
Douglas Bay
EPL2027E
Rocky Point
Douglas Point
Anichab
Pan
Marshall Rocks
Staple Rock
Anichab Rocks
1607A
ML32
Staple
Basin
Conical
Beach
Boat Bay
Rocks
Marshall Fork
Dumfudgeon
Rocks
EPL1946
ML111
Dagger
Rocks
Scale (m)
0
5000
10000
15000
ML51
Diaz Point
Extension
ML36G
Mercury Island
EPL2027D
ML36F
Angra Point
Penguin Island

FIGURE 53

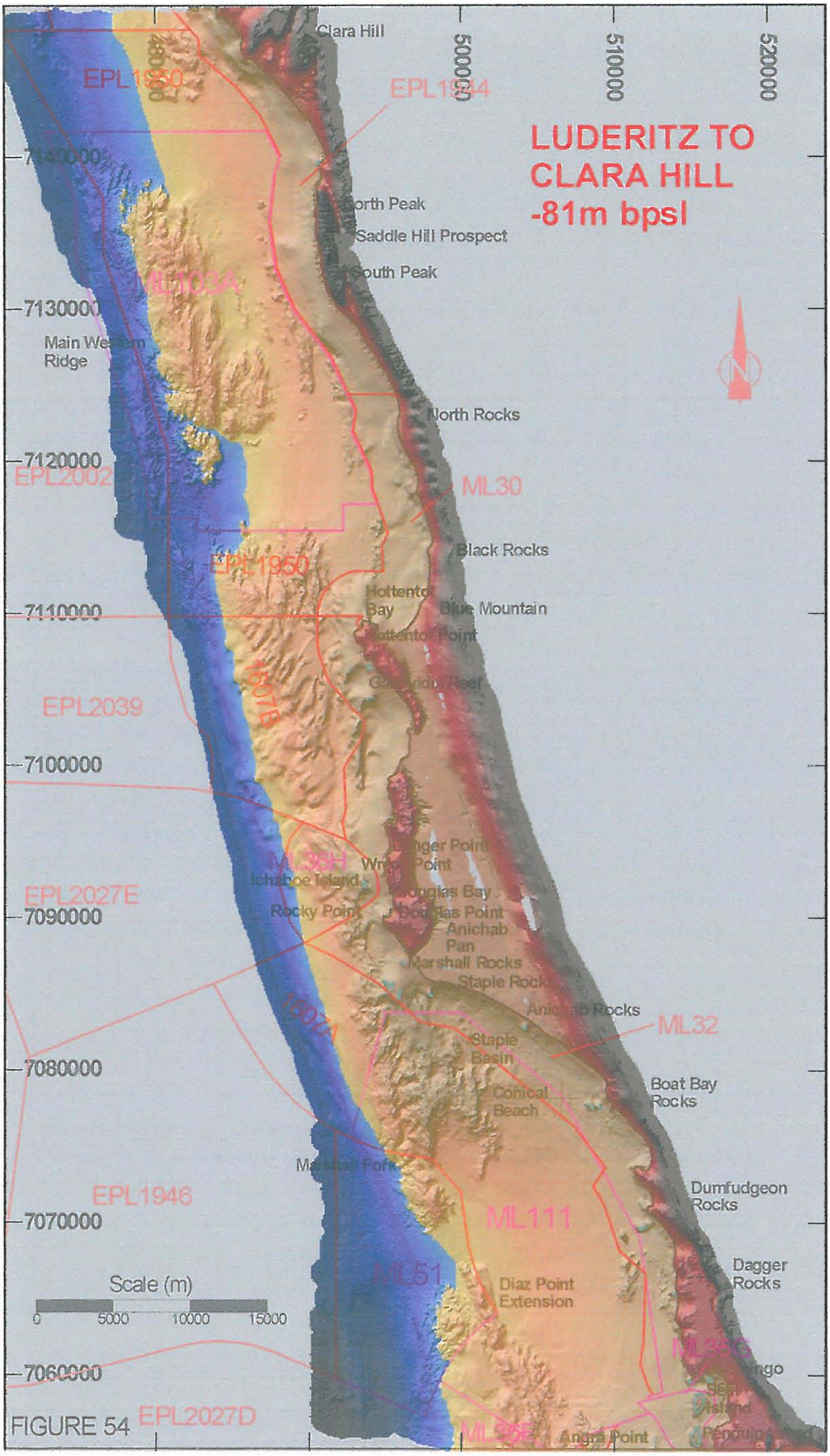
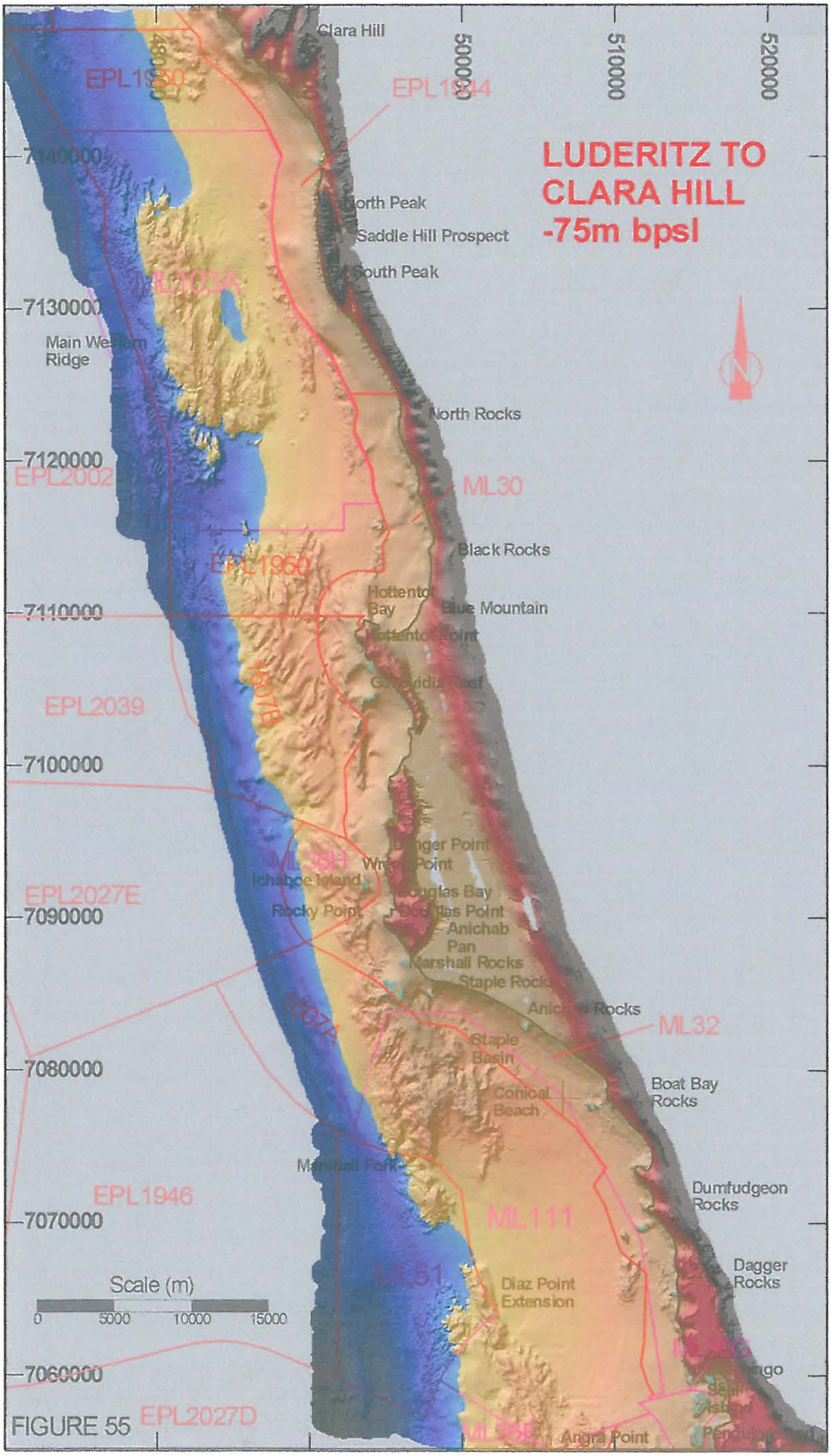

LUDERITZ TO CLARA HILL -81m bpsl
Clara Hill
North Peak
Saddle Hill Prospect
South Peak
Main Western Ridge
North Rocks
ML30
Black Rocks
Hottentot Bay
Blue Mountain
Hottentot Point
Gazellridge Reef
Danger Point
Wreck Point
Ichaboe Island
Rocky Point
Douglas Bay
Douglas Point
Anichab Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
ML32
Staple Basin
Conical Beach
Boat Bay Rocks
Marshall Fork
Dumfudgeon Rocks
Dagger Rocks
Diaz Point Extension
Angra Point
Penguin Island
Seal Island
ML111
ML51
ML36H
ML36E
ML36G
ML103A
1507B
1507A
EPL1950
EPL1944
EPL2002
EPL2039
EPL2027E
EPL1946
EPL2027D
480000
490000
500000
510000
520000
7140000
7130000
7120000
7110000
7100000
7090000
7080000
7070000
7060000
Scale (m)
0
5000
10000
15000
N

FIGURE 54



LUDERITZ TO CLARA HILL
-75m bpsl
Clara Hill
480000
500000
510000
520000
EPL1950
EPL1944
7140000
North Peak
Saddle Hill Prospect
South Peak
ML103A
7130000
Main Western Ridge
North Rocks
7120000
EPL2002
ML30
Black Rocks
EPL1950
Hottentot Bay
Blue Mountain
7110000
Hottentot Point
Reef
EPL2039
1607B
7100000
Danger Point
ML36H
Wreck Point
Ichaboe Island
EPL2027E
Douglas Bay
Douglas Point
7090000
Rocky Point
Anichab Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
ML32
1607A
Staple Basin
7080000
Conical Beach
Boat Bay Rocks
Marshall Fork
Dumfudgeon Rocks
EPL1946
7070000
ML111
Dagger Rocks
Scale (m)
0
5000
10000
15000
ML51
Diaz Point Extension
7060000
EPL2027D
Angra Point
Seal Island
Penguin

FIGURE 55

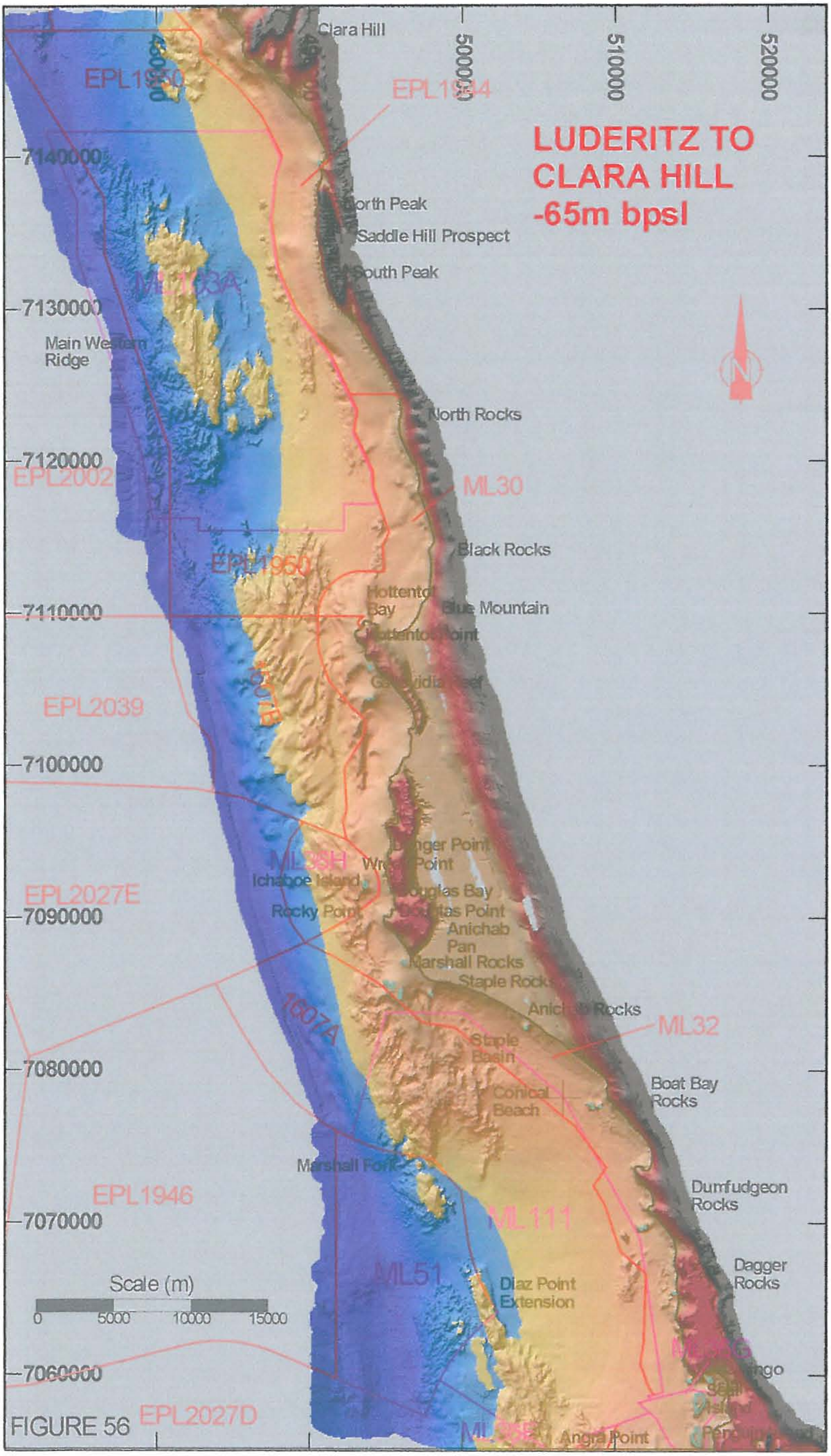

LUDERITZ TO CLARA HILL
-65m bpsl
Clara Hill
North Peak
Saddle Hill Prospect
South Peak
North Rocks
Black Rocks
Hottentot Bay
Blue Mountain
Hottentot Point
Main Western Ridge
Ichaboe Island
Rocky Point
Wreck Point
Douglas Bay
Douglas Point
Anichab Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
Staple Basin
Conical Beach
Boat Bay Rocks
Marshall Fork
Dumfudgeon Rocks
Dagger Rocks
Diaz Point Extension
Angra Point
EPL1950
EPL1944
ML103A
EPL2002
EPL1950
EPL2039
1607B
ML30
ML36H
EPL2027E
1607A
ML32
EPL1946
ML111
ML51
EPL2027D
480000
490000
500000
510000
520000
7140000
7130000
7120000
7110000
7100000
7090000
7080000
7070000
7060000
N
Scale (m)
0
5000
10000
15000

FIGURE 56

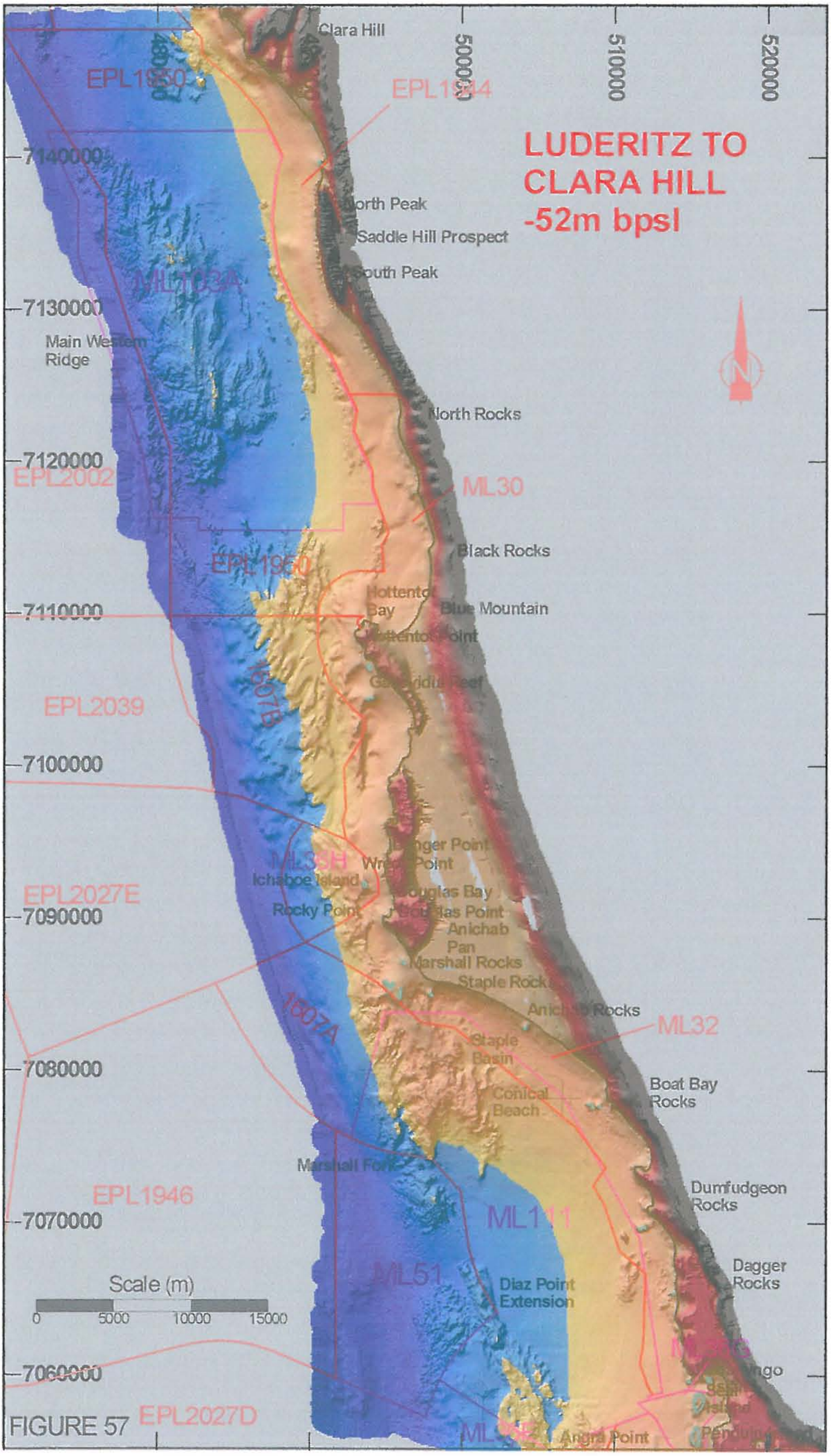

LUDERITZ TO
CLARA HILL
-52m bpsl
Clara Hill
North Peak
Saddle Hill Prospect
South Peak
Main Western
Ridge
North Rocks
Black Rocks
Hottentot
Bay
Blue Mountain
Hottentot Point
Gazeridus Reef
Danger Point
Wreck Point
Ichaboe Island
Rocky Point
Douglas Bay
Douglas Point
Anichab
Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
Staple
Basin
Conical
Beach
Boat Bay
Rocks
Marshall Fork
Dumfudgeon
Rocks
Dagger
Rocks
Diaz Point
Extension
Angra Point
EPL1950
EPL1944
ML103A
EPL2002
EPL1960
EPL2039
1607B
1607A
ML35H
EPL2027E
ML30
ML32
EPL1946
ML111
ML51
EPL2027D
480000
500000
510000
520000
7140000
7130000
7120000
7110000
7100000
7090000
7080000
7070000
7060000
Scale (m)
0
5000
10000
15000
N

FIGURE 57

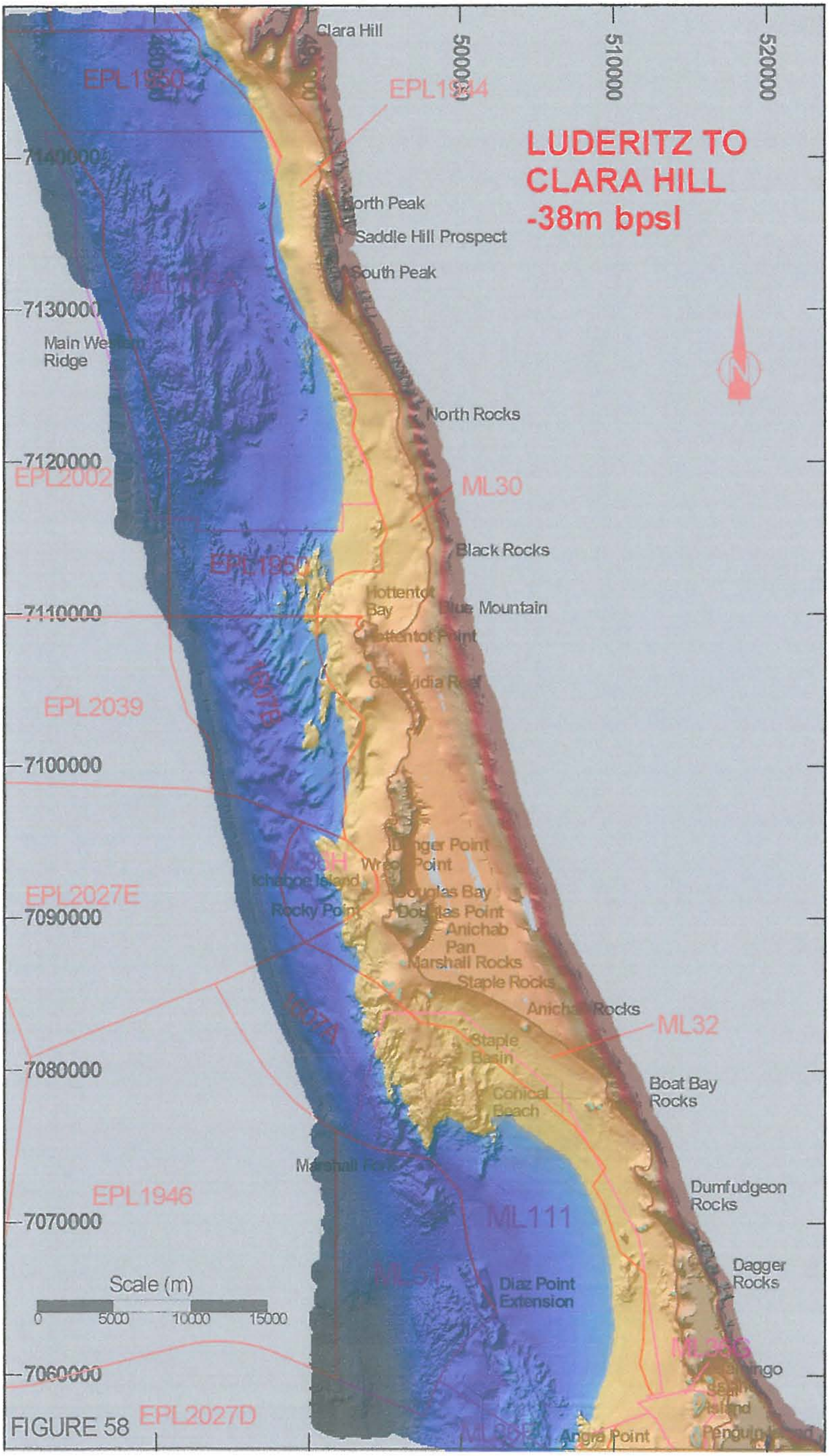
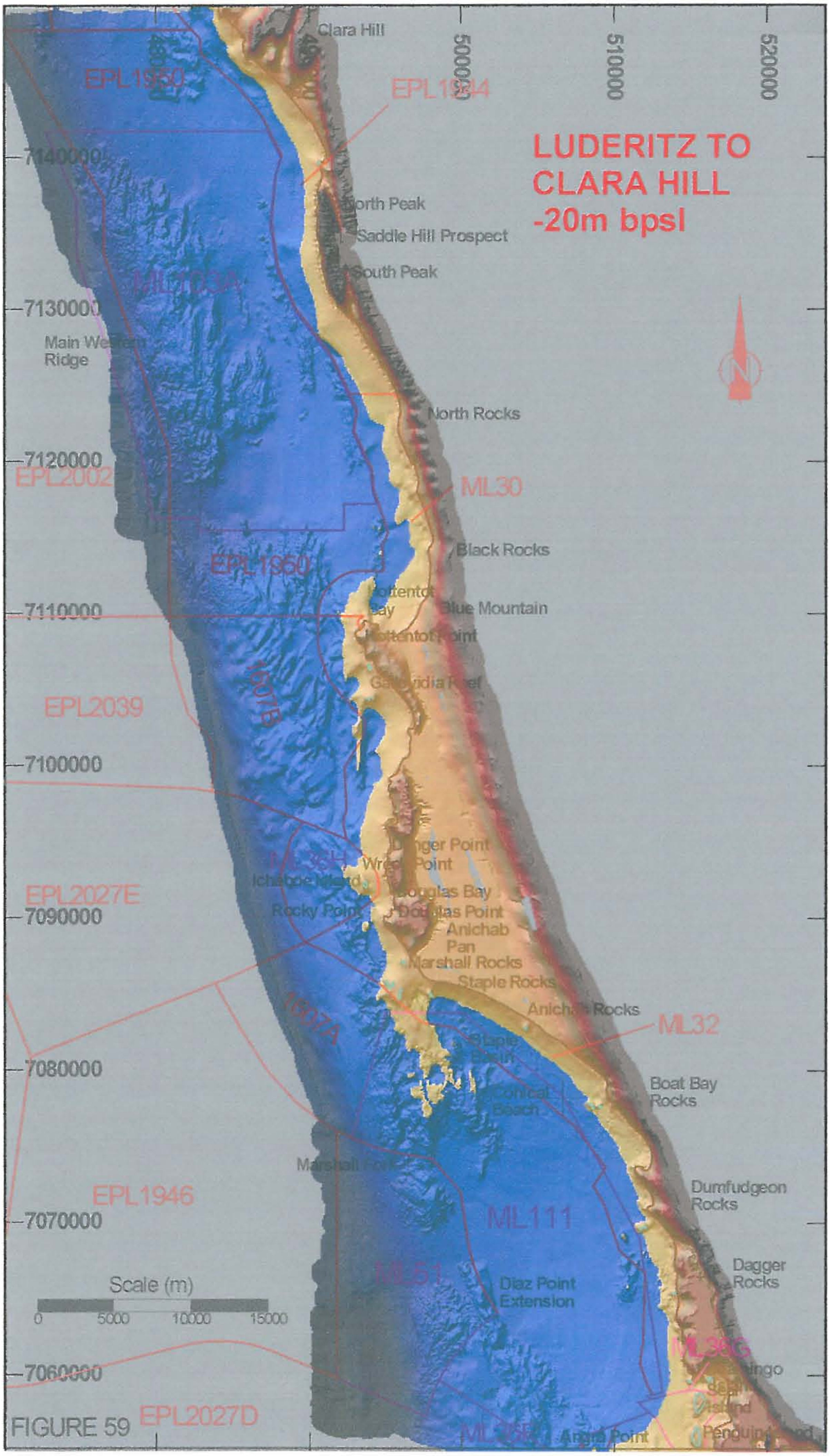

LUDERITZ TO CLARA HILL -38m bpsl
Clara Hill
500000
510000
520000
EPL1950
EPL1934
North Peak
Saddle Hill Prospect
South Peak
7140000
7130000
Main Western Ridge
North Rocks
7120000
EPL2002
ML30
Black Rocks
EPL1950
Hottentot Bay
Blue Mountain
7110000
Hottentot Point
Gazavidia Reef
EPL2039
1607B
7100000
Danger Point
Wreck Point
ML36H
Ichaboe Island
Douglas Bay
EPL2027E
Rocky Point
Douglas Point
7090000
Anichab Pan
Marshall Rocks
Staple Rocks
Anichab Rocks
ML32
1607A
Staple Basin
7080000
Conical Beach
Boat Bay Rocks
Marshall Fork
Dumfudgeon Rocks
EPL1946
ML111
7070000
Dagger Rocks
ML51
Diaz Point Extension
Scale (m)
0
5000
10000
15000
ML36G
7060000
EPL2027D
ML36F
Angra Point
Penguin Island

FIGURE 58



LUDERITZ TO CLARA HILL -20m bpsl

FIGURE 59

regressions lie relative to the coast. These levels correspond well with 75 m bpsl drop (75 000 and 58 000 ya) noted by Andel and Tzedakis (1996), the 20 m bsl (47 000 and 25 000 ya) stillstand recognised by Tankard (1976), Murray *et al.* (1970) and the -18 m to -24 m terrace level interpreted by O'Shea (1971) and the -70 m bpsl drop (39 000 to 36 000) proposed by Andel and Tzedakis (1996). If the 13 m thick Holocene mud, wedged up against the Precambrian bedrock, is added to the -112 m depth interpreted from the bathymetry then the Pleistocene (19 000 to 18 000 ya) eustatic sea-level of -123 m to -130 m depth range (Emery and Garrison, 1967; Tija, 1963). Resources identified in the same region lie predominantly in the -52 m to -55 m, -62 m to -66 m, -72 m to -73 m and -75 m to -77 m water depth ranges correlating well with the sea-levels identified (Refer: Figure 50). The lack of resources identified in water depths shallower than 25 m is most likely due to the fact that the mining companies active in the area have not yet focussed on these areas due to technical considerations relating to airlift mining, rather than them being poorly mineralised. Many diver operators have mined in the 0 m to 25 m water depth range but formal resources estimations are seldom declared due to the small, *ad hoc* mode of operation.

8.4.3 DETAILED TERRACE LEVEL INVESTIGATION OF SADDLE HILL PROSPECT

On the west coast, following years of sampling, mining and resource delineation particular terrace levels can be associated with increased diamond occurrence. Many of these terrace levels occur within the depth range of HBG.

Historical production results show that certain palaeo-shorelines are preferentially mineralised. Wave-cut "cliffs" act as natural barriers, concentrating diamonds along their bases (Le Roux, 1986). Gullies, potholes, ridges and depressions eroded into well developed wave-cut terraces are also known for their diamond entrapment potential (Murray, *et al.*, 1970; Jacob, 2001). It can broadly be assumed that the better developed the wave cut terrace and the longer the duration of the stillstand, the greater the potential to concentrate diamonds at that particular elevation, provided the supply of diamonds is relatively constant. Bearing the former in mind, it is plausible that a narrow, well developed terrace, eroded into a steep seabed gradient over a long duration, may have greater diamond concentrating potential than a wider one, of shorter duration, eroded at a locality more conducive for terrace formation.

Erosion of the inner shelf during sea-level still-stands has formed seaward sloping wave-cut terraces, backed by steeper dipping wave-cut "cliffs". Erosion is mainly by mechanical wave abrasion and "quarrying" (wave shock, wave hammer, air compression and release), but water layer weathering (hydration, oxidation, rock breakdown by salt crystallisation and swelling of grains) and sub-aerial weathering also play a role (Martinez and Harbuagh, 1993). The "nick-point" marks the point of change in gradient between the base of the "cliff" and the landward end of the terrace. Studies suggest that the "nick-point" is cut at the Mean High Water Springs (MHWS) and that the terraces are actively cut to surf-base (Bradley and Griggs, 1976). Nick-points can therefore be used to identify and map the depth and location of ancient shorelines both above and below present sea-level. The platform morphology is believed to be the result of the interaction between the angle of the wave front relative to the coastline, wave energy in the surf zone and sediment transport in the longshore direction (Bradley and Griggs, 1976). The "cliff" at the landward end of the terrace may vary in gradient and height depending on a number of variables, the most important being the bedrock structure and lithology. The formation of well-developed wave-cut terraces depends on the following:

a) The slope (gradient) into which the terrace is cut (O'Shea, 1971);
b) Bedrock lithology and dip of bedding or fold/shear planes (Jacob, 2001);
c) Structure - orientation of joints, fractures and other lineaments (Murray, *et al.*, 1970; Jacob, 2001);
d) The stillstand duration and the number of times the elevation has been revisited (O'Shea, 1971);
e) Wave and swell conditions (O'Shea, 1971);
f) Availability of abrading agents (O'Shea, 1971; Jacob, 2001).

The terrace levels identified can be compared to diamond recovery depths recorded during prospecting. Depths at which diamonds are known to occur can then be extrapolated from areas where sampling has taken place to un-sampled areas. Therefore terrace levels studies can be useful in delineating and prioritising high potential diamond placer targets and thereby reducing the exploration costs associated with resource delineation. The consistency of various terrace level elevations along the central Namibian west coast would suggests that there has been relatively little warping since their formation. In conclusion, the submarine terraces identified in HBG (Rau, 1995), from which the majority of the results presented in this section have been extracted, are compared to terrace levels identified during detailed study of the Lüderitz Bay Grant terraces (Rau, 1996).

8.4.3.1 TERRACE LEVEL INTERPRETATION METHODOLOGY

The criteria listed by Zeuner (1958) for recognising terraces along erosional shorelines are: 1) presence of an abrasion platform; 2) a cliff-platform junction (nick-point); and 3) an undercut or notch at the nick-point and 4) lines of rock boring organisms.

The SH and HB prospects of the study area were selected to do the detailed terrace level study because the they provide long continuous sections of reef across which many profiles can be compared. Terraces were identified using 57 coast-perpendicular bedrock profiles derived by adding sediment thickness to the bathymetric data. From the profiles the following information was extracted:

- **Nick point depth** - where necessary, seismic data were used to obtain the correct nick point depth beneath recent, unconsolidated sediment cover;
- **Terrace end depth** - depth at the seaward end of the terrace
- **Direction** - west facing terraces, east facing terraces and coast-parallel depressions were identified and interpreted separately;
- **Ranking** - terraces were assigned a ranking on the basis of the degree of maturity from 1 (poorly developed) to 3 (well developed). In order to reduce errors inherent in this subjective methodology all rankings were allocated by the author and should therefore be relatively consistent;
- **Width** - coast-perpendicular width of the terrace was measured (m);
- **Gradient** - angle of the slope into which the terrace was eroded. Rated from 1 (0^0 to 6^0), 2 (6^0 to 10^0) and 3 (>10^0) using a protractor.

8.4.3.2 RESULTS OF TERRACE LEVEL STUDY

Over one thousand nick points were identified on the 57, A0 sheets of coast-perpendicular bedrock profiles during this study. As not all inflections noted on the bedrock are necessarily indicative of wave eroded terraces the frequency, terrace width, coast-parallel continuity, gradient and rank can be used to distinguish the well- from the poorly developed terraces.

The combination of qualitative and quantitative methods used to assess and interpret the terraces identified in the study area and pertinent observations are described below. The terrace profiles were subsequently transposed onto a plan view A0 map and used in conjunction with the graphs to identify the most prominent terraces, summarised in Section 8.4.5. These profile sections are too volumous to include, but 2 pinger sections from the north and 2 from the south of the study area are included in Appendix 2.

8.4.3.2.1 Depth VS Nick-point Frequency

- **Westward facing terraces (Figure 60)**

Nick point frequency plots, interpreted from coast-perpendicular seafloor profiles, are the most frequently used technique to distinguish sea-level stillstands along the west coast. In this study the thickness of the overlying seismically transparent mud was taken into account when determining the nick-point and toe elevation of the terrace. Where frequencies are low, near the maximum and minimum depth range of the study area, results should be interpreted with caution.

- **Eastward facing terraces (Figure 60)**

These terraces did not face the full erosive force of the predominant southwesterly swell and are not as well developed as the westward facing terraces. Generally their elevations correspond to westward facing terrace levels, but this is not always the case. On close examination it was noted that the eastward facing terrace are on average 1 m deeper than the westward facing terraces (Refer: Figure 60). Intuitively one would expect the westward facing terraces, that take the full impact of the waves, to be more deeply eroded. The reason for this apparent anomaly is not clear at this time. Data frequency, for the eastward facing terraces, in the shallower and deeper depth ranges is low and these results may not be representative of terraces along the central Namibia coast.

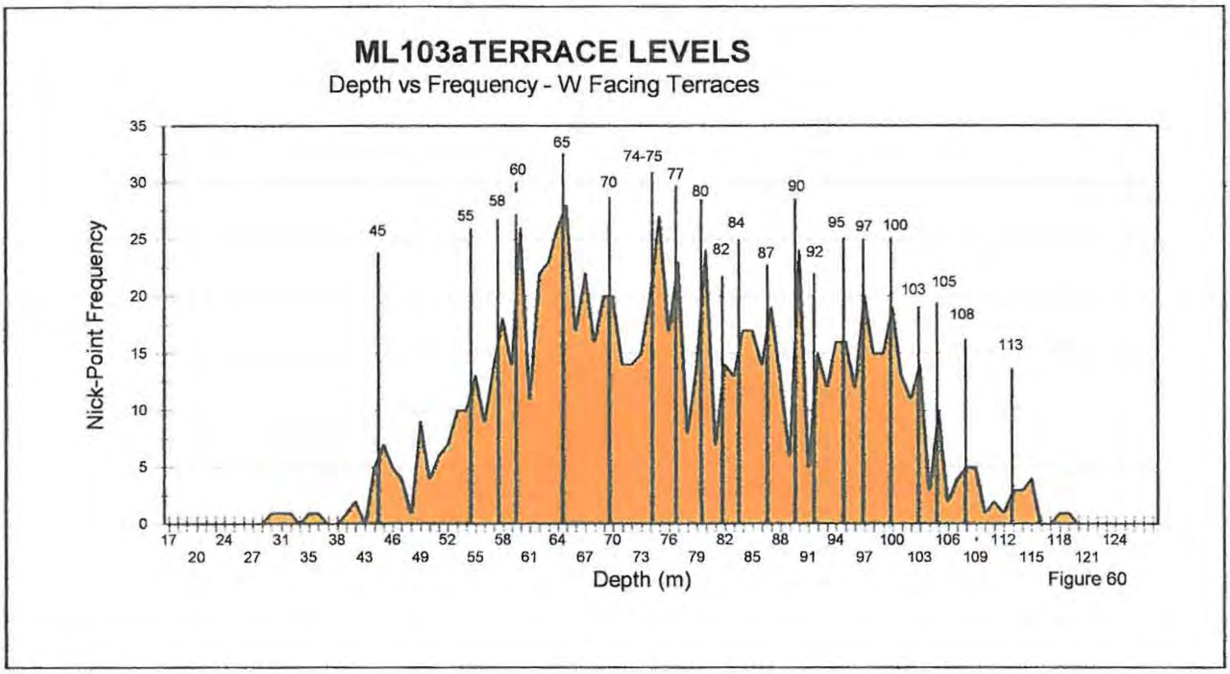
- **Coast-parallel depressions (Figure 60)**

The nick point frequency peak at -68 m to -78 m on this graph, represents the coast-parallel depression in the central basin between HB and the MWR. This depression would have been sheltered from the southwesterly storm swell by the MWR. Erosion is likely to have been predominantly by refracted swells moving around the southern and northern edges of this reef, a phenomenon regularly associated with coast-parallel linear depressions. During regressional periods aeolian processes may also have contributed to the erosion of this linear depression, orientated parallel to the dominant southerly storm winds. During regressions of between -54 and -65 m tidal scouring, by water exiting around the northern edge of the MWR could also have contributed to the erosion of this feature. The peak in the graph in the -94 m region corresponds to the profiles intersecting gullies branching off **(AM)**. These results will be skewed by the position of the profile intersections relative to this feature but do give an indication of the base-level of those portions of the channel.

8.4.3.2.2 Depth vs Rank and Frequency

- **Westward facing terraces (Figure 61)**

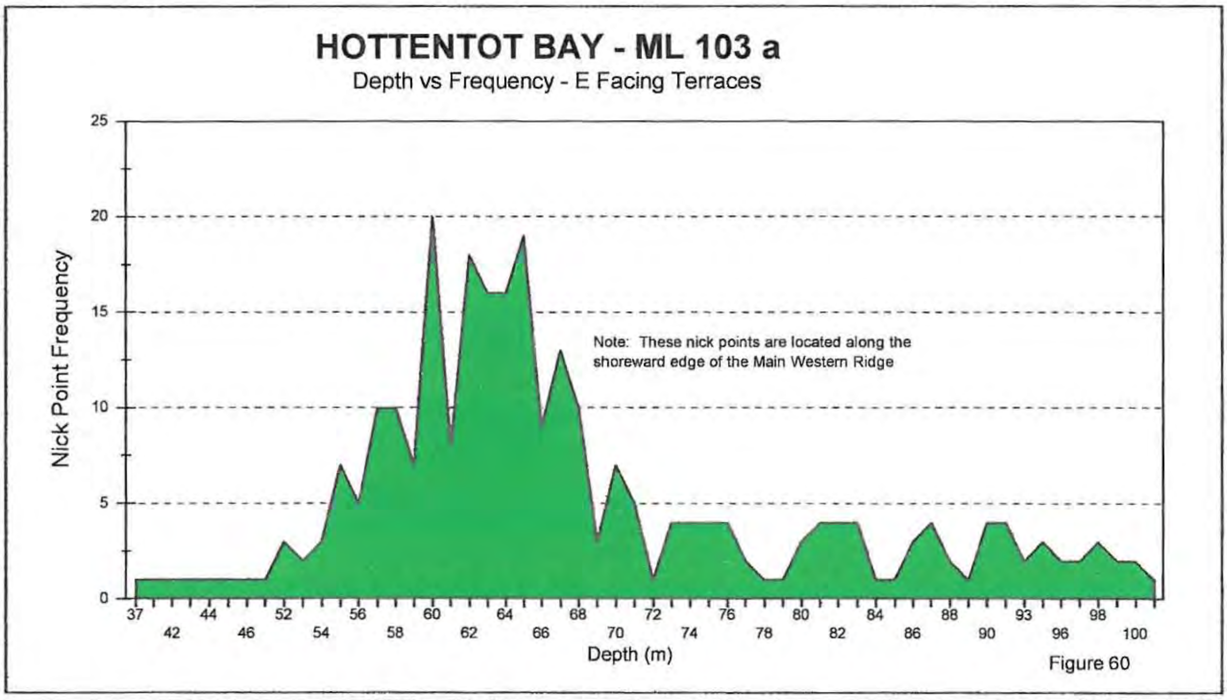
Rank was divided by frequency to examine the average development of the terraces on individual elevations more carefully. Values of 2 and more are considered significant because they indicate that the average



ML103aTERRACE LEVELS

Depth vs Frequency - W Facing Terraces

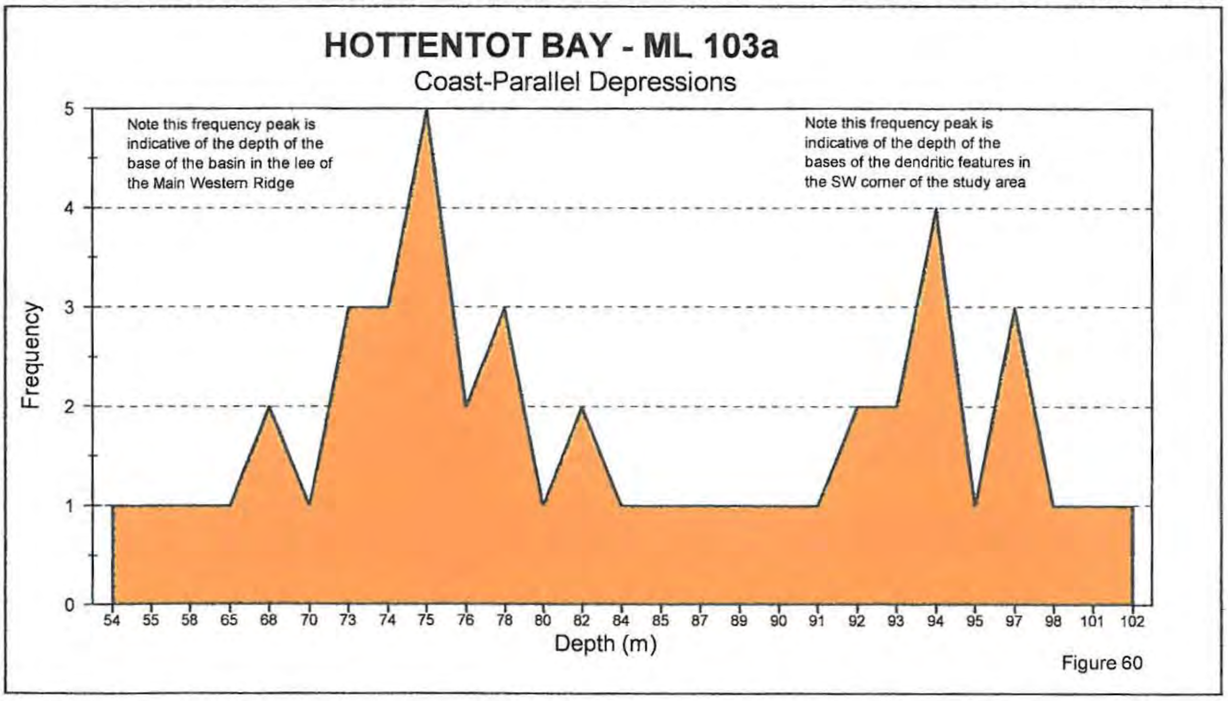
Figure 60



HOTTENTOT BAY - ML 103 a

Depth vs Frequency - E Facing Terraces

Figure 60



HOTTENTOT BAY - ML 103a

Coast-Parallel Depressions

Figure 60

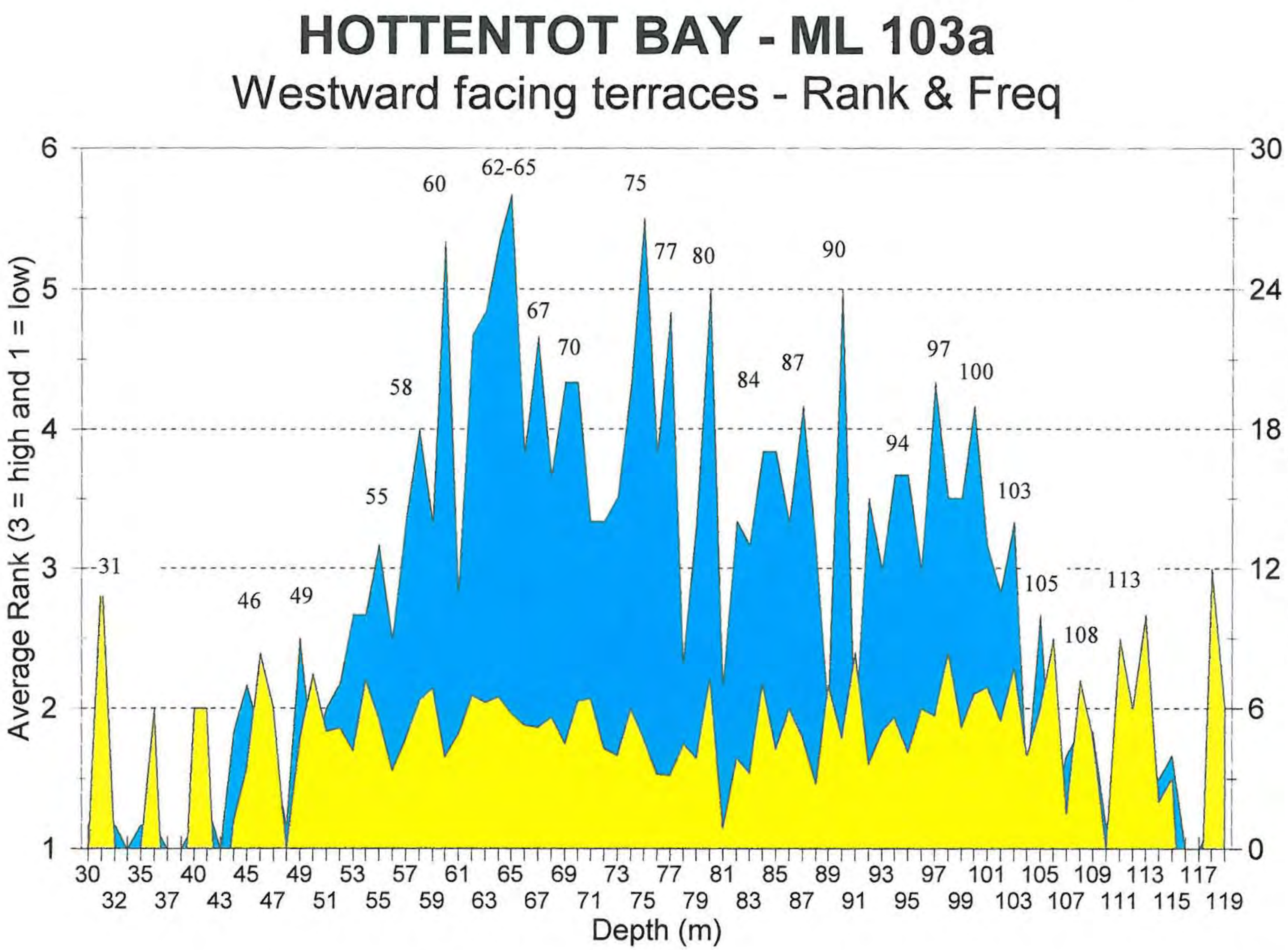

HOTTENTOT BAY - ML 103a
Westward facing terraces - Rank & Freq
Average Rank (3 = high and 1 = low)
Frequency of Nick Points
Depth (m)
1
2
3
4
5
6
0
6
12
18
24
30
30
32
35
37
40
43
45
47
49
51
53
55
57
59
61
63
65
67
69
71
73
75
77
79
81
83
85
87
89
91
93
95
97
99
101
103
105
107
109
111
113
115
117
119
31
46
49
55
58
60
62-65
67
70
75
77
80
84
87
90
94
97
100
103
105
108
113

Figure 61

terrace at that elevation is moderately (2) to well (3) developed. Where terrace frequencies are very low at the deep and shallow limits of the data set the results are easily biassed.

- **Eastward facing terraces**

A large part of this data set is of fairly low frequency(<5 terraces) easily biassing results and therefore have not be included.

8.4.3.2.3 Depth vs Average Terrace Width and Bedrock Gradient

- **Westward facing terraces (Figure 62)**

O'Shea (1971) used a terrace width of 200 m over which the elevation must not have dropped by more than 2 m to as arbitrary measure of whether or not the terrace was well developed. In this study terrace width and gradient were both recorded. An inverse relationship (ie. mirror image) between these two parameters is expected and for the most part, this is true. In most alluvial diamond concentration processes the longer the duration, the greater the opportunity for winnowing and concentration of diamonds and the higher the grade. In similar bedrock lithology environments it is intuitive that a relatively wide terrace, eroded into bedrock with a steep gradient, would require a longer duration to form, than a similar width terrace eroded into a gentler gradient. Alternatively, repeated visits to the same sea-level during the transgressive and regressive cycles would result in continued erosion and ultimately, better terrace development. Broadly speaking, it can be assumed that more mature terraces have had a longer period to concentrate diamonds and are considered higher potential targets.

- **Eastward facing terraces**

The relatively low easterly facing terrace frequencies can easily bias results and therefore they have not been included in this examination.

- **Coast-parallel depressions (Refer: Figure 60)**

Again, the relatively low number of coast-parallel depressions identified can lead to biassed results and should be interpreted with caution. The peaks at -74 m to -78 m bsl corresponds to the base of the large coast-parallel depression in the lee of the MWR. The widest of these depressions occur at -74 m to -76 m and at -89 m. The -94 m bsl peak corresponds to the base level where the profiles intersected **(AM)** to the south of the prospect area. Peaks in the coast-parallel depression graph, occur at similar elevations to some of the significant eastward and westward facing terraces showing that they are formed on the gentler gradients associated with some of the more prominent terrace levels. These in turn can be linked to important sea-level stillstand periods.

HOTTENTOT BAY - ML 103 a

Av.Terrace Width and Seafloor Gradient

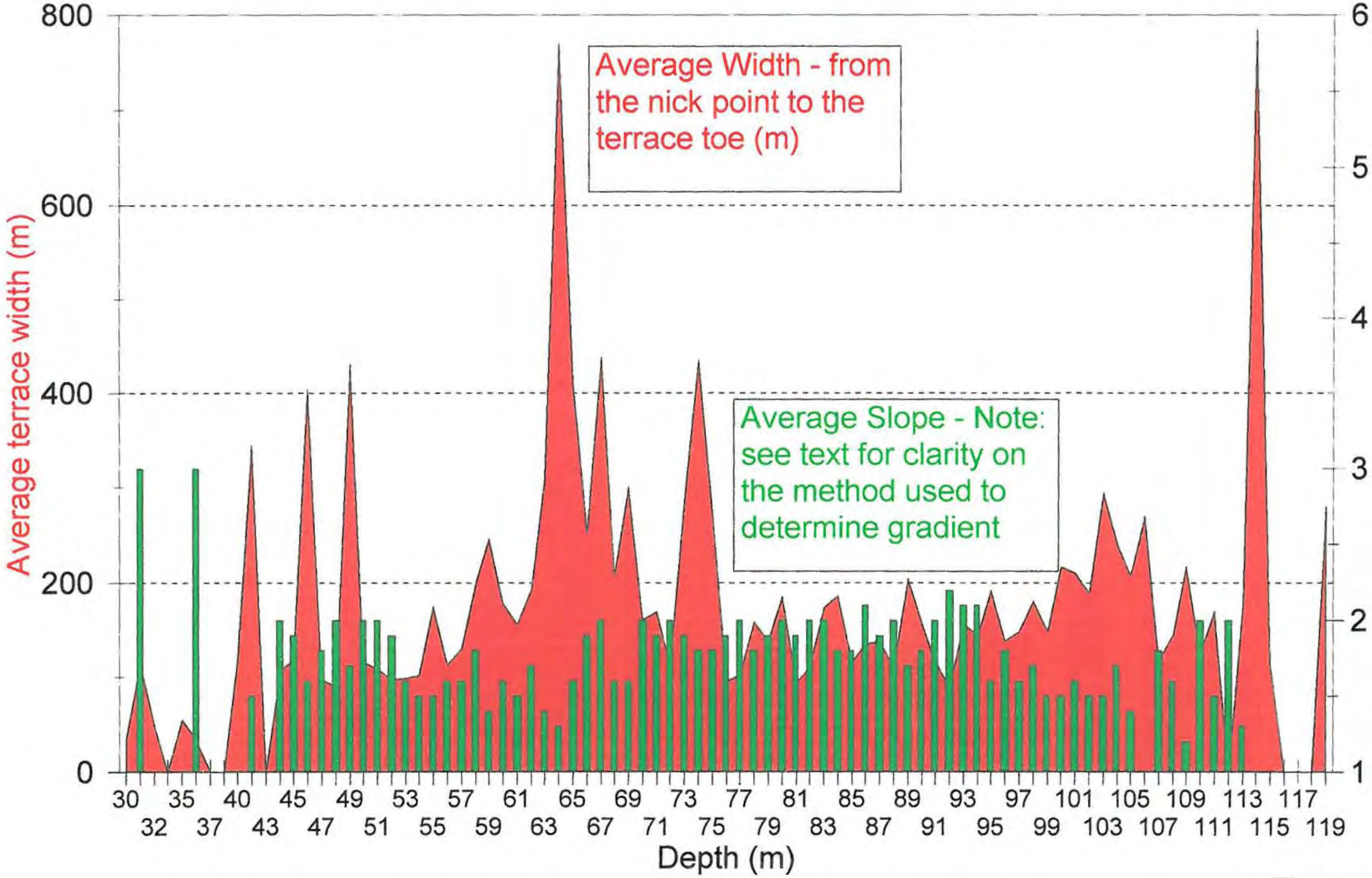


Figure 62

8.4.3.3 DISCUSSION

The terrace level results presented in this study are the most comprehensive completed along the central Namibian inner shelf. The -113 m, -103 m, -98 m, -94 m/-95 m, -86 m/-87 m, -80 m, -74 m/-75 m, -70 m, -64 m/-65 m, -58 m/-59 m, -46 m and -31 m have been identified as being best developed within the depth ranges covered by the study.

The majority of the terraces were interpreted off the seaward face of the MWR and reefs in HB which have little sediment on them. Where recent sediment was overlying the terrace, these units were taken into account in an effort to improve the accuracy of the interpretation. Sea-level studies have shown that since early Holocene times the west coast is experiencing a transgressive marine cycle (Vail, *et al.*, 1977, Moore, 1982; Compton et al., 2001). The submarine terrace levels in the SHP and HBP areas are therefore discussed from the deepest to the shallowest terrace depth. However, the format used does not necessarily wish to imply that the order is sequential in terms of terrace age. Based on the results of this detailed study the following 20 terrace levels are identified as being best developed:

- **-113 m** - terraces are well developed at this elevation and correlate with the intersection between the phosphatic horizon and the base of the MWR. However, this near-surface phosphorite horizon is not representative of the major inner shelf inflection, where the Cretaceous strata intersects the Precambrian bedrock. This inner shelf inflection that occurs at -123 m to -130 m bpsl, about 15 m deeper, was formed during the Pleistocene (19 000 to 18 000 ya) sea-level regression (Tija, 1963; Emery and Garrison, 1967; Moore, 1982) before the post-glacial rise to present sea-level. This -128 m bpsl is 9 m above the average depth of -137 m noted by Shepard (1963) for the global continental shelf break. The eastward facing terraces and coast-parallel depressions do not reach this depth.

- **-108 m** - a frequently occurring elevation with well developed terraces, but of short average coast-perpendicular width.

- **-103 m** - terraces at this stillstand elevation occur relatively frequently on the westward face of the MWR. It is beyond the depth range of the eastward facing terraces.

- **-100 m** - at this elevation, frequent, well developed, relatively narrow westward facing terraces occur. The NNW trending section within **(AM)** occurs at this elevation as well as the central portion of the MWR. Eastward facing terraces occur infrequently at this elevation are but well developed and are, on average, wide.

- **-98 m** - terraces at this stillstand elevation are well developed and occur frequently on all the graphs produced. It is possible that the terraces from -103 m to -98 m are indicative of subtle variations along a single strandline eroded at the same sea-level stillstand. The variations could be related to differences in bedrock hardness or minor tectonic changes, post formation.

- **-94 m to -95 m** - there is a 1 metre difference between the westward and eastward facing terraces at this elevation, respectively. It is not clear why the eastward facing terraces, that would have experienced less erosion from the westerly swell, should be deeper. The **-94 m** frequency peak in the coast-parallel depression graph correlates well with westerly facing terraces noted at this elevation.

- **-84 m to -87 m** - a well-developed stillstand elevation evident on both the westward and eastward facing terraces. Modelling shows a significant westerly facing embayment would be present between BMP and SHP at this sea-level elevation and waves would be pushing far up the western side of **(AM)** reworking sediments deposited within this feature.

- **-80 m** - a very frequently occurring, well-developed stillstand elevation even though the eastward facing terraces at this elevation are relatively narrow. The modelled sea-level at this elevation shows an island in the southwestern corner of the SHP as well as a number of reefs and gullies around the northern tip of the MWR.

- **-77 m** - examination of the frequency plot alone suggests that this is an important stillstand elevation. However, the assigned rankings show that the west- and east-facing terraces are poorly developed and the former are narrow. This could imply that the stillstands at this elevation were short lived or that this elevation was not frequently revisited during transgressive/regressive cycles, or both.

- **-74 m and -75 m** - an important terrace elevation range with peaks in all the graphs compiled. The frequency of westward facing terraces is slightly greater at **-74 m** than at **-75 m**. The average width of the eastward facing terraces at **-75 m** is greater than at **-74 m**. At the -74 m elevation, an inverse relationship exists between terrace width and gradient indicating that a wide terrace has been eroded into a relatively steep bedrock gradient. This elevation may correlate with the 75 000 and 58 000 ya sea-levels drop to 75 m bpsl off the west coast noted by Andel and Tzedakis (1996).

- **-70 m** - terraces at this elevation are very well developed. However, westward facing terraces at this level are relatively narrow. This level may correspond with -70 m bpsl interpreted by Andel and Tzedakis (1996) to be associated with a regression that occurred 39 000 to 36 000 ya.

- **-67 m** - terraces at this elevation are well developed toward both the west and east. However, westward facing terraces are moderately developed and eastward facing terraces are of medium width. At the -67 m elevation, an inverse relationship exists between terrace width and gradient indicating extensive erosion into a relatively steep bedrock gradient.

- **-62 m to -65 m** - this is a very prominent stillstand elevation range. Based on the results it would appear as if the **-64 m** elevation is best developed on the westward facing terraces while the **-65 m** level is the more dominant of the eastward facing terraces.

- **-60 m** - Numerous west- and east-facing terraces occur at this level. If this study only examined nick point frequency this would have appeared to be one of the most prominent stillstand elevations. However, short average widths on both the westward and eastward facing terraces and poor development on the former, indicate that stillstands at this elevation were short-lived.

- **-58 m to -59 m** - The **-58 m** is a very prominent stillstand elevation. Westward facing terraces are of moderate width. The **-59 m** is also a prominent terrace level, but occurs less frequently than the **-58 m** level.

- **-55 m** - this stillstand elevation occurs frequently on both the westward and eastward facing terraces. Westward terraces are well formed and of moderate width, but eastward facing terraces at this elevation are poorly developed and narrow.

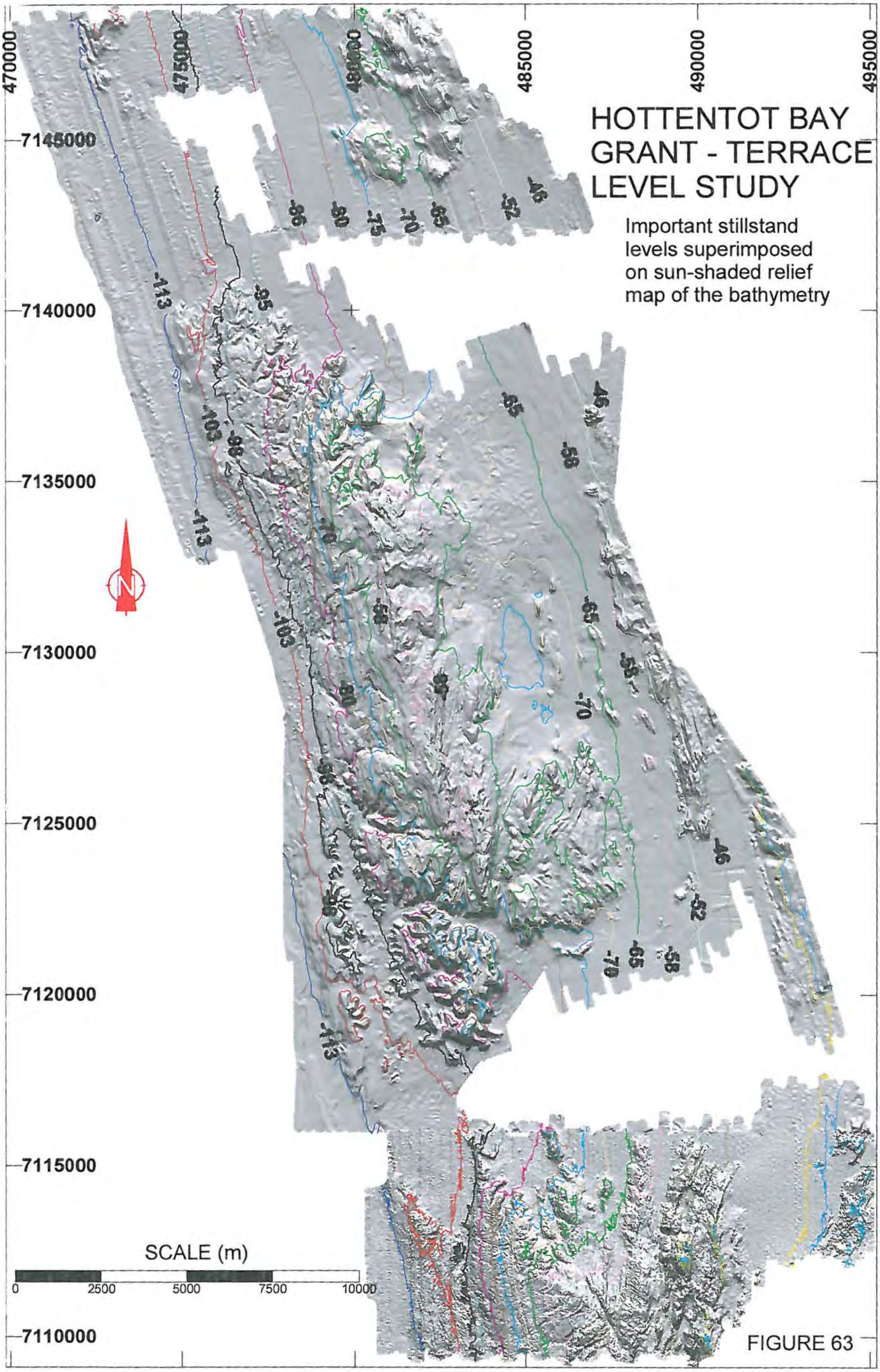
- **-52 m** - terraces are of short average width, but are well developed and occur frequently. This elevation is poorly developed along the westward facing terraces.

- **-49 m** - occurs frequently and are of long average width but are not very well developed. There are very few eastward facing terraces at this level.

- **-46 m** - both the west and east facing terraces this elevation are well developed, although of low frequency and width, particularly along the eastward facing terraces.

- **-31 m** - this terrace level only occurs once in the prospect area. However, it is well developed and longer than the terraces around it.

Of the above twenty submarine terraces identified the -113 m, -103 m, -98 m, -94 m/-95 m, -86 m/-87 m, -80 m, -74 m/-75 m, -70 m, -64 m/-65 m, -58 m/-59 m, -46 m and -31 m are interpreted to be the best developed. Examination of the frequency graphs (Refer: Figure 60) show these terrace levels to be part of a higher period cyclicity superimposed on a lower period cycle which has peaks in the 60 m to 65 m, 74 m to 77 m, 84 m to 87 m and 95 m to 100 m range. Toward the deep and shallow ends of the depth range present within SHP and HBP areas, where terrace frequencies are low, confidence in the accuracy of the interpretation decreases accordingly. The terraces highlighted during the modelling of the region between Lüderitz and Clara Hill at -112 m, -100 m, -87 m, -82 m, -75 m, -65 m, -52 m, -38 m, -29 m and -20 m correlate well with those identified during this more detailed study (colour coded for easy comparison) as well as with those identified in the literature. The small differences are most likely related to the latter being derived from bathymetry alone and do not account for recent sediments deposits situated upon the terrace, that were taken into account during the more detailed study. The -35 m and - 20 m, identified during the more regional study, lie landward of ML 103a and EPL 1950 and therefore cannot be accurately compared. Figure 63 shows the positions of the best developed stillstand elevations, superimposed on a shaded relief map of the bathymetry of the study area.



HOTTENTOT BAY GRANT - TERRACE LEVEL STUDY

Important stillstand levels superimposed on sun-shaded relief map of the bathymetry

FIGURE 63

In spite of attempts to accurately define stillstand elevations on the inner shelf in central Namibia, in a few instances this was not possible. There is a slight depth discrepancy between the westward and eastward facing terraces in the study area with the latter being on average 1 m deeper. The reason for the eastward facing terraces being 1 m lower than the westward facing terraces is not known, but may be related to localised structural movements or coast-parallel tidal erosion along the eastern periphery of the MWR. It was noted on the cross-line profiles the eastward facing terraces often dipped westward making the nick point slightly deeper than the depth at the toe of the terrace. Maybe the methodology used to determine the elevation of the nick point on eastward facing terraces should not be the same as that used for westward facing terraces. This depth difference occurs at the **-64 m/-65 m, -74 m/-75 m, -84 m/-86 m** and at **-94 m/-95 m** levels.

Resources identified along the inner shelf of central Namibia lie predominantly in the -52 m to -59 m, -62 m to -66 m, -72 m to -73 m and -75 m to -77 m water depth ranges (Refer: Figure 50). They correlate well with the terraces identified at -55 m, -62 m to -65 m, 70 m, 74 m to 75 m and 77 m elevations, during this detail terrace level study.

An equally detailed terrace level study was completed in ML 51 (Rau, 1996). An interpretation of the ML 51 and ML103a nick point frequencies is shown in **(Figure 64)**. Extrapolation of these important terrace levels can be used to assist in target prioritisation in other un-sampled regions along the central Namibian inner shelf.

8.5 SEDIMENT DYNAMICS STUDY

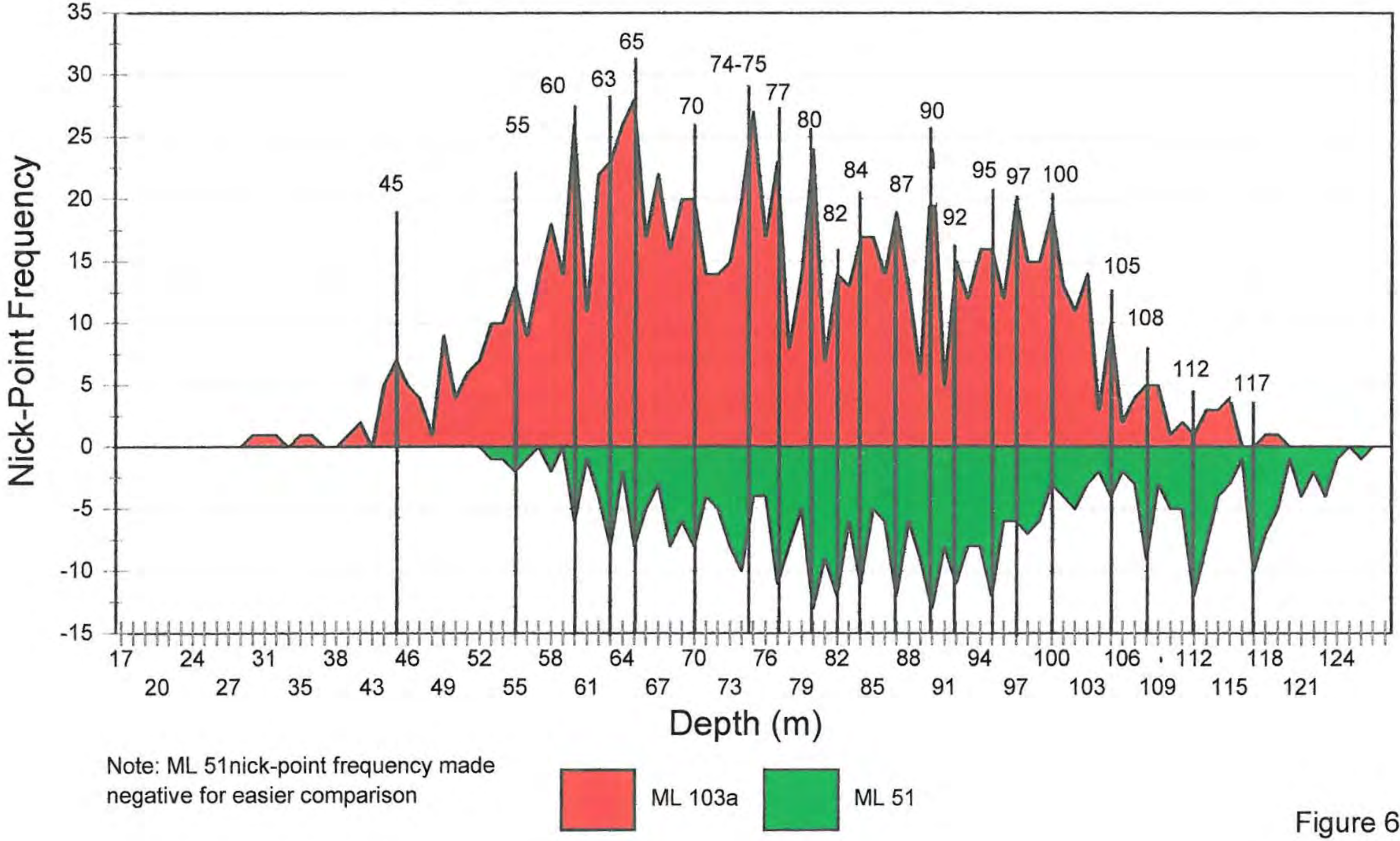
8.5.1 INTRODUCTION

Sediment dynamic studies involve the use of accredited application software and formulae for wave refraction modelling, to determine the wave angle and the orbital wave velocity at the seabed. The wave angle and orbital velocity are closely related to the bedload transport direction and entrainment velocity of sediment grains on the seafloor. Orbital velocities required to move diamonds of specific sizes can be empirically determined and therefore areas of diamond entrainment, transport and deposition can be modelled and targets identified.

Wind generated waves at various periods and amplitudes propagate away from a point of origin. The strength of the wind, duration and fetch determine the wave dimensions (De Decker, 1986). Interactions between wave sets can cancel or superimpose each other, creating a new wave spectrum. No modelled wave equation can take all possible permutations into account. Linear (or Airy) wave theory the simplest equation assumes a sinusoidal curve for the waves. Swart (1983) developed the more complex vocoidal wave theory that provides better results over a broader range of water depths. De Decker (1986) compared the linear and vocoidal equations for a depth of 15 m bpsl using a correlation curve for horizontal orbital velocity (Komar, 1976a) on the seabed beneath the wave crest. A near perfect correlation showed that these equations provide very similar results at this depth.

ML103a & ML51 TERRACE LEVELS

Depth vs Nick-Point Frequency



Note: ML 51nick-point frequency made negative for easier comparison

Figure 64

Wave theory is highly complex and beyond the scope of this study. However, there are some important factors that need to be considered when modelling and interpreting results using wave refraction software packages. The majority of modelling software packages are used for coastal engineering purposes. That is, modelling of sand movement in response to the building of breakwaters and other man-made structures that offset the dynamic equilibrium of a log-spiral bay or coastline. Wave modelling software is commonly used to assess beach sand replenishment and approach channel re-sedimentation rates (de Vriend, 1999). These engineering applications require strict control on input parameters and often are preceded by long duration current, wave direction, period and height, incident wave angle, grain size, sediment composition, bottom friction, water depth and other measurements. In many instances once the parameters have been measured in as much detail as possible, scale models are built and wave conditions simulated in large wave tanks in order to assess the accuracy of the computer modelled results. The time and expense is warranted because if a large civil structure is constructed and the change in sediment dynamics results in the collapse of the structure and fatalities, or all the sand being stripped from the local tourist beaches in the future due to changes in the dynamic equilibrium of the bay, the repercussions could be financially disastrous. Despite the time and effort that is placed in accurately modelling sediment movement many of the structures that have been designed, based on computer, have still failed. In fact structures designed to trap and create sandy beaches have had the opposite effect increasing erosion dramatically (Gómez-Pina, 1999). Hindsight analyses of these coastal engineering disasters indicate that, most often, the modelling errors lie in the difficulty of accurately defining the input parameters. Measurements taken at specific localities are not necessarily representative of the whole area under consideration. Each parameter is measured and input individually where in actuality they are inter-related and may respond differently even if they are run by the mathematical algorithms in a different order. Additionally, as each run is made for a single set of parameters, no allowance is made for the constant variation in wave approach angle and iterative response in reaction to the dynamic nature of the sea.

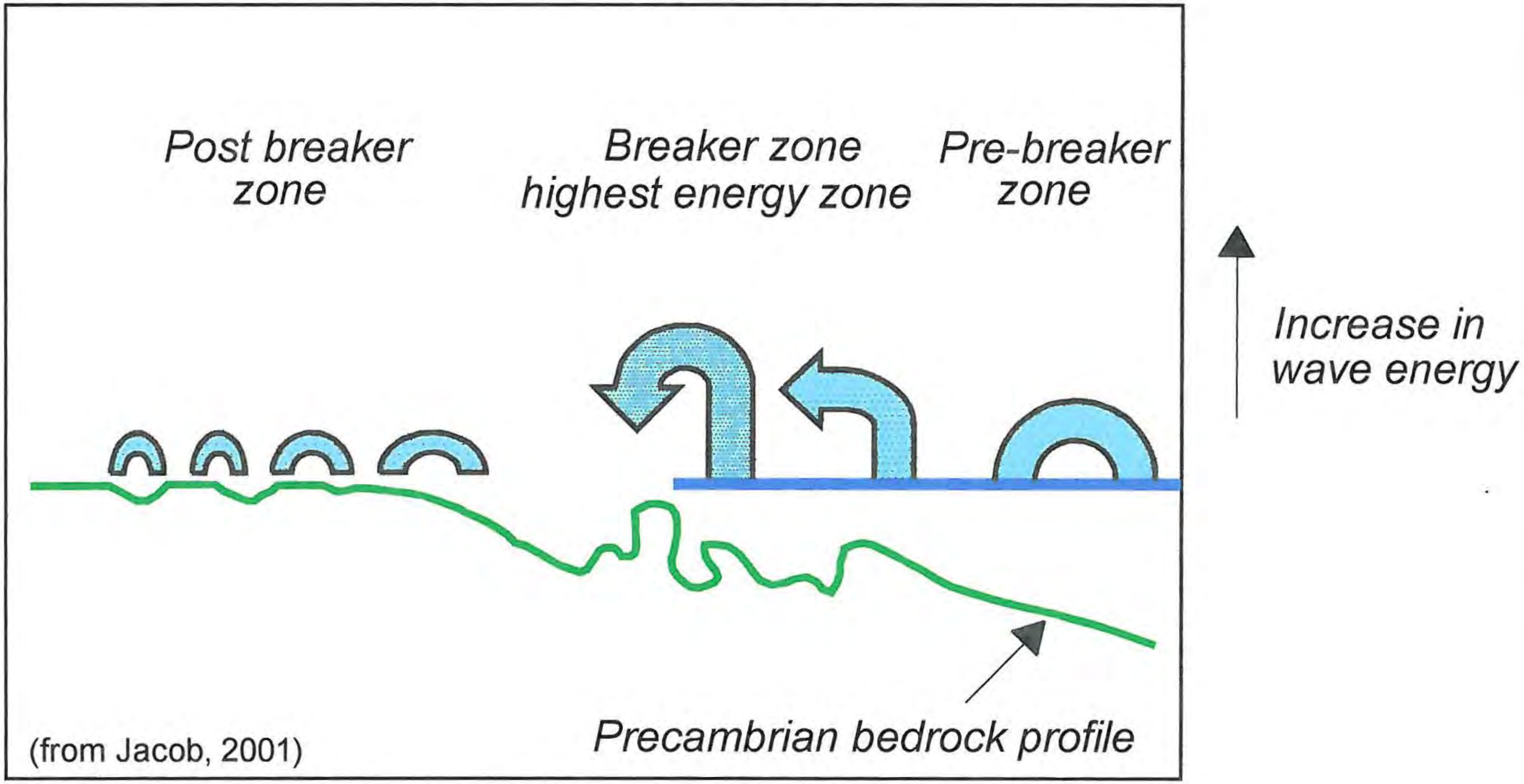
As the programmers continually update and modify their programmes and increase computational power to allow more complex modelling so the results are improving. Given that the west coast marine placers were deposited a long time ago it becomes increasingly difficult to accurately define the input parameters. For example, in order to consider a marine deposits of Miocene age the sea-level, wave parameters, directions and seafloor sedimentological parameters for that time need to be defined and simulated. The numerous transgressions and regressions, partially or fully reworking the placer deposit, also need to be taken into account. Sediment dynamic studies can be used to define zones of high diamond placer potential provided the limitations inherent in the modelling are recognised and taken into account during the interpretation of the results. Sediment dynamic modelling should be used in conjunction with other exploration methods.

Wave refraction modelling software like RCPWAVE, developed by the US Corps of Engineers, can be used to model regional sediment dynamic trends, particularly when these models can be fine tuned using areas of known mineralisation. A more detailed description of RCPWAVE and the wave theory on which it is based is given in Appendix 1. RCPWAVE was modified by MCG to simulate the orbital velocity on the seafloor specifically for west coast diamond exploration purposes. Orbital velocity can be defined as the orbital motion of water particles under a wave crest. Sediment transport occurs as shoaling waves become steeper and the orbital motion of the water particles, which in deeper water are closed circles, become distorted, fail to close and result in the nett movement of water and sediment particles in the direction of wave motion. The orbital velocity is directly related to the entrainment velocity which is the velocity at which a particle of specific density and hydraulic properties is transported. Particle shape and size, armouring and particle to bedrock surface friction influence the velocity of entrainment. On the west coast the bedrock is generally rugged and orbital velocities required to entrain and transport the diamondiferous gravel are relatively high. Nevertheless, De Decker (1986) calculated that average west coast wave conditions can transport 1 mm to 2 mm grains at a depth of 30 m bpsl while storm waves can move medium sized cobbles (10 cm) at 15 m bpsl. De Decker (1986) suggests that wave processes operating since the Late Tertiary, have distributed diamonds along the entire west coast and that diamond placers are formed due to concentration of the heavy mineral fraction by the selective entrainment of the lighter component.

The high-energy wave-dominated environment along the inner shelf of the west coast is likely to have played an important role in the concentration of diamonds. Low wave energy areas in the lee of reefs, gullies, basins and linear depressions are well suited for diamond placer development. Placer preservation potential is an important factor in the formation of marine placer deposits. Diamonds can be concentrated in a specific locality by a storm from one direction, only to be flushed out by a storm swell from another direction. Sediment dynamics studies using different initial wave directions, are able to show areas of sediment transport, deposition and preservation by simulating orbital wave velocity on the seafloor. Examination of resource areas defined on the inner shelf shows that features, orientated in such a way as to allow the introduction of gravel and diamonds into the feature but well topographically confined to retain the heavy mineral component once introduced are best suited for diamond placer formation. Sediment dynamic modelling shows these areas as having high orbital wave velocity zones leading into them but low orbital wave zones within the feature itself. A simulated run from a specific wave front direction may show a particular feature to be well suited to diamond entrapment and preservation but poorly suited from another wave direction. A change in the simulated sea-level may indicate the transport of gravels and diamonds out of a morphological feature well suited for diamond entrapment at a previously simulated deeper sea-level. Therefore all the simulated sea-levels from all initial wave angles need to be compared to evaluate and delineate target areas with high diamond placer preservation potential.

The wave refraction programme can only model orbital wave velocity until the modelled storm wave breaks. In the turbulent zone after the wave has broken the water body is highly chaotic and cannot be modelled. The highest energy zone is situated at the point the first wave breaks (Martinez and Harbuagh, 1993) but it can however be assumed that in storm conditions the swash zone will be of relatively high energy, capable of transporting gravels up to about 2 m above the simulated sea-level (Figure 65). Well developed trapsites within this swash-zone are likely to concentrate diamonds being transported along the seafloor surface. In assessing sediment dynamic modelling results each modelled scenario's interpretation must be evaluated in conjunction with every other simulated initial wave front direction and sea-level.

SCHEMATIC REPRESENTATION OF WAVE ENERGY AND ITS RELATIONSHIP TO DEPTH OF INCISION IN THE BEDROCK



(from Jacob, 2001)

Figure 65

8.5.2 SEDIMENT DYNAMIC MODELLING - SHP AND HBP

Detailed sediment dynamic modelling of the SHP and HBP areas was completed by the author in 1999 and this section is largely based on a summary of the results presented in that study (Rau, 1999).

The revised model for placer formation, presented later in this thesis, proposes that the diamond placer deposits in the study area have been deposited by a combination of fluvial, aeolian and marine processes. Subsequent to their deposition during the numerous Plio/Pleistocene transgressions and regressions these deposits have been reworked by wave-action. Sediment and diamond re-distribution patterns can be obtained by modelling sediment movement and deposition. Based on the terrace level study and elevations where the highest diamond grades were obtained, during sampling in the area, the -95 m, -84 m, -74 m, -60 m, -46 m and -31 m bpsl sea-levels were selected for the sediment dynamic modelling in the study area.

The limited bathymetry of the SHP and HBP areas did not cover the seafloor outside of these depth ranges. Therefore the well developed -20 m and -112 m bpsl terrace depths could not be modelled. In order to run the wave refraction programme certain assumptions must be made with regard to the wave conditions. Inputs used for this study are as follows:

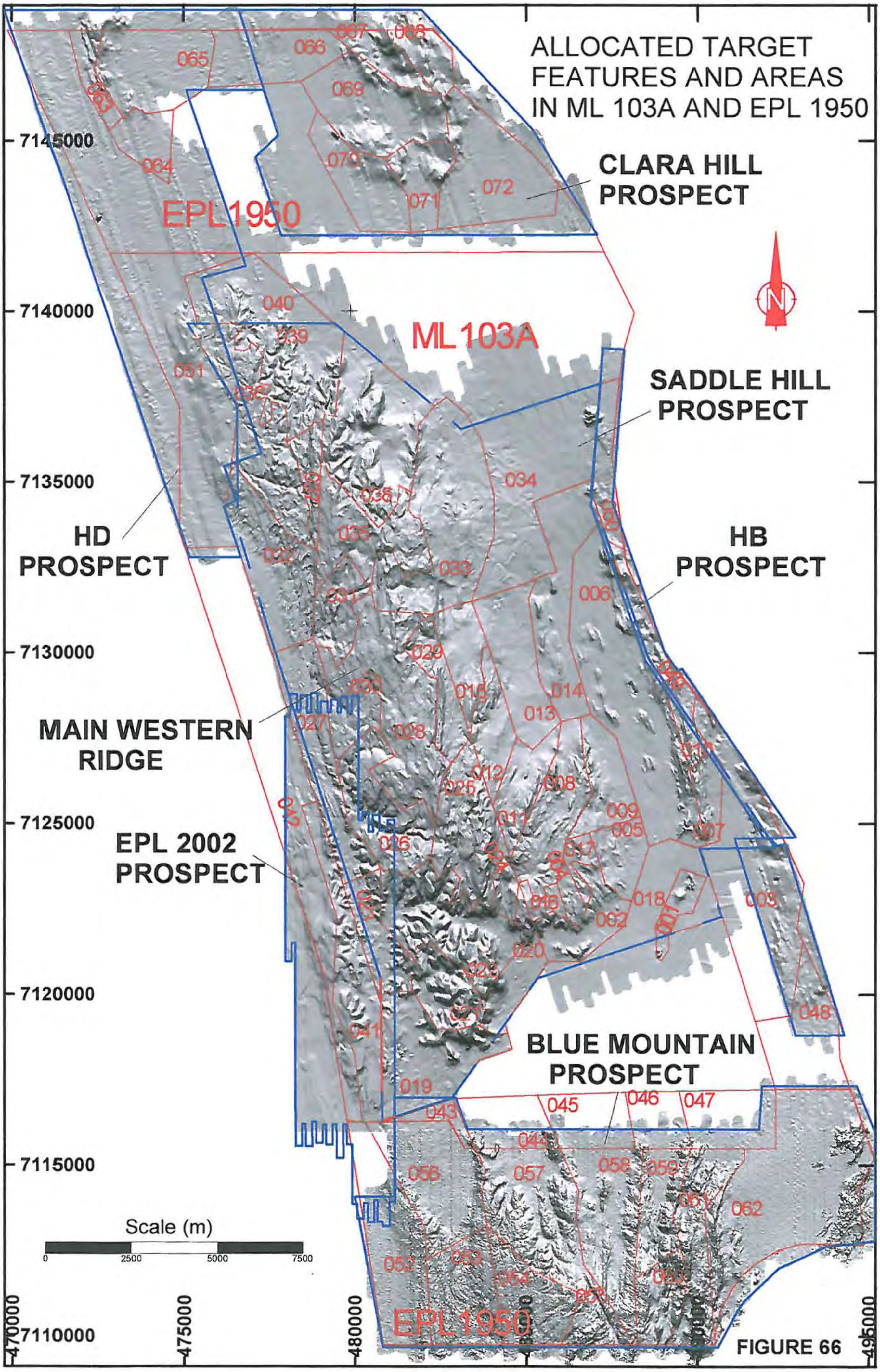
a) **Wave direction** - the majority of Quaternary sea-level fluctuations along the west coast are believed to have been caused by glaciation (Refer: Section 8.4). During glacial periods the cyclonic and anti-cyclonic zones in the southern hemisphere contract toward the equator in response to the growing polar ice caps and northward translation of the circum polar current. The swell fetch area would move northward and therefore the westerly swell component in SHP area would be more prevalent during glacial maxima periods. The study modelled swell front directions approaching from the WSW, SW and SSW for the selected terraces levels. Wave direction from the NW was shown by Roussouw *et al.* (1982) to be insignificant, but highest in spring (1.6%) and winter (1.4%) and were not modelled.

b) **Swell height and period** - Roussouw *et al.*, (1982) calculated using waverider data that 1 in 1000 (i.e. 0.01% exceedence) wave at Oranjemund was greater than 7.5 m while 2.59% exceeded 6 m at Lüderitz. Roussouw *et al.*, (1982) calculated that the median value for period for peak wave energy was 12.5 s. For modelling purposes a swell height of 6 m and a period of 12 s was used for this study.

8.5.3 LAYOUT AND CONTENT OF THE DIAGRAMS

ML 103a was subdivided into 40 regularly shaped features by the author and EPL 1950 into features 41 to 72 by Namco's in-house geologists (Figure 66).

A composite shaded relief map of ML 103a (Features 1 to 40) with the orbital velocity vectors superimposed for each of the initial wave directions run (SSW, SW and WSW) was generated for each of the modelled palaeo sea-levels. To aid the interpretation the orbital velocity zones are highlighted for each of the initial wave front



ALLOCATED TARGET FEATURES AND AREAS IN ML 103A AND EPL 1950

FIGURE 66

directions and palaeo-sea-levels and superimposed on the shaded relief maps of the study area (Figures 67 to 84). The zones are divided into:

Red Hatch - Heavy mineral/gravel transport (High Energy Zone - orbital wave velocity > 1 m/s)

Green Hatch - Heavy mineral/gravel deposition (Moderate Energy Zone - orbital wave velocity 0.75 to 1 m/s)

Blue Hatch - Heavy mineral/gravel preservation (Low Energy Zone - orbital wave velocity < 0.75 m/s)

Magenta Line - simulated sea-level. The transparent section between the magenta line and the simulated sea-level is representative of the highly chaotic swash zone where waves cannot be modelled by RCP Wave.

These orbital velocity intervals were kept consistent throughout the study. The entrainment velocity of diamonds will vary slightly from area to area depending on the bedrock roughness, degree of armouring, pebble shape and percentage cohesive material within the gravel matrix. Therefore, the boundaries between the velocity zones should be considered as being gradational. Every 5th velocity vector was superimposed to give an indication of the direction of transport. At a more detailed scale every vector can be displayed. Some sediment areas in the concession are circled and numbered for easier referencing in the text. The numbers or colours of the numbers do not have any specific meaning; they are simply a means of clearly drawing the readers attention to areas under discussion. The circles and numbers are consistent for one sea-level but do not necessarily correspond to circles and numbers on other sea-levels (ie. Area 1 on the -95 m sea-level is not in the same area as Area 1 at the -74 m sea-level).

8.5.4 EVALUATION OF SEDIMENT DYNAMIC RESULTS

Comparisons of different initial wave angles at the simulated sea-levels, identified zones of high energy (transport), deposition/winnowing and low energy (preservation) and their relationship to the sample results. These results can be used for the delineation and prioritisation of marine diamond placers.

The relationship between mineralised samples and moderate and low orbital velocity zones (deposition/ preservation areas) in sampled features, provides support for the usefulness of this technique in prioritising targets that have not yet been prospected. Examination of the figures produced reveals that most of the well mineralised areas have high energy orbital velocity zones to their west (introducing gravel and diamonds) which are not subsequently eroded by high orbital velocity zones simulated from another wave front direction or sea-level elevation. For example, if the area at the central and south of Feature 12, and the top of Feature 11 is examined using the three simulated runs at -31 m, the following is evident:

- High bedload energy zones from the SSW and WSW are able to introduce diamonds into the same relatively well mineralised area in the central portion of Features 12 and 13 (Figures 82 and 84).

- An initial storm wave direction from the SW (Figure 83) generates a high energy zone stretching through the central part of Feature 11 toward the east (terminates at the mineralised top end of Feature 8) transporting gravel and diamonds that may have been deposited in Features 11 and 12, to the east. This high energy zone misses the well mineralised area (a high preservation potential area). A high energy zone also passes immediately to the north of the well mineralised portion of Feature 12 through Features 13, 14 and 6 covering 15 negative sites and 2 positive sites (Figure 83).

- The few un-mineralised samples immediately below the cluster of 6 mineralised samples in Feature 12 are in an area of high preservation potential. A long thin high energy zone could transport diamonds into a portion of this area from the SSW. This contradictory result shows that wave refraction modelling techniques have their limitations and should be evaluated in that light (Refer: Figures 82).

- Based on the original geophysical survey interpretation and morphology there is no obvious reason why the northern row of samples in Feature 13 should have not yielded a single diamond. If the WSW orbital velocity diagram is examined (Figure 84) it is clear that this row is located along the southern edge of a high orbital velocity train.

Each sea-level examined, is discussed individually from deepest to shallowest corresponding to the Flandrian rise to present sea-level. In this section areas have been prioritised solely on the results of the sediment dynamics study for inclusion in the overall prioritisation matrix presented in Chapter 9. A summary of each of the features examined is given in Table 31 below.

TABLE 31: Summary of the interpretation of the SHP and HBP sediment dynamics study.

Reference	Area	Comment
Level -95 m Figs. 67,68,69	Coast	Generally straight and featureless from 7 126 000 northwards. N facing embayment at the northern edge of ML 103a. The reef in the S is very shallow, forming islands in places. The reef protects the depression (Area 2) from the high energy storm swell from the W.
Level -95 m Figs. 67,68,69	Area 1	N facing embayment with high preservation potential at all sea-levels from all directions. At -74 m (WSW) this area transforms into a high energy zone. At -74 m (SSW and SW) a portion of this area is still located in a depositional energy zone.
Level -95 m Figs. 67,68,69	Area 2	Long (6 km) NNW trending depression, well protected from the westerly storm swell by a large reef. Good probability of diamonds from the west being washed over the reef into the calm zone in the E by the breaking swell. Well orientated for introduction of aeolian diamonds at > 120 m lowstands. Transforms into a high velocity zone at the -84 m and -74 m sea-levels, significantly reducing preservation potential. However, some relatively low energy deposition zones occur within this high energy zone (Figs.70,71,72,73,74 and 75). These low energy areas should be preferentially targeted.
Level -84 m Figs. 70,71,72	Coast	Generally straight and featureless from 7 126 000 northwards. A N facing embayment is present along the northern edge of the MWR. To the S the coastline inflects eastward into the palaeo-drainage channel (Features 21,22 & 26) forming westerly facing embayments.

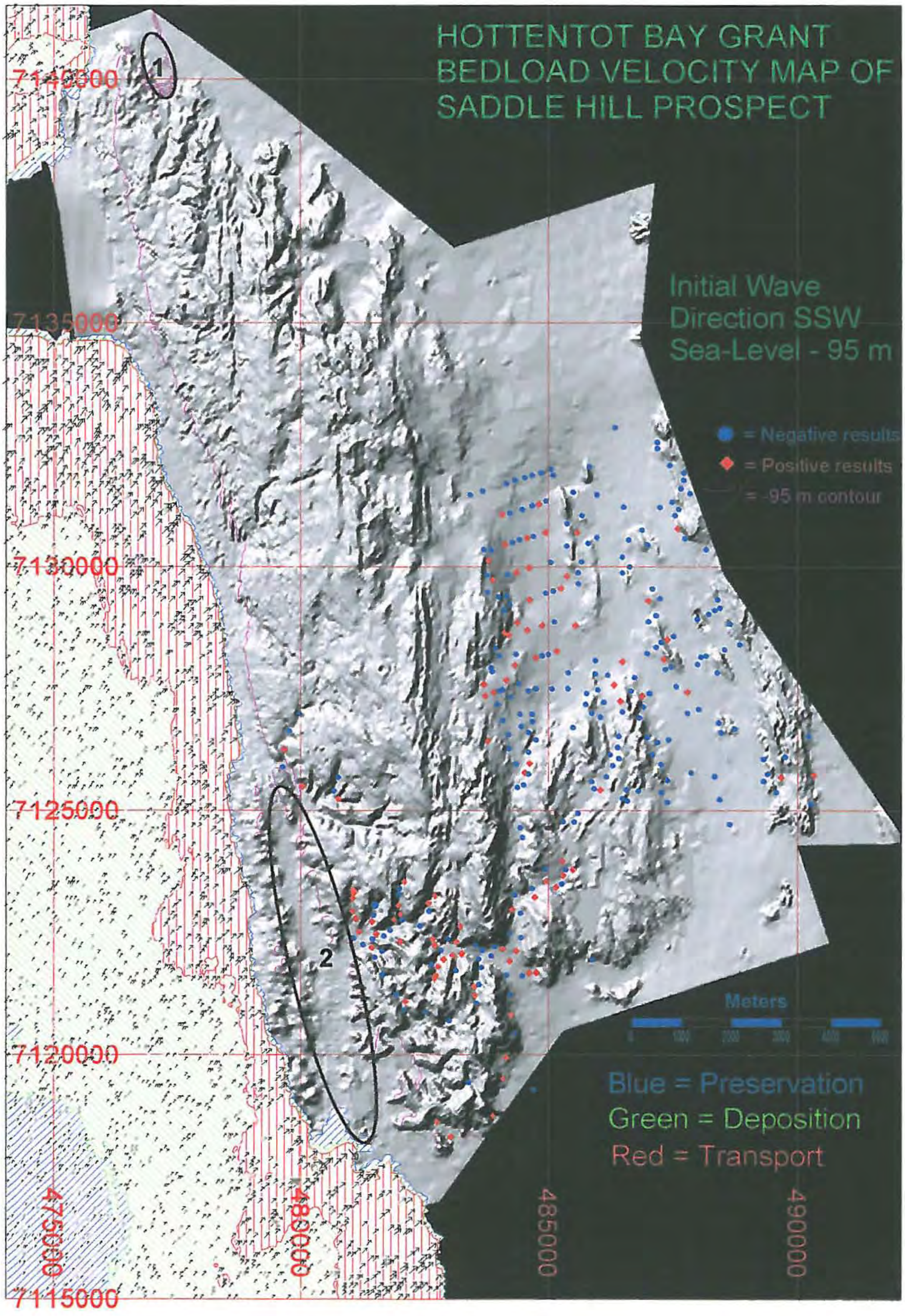

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction SSW
Sea-Level - 95 m
● = Negative results
◆ = Positive results
= -95 m contour
Meters
0
1000
2000
3000
4000
5000
Blue = Preservation
Green = Deposition
Red = Transport
1
2
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000

Figure 67

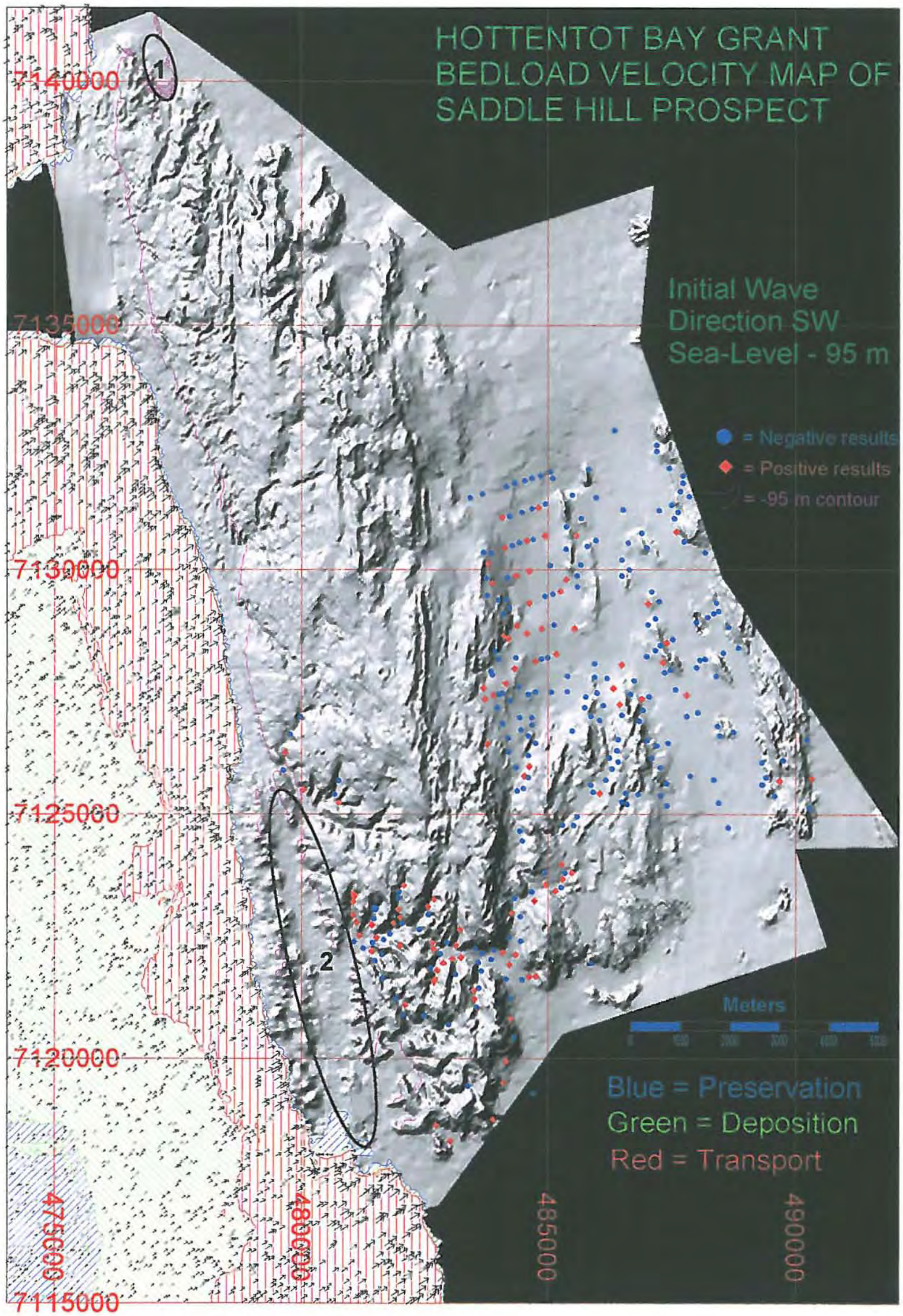

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction SW
Sea-Level - 95 m
● = Negative results
◆ = Positive results
= -95 m contour
Meters
Blue = Preservation
Green = Deposition
Red = Transport
1
2
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000

Figure 68

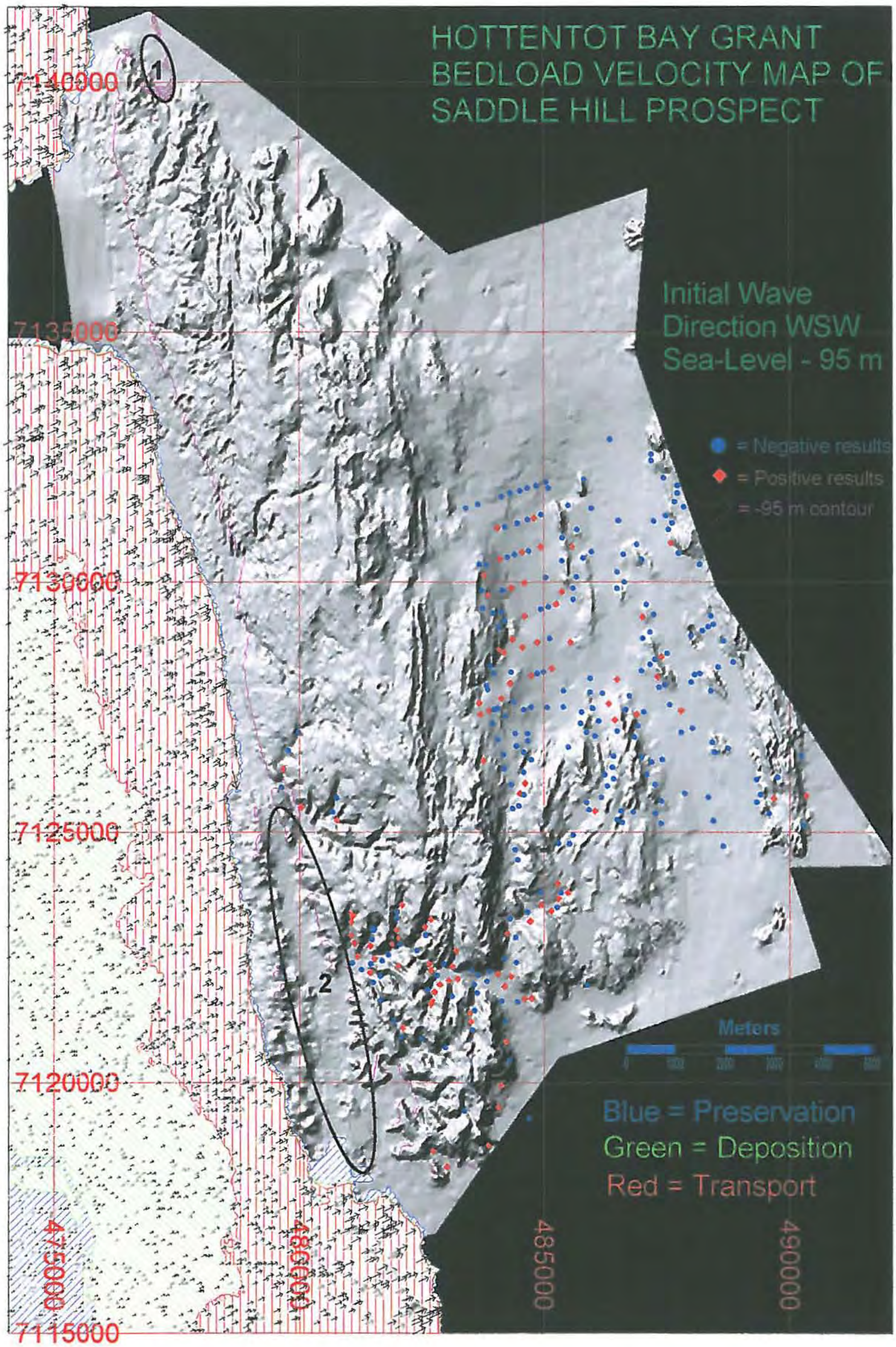

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction WSW
Sea-Level - 95 m
● = Negative results
◆ = Positive results
= -95 m contour
Meters
0
1000
2000
3000
4000
5000
Blue = Preservation
Green = Deposition
Red = Transport
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000
1
2

Figure 69

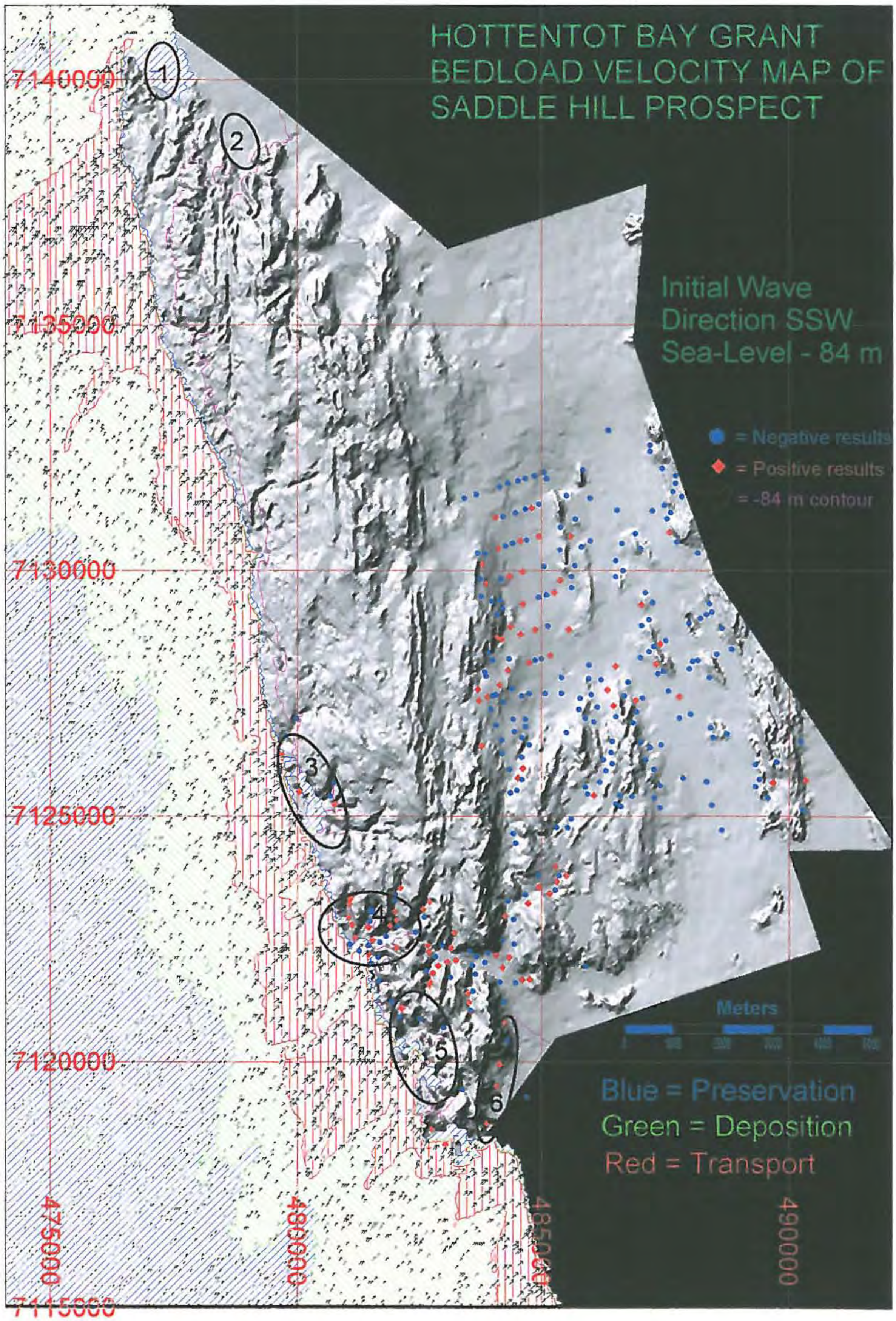

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction SSW
Sea-Level - 84 m
● = Negative results
◆ = Positive results
= -84 m contour
Meters
Blue = Preservation
Green = Deposition
Red = Transport
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000
1
2
3
4
5
6

Figure 70

Reference	Area	Comment
Level -84 m Figs. 70,71,72	Area 1	As for Area 1, -95 m level, this area is still a high preservation potential area. Waves refracting around the northern part of the MWR will introduce diamonds into this N facing embayment. At -74 m (WSW) this area transforms into a high energy zone. At -74 m (SSW and SW) a portion of this area is still located in a depositional energy zone.
Level -84 m Figs. 70,71,72	Area 2	Corresponds to Area 1 at -74 and -60 m. This area in the swash zone would be protected from the storm swell by the reef to the W. At the -60 m level this area is well situated for diamond introduction during storms from the SSW (Fig.76).
Level -84 m Figs. 70,71,72	Area 3	Corresponds to Area 9 at -74 m. The high preservation potential area in Feature 26, which has already produced some good sampling results, is well situated for diamond introduction from the SW. Some portions of this area transform into high energy zones at the - 74 m level. However, the extent of the easterly transport does not appear to be sufficient to remove diamonds from this palaeodrainage system. At the -60 m level the sediment portion of this feature is W of the high energy zone (i.e. High preservation).
Level -84 m Figs. 70,71,72	Area 4	Corresponds to the W of Area 6 at -74 m. Resource area with high potential. Useful to examine why this is so. Good evidence for diamond transport into the feature from the W at the - 84 m and - 74 m levels. The high energy across the central channel terminating at the closures of the well confined S facing channels explains the relatively higher grades found in these areas. The velocity vectors are perfectly orientated for transport into these features. This also explains why the S facing channels had higher grades than the N facing ones in Feature 022 W. The high energy zone across the most westward of these S facing embayments (highest sampling grades) was not sufficient to transport the diamonds out of the channel. The small inflection in the high energy zone (red hatching) at the mouth of this channel suggests that the energy within the sediment area of the channel is lower than rocky areas bounding it.
Level -84 m Figs. 70,71,72	Area 5	A portion corresponds to Area 8 at -74 m. Similar in morphology to Areas 3 and 4. The eastern edge of this morphological feature is well situated for diamond deposition at the - 74 m level. However, at the - 60 m level high energies are present along this edge at all initial wave angles. The velocities and angles suggest that at the -60 m level some diamonds in this area may have been reworked and transported over the saddle to the NE into the eastern portion of Feature 022 which is protected against the storm swell by the rocky reef to the W.
Level -84 m Figs. 70,71,72	Area 6	This area is well situated for the introduction of diamonds around the southern edge of the MWR. At -74 m it is also a high preservation area. At -60 m, particularly from the WSW and the -46 m zone from the SSW and SW this area transforms into a high energy zone transporting diamonds to the E. There are few obstacles to restrict this eastward transport reducing the preservation potential of this area considerably.
Level -74 m Figs. 73,74,75	Coast	Interesting coastline with a north facing embayment in the N of the area, a back barrier lagoon/deflation pan environment and a island to the S of Feature 22.
Level -74 m Figs. 73,74,75	Area 1	Refer to Area 2, -84 m for comments regarding the potential of this area.

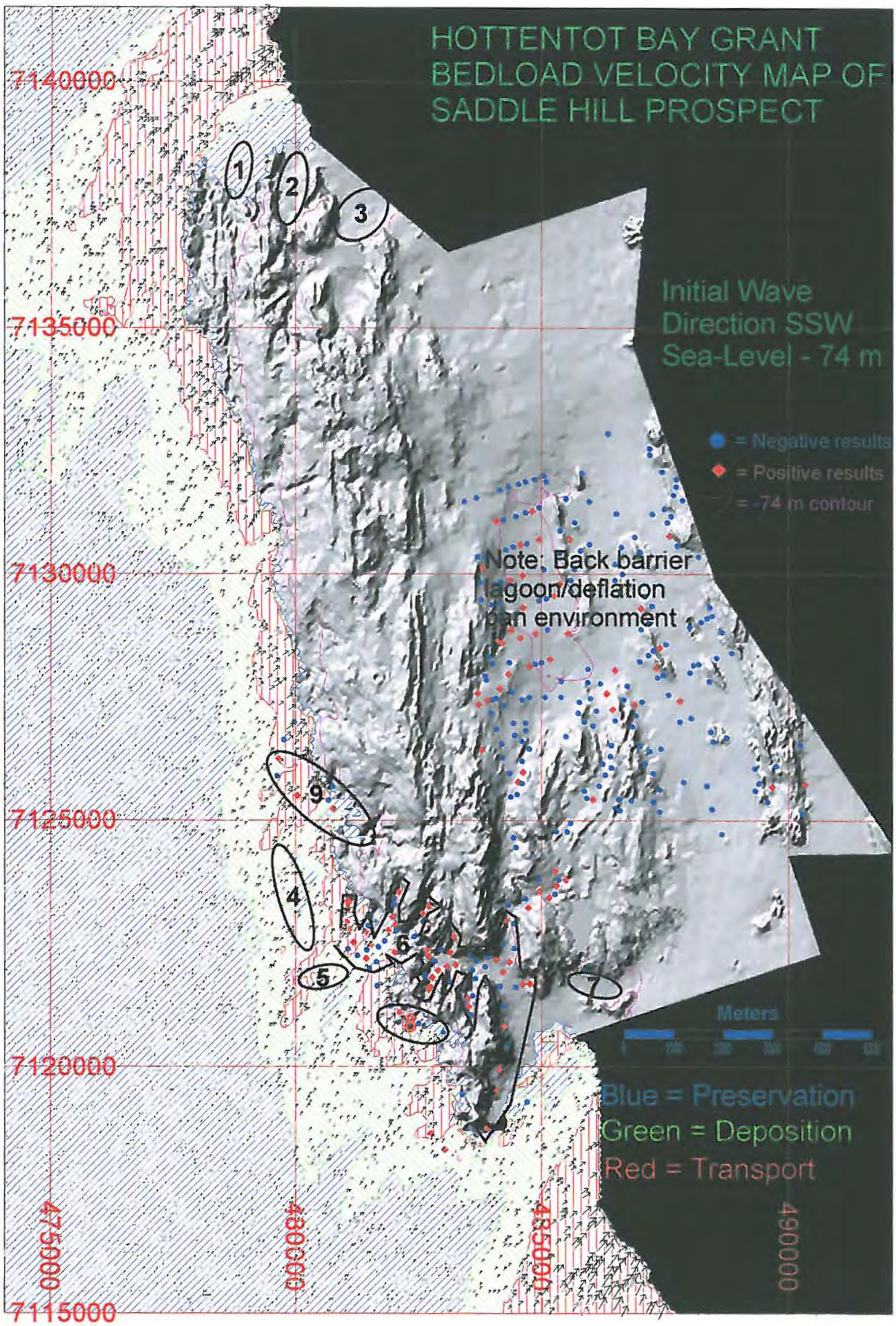

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction SSW
Sea-Level - 74 m
● = Negative results
◆ = Positive results
= -74 m contour
Note: Back barrier
lagoon/deflation
pan environment
Meters
Blue = Preservation
Green = Deposition
Red = Transport
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000
1
2
3
4
5
6
7
8
9

Figure 73

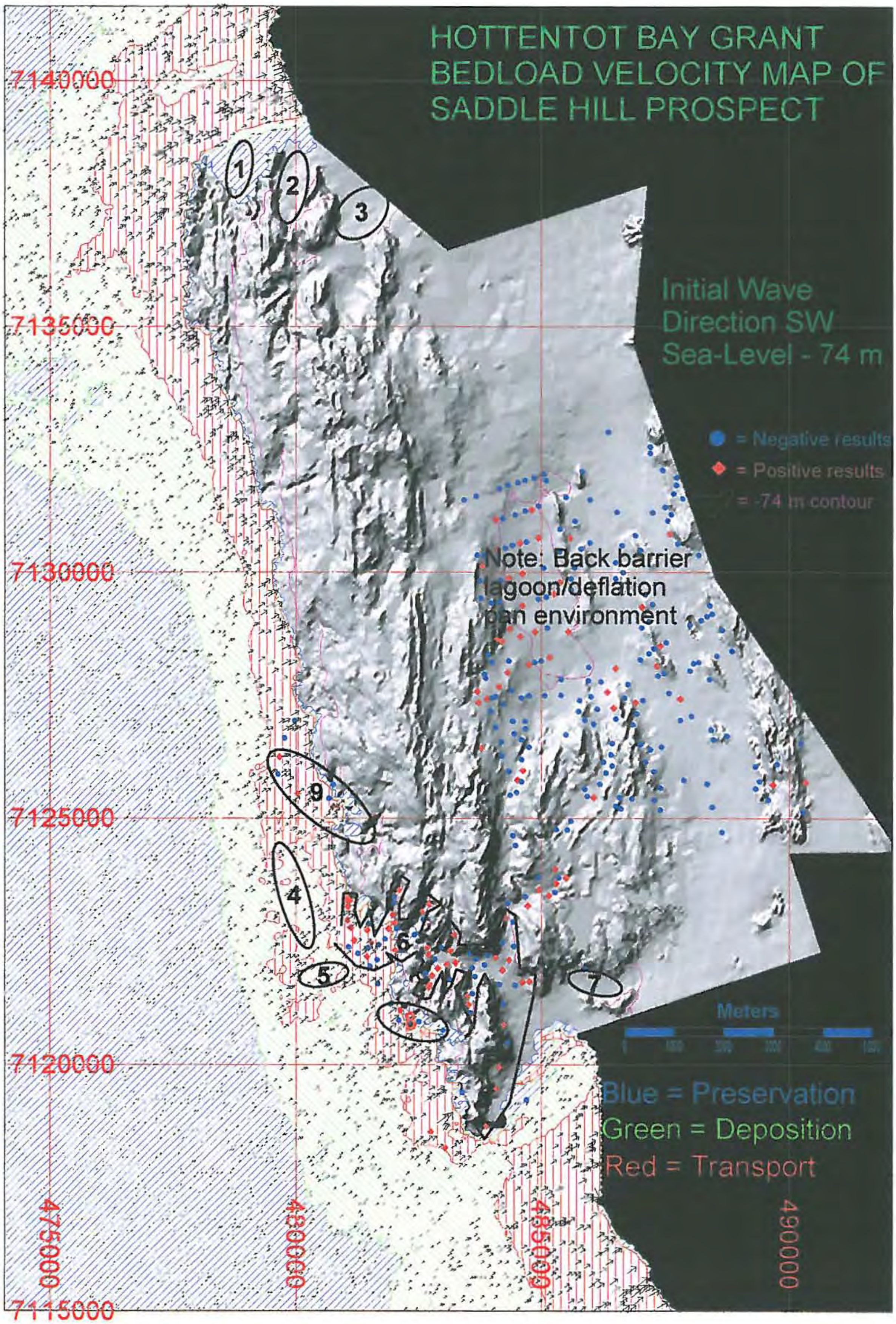

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction SW
Sea-Level - 74 m
● = Negative results
◆ = Positive results
= -74 m contour
Note: Back barrier
lagoon/deflation
pan environment
Meters
Blue = Preservation
Green = Deposition
Red = Transport
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000
1
2
3
4
5
6
7
8
9

Figure 74

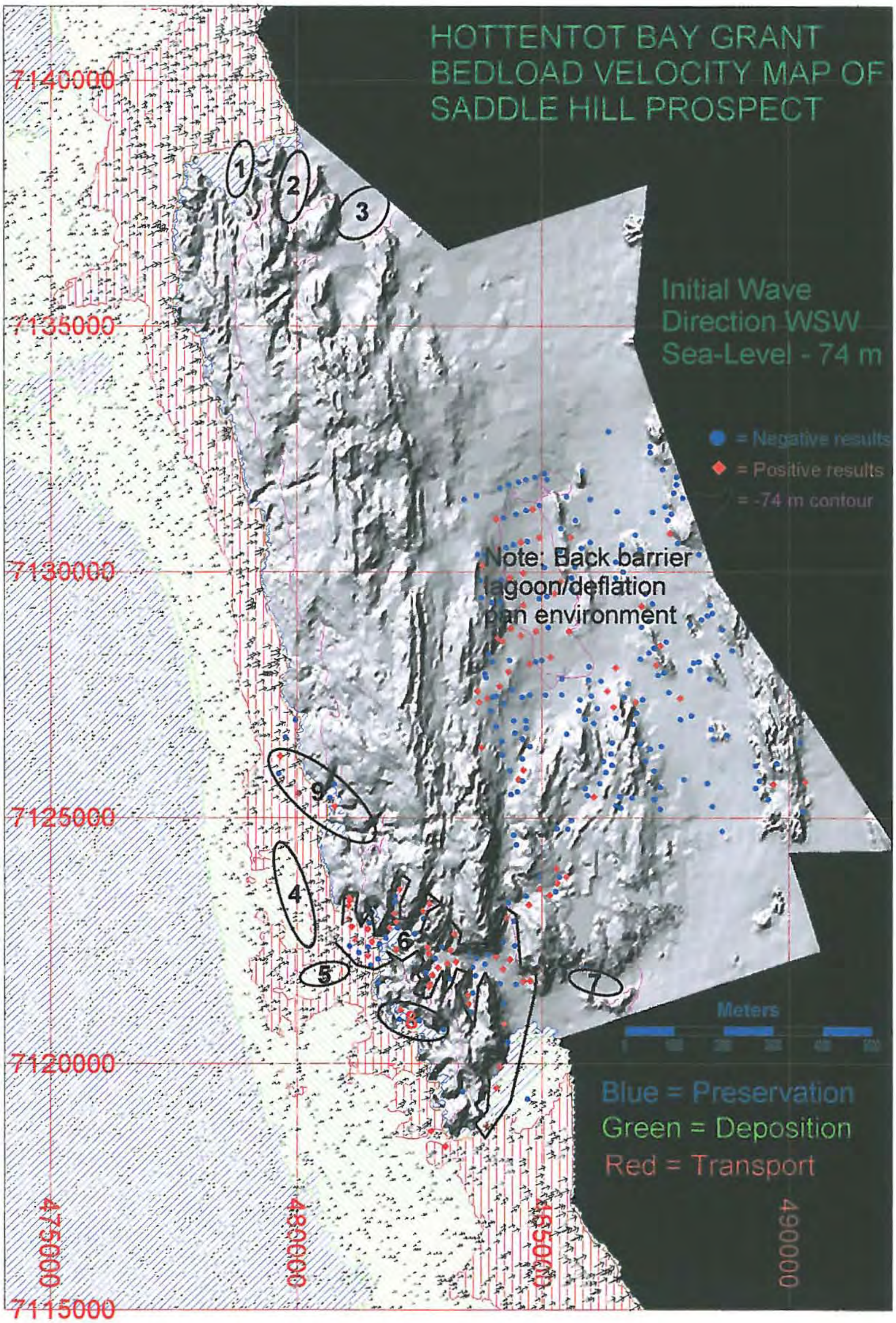

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
Initial Wave
Direction WSW
Sea-Level - 74 m
● = Negative results
◆ = Positive results
= -74 m contour
Note: Back barrier
lagoon/deflation
pan environment
Meters
Blue = Preservation
Green = Deposition
Red = Transport
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000
1
2
3
4
5
6
7
8
9

Figure 75

Reference	Area	Comment
Level -74 m Figs. 73,74,75	Area 2	Corresponds to Area 2 at -60 m, -46 m and -31 m. N facing embayment protected from the westerly storm swell by a prominent NS trending reef. Well positioned for diamond deposition at the -60 m SSW level but high energy zones at -60 m SW and WSW will reduce the preservation potential in portions of this feature (Figs.77 and 78).
Level -74 m Figs. 73,74,75	Area 3	N facing embayment protected from the westerly storm swell by a prominent headland. Preservation potential reduced by a high energy zone passing through the northern portion of this ellipse (-46 m SW) and the southern portion of the ellipse (-46 m WSW). With no major obstruction to the E, this will reduce the preservation potential within this area.
Level -74 m Figs. 73,74,75	Area 4 & 5	Refer to Area 2, -95 m for comments regarding the potential of this area. These relatively lower energy zones together with the few at the -60 m level (not circled) within this predominantly high energy environment should be selectively targeted for initial sample sites when prospecting this feature.
Level -74 m Figs. 73,74,75	Area 6	Refer to Area 4, -84 m for some comments regarding the potential of this area. It is interesting to note that the preservation potential of the area that contains the cluster of positive samples in the central portion of Feature 22 is predominantly in a deposition or low energy zone. The only exception to this trend is -60 m WSW. In this case any diamonds deposited in the central portion of the feature may be remobilised and transported to the east of the feature and deposited at the cluster of five positive sample sites. The preservation potential of this area in turn may reduced by the high energy zone at -46 m SW and -46 m WSW if the diamonds could be lifted over the significant reef to the E. At -46 m WSW diamonds from Feature 22 could be transported into the SW end of Feature 8. The cluster of negative samples has a high velocity zone passing through it at -60 m SW, -60 m WSW, -46 m SSW, -46 m SW and -46 m WSW reducing the preservation potential of this area dramatically and may explain the low grade samples.
Level -74 m Figs. 73,74,75	Area 7	Situated in a W facing embayment. No clear indication of high energy transport of diamonds into this area (situated along the northern edge of a high velocity transport zone at -60 m). Generally good preservation potential except for -46 m WSW where a high velocity zone passes through the southern portion of the ellipse. With no clear obstruction to prevent the diamonds being transported further east this storm direction would reduce preservation potential in this area.
Level -60 m Figs. 76,77,78	Coast	The MWR forms a large island 14 km long (NNW trending) and 100 m wide. The coastline is straight and featureless and passes through the central part of Feature 6. The large island is breached to the W of ellipse 7, and in Feature 24 and almost breached to the W of ellipse 8.
Level -60 m Figs. 76,77,78	Area 1	Refer to Area 2, -84 m and Area 1 at -74 m for comments regarding the potential of this area.
Level -60 m Figs. 76,77,78	Area 2	Refer to Area 2 at -74 m, -46 m and -31 m for comments regarding the potential of this area.

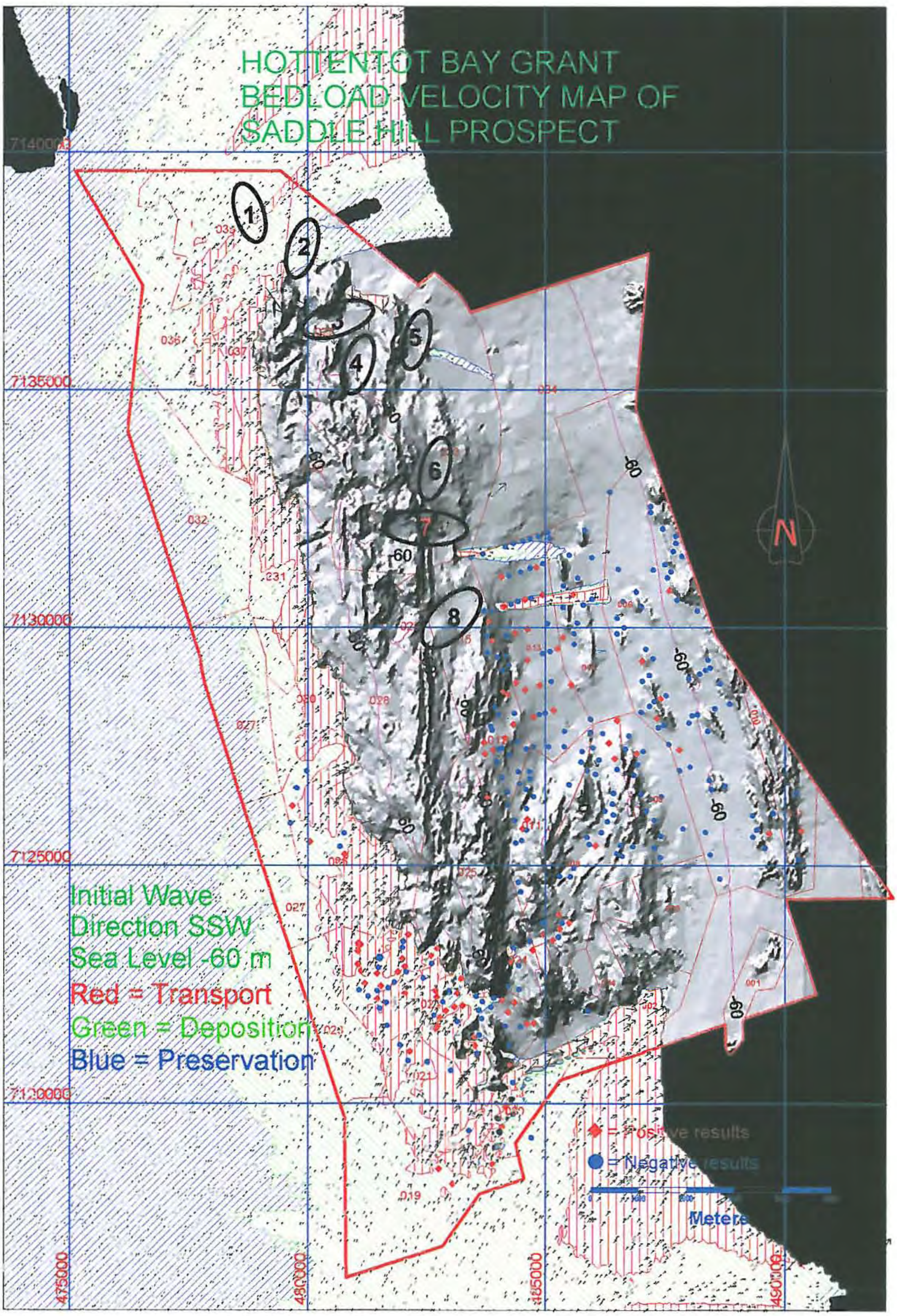

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
7140000
7135000
7130000
7125000
7120000
475000
480000
485000
490000
1
2
3
4
5
6
7
8
-60
N
Initial Wave
Direction SSW
Sea Level -60 m
Red = Transport
Green = Deposition
Blue = Preservation
◆ = Positive results
● = Negative results
0
1000
2000
Meters

Figure 76

Reference	Area	Comment
Level -60 m Figs. 76,77,78	Area 3	Corresponds to Area 3 at -46 m and Area 3 at -31 m. A eastward facing sediment area landward of a prominent reef immediately to the N of the island formed at this sea-level. High preservation at all sea-levels from all directions except at -46 WSW where a high velocity zone which will reduce the preservation potential within this area.
Level -60 m Figs. 76,77,78	Area 4	Corresponds to Area 4 at -46 m and Area 4 at -31 m. North facing embayment on the NE edge of the large island at this sea-level. Well situated for the introduction of diamonds into this area, particularly at -46 m WSW. Preservation potential at the northern edge of this area is less than that at the southern edge.
Level -60 m Figs. 76,77,78	Area 5	Corresponds to Area 5 at -46 m and Area 5 at -31 m Well located for diamond introduction, particularly at the -46 m level SW and WSW. High preservation potential at all sea-levels. May be a possibility that diamonds are not lifted over the large reef that separates Areas 4 and 5.
Level -60 m Figs. 76,77,78	Area 6	Corresponds to Area 6 at -46 m and Area 6 at -31 m. Well located for diamond introduction, particularly at the -31 m level SW and WSW. High preservation potential at all sea-levels. May be a possibility that diamonds are not lifted over the MWR at the -31 m level but this feature is located immediately to the NE of the lowest point "saddle" in this large reef.
Level -60 m Figs. 76,77,78	Area 7	Corresponds to Area 7 at -46 m and Area 8 at -31 m. Well located for diamond introduction, particularly at the -46 m level. Preservation potential in a portion of this area is reduced by a high energy zone at -31 m SSW. This area is located immediately to the W of the lowest point "saddle" in the large reef that bounds the western edge of ML 103a.
Level -60 m Figs. 76,77,78	Area 8	Corresponds to Area 9 at -46 m and at -31 m. This area is located immediately to the W of another low point "saddle" in the large reef that bounds the western edge of ML 103a. Diamonds being transported northward by littoral currents along the western edge of the reef can more readily be lifted over the reef at this point. Therefore, this area is well located for diamond introduction, particularly at the -31 m level. The preservation of the southern portion of this Area may be reduced by the high energy zone at -46 m.
Level -46 m Figs. 79,80,81	Coast	What was an island at -60 m is now a large, coast-parallel offshore reef shallow enough to cause the storm swell to break. This results in a relatively calm "high preservation" area in practically the entire central portion of ML 103a. Therefore, at this sea-level, in this central basin, the potential of an area may be determined more by the possibility of diamonds being introduced into the feature than by the preservation potential. The coastline is located along the eastern boundary of the ML 103a.
Level -46 m Figs. 79,80,81	Area 1	Refer to Area 2 at -84 m and Area 1 at -74 m, -60 m and -31 m for comments regarding the potential of this area.
Level -46 m Figs. 79,80,81	Area 2	Refer to Area 2, -74 m, 60 m and -31 m for comments regarding the potential of this area.
Level -46 m Figs. 79,80,81	Area 3	Refer to Area 3, -60 m and -31 m for comments regarding the potential of this area.

Reference	Area	Comment
Level -46 m Figs. 79,80,81	Area 4	Refer to Area 4, -60 m and -31 m for comments regarding the potential of this area.
Level -46 m Figs. 79,80,81	Area 5	Refer to Area 5, -60 m and -31 m for comments regarding the potential of this area.
Level -46 m Figs. 79,80,81	Area 6	Refer to Area 6, -60 m and -31 m for comments regarding the potential of this area.
Level -46 m Figs. 79,80,81	Area 7	Refer to Area 7, -60 m and Area 8 at -31 m for comments regarding the potential of this area.
Level -46 m Figs. 79,80,81	Area 8	Small area immediately north of the saddle in the MWR. Preservation potential reduced by a high energy zone at -31 m SW.
Level -46 m Figs. 79,80,81	Area 9	Refer to Area 8 at -60 m and Area 9 at -31 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Coast	At this sea-level the coastline is to the east of the prospect boundary. Orbital energy increases across the MWR but the waves do not shoal and break.
Level -31 m Figs. 82,83,84	Area 1	Refer to Area 2, -84 m and Area 1 at -74 m -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 2	Refer to Area 2, -74 m -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 3	Refer to Area 3, -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 4	Refer to Area 4, -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 5	Refer to Area 5, -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 6	Refer to Area 6, -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 7	Corresponds to Area 4 at -60 m and -46 m. This Area was annotated to draw attention to the large percentage of positive results along the fringes of high energy zones in the sampled areas. This is likely to hold true for the unsampled portions of ML 103a and EPL 1950 as well. Therefore if samples are selected in the northern central portion of the basin they should initially be located along the fringes of these high bedload velocity zones.
Level -31 m Figs. 82,83,84	Area 8	Refer to Area 7, -60 m and -46 m for comments regarding the potential of this area.
Level -31 m Figs. 82,83,84	Area 9	Refer to Area 8, -60 m Area 9 at -46 m for comments regarding the potential of this area.

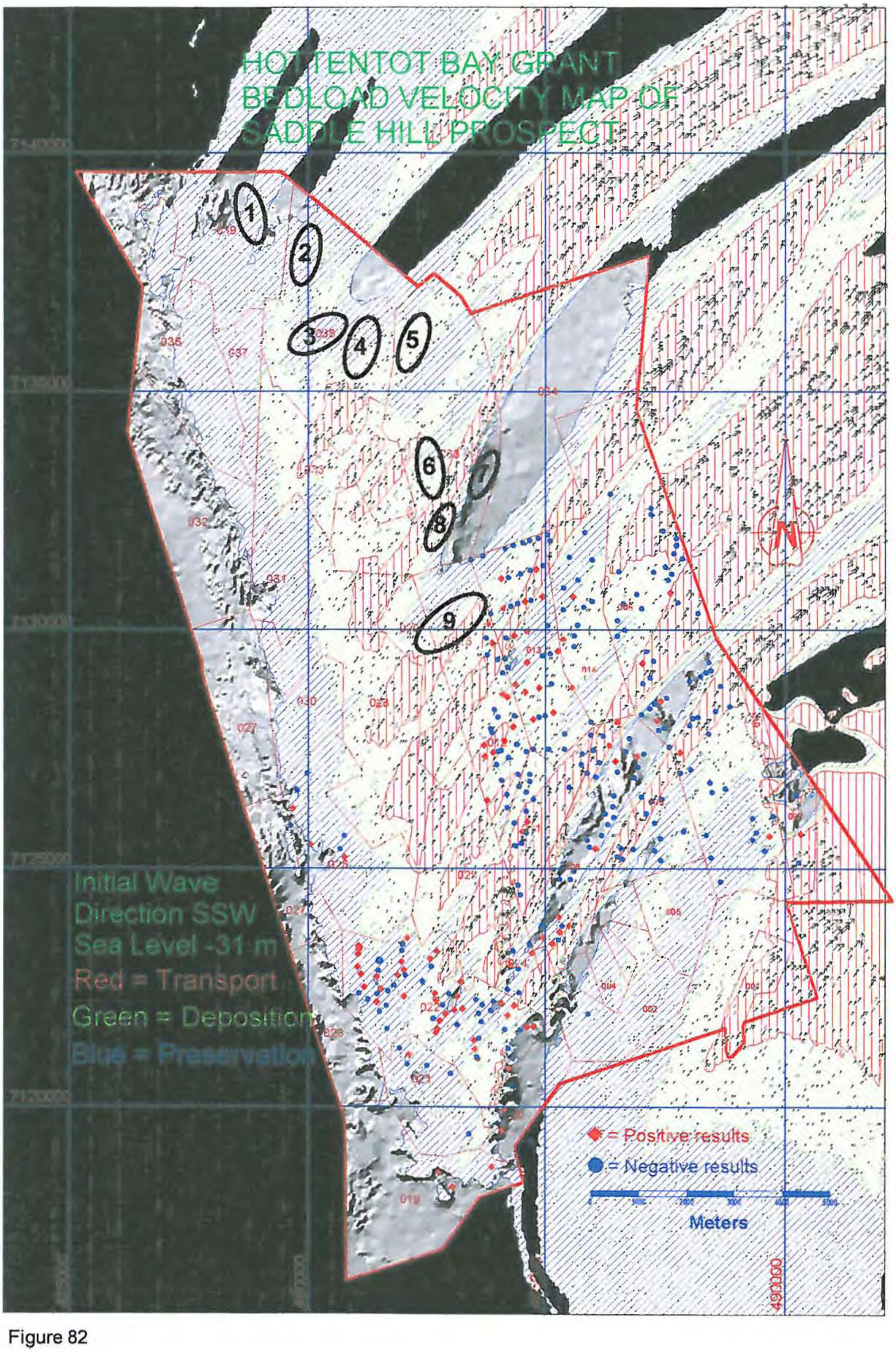

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
7140000
7135000
7130000
7125000
7120000
490000
1
2
3
4
5
6
7
8
9
Initial Wave
Direction SSW
Sea Level -31 m
Red = Transport
Green = Deposition
Blue = Preservation
◆ = Positive results
● = Negative results
0
1000
2000
3000
4000
5000
Meters
N

Figure 82

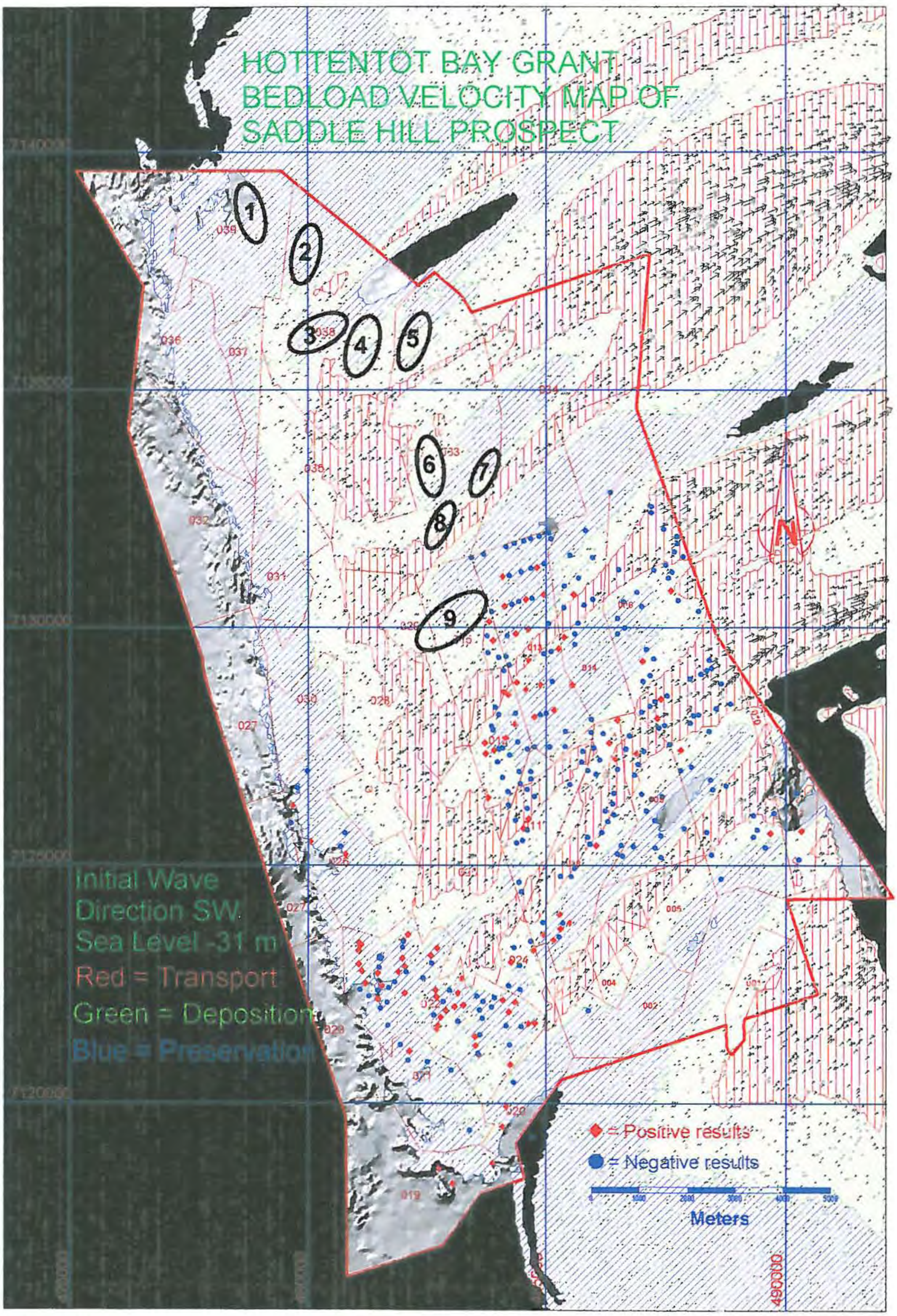

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
7140000
7135000
7130000
7125000
7120000
1
2
3
4
5
6
7
8
9
Initial Wave
Direction SW
Sea Level -31 m
Red = Transport
Green = Deposition
Blue = Preservation
◆ = Positive results
● = Negative results
0
1000
2000
3000
4000
5000
Meters
490000

Figure 83

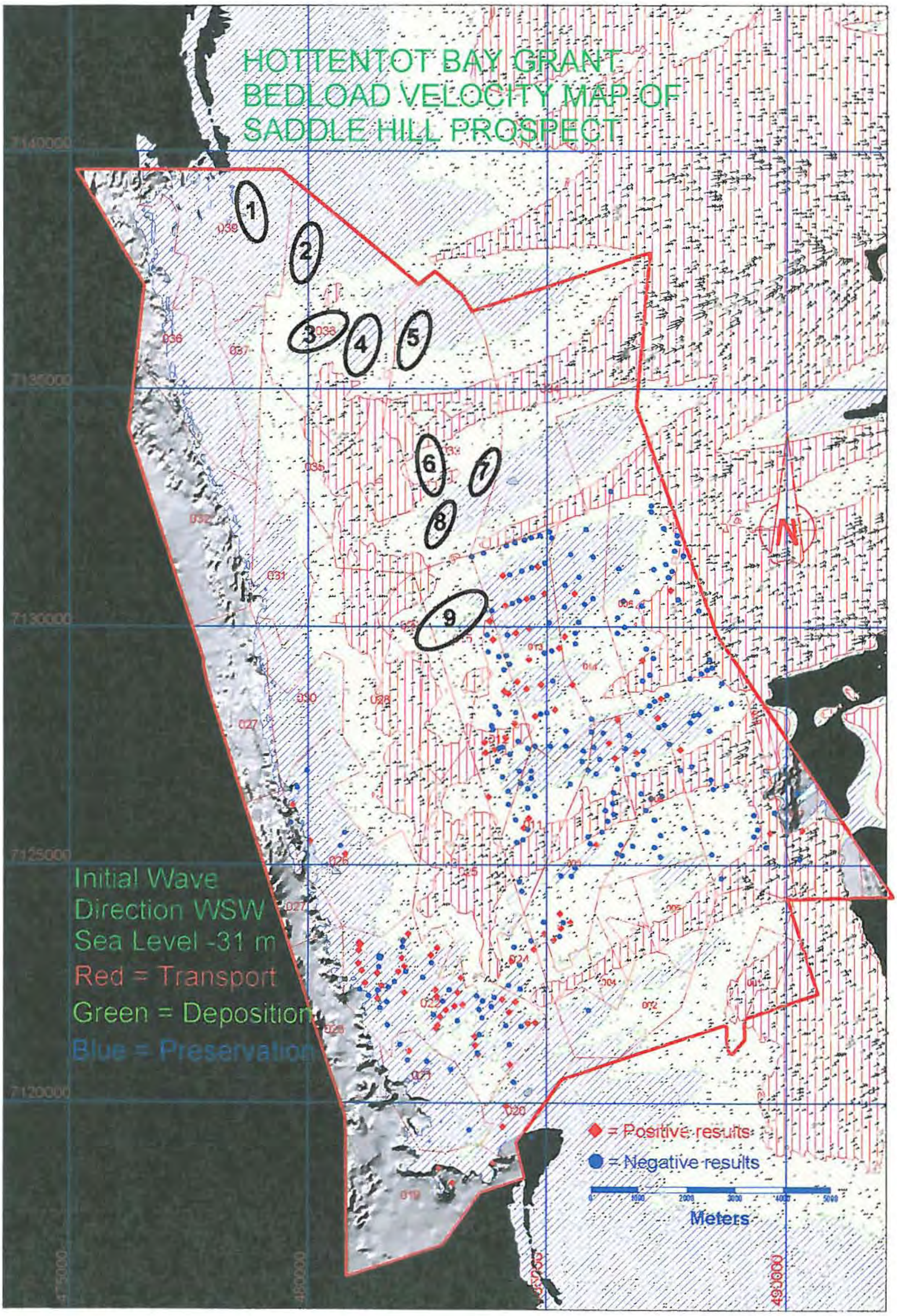

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
7140000
7135000
7130000
7125000
7120000
475000
480000
485000
490000
1
2
3
4
5
6
7
8
9
N
Initial Wave
Direction WSW
Sea Level -31 m
Red = Transport
Green = Deposition
Blue = Preservation
◆ = Positive results
● = Negative results
0
1000
2000
3000
4000
5000
Meters

Figure 84

8.5.5 PRIORITISATION OF TARGET AREAS

This sediment dynamics study examined selective targets at specific sea-levels under storm conditions from the SSW, SW and WSW. Incident storm swells of 6 m at a 12 s period were used to simulate orbital velocity conditions on the sea-floor at the various sea-levels modelled.

The sediment dynamics within selective morphological features at the various incident angles and sea-levels were examined. These features included areas that had already been sampled. A good correlation was found to exist between the composite sediment dynamic diagram interpretation and the sample results. Based on this positive correlation in the sampled areas, the study was expanded to select high priority target areas in the un-sampled areas of SHP and HBP. Results of the sediment dynamics study are summarised in Table 32.

TABLE 32: Prioritisation of target areas according to the sediment dynamic study (Figure 85).

Reference	Rank (1 = Poor, 5 = Excellent)
A	2
B	4
C	3
D	1
E	3
F	4
G	3
H	3
I	2
J	3
K	2
L	4
M	2
N	2
O	5
P	5
Q	3
R	3
S	3
T	3
U	5

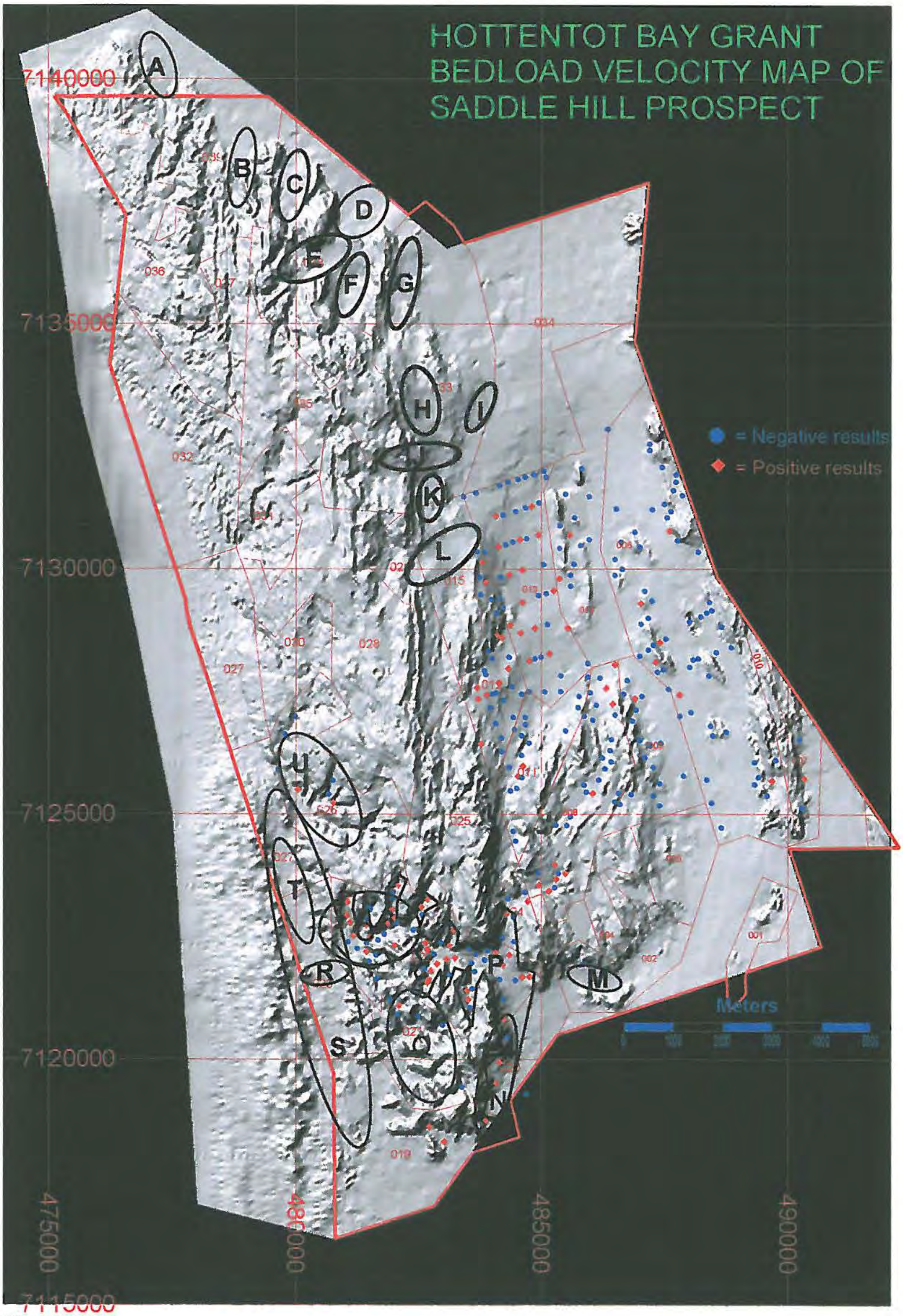

HOTTENTOT BAY GRANT
BEDLOAD VELOCITY MAP OF
SADDLE HILL PROSPECT
● = Negative results
◆ = Positive results
Meters
7140000
7135000
7130000
7125000
7120000
7115000
475000
480000
485000
490000
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
R
S
T
U
V

Figure 85

8.5.6 DISCUSSION

The results of this study show that on a broad scale diamond deposition trends can be modelled using sediment dynamic software and used to select and prioritise target features. The broad correlation of diamond recovery with orbital velocity on the seafloor, highlights the importance of "preservation potential", a critical factor in the formation of marine placer deposits.

The erosion of the Cretaceous kimberlites together with other potential sources has resulted in the deposition of millions of carats along the west coast. The ability of a specific topographical feature to preserve diamonds is paramount in the formation of enriched marine diamond placer deposits. Considering these large volumes of diamonds deposited within the coastal system, and the long time frames, almost every linear depression, basin, terrace floor and channel is likely to have had diamonds pass through it. The ability of the feature to accumulate heavy minerals/diamonds without them being flushed by, either a storm from a different direction, or by fluvial and/or aeolian action at a later stage, is probably the single most important factor in the formation of high grade deposits along the west coast. Provided, of course, that the wave energy is not too low to preclude the winnowing of lighter fractions, that will dilute the deposit. Wave and sediment dynamic software, incorporating a orbital wave velocity algorithm, is most useful in modelling bedload velocity zones on the seafloor, at selected sea-levels. Hindsight modelling conducted on defined high grade areas, shows these features to be moderate to low energy zones, no matter what initial wave angle, height or water depth is modelled. In ML 103a the majority of positive sample sites are located along the periphery of high orbital velocity zones in moderate energy zones. As with most simulation techniques, it is not infallible, and there are some target features that show good diamond placer preservation potential, but have not produced good sampling results to date. Therefore sediment dynamic results should be reviewed in conjunction with all the other parameters that play a role in marine diamond placer formation. These critical parameters are reviewed in greater detail in Chapter 9.

9. AN INTEGRATED APPROACH FOR TARGET SELECTION AND PRIORITIZATION

9.1 INTRODUCTION

The detailed literature review, geophysical interpretation, terrace level study and sediment dynamic modelling presented in this study provides a sound platform for evaluating models for diamond placer formation in central Namibia.

All available historical and current geophysical survey interpretations (offshore and onshore), sampling results and resource/reserve estimations for central Namibian marine placer deposits were examined in detail during this study. These form the foundation of the revised model for placer formation on the inner shelf in this area and the derived target selection and prioritisation matrix. Furthermore, landscape development theories (Refer: Chapter 5) were reviewed to ensure that the model falls within accepted bounds for the coastal plain evolution. Target features (Refer: Figure 66) are prioritised using a matrix presented during the latter part of Chapter 9.

9.2 REVISED MODEL FOR THE FORMATION OF MARINE DIAMOND PLACERS IN CENTRAL NAMIBIA

A revised model for the formation of marine placer deposits in central Namibia, is presented in this section. The model addresses the issues of placer location, grade distribution and average diamond size variation. The target and prioritisation table formulated is based on the model proposed for these inner shelf placer deposits.

The various processes proposed for the evolution of aeolian, fluvial and marine placer deposits have never been drawn together to form an integrated, holistic model. This is what is now presented here. While Corbett (1996) examined the interactions between the sea-level movement and the palaeodune systems (Refer: Section 5.3.4) stretching north of the Orange River and within the aeolian corridors (Corbett, 1989), the processes occurring thereafter were not addressed. It should be noted that a number of the individual components presented in the revised model have been proposed from the very earliest investigations undertaken by geologists along the west coast. More recent studies have been developed largely from these earlier theories include some proposed in the revised model. While both the old and the new theories have been reviewed within preceding sections, only the latest and most pertinent aspects relating to the revised model are presented in this section. References are made to the relevant sections should additional detail be required.

Using field tests that recorded wind speeds and sediment dynamics within N-S trending wind corridors, Corbett (1989) demonstrated that the historically mined diamond placers in corridors between Chameis Bay and Elizabeth Bay area are formed by aeolian processes (Refer: Section 5.3.2) . The following conclusions from

Corbett's (1989) study are incorporated into the revised model for placer formation in central Namibia, which are proposed in this study:

- Deposition and subsequent erosion of raised marine placers along the rim of embayments by the prevailing southerly winds and introduction of diamonds into northward trending aeolian corridors at specific transgressive and regressive sea-level stillstands elevations.
- Bedload size- and shape-sorting by the incorporation of different populations into kinematic waves travelling at different speeds during phases of saltation and creep within the corridors.
- Diamond concentration where the northward transport of diamonds is disrupted by micro-topographical features or bottle-necks.
- Grade enrichment by the erosion of higher elevation terraces and sheetwash processes, during infrequent storm events within the corridors. Corbett's (1989) model suggests localised enrichment by sheetwash processes within specific aeolian corridors and is therefore on a more localised scale than the mechanisms proposed in the revised model, presented below.

Jacobs (2001) studied the beach placer deposits north of the Orange River Mouth. Conclusions were based on data obtained from structural and lithological mapping, resource data and highly accurate digital terrain models of the bedrock topography. The following results from her study have been considered in the revised model presented in this study:

- The quality of the trapsite is directly linked to the depth of incision into the bedrock. The deepest incision generally occurs on the seaward end of marine terraces.
- The abundance of abrasive agents affect the type of gully formed. Near river mouths where boulders are plentiful, swash parallel gullies form. Strike gullies occur where boulders are scarce and joint gullies develop in areas where structural features in the bedrock are dominant. Bedding and shear plane trends and dips also play a role in determining the dominant gully type developed.

Jacob's (2001) conclusions are particularly applicable to the dominantly wave-formed, raised terrace deposits (Murray *et al.*, 1970) between the Orange River and Chameis Bay.

Using the results from previous studies, as well as the detailed investigation of HBG presented in Chapter 8, a revised poly-cyclic model for the formation of diamond placers in central Namibia is proposed. This model which includes marine, aeolian and fluvial processes, accounts for the placer location, grade distribution and average diamond size variations and characteristics observed along the central Namibian inner shelf. Figures 86 and 87 are diagrammatic representations of the revised model proposed and should be viewed in conjunction with the text. The model can be summarised as follows:

DIAMOND PLACER FORMATION - SOUTHERN NAMIBIA

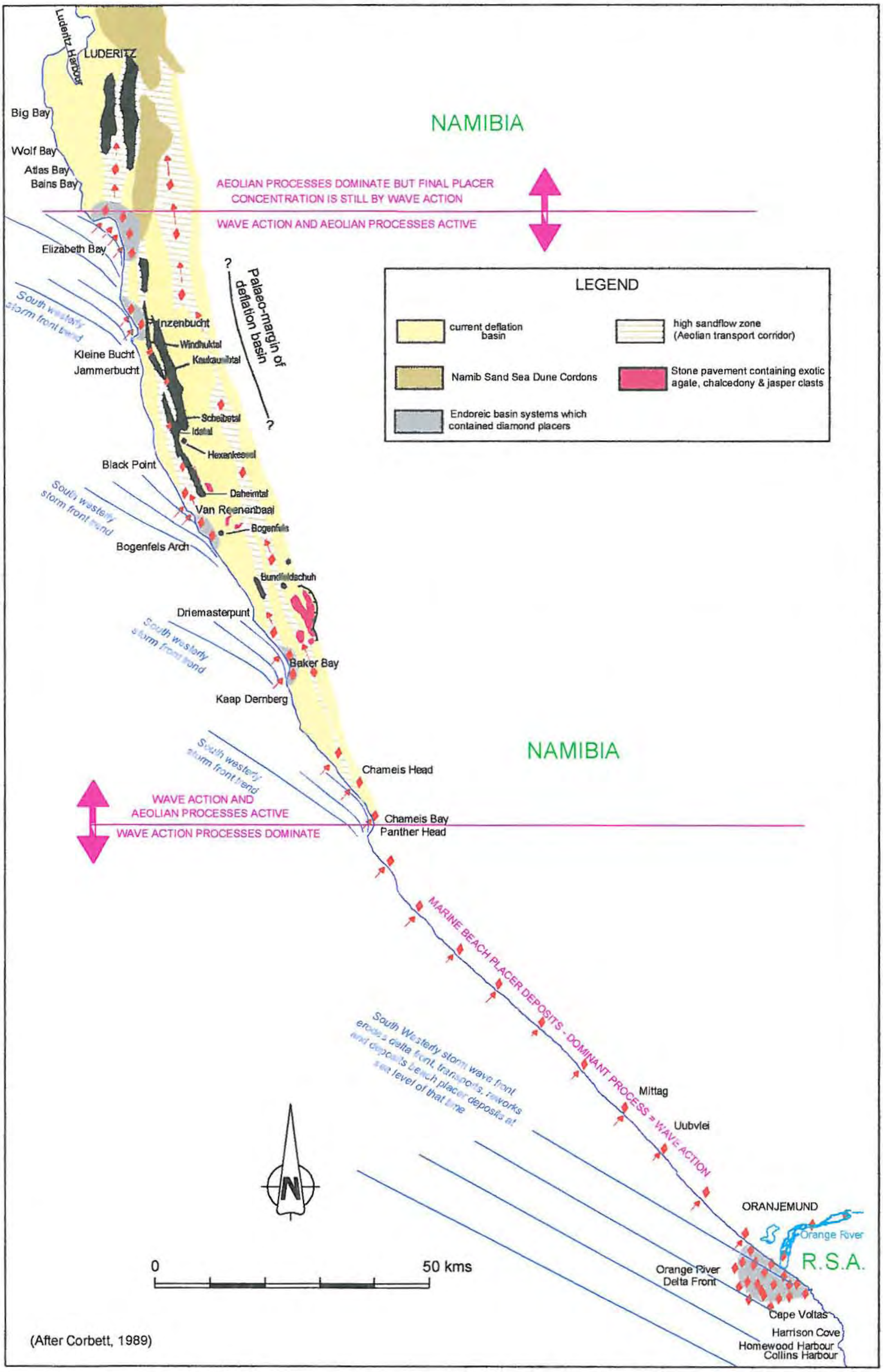
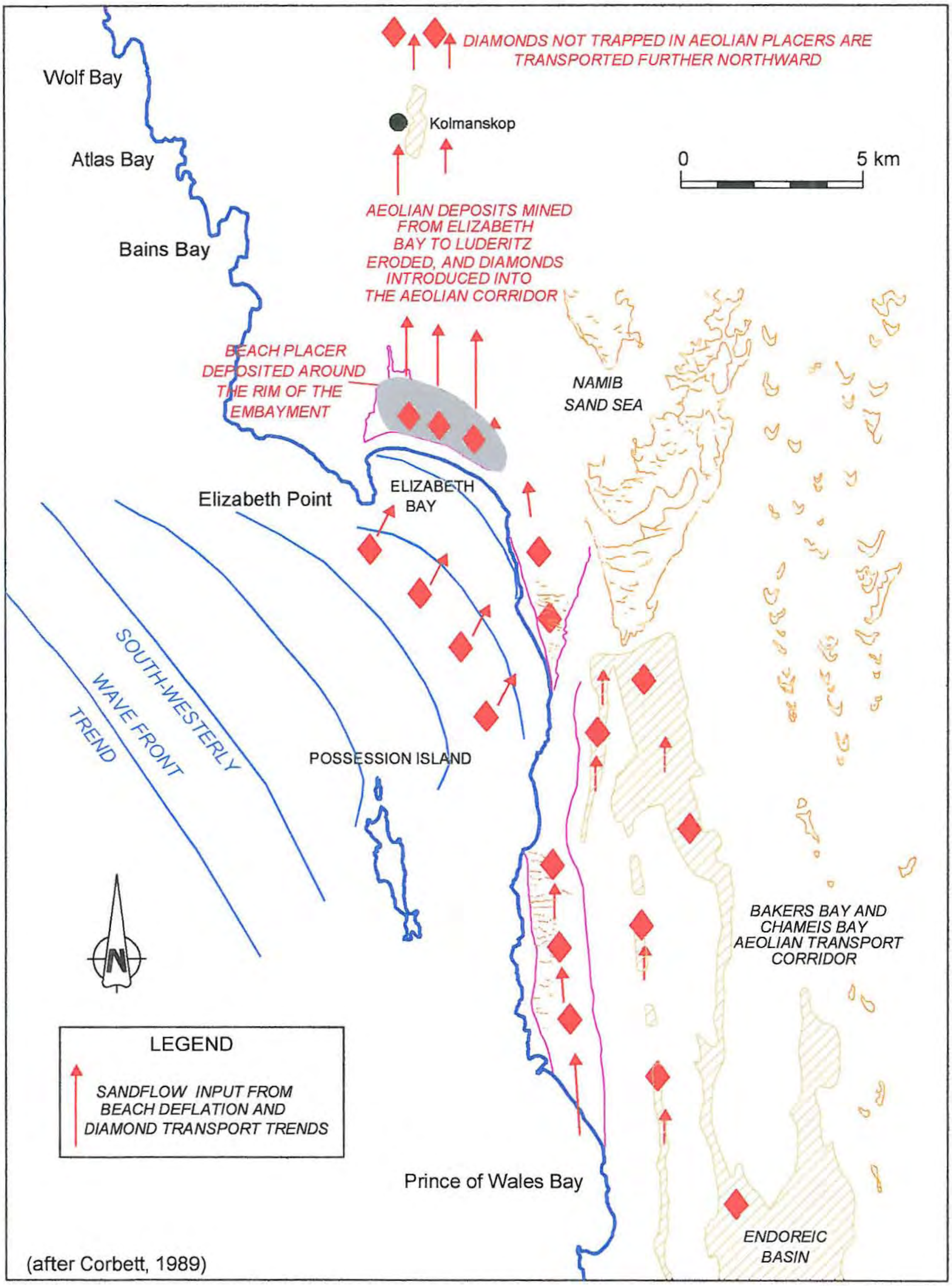


Figure 86a

EROSION OF MARINE PLACER DEPOSITS AND DIAMOND INTRODUCTION INTO AEOLIAN CORRIDORS



(after Corbett, 1989)

Figure 86b

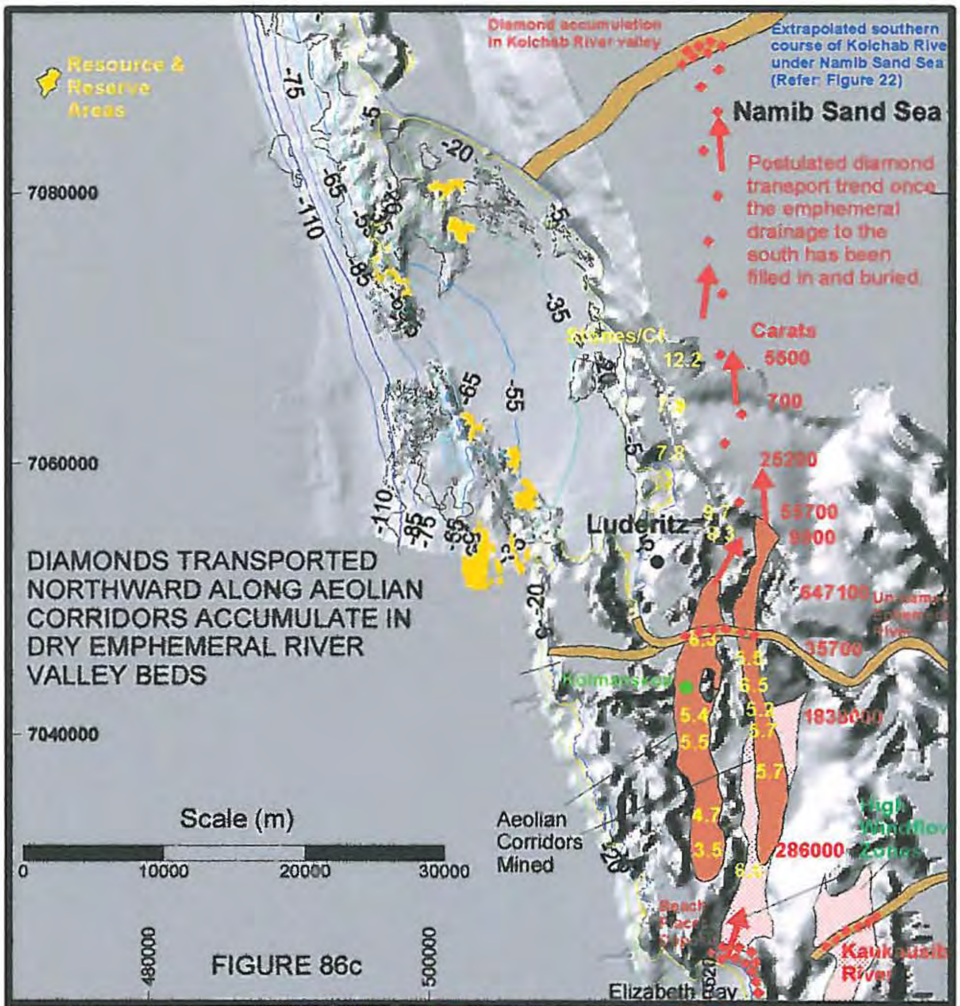


FIGURE 86c

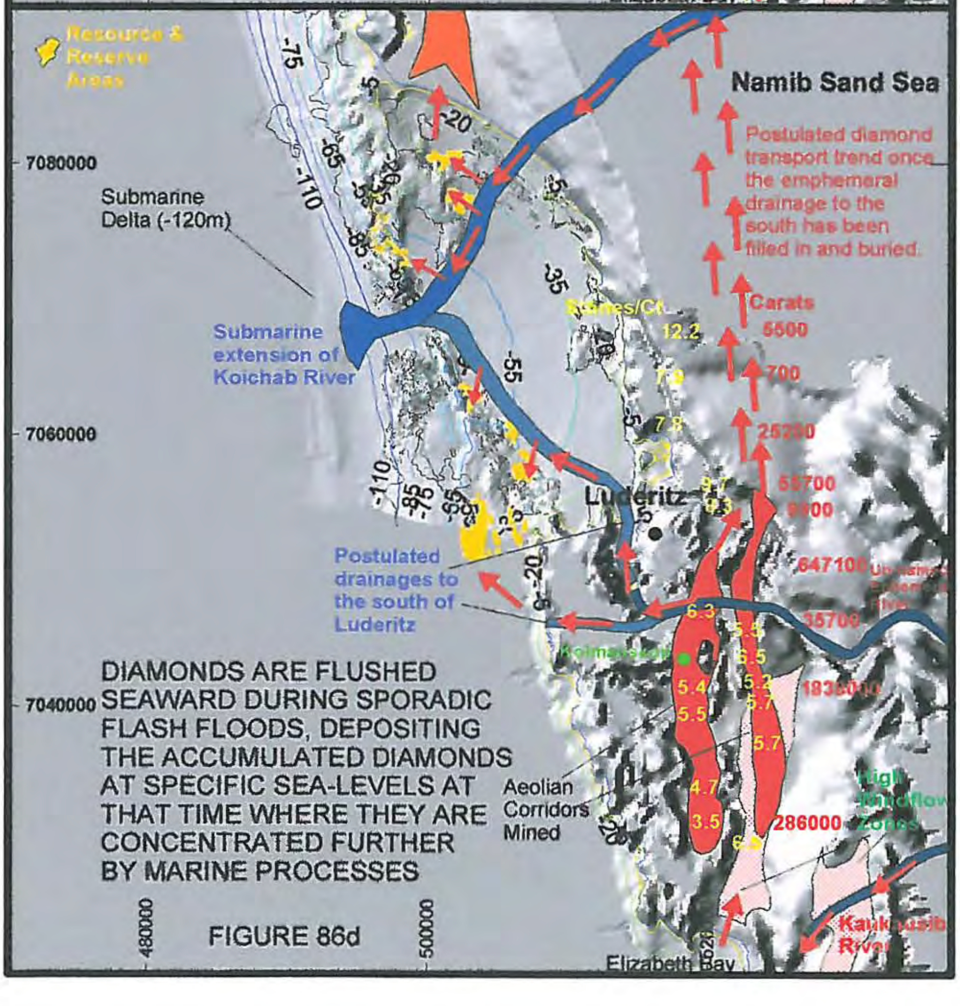


FIGURE 86d

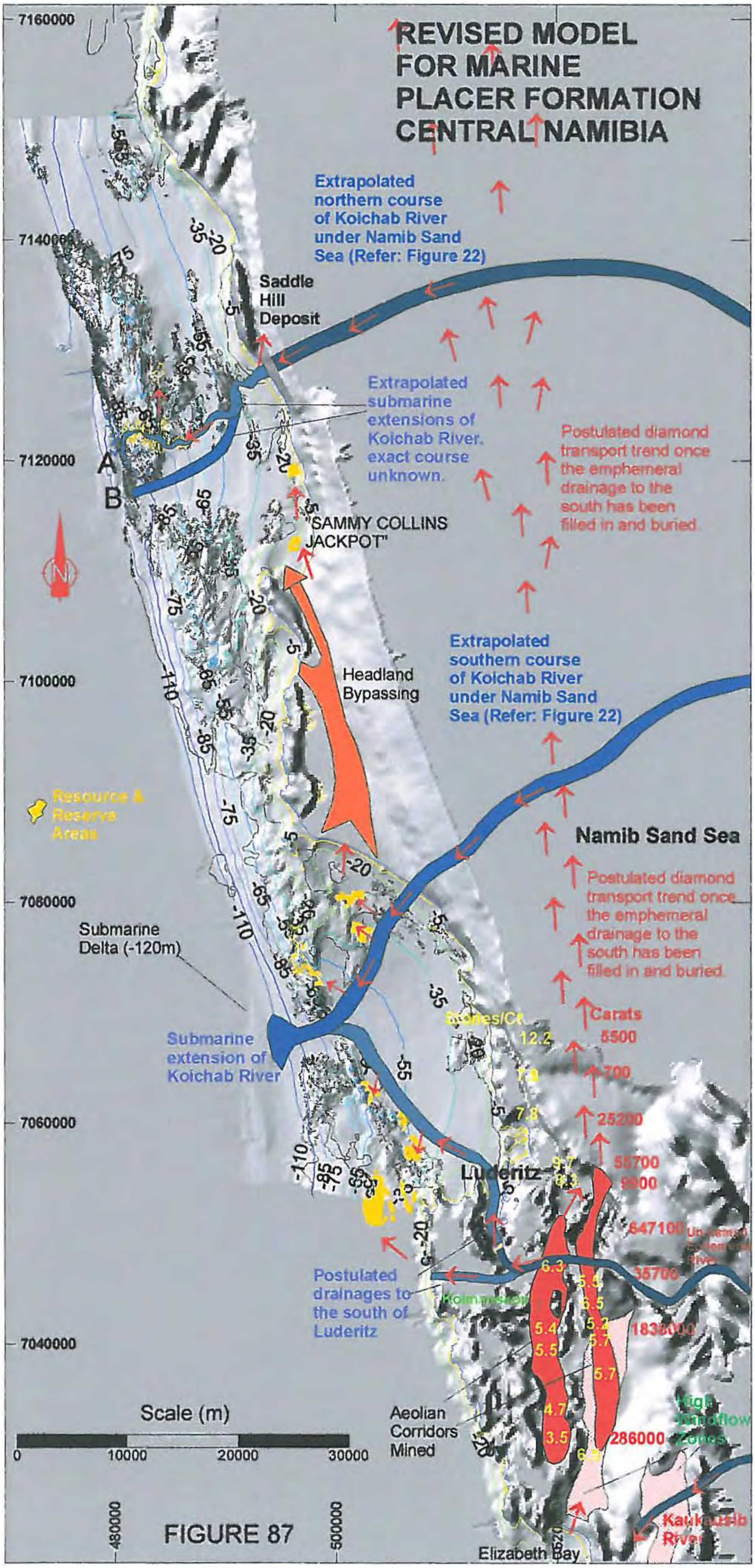

REVISED MODEL FOR MARINE PLACER FORMATION CENTRAL NAMIBIA
7160000
7140000
7120000
7100000
7080000
7060000
7040000
480000
500000
Extrapolated northern course of Koichab River under Namib Sand Sea (Refer: Figure 22)
Saddle Hill Deposit
Extrapolated submarine extensions of Koichab River. exact course unknown.
Postulated diamond transport trend once the emphemeral drainage to the south has been filled in and buried.
A
B
"SAMMY COLLINS JACKPOT"
N
Headland Bypassing
Extrapolated southern course of Koichab River under Namib Sand Sea (Refer: Figure 22)
Resource & Reserve Areas
Namib Sand Sea
Postulated diamond transport trend once the emphemeral drainage to the south has been filled in and buried.
Submarine Delta (-120m)
Submarine extension of Koichab River
Stones/Ct
Carats
5500
700
25200
55700
9900
647100
Un-named Ephemeral River
35700
1838000
286000
12.2
7.8
9.7
8.3
6.3
5.5
6.5
5.4
5.2
5.7
4.7
3.5
6.3
Luderitz
Kolmanskop
Postulated drainages to the south of Luderitz
High Windflow Zones
Aeolian Corridors Mined
Kaukausib River
Elizabeth Bay
Scale (m)
0
10000
20000
30000
-5
-20
-35
-55
-65
-75
-85
-110

FIGURE 87

1) **Diamonds, predominantly from Cretaceous aged kimberlites, were eroded in the interior of southern Africa (Refer: Chapter 4), transported by the Kalahari River and deposited as a deltaic sequence at the Orange River mouth (Refer: Section 4.2.2.3).**

2) **The deltaic front was eroded by storm swells and diamondiferous gravels were deposited along palaeo-shorelines during marine transgressions and regressions, at levels both above and below present sea-level, to the north and south of the river mouth. Abundant boulders and pebbles debouched by the Orange River occur mainly south of Chameis Bay, but are found as far north as Van Reenen's Bay (Jacobs, 2001) and further.**

3) **From Chameis Bay to Elizabeth Bay aeolian influences would have played a more dominant role in northward transport of diamonds (Corbett, 1989), though marine processes remain operative.**

4) **Diamonds and gravels were deposited by refracting waves, along shorelines and around the rims (Figure 86a) of north- eg. Chameis Bay and Bakers Bay and south - eg. Bogenfels and Elizabeth Bay facing embayments (Corbett, 1989).**

Gardiner (1955) recognised that headlands obstructed longshore drift, depositing sediments on their up-drift side, forming beaches parallel to waves being refracted around the headland. Hallam (1964) recognised that diamondiferous beaches at Peacock Bay were preferentially preserved in the high energy zone immediately up-drift of a headland. In the lee of the headland, the wave energy reduces dramatically and once deposited in the north-facing bay, the heavy minerals accumulate on the beach and in the centre of the bay. The high energy tail of the bay where there is maximum flux of sediment is also favourable for the concentration of heavy minerals (Hallam, 1964). Corbett (1989) states that south-facing bays are also good diamond depositories along the Namibian coast. Corbett (1989) attributes the resources identified in the Fiskus Sandstone Beds at Elizabeth Bay to aeolian processes reworking marine terraces deposited along the rim of a south facing embayment immediately to the south of that area.

5) **The strong southerly gales eroded these raised beach placers and introduced diamonds into northward trending (Figure 86a) aeolian corridors (Corbett, 1989).**

Corbett's (1989) modelling of a marine transgression in the south-facing Bogenfels re-entrant shows that this locality would have been suitable for the generation of major aeolian transport corridors. Furthermore, a significant, coast-perpendicular topographical high which currently manifests itself as the headland between Elizabeth Bay and Lüderitz, is likely to have formed a significant barrier to the northward transport of diamondiferous gravels by marine processes. Given the high rates of erosion measured on the coastal plain and the resultant landscape lowering that has occurred, (Refer: Section 5.2) it is probable that this barrier was far more prominent in the past, than in its present denudated form. The inflection from a NNW trending coastline in South Africa to a NW trending coastline between Oranjemund and Lüderitz (Refer: Section 3.1), coupled with the predominant southwesterly storm wind regime (Rogers, 1977) would also have contributed toward the dominance of aeolian processes north of Elizabeth Bay.

The revised model, developed from this study, suggests that from Elizabeth Bay to Walvis Bay, aeolian mechanisms dominate the marine processes proposed in previous studies, in the northward transport of diamonds. This area can be correlated with similar sand bypasses described by Corbett (1989) between Chameis and Elizabeth Bays to the south, but on a larger scale. Examination of satellite images of central Namibia show the current extent of this bypass in the form of the Namib Sand Sea. Though the Namib Sand Sea is described by Corbett (1996) as a "zone of nett Cainozoic accumulation", this does not necessarily preclude the continual northward movement of sediments and diamonds through the area. "Zone of nett accumulation" would imply that diamond placer concentration by aeolian processes may be limited, but does not necessarily preclude northward transport of diamonds.

6) **A percentage of the diamonds creeping and saltating northward along wind corridors extending northwards from Elizabeth Bay and other localities along the southern Namibian coastline, were concentrated into aeolian placers deposits where suitable trapsites occur (Corbett, 1989). However, it is hypothesised that numerous diamonds were transported further northwards by the wind (Figure 86b) and subsequently concentrated into marine placers, using a process developed from this particular study not previously proposed for these deposits.**

Current mining at Elizabeth Bay and historical recoveries at many localities in the area, most notably Kolmanskop, offer ample evidence of the northward transport of diamonds along aeolian corridors north of Elizabeth Bay. Figure 87 gives an indication of diamond recoveries between Elizabeth Bay and Kolmanskop. These diamond placer deposits are contained predominantly in the Pliocene/Pleistocene aged Fiskus Sandstone beds (Corbett, 1989). It is evident from the landscape evolution for that area, and particularly the extents and evolution proposed for the Tsondab Sandstone Formation (Refer: Section 5.3.1), that similar processes have been active since pre-Miocene times. Given that diamonds are purported to have been present on the west coast plain since early Eocene times (Refer: Section 5.2), it is probable that diamonds have been transported northwards by aeolian processes for well over 20 million years. Given these time frames and the high rates of aeolian transport (Refer: Section 5.3.2), it is conceivable that diamonds being transported northwards in different pulses, along different diamond corridors, at elevations both above and below present sea-level, extend for hundreds of kilometres north of Elizabeth Bay. Corbett (1989) believes that diamond introduction into aeolian corridors was a cyclical process with the corridor being active for a period, but cut off by a change in sea-level. Many of the diamonds introduced into these aeolian systems are trapped by bedrock micro-topography or within indurated units (Corbett, 1989). The incessant abrasion and deflation could easily result in remobilisation of a significant number of these diamonds at later times and their continued northward transport. Preservation of the aeolian placer deposits is often dependent on their immobilisation as evidenced by the indurated, diamondiferous gritstones being mined at Elizabeth Bay (Namdeb Annual Report, 2002). Sampling at a very similar southward facing log-spiral bay at Anichab Pan produced few diamonds (Refer: Section: 6.2.2). The surface of this pan is heavily wind ablated and it is probable that any aeolian placers deposits that may have existed in this wind corridor have been eroded and deposited within the Gallovidia Reef and Hottentot Bay (ML 30) areas. The absence of a northern closure or obstruction in Anichab Pan would have precluded diamond concentration further northwards within the corridor itself using the processes described by Corbett (1989) for the area to the south. The diamonds recovered by Mr Sammy Collins were most likely deposited by these means at the -20 m sea-level (Refer: Figures 20 and 87).

7) **Aeolian processes transported the diamonds northward along the corridors until a coast-perpendicular perennial/ephemeral drainage was intersected, (Figure 86c) trapping the northward migrating diamonds. The diamonds accumulated within the river valley until one of the infrequent flash floods on the escarpment washed them into the sea, depositing them at the particular sea-level elevation of that time (Figure 86d).**

The correlation between enriched marine placer deposits and river mouths along the west coast was noted during the very earliest geological examinations along the west coast deposits. Subsequent models have related this increased grade to: 1) the erosion of diamondiferous palaeo-shorelines located at higher elevations (Refer: Section 4.2.3.1), 2) a primary source in the interior (Refer: Section 4.2.2.1), or 3) erosion of Dwyka Tillites along the escarpment (Refer: Section 4.2.2.1). This is **not** what is being proposed in the revised model. While it is not refuted that erosion of terraces at higher elevations may have contributed to some of the deposits at the mouths of ephemeral drainages in central Namibia, the author does not believe that they are the main contributing factor because, once they have been eroded, no additional diamonds can be derived from this source. Therefore, while they could be used to account for placers found at a limited number of lower elevation sea-levels, they do not account for the deposits located at numerous levels, spanning long time periods (Refer: Section 8.4), located in the study area. To explain the distribution of all the resources and reserves identified in central Namibia a more sustainable diamond source mechanism, such as the one proposed in this study (Point 7), is required.

The Kaukausib River, Un-named river (eastern extents shown on the 1:250 000 topography sheet of Lüderitz), Koichab River, Tsauchab and Tsondab Rivers enter the Atlantic at Elizabeth Bay, Griffith Bay/or south of Halifax, Anichab/Hottentot Bay, south of Meob Bay and Conception Bay, respectively. Fossils from the sediments intercalated with the Kaukausib Travertine indicate a Pliocene age for these alluvial sediments immediately south of Elizabeth Bay, which were previously thought to be of Miocene age or older (Pickford and Senut, 1999). These coast-perpendicular drainages intersect the aeolian corridors, and have retarded the northward migration of the Namib Sand Sea (Refer: Section 5.4). More importantly the barrier formed by the water (when flowing), valley (wind shadow), vegetation growing in the valley (groundwater supply available) and gravel carried down from the escarpment (boulder beds left by the previous flood), would trap the northward saltating and creeping diamonds. These diamonds would accumulate until a flash flood on the escarpment washed them westward into the sea. Pickford and Senut (1999) reviewed Late Quaternary palaeo-climates in the Namib Desert and concluded that there is little evidence for long periods of precipitation. However, Ward (1987) suggests that there is evidence for increased run-off from the escarpment east of the desert which produced more frequent and/or longer duration flows of rivers along the coastal plain (Refer: Section 5:4). The close correlation between the coastal drainages and the marine diamond placer deposits could explain why the first geologists studying these deposits (Merensky, 1909) mistakenly considered these ephemeral coastal streams to have directly tapped a primary source (Refer: Section: 4.2.2.3). The merits of the various models for the origin of the west coast diamonds and drainage evolution have been reviewed in detail in Chapter 4 and based on deductions from examination of the literature, it seems improbable that the diamonds in central Namibia are derived from erosion of the Dwyka tillite along the edge of the escarpment. The Namib Sand Sea, though itself presumably of low grade due to the high degree of sand dilution, would nevertheless over long time frames carry a significant quantity of diamonds northward. It is postulated that at these coast-perpendicular drainages, the heavy mineral component would be segregated from the lighter sand component. The heavy mineral component, once caught in the gravel, vegetation or wind shadow within the river valley, cannot be easily removed, while the lighter sand fraction which is far more susceptible to wind entrainment, would be transported away. Similarly, should the river be flowing slowly, the fine sediment fraction can be transported to the coastline while the heavy mineral component would require much higher flow rates to be transported, effectively creating a means of winnowing these low grade deposits. During the sporadic flash floods, the gravel and heavy minerals that have accumulated, would be transported to the coast and further concentration by marine processes would occur. Ward's (1987) study of the Kuiseb River examines sedimentary deposits formed during flash floods (Refer: Section 5.4) and can be used to draw parallels with ephemeral drainage evolution further to the south along the coastal plain, as the prevailing conditions are likely to have been very similar (Refer: Section 5.2).

8) **Owing to the sporadic nature of the flash floods and resultant time differences for diamond deposition at the mouths of these ephemeral drainages, deposits may occur at different sea-level elevations, particularly in light of the rapid sea-level fluctuations that occurred in the Plio/Pleistocene period.**

The diamondiferous gravels deposited during a flash flood would be winnowed by wave action and preferentially distributed along palaeo-shorelines at specific elevations present at that time. If the rapid, large sea-level fluctuations that occurred in the Plio/Pleistocene (Refer section: 8.4) are considered in the light of the sporadic nature of the flash floods, particularly those after the full establishment of the Namib Desert in the late Miocene (Refer: Section 5.3.1), a means of bathymetrically separating the preferentially enriched shorelines from the poorly mineralised levels can easily be envisaged.

Aeolian diamond size sorting due to differential transportation rates for the different sediment size fractions results in the segregation of average diamond size populations (Corbett, 1989). This concept can be developed further and used with the revised model, proposed in this thesis, to explain the average diamond size variations noted at the different sea-levels within the study area (discussed in greater detail below). The mechanisms proposed for this new model advocate preferential diamond enrichment being a function of the chronology of the flash floods and the specific sea-level elevation present when they occurred. That is, the longer the stillstand, the greater the diamond accumulation in the river and the better the chance of one or more flash floods occurring, thereby enriching that specific palaeo shoreline. The close association between the resource areas defined for this section of the coast (De Decker, 2001) and the extrapolated palaeo-drainage distribution along the coast lends credence to the model proposed (Figure 87). Furthermore, if the well defined sea-level stillstand elevations established for the west coast (Refer: Section: 8.4) are superimposed, the close association between the drainages, the well defined stillstand elevations and currently defined resources is highlighted even more clearly (Refer: Figure 87). Note the close relationship between the Koichab River (northern exit point) at the -70 m transgression (36 000 to 39 000 ya and 75 000 and 58 000 ya) and the northeastern end of SHP, Feature 22. A similar correlation is also evident in Feature 19 of ML 51, Marshall Fork (Koichab River - Anichab exit point - Refer: Section 6.2.3) and Diaz South at the -65 m level. Furthermore, resources identified in Staple Basin, Conical Beach and Features 11 and 12 of ML 51 correspond to the -22 m, -30 m, -65 m and -75 m bpsl stillstands, respectively (Refer: Figure 87). The early Holocene "optimum" period was a globally wet period (Adams, 2002) and corresponds to a minor alluvial phase that may have been responsible for the diamonds deposited, concentrated and mined along the rim of the northerly facing embayment at Saddle Hill Prospect at the 6 m to 8 m asl elevation (Refer: Section 6.2.2). These diamonds may have been introduced from the east by the Koichab River if it was still active at that time, or from the west by wave action reworking gravels deposited within Hottentot Bay at an earlier stage, either by headland bypassing (aeolian) or fluvial processes (Refer: Point 6 above).

9) **The order in which the proposed process occurred is important in evaluating the relative ages of the marine resources/reserves identified in central Namibia. Given the geometry of the Namib Sand Sea and the dominant southerly wind direction, it is probable that the evolution of the postulated marine diamond placer formation process would have started in the south and progressed northwards with time.**

The most southerly drainage would have retarded the northward migration of the sand sea first. The northward migration of aeolian sediments would have eventually clogged up this westward flowing drainage and filled in the river valley. Diamonds would then have been transported across the buried channel and would have continued northward until the next ephemeral drainage was intersected, where the same process of northward retardation, flushing during flash floods, deposition and marine placer formation would be repeated further northward along the central Namibian coast. However, the further northward the diamonds were transported, the greater the likelihood of them being trapped within the aeolian corridor, resulting in a smaller population available for flushing coastward accumulating in the ephemeral drainage. This process, where the western extents of the coastal ephemeral drainages are terminated by the encroaching Namib Sand Sea, is postulated to be on a river-to-river basis (Refer: Section 5.4). However, in the case of the Koichab River, the river appears to first have been deflected from its exit south of Anichab pan, to one further northward (south of Saddle Hill - Figure 87), before being terminated altogether (Refer: Section 6.2.3).

10) **During flash floods, diamonds are deposited into the swash zone by the ephemeral drainage and subsequently winnowed within suitable bedrock trapsites, normally to the north of the river**

mouths, forming enriched marine placer deposits.

The grade of the deposit is dependent on placer preservation potential which in turn is a function of: 1) depth of incision into the bedrock, 2) orientation of the feature with respect to the prevailing aeolian and marine storm directions (during regressions), 3) the susceptibility of the feature to be flushed by fluvial action during marine regressions, and 4) the presence of protective capping horizons whether they be clay or indurated horizons.

While the revised model suggests that aeolian processes may be dominant in central Namibia, it does not necessarily preclude concentration by marine processes as previously postulated for the development of these marine placer deposits. In fact the larger clasts deposited at the mouths of these ephemeral drainages during the fish floods would act as traps for diamonds being transported northward by littoral processes. Thereby further enhancing the diamond enrichment potential in the vicinity of these emphemeral drainages.

Successful marine placer resource delineation on the inner shelf along the west coast is largely dependent on the geologists ability to identify high preservation features, into which diamonds can be easily introduced, but cannot be readily removed by terrestrial or sub-aqueous erosion processes.

9.2.1 OBSERVATIONS SUPPORTING THE REVISED MODEL

The majority of the resource areas currently identified between Lüderitz and Clara Hill can be accounted for by the revised model presented in this thesis. It is feasible that this poly-cyclic mechanism of marine placer formation proposed for central Namibia is also valid for northern Namibia, and possibly even along certain portions of the Namaqualand coast.

This model can explain the following phenomena observed along the central Namibian coast:

- **The patchy alongshore distribution of economic diamond placers in central Namibia: -** The transport mechanism proposed would result in diamonds bypassing certain areas, opposing previous theories that suggested the diamonds were shuffled along by wave action and littoral drift set up by a wave front direction orientated obliquely to the coast. By implication, longshore drift would distribute diamonds all along the palaeo-shoreline. To account for the patchy distribution of marine placer deposits, previous models argued that the bedrock morphology along these stretches was not conducive to placer formation, but these models could not account for the paucity of diamonds within well developed trapsites, albeit in small volumes, within these areas.

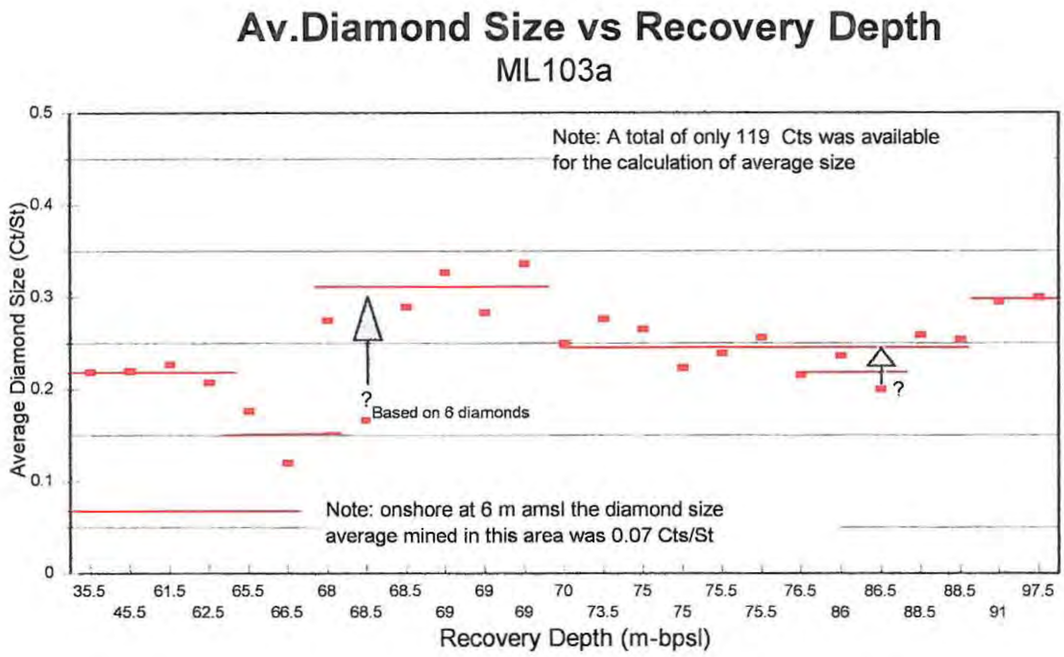
- **Average diamond size population differences noted at different sea-levels at HBG**: - Distinct average diamond size differences are evident between the onshore deposits historically mined at Saddle Hill (0.05 to 0.08 cts/st - Refer: Section 6.1.2) and those recovered directly offshore with larger average size of 0.27 cts/st (De Decker, 2002). However, diamonds as small as 0.08 cts/st have been recovered by Namco

(Namco daily log sheets, 1996) and the difference cannot be accounted for by a difference in the lower mesh size of gravel screening sieves. Diamond size sorting north and south of secondary point sources along the west coast has been well documented. However, based on diamond size distribution curves for CDM's raised beach deposits, by the time Chameis Bay has been reached, the diamonds have been well sorted (Figure 50 - seen by the flattening of the curve) and have an average size of about 0.2 ct/st to 0.3 ct/st (Schneider and Miller, 1993). Therefore, coast-perpendicular differences in average diamond size observed in the study area, at the same distance from the point source, cannot easily be accounted for by long-shore sorting by wave-action processes (Figure 88). Aeolian size sorting, well documented by Corbett (1989), coupled with the revised model presented here, can account for the differences noted in average diamond sizes at different sea-levels within the same area, in the following way:

- Aeolian processes erode raised palaeo-beach terraces located along the rim of an embayment or along a former shoreline deposited during former marine regressions (Corbett, 1989). The larger diamonds are generally located within micro-topographical features in the bedrock in the basal, coarser portion of the gravel horizon. A significant percentage of the smaller diamond population is also trapped within the basal unit, but can also occur scattered on finer-grained concentration surfaces throughout the upper portion of the gravel profile. This segregation occurs due to the difference in the hydrological properties between larger and smaller diamonds and the tendency of each to be deposited with gravel size fractions of equal hydrological equivalence. Therefore, the smaller diamonds within the upper portion of the profile can be mobilised and transported northward by aeolian processes long before the larger population, concentrated preferentially towards the base of the gravel sequence, is eroded from the terrace deposit and introduced into the corridor.

- Furthermore, there is a difference in the speed at which the different diamond size fractions can be transported by the wind (Corbett, 1989). The smaller diamonds can saltate during wind storms while the bigger diamonds tend to creep more slowly (Corbett, 1989). Furthermore, the smaller population will tend to be moved more frequently because less wind force is required to mobilise the smaller size fraction. The bigger, slower moving population also has a greater chance of being trapped in micro-topographical features within the corridors than the smaller, more mobile population. These aeolian processes can exacerbate the size sorting differentiation that occurs as the diamonds are transported northward along the corridors.

- The transport, which is largely a function of collision of saltating grains (Corbett, 1989), along the wind aligned corridors is relatively fast. Smaller diamonds can more easily be entrained on the stoss slope of barchan dunes that can move at rates of between 35 to 60 m per year (Corbett, 1989). Therefore, even at 2 m per year a diamond could move 1000 km in 0.5 million years. However, it is evident from Corbett's (1989) study that diamonds are likely to get stuck at bottle-necks and then remobilised at a later stage in a "*staccato*" type movement, making accurate estimation of rates of movement difficult. However, the abrasive power of the aeolian processes along the west coast can easily re-mobilise trapped diamonds, given time, transporting them further northward. During the 80 km traverse between


Av.Diamond Size vs Recovery Depth
ML103a
Average Diamond Size (Ct/St)
0.5
0.4
0.3
0.2
0.1
0
Note: A total of only 119 Cts was available for the calculation of average size
? Based on 6 diamonds
?
Note: onshore at 6 m amsl the diamond size average mined in this area was 0.07 Cts/St
35.5
45.5
61.5
62.5
65.5
66.5
68
68.5
68.5
69
69
69
70
73.5
75
75
75.5
75.5
76.5
86
86.5
88.5
88.5
91
97.5
Recovery Depth (m-bpsl)

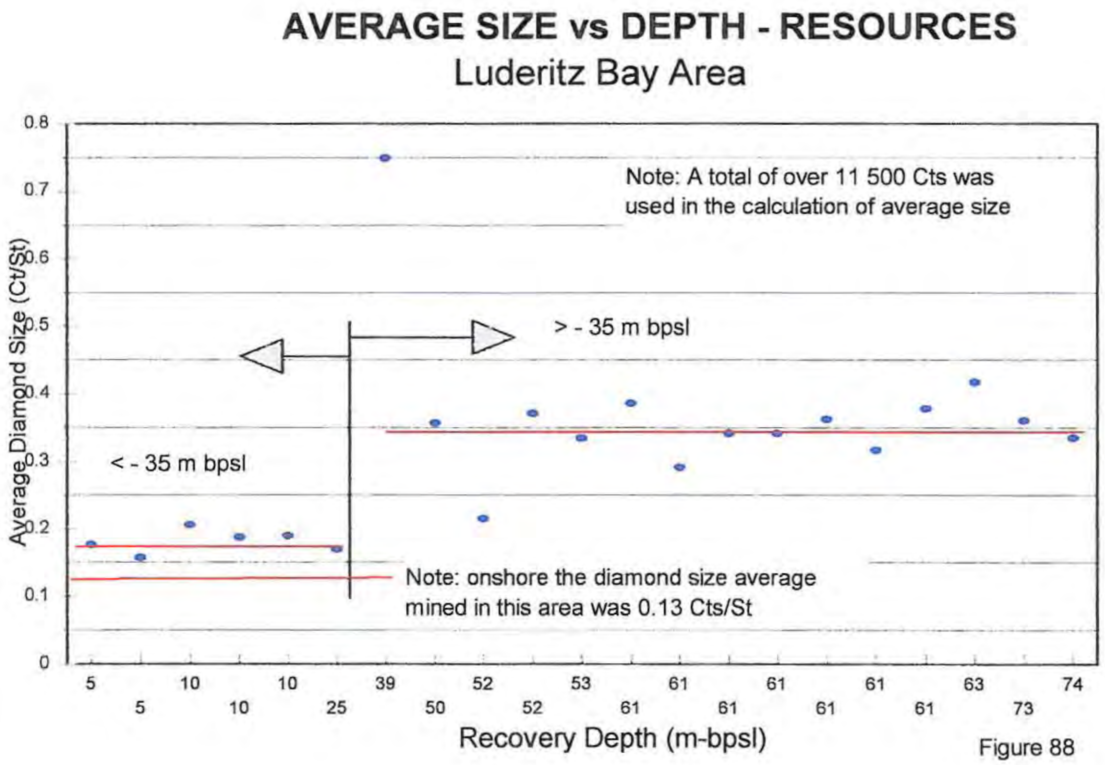

AVERAGE SIZE vs DEPTH - RESOURCES
Luderitz Bay Area
Average Diamond Size (Ct/St)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Note: A total of over 11 500 Cts was used in the calculation of average size
> - 35 m bpsl
< - 35 m bpsl
Note: onshore the diamond size average mined in this area was 0.13 Cts/St
5
5
10
10
10
25
39
50
52
52
53
61
61
61
61
61
61
61
63
73
74
Recovery Depth (m-bpsl)

Figure 88

Elizabeth Bay and the Koichab River, the smaller diamond population can easily be separated from the larger average sized, slower moving diamond population.

- It is postulated in the revised model that the smaller diamonds population could reach the coast-perpendicular ephemeral drainage thousands to tens of thousands of years before the larger population. Therefore it can be argued that this segregated smaller diamond population could be flushed into the sea by an isolated flash flood long before the larger diamond population has arrived. Given the rapid sea-level fluctuations during the Plio/Pleistocene period the proposed mechanism could explain variations noted in diamond size populations at different elevations in the HBG study area. That is, it can be postulated that the diamonds at the sea-level elevation present at the time the small diamonds are flushed out will, on average, be of a smaller size than those associated with the slower, larger average size, deposited by the ephemeral drainage at a later sea-level.

Presumably, similar size sorting processes could occur within the alluvial systems flowing from the interior as well, which would account for the coast-perpendicular average diamond size variations noted by Keyser (1972) at Alexkor, near the Orange River mouth. That is, soon after the onset of a wet period the smaller diamonds would be flushed out at the coast and be deposited at sea-levels present at that time, while the sea-level could have changed significantly by the time the larger average stone size population arrived at the coast.

- **The number of carats estimated to lie within the central Namibian inner shelf area:** - Pickford and Senut (1999) have dated the diamondiferous sediments in the Lower Orange River Valley as 19 Ma, suggesting the presence of diamonds along the southern Namibian coast since at least Miocene times (Refer: Section 5.2). Therefore it is probable that the Tsondab and Fiskus Sandstone Formations, deposited during the early stages of the Namib Desert Phase, would contain aeolian diamond deposits (Refer: Section 5.3.3). Considering that over 11 million carats were trapped and mined from the aeolian corridors north of Elizabeth Bay, it is not difficult to envisage, given the time frames, that many more diamonds must have passed through and must continue to be transported north of Kolmanskop. These deposits may be concentrated in specific localities, but as a whole, given the sand dilution, these deposits are most likely to be of low grade. Nevertheless, subsequent erosion of these underlying Tsondab sandstones by the modern Namib Sand Sea would introduce additional diamonds into the population moving northwards. Corbett (1989) postulates that diamond introduction could have occurred at numerous sea-levels both above and below present sea-level. Diamonds would be introduced into the corridor corresponding to that sea-level only to be shut off by a subsequent transgression or regression. The various corridors would intersect an ephemeral drainage at some point along the coastal plain, potentially enabling the build-up of diamonds at a number of localities along the river valley. While each intersection point may not necessarily contain a significant accumulation of diamonds, they could all be flushed seaward simultaneously during a single flash flood, resulting in the deposition of a large number of diamonds at the river mouth. As the proposed model is cyclical, the process can be repeated numerous times at different sea-levels. The duration of the process can account for the estimated resource/reserves defined along the central Namibian inner shelf.

- **Almost all the currently defined resource/reserve areas identified on the inner shelf between Lüderitz and Clara Hill (Refer: Figure 87):** - The majority of the marine diamond placer deposits that have been mined and most of the currently defined resource/reserve areas, north of the Kaukausib River mouth (Elizabeth Bay), Un-named drainage[3] (Lüderitz Bay, Diaz Reef[4], Halifax[3]), Koichab (Marshall Fork, Saddle Hill, ML 103A - Features 22, 12[5] and 13[5]), Tsauchab (Meob Bay) and Tsondab (Conception Bay) can be accounted for using the revised model.

- **The low number of exotic clasts associated with the diamondiferous gravels**: - Based on onboard logs and personal observation it is immedately apparent that there are very few "exotic clasts"associated (generally < 5%) with the diamondiferous gravels unlike the gravels further south nearer the mouth of the Orange River. The majority of these "exotics" are in the plantfeed sized material which could be transported by aeolian processes. Larger clasts are predominantly sub-angular to sub-rounded bedrock material that has been locally derived.

9.3 TARGET PRIORITISATION CRITERIA

The high costs associated with marine sampling restricts the number of target features and samples collected within each feature. It is therefore imperative that the best target features are selected and resources defined as soon as possible, particularly where publically owned exploration companies are relying on investors to continue to fund prospecting programmes. Target selection, prioritisation and well co-ordinated prospecting programme management are critical components in the longevity of marine diamond mining companies along the west coast.

A target prioritisation matrix can be derived once the controls on the formation of the placer deposit have been established. A good understanding of the model of placer formation and diamond distribution is essential in order to weight each matrix component correctly.

In order to minimise the number of samples used, the current trend is to first place widely-spaced, first-phase samples within the feature and then to collect second-phase, in-fill samples based on the initial results. Once sampling has been completed and results are available, the weighting of the parameters within the prioritisation matrix should be re-examined using hind-cast modelling. In this way the matrix can be fine-tuned and used to improve target selection and prioritisation in future prospecting programmes.

A matrix for target prioritisation, based on the detailed examination of the geological, geophysical and oceanographical data within the study area and adjacent onshore strip and the proposed model for marine

---

[3] The extrapolated flow direction of this drainage remnant bpsl. is not clear from the literature.

[4] As no drainage remnant is preserved in this area this deduction is speculative at this time.

[5] Further wind transport is likely to have been involved in the formation of these deposits.

placer formation in central Namibia, is presented below (Table 33). It is important to take economic considerations into account, as the feasibility of mining the target profitably is a function of these parameters. The average diamond value, mining rate, operating costs and mining technology employed would be some of the economical and engineering parameters to be considered. The numerous financial and engineering considerations necessary to facilitate proper evaluation of the economic extraction of the placer deposit are beyond the scope of this study and are not considered in the matrix. However, the most fundamental technical consideration in marine diamond mining, the overburden thickness, which impacts significantly on the prospectiveness of all targets, has been included.

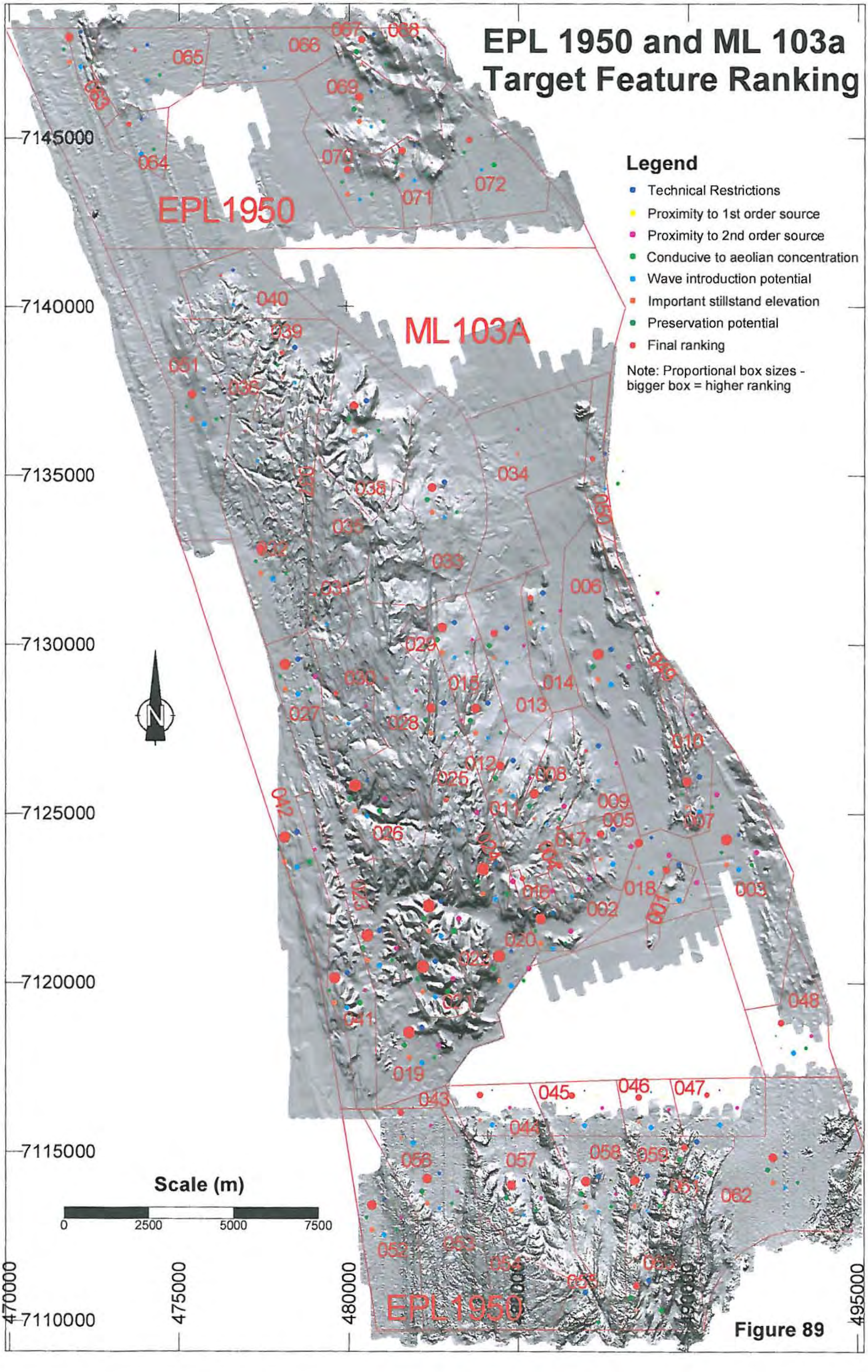
A ranking matrix (Table 33) has been compiled for the 72 features in HBG and Figure 89 gives a plan view representation of the rankings assigned to the feature for each category. Each parameter is colour coded and the size of the point is proportional to the ranking (i.e 1 = small and 3 = large dot - Refer: Figure 89)).

TABLE 33: Prioritisation matrix for the inner shelf of the central Namibia.

Factor	**Note Number**	**Requirements**	**Colour**
Technical restrictions	Note 1	Mineable area using existing mining technology	Blue
Proximity to a first order alluvial diamond point source	Note 2	Understanding of the drainage evolution of southern Africa and regional scale landscape evolution processes.	Yellow
Proximity to a second order alluvial diamond point source	Note 3	Understanding of the coastal evolution of the west coast and local scale landscape evolution processes.	Magenta
Proximity to an aeolian corridor	Note 4	Bathymetry and elevation map for the area	Lime
Conduciveness to diamond introduction by wave-action	Note 5	Aeolian, fluvial and sediment dynamics modelling	Cyan
Terrace levels and sea-level stillstands	Note 6	Map based on high resolution bathymetry and seismic interpretation and terrace level modelling	Orange
Preservation potential of the feature	Note 7	High resolution bathymetry and sediment dynamics modelling	Green
Overall ranking of the feature	Note 8	The cumulative total of parameters 2 to 7. Parameter 1 indicates how easily it can be mined	Red

Notes:

The formation of an enriched diamond placer deposit can be divided into two fundamental parts 1) diamonds must be passing through or deposited within the feature and 2) conditions within the feature must be conducive to the entrapment of the heavy minerals while the light material is removed. Parameters 2 to 6 deal with diamond introduction, while 7 evaluates diamond preservation.



EPL 1950 and ML 103a Target Feature Ranking

Figure 89

Note 1. Overburden thicker than 8 m would currently preclude economical extraction, thereby excluding the feature from further consideration. Mining rate is closely correlated with the profitability of a deposit and therefore most resources defined on the west coast do not exceed 5 m sediment thickness. The size of the feature is important in that large mining tools, working in the -30 m to -120 m water depth range, can only safely and economically mine in features that cover an area of greater than about 25 m^2. Should the feature contain very little or no sediment it too holds little potential for diamond recovery. Excessive shell and/or clay can complicate beneficiation, but do not preclude the feature from consideration. The ranking is based on the percentage of the sediment-covered portion of the feature that is less than 5 m and less than 8 m. The categories are: 1 = < 25% < 5 m and/or < 50% < 8 m or very little or no sediment in the feature; 2 = < 50% < 5 m and/or < 75% < 8 m; 3 = > 50% < 5 m and/or > 75% < 8 m. This would effectively give an indication of what percentage of the feature is prospective. Many of the features cover large areas and therefore cases may exist where a highly prospective small target is located within a feature that is poorly ranked overall. Each feature needs to be assessed using all the other criteria first, then assessed on its own merits using this parameter which is designed to give an indication of the practicality of mining the target economically.

Note 2. The geological understanding of the drainage evolution in southern Africa is still relatively poor, but as more studies and prospecting is undertaken so the understanding will improve (Refer: Section 4.2.2.2). Co-operation between diamond exploration and mining companies is improving and as more previously confidential data are shared, so the current models will be developed and target area selection enhanced. This parameter would be more pertinent when evaluating a number of licence areas along the west coast. Seeing as only HBG is being evaluated and the Orange River is the only drainage, that drains the interior, thought to have supplied diamonds to HBG it is not a critical component in this study. Therefore, all features have been given the same ranking with regard this parameter (i.e. all ranked 1).

Note 3. This ranking criterion is based specifically on the model proposed for central Namibia but could potentially apply to many of the coast perpendicular ephemeral drainages on the coastal plain along the west coast. In areas where wave-action processes dominate, e.g. immediately north of the Orange River mouth (Jacob, 2001) this factor may not be as important in the prioritisation of targets. Features proximal, immediately to the north of potential western extensions of ephemeral drainages are ranked 3; while those < 5 km are ranked 2; and if > 5 km away are assigned a ranking of 1.

Note 4. Northern closures of aeolian corridors and re-entrant embayments at the northern end of headland by-passes have been shown to be conducive to diamond placer formation (Corbett, 1989) along the central Namibia coastline. Aeolian placer formation would have been active on the inner shelf during periods of marine regression, re-working marine placer deposits, transporting diamonds further northward and depositing them once again. Sediment in linear depressions and embayments with topographical closures to the north, east and west have been assigned a ranking of 3; if bounded by rock to the north-east, north-west or east, 2; and if open to the north-east or north-west, 1.

Note 5. Parameter 5 looks at conduciveness of diamond introduction specifically by wave action. The sediment dynamic modelling of orbital velocity on the seafloor was used to assist in the quantification of this parameter where available in the SHP and HBP areas. Features that have high orbital velocity transport zones introducing diamonds into the feature from the west are ranked 3 if no bedrock obstruction which precludes introduction from the SSW to W quadrant exists; those with an obstruction are ranked 2 and features poorly suited to diamond introduction are ranked 1. No orbital velocity data are currently available in BMP and CHP and therefore a subjective assessment of this parameter in features in these areas was required.

Note 6. The revised model of marine placer formation presented in this thesis emphasises that the more regularly frequented, longer enduring still-stand elevations on the inner shelf of central Namibia have a better chance of being mineralised. The high potential elevations recognised in the detailed terrace level study in HBG are used to rank features from 3, which correlate well with an important still-stand elevation, to 1 where they cannot be correlated with still-stand elevations.

Note 7. This ranking criterion indicates the potential of the feature to retain diamonds deposited within it from subsequent marine, fluvial and aeolian re-distribution. Factors affecting the preservation potential of a feature would include a) How deep the feature has been eroded into the bedrock, b) orientation of the feature relative to the dominant storm direction, c) whether the deposit is capped by a protective layer (clay or indurated layer), d) size of the gravel clasts and gravel unit thickness e) bedrock micro-topography and f) whether the feature can be easily eroded by aeolian or local fluvial processes during marine regressions. The shape and morphology of the feature can be determined using the bathymetry and seismic data (i.e. bathymetry minus the sediment thickness gives the bedrock morphology). The sediment dynamics study results were used to corroborate assessments made in SHP and HBP. This critical parameter in the formation of marine placers was ranked from 3 (best preservation potential) to 1 (worst preservation potential).

Note 8. The overall ranking of the feature was determined by adding parameters 2 to 7 and then normalising the result to 5. Therefore 5 would be the perfect target feature, while 1 would indicate a poor feature. Figure 89 gives a colour coded visual indication of the ranking of the features together with their normalised score.

10. SUMMARY AND CONCLUSIONS

This thesis briefly reviews the history of diamond mining in southern Africa and the regional setting of the Namibian coastline and continental shelf. Models involving the origin and transport of diamonds to the west coast are examined in the context of potential secondary source points along the coast. Large- and small-scale processes that transported, winnowed and formed the diamond placer deposits are reviewed. Historical investigations in and adjacent to the study area are presented to augment the more recent geophysical survey interpretations. The detailed survey interpretations provide a sound platform for terrace level and sediment dynamic modelling. All the reviewed data and results are used to present a revised, poly-cyclic, holistic, model for marine diamond placer formation along the central Namibian inner shelf. A matrix for target delineation and prioritisation is derived from the revised model and applied within the study area.

There are currently divergent views on the origin of the west coast diamonds. The diamond source is fundamental in understanding the potential size, number and distribution of secondary point sources along the coast. The unravelling of post-Cretaceous landscape evolution in southern Africa is not an easy task due to the age of the deposits, the extensive erosion that has occurred and the resultant paucity of contiguous land surfaces. There is no unequivocal evidence to support the origin of the west coast marine diamonds being predominantly derived from the erosion of Dwyka tillite or from Cretaceous aged kimberlites but the numerous Cretaceous kimberlites in the interior of southern Africa are currently considered to be the dominant source of west coast diamonds.

The Orange and Olifants Rivers are recognised as the two major source points through which diamonds were introduced into the marine environment from their origin in the hinterland. However, diamond population distribution patterns along the west coast suggest that the currently recognised drainage evolution models proposed may be a bit simplistic. Other rivers that are also considered to have acted as significant secondary source points are the Holgat, Buffels, Swartlintjies, Spoeg, Groen and Ugab Rivers. The erosion of the early Tertiary sediments on the coastal plain, particularly the raised marine terraces at the 30 m, 50 m and 90 m elevations, are likely to have contributed to the marine placer deposits at lower elevations.

The intertwined roles of both the regional and smaller scale coastal processes and significance of aeolian, alluvial, and marine processes in the poly-cyclic enrichment of marine placer deposits along the west coast of southern Africa need to be understood in order to enable considered identification and prioritisation of target areas. Corbett (1989) showed that deposition and subsequent erosion of raised marine placers along the rim of embayments by the prevailing southerly winds, introduces diamonds into northerly trending aeolian corridors at specific sea-level stillstands. Furthermore, Corbett (1989) demonstrated that bedload size and shape sorting takes place by the incorporation of different populations into kinematic waves travelling at different speeds during phases of saltation and creep. He suggests that diamond concentration occurs where the northerly transport of diamonds is disrupted by micro-topographical features or bottle-necks and that erosion of higher elevation terraces and sheetwash processes within the aeolian corridors enrich the grade further. Ward's (1987) detailed description of the Cenozoic succession in the Kuiseb Valley is used to draw parallels and give insight into the processes that are likely to have occurred within the Koichab River, adjacent to the study area as they are located in very similar geomorphological settings. Based on these inferences, it is postulated that the Koichab River would have at some stage formed the northern boundary of the Namib Sand Sea and/or its Miocene aged predecessor the Tsondab Sandstone. Similar "flushing" episodes during sporadic flood events, followed by extended periods of aeolian deposition and river choking as interpreted from the Kuiseb River sediments (Ward, 1987) are postulated to have occurred in the Koichab River channel until its valley was finally totally in-filled.

A detailed bathymetry map of the area between Lüderitz Bay and Clara Hill covering 1 440 km^2 of the inner shelf was compiled. The bathymetry map of the study area was interpreted from a combination of swath and single beam echo-sounder data. From this interpretation it can be ascertained that the water depths in HBG area range from -20 m on the southeastern landward side of Blue Mountain Prospect (BMP) to -119 m along the seaward boundary. The bathymetry of the study area highlights two prominent, fine sediment-filled, coast-perpendicular depressions that divide the large coast-parallel ridges into segments. From the shaded relief map of the bathymetry it is evident that the morphology of the area is strongly controlled by the structure.

- BMP is characterised by prominent submarine northerly trending ridges separated by sediment filled basins. A 14 m to 18 m high, northerly trending reef in the -23 m bpsl to -56 m bpsl water depth range is located along the eastern edge of the study area HB Prospect (HBP).

- The water depth in Clara Hill Prospect (CHP) ranges from -40 m in the east to -91 m in the southwest. The bathymetry in CHP shows this area to be at similar depths to Blue Mountain East.

- In the northwest corner of the study area (HDP), a small bedrock outcrop, most likely a westerly remnant of the Precambrian basement and the northerly extension of the MWR in Saddle Hill Prospect (SHP) is present. The water depth in the HD Prospect (HDP) area ranges from -84 m in the east to -119 m in the west.

- The MWR, the most prominent feature in SHP, reaches a minimum depth of -50 m bpsl. Sediment/rock contact depth averages -68 m and -112 m bpsl along the eastern edge and western edges of this reef, respectively. Between the MWR and HBP there is a sediment filled basin that reaches a maximum water depth of -76 m.

Various methods were required to create the side-scan mosaics essential for interpretation. "Cut-and-paste" mosaics were made from photo-reduced thermal records for the early geophysical data while later mosaics were all digitally compiled. A sonographic facies discrimination system using seafloor micro-topography, developed by Marine and Coastal Geoscience (Pty) Ltd specifically to suit the needs of the west coast diamond exploration industry, was used for all side-scan sonar interpretations.

- The BMP area comprises a number of north-south-trending ridges separated by large sediment filled depressions. Approximately 30% of the area is sediment covered.

- The HBP area that lies along the eastern margin of SHP has three predominantly low rock (LR) to subdued rock (SR) outcrops named HB North (HB-N), HB Central (HB-C) and HB South (HB-S) separated by fine sand (fs).

- Onshore, abutting the shoreline, there are a number of hillocks forming a headland at Clara Hill. The large reef named CHP, comprising mainly low rock (LR) surrounded by fine sediment (fs), forms the offshore extension of the headland.

- Three small LR to moderate rock (MR) reefs occur in the northwestern corner of the study area (HDP). They are surrounded by fs with phosphatic sediments evident along the western edge of the area, in water depths exceeding -112 m bpsl.

- In SHP the MWR, though bathymetrically significant, is relatively smooth on a micro-topographical scale comprising predominantly LR. The relatively limited number of structural features present have been exploited by erosional forces to form fs, coarse sand (cs) and coarse sediment veneer (csv) filled gullies, mega-gullies and dendritic shaped features. In the lee of this large reef (MWR) lies a predominantly fs-filled basin.

Good quality, high resolution seismic interpretations form an integral part of successful diamond placer target delineation and prioritisation on the inner shelf of the west coast. Sediment isopach maps of acoustic basement were interpreted from a combination of digital and analog chirp, pinger, boomer and airgun records. In certain areas the pinger and airgun spot-depths correlated poorly because of the pinger's inability to penetrate surficial indurated horizons which could easily be penetrated by the more powerful airgun.

- For the eastern two thirds of BMP the majority of the interpreted pinger and airgun bedrock spot depths correspond well. However, toward the west of this area the seismic stratigraphy is more complex with the pinger's acoustic signal terminating on an internal horizon far shallower than the Precambrian bedrock detected by the airgun. Along the northwestern edge of BMP, sediment thicknesses reach a maximum of 28 m while in the central and eastern portions maximum thicknesses of 10 m to 13 m are reached. Seismic penetration of the coarse sediments located in the numerous northerly trending linear depressions in BMP was poor but results have been interpreted, based on limited penetration, to be less than 3 m to 5 m thick and these areas are therefore highly conducive prospecting targets.

- The seismic stratigraphy in HBP was relatively straightforward with sediment thicknesses increasing rapidly along the western edge of the northerly trending reefs as well as to the north and south of these reefs. Along the western and northwestern edge of HB-N a deep sediment trough is present reaching up to 25 m thicknesses, excluding this area from diamond extraction using present mining techniques.

- For CHP, pinger and airgun bedrock spot depths corresponded well and show the Precambrian basement dips relatively steeply to 17 m beneath the seafloor, towards the west of Clara West and to 8 to 12 m to the west of Clara East. Sediment thickness in the SE corner south of Clara East reach a maximum of 25 m, rise to about 8 m to the south of Clara West, then dip down to a maximum thickness of about 18 m, southwest of Clara West, before rising again to about 12 m along the western edge of this area.

- Along the western boundary of HDP the airgun penetrated surficial indurated horizons and resolved the Precambrian bedrock at about 58 m below the seafloor. This westward dipping basement bedrock outcrops in the south (MWR) and north of the HDP area. Along the western boundary of HDP an indurated horizon precluded penetration by the pinger, except in those areas where patches of mud were present or where the indurated surface was eroded or pinched out. This indurated horizon has similar acoustic properties to other horizons, occurring at similar depths elsewhere in the study area, interpreted as being phosphatic pavement. Gently westward dipping, acoustically transparent Holocene muds have been deposited into the recess formed by the more steeply dipping Precambrian basement, along the eastern edge of HDP.

- Large coast-perpendicular, thick (>5 m) sediment covered areas are present to the south, northeast and north of the MWR separating the bedrock in SHP from that in BMP and CHP and HDP respectively. The sediment in the coast-parallel linear depression that separates the MWR from HBP is on average < 5 m thick, making it highly conducive for marine diamond placer exploration.

Marine placers are formed along palaeo-strandlines during periods of marine transgression and regression making eustatic and local sea-level fluctuations important components in the exploration and evaluation of marine placer deposits on the inner shelf. The detailed bathymetry map for the area between Lüderitz and Clara Hill allows for the thorough investigation of the terrace levels off the central Namibian coast. Well defined nick-points eroded into coast-parallel reefs were used as the main criteria to decide the position of the most prominent still-stand elevations and detailed modelling has highlighted the -20 m, -35 m, -55 m, -65 m, -75 m, -82 m, -87 m, -100 m and -112 m levels as being the best developed terrace levels. These levels correspond well with 75 m bpsl drop (75 000 and 58 000 ya) noted by Andel and Tzedakis (1996), the 20 m bpsl (47 000 and 25 000 ya) stillstand recognised by Tankard (1976) and Murray *et al.* (1970) and the -18 m to -24 m terrace level interpreted by O'Shea (1971) and the -70 m bpsl drop (39 000 to 36 000) proposed by Andel and Tzedakis (1996). If the 13 m thick Holocene mud, wedged up against the Precambrian bedrock, is added to the -112 m depth interpreted from the bathymetry then the Pleistocene (19 000 to 18 000 ya) eustatic sea-level of -123 m to -130 m depth range (Emery and Garrison, 1967; Tija, 1963) also corresponds well. On the west coast, following years of sampling, mining and resource delineation, particular terrace levels can be associated with increased diamond occurrence. Many of these terrace levels occur within the depth range of HBG. Resources identified in the same region lie predominantly in the -52 m to -55 m, -62 m to -66 m, -72 m to -73 m and -75 m to -77 m water depth ranges and correlate well with the sea-levels identified. The lack of resources identified in water depths shallower than 25 m is due to the fact that the mining companies active in the area have not yet focussed on these areas due to technical considerations relating to airlift mining. However, many diver operators have mined, *ad hoc*, within the 0 m to -25 m bpsl water depth range.

In a even more detailed study of HBG, over one thousand nick-points were identified from coast-perpendicular bedrock profiles. As not all inflections noted on the bedrock are necessarily indicative of wave eroded terraces, the frequency, terrace width, coast-parallel continuity, gradient and rank were used to distinguish the well- from the poorly developed terraces. The -113 m,-103 m, -98 m,-94 m/-95 m,-86 m/-87 m,-80 m,-74 m/-75 m,-70 m, -64 m/-65 m, -58 m/-59 m, -46 m and -31 m have been identified as being best developed within the study area.

Sediment dynamic studies involve the use of accredited application software and formulae for wave refraction modelling, to determine the wave angle and orbital velocity at the seabed. The wave angle and orbital velocity are closely related to the bedload transport direction and entrainment velocity of sediment grains on the seafloor. Orbital velocities required to move diamonds of specific sizes can be empirically determined and therefore areas of diamond entrainment, transport and deposition can be modelled and targets identified. The sediment dynamic results show that on a broad scale, diamond deposition trends can be simulated. Therefore, they can effectively be used to select and prioritise target features in the presently un-sampled portions of HBG.

The detailed literature review, geophysical interpretation, terrace level study and sediment dynamic modelling presented provides a sound platform for evaluating process models for diamond placer formation in central Namibia. A revised, holistic hypothesis for the concentration of diamonds along the central Namibian coastal plain into discrete, marine diamond placer deposits can be summarised as follows:

1) Diamonds, predominantly from Cretaceous aged kimberlites, were eroded in the interior of southern Africa, transported by the Kalahari River and deposited at the Orange River mouth.

2) The Orange River deltaic front was eroded by the storm swell, and diamondiferous gravels would have been deposited along palaeo-shorelines during marine transgressions and regressions, at levels both above and below present sea-level, to the north and south of the Orange River mouth.

3) From Chameis Bay to Elizabeth Bay, due to the more northwesterly orientation of the coastline and a headland formed by a topographical high, aeolian influences would have played a more dominant role in the northward transport of diamonds, though marine processes remained operative.

4) Diamondiferous gravels were transported northward by wave action and deposited by refracting waves along shorelines and the rims of north and south facing embayments.

5) The strong southerly gales eroded the raised beach placers in southern Namibia and introduced diamonds into northerly trending aeolian corridors.

6) A percentage of the diamonds creeping and saltating northward along wind corridors extending northwards from Elizabeth Bay and other localities along the southern Namibian coastline, were concentrated into aeolian placers deposits where suitable trapsites occur. However, it is proposed that numerous diamonds were transported further northwards by aeolian processes, beyond the areas mined south of Lüderitz, within

the Tsondab and Namib Sand Sea systems.

7) Northward transport of the diamonds along the aeolian corridors and within the sand seas continued until a coast-perpendicular perennial/ephemeral drainage was intersected. The water (when flowing), wind shadow (coast-perpendicular depression formed by the river valley), vegetation, and bedrock rubble (deposited by prior floods draining from the escarpment) preferentially trap the creeping and saltating diamonds, while the lighter sediments continue northwards or westwards by aeolian or fluvial processes (when flowing), respectively. The diamonds accumulated within the river valley until a flash flood on the escarpment flushed them into the sea and deposited them at the particular sea-level elevation of that time.

8) Owing to the sporadic nature of the flash floods in the arid conditions along the west coast, the resultant diamond deposition at the river mouth may have occurred at different sea-level elevations, particularly considering the rapidity of sea-levels fluctuations in the Plio/Pleistocene period.

9) The order in which the proposed process occurred is important in evaluating the relative ages of the marine placer deposits. Given the geometry of the Namib Sand Sea and the dominant southerly wind direction, it is probable that the evolution of this diamond placer formation process would have started in the south and progressed northwards as each ephemeral drainage was overcome by the northward migrating sand of the Namib, and its valley filled-in.

10) Diamonds deposited into the swash zone by these ephemeral drainages during the flash floods would have subsequently winnowed into placer deposits within suitable bedrock trapsites, predominantly to the north of the river mouths. Redistribution and concentration by wave-action processes formed marine placer deposits in features conducive to diamond introduction and also having high preservation potential.

The model that falls within the geomorphic evolution of southern Africa and the Namibian coastal plain, addresses the issues of placer location on the inner shelf between Lüderitz and Clara Hill as well as accounting for the average diamond size variations observed at different sea-levels in the study area. Based on this model a matrix for the delineation and prioritisation of marine placer deposits on the inner shelf is developed and applied to the study area. The top ten target features identified in the study area are, in order from highest to lowest; Features 22, 24, 21, 26, 19, 20, 23, 2, 6 and 3. These rankings compare favourably with sampling results and resources identified within HBG. Features 12, 8 and 15, which also have moderate sampling results, are ranked within the top 20 out of 72.

The revised model for the evolution of marine placer deposits presented in this thesis was devised using information from the central Namibian inner shelf and therefore should be appropriate for target selection and prioritisation within this region. However, it is possible that the same processes were active all along the west coast and that the revised model and therefore the prioritisation matrix is applicable in these areas, particularly the marine placer deposits along the northern Namibian coast, which appear to have been formed in a similar way to that proposed for the study area. However, other deposits along the west coast should be examined in detail, assessed on their own merits and the prioritisation matrix modified accordingly, before being unilaterally applied.

REFERENCES

African Mining, 2001. Mount Burgess on the trail of diamonds at Tsumkwe. In: **African Mining:** Arther Tassel (Ed.), **Revealing Africa's Mineral Wealth**. Brooke Pattrick Publishing (Pty) Ltd. 6 (6): 40.

African Mining, 2002. Country Focus: Namibia - Mount Burgess Mining. In: Arther Tassel (Ed.), **African Mining: Revealing Africa's Mineral Wealth**. Brooke Pattrick Publishing (Pty) Ltd. 7(4): 12-13.

Adams, J., 2002. Sudden climatic transitions during the Quaternary. **WWW.members.cox.net/quaternary.** (Unpub.).

Allsopp, H.L., 1986. Cited In: Moore, J.M. and Moore, A.E. (in prep). The Roles of Primary Kimberlitic and Secondary Dwyka Glacial Sources in the Development of Alluvial and Marine Diamond Deposits in Southern Africa.

Allsopp, H.L., Bristow, J.W, and Skinner, E.M.W., 1985. The Rb-Sr geochronology of the Colossus kimberlite pipe, Zimbabwe. **Trans. of the Geol. Soc. of S. Afr.**, 88: 245-248.

Allsopp, H.L., Bristow, J.W, Smith, C.B., Brown, R., Gleadow, A.J.W., Kramers, J.D and Garvie, O.G., 1989. A summary of radiometric dating methods applicable to kimberlites and related rocks. In: Kimberlites and related rocks, their composition, occurrence, origin and emplacement. Vol. 1, Ross, J. (Ed). Proceedings of the Fourth International Kimberlite Conference, Perth, 1986, **Geol. Soc. of Austr.,** 14: 343-357.

Andel and Tzedakis, 1996. Cited In: Adams, J., 2002. Sudden climatic transitions during the Quaternary. **WWW.members.cox.net/ quaternary.** (Unpubl..).

Bagguley, J.G., 1996. **The Application of Seismic and Sequence Stratigraphy to the Post-Rift Megasequence Offshore Namiba**, Unpublished PhD. Thesis, Oxford Brookes University.

Beetz, W., 1926. Die Tertiärablagerungen der Küstennamib. In: E. Kaiser (Ed.). **Die Diamantenwüste Südwest-Afrikas**, D. Remeir, Berlin, 2: 1-54. (Cited in Pickford and Senut, 1999).

Beetz, W., 1938. Farms near Brandvlei, Calvinia District, optioned by Anglo Transvaal Company: Unpublished internal memorandum, De Beers Consolidated Mines, p. 1-8. (Cited in De Wit, M.C.J, 1999.)

Bestler, H., 1996. **Stuttgarter Geographische Studien**. 96: 241.

Bestler, H., 1996. The Tsondab Sandstone in Namibia and its significance for the Namibian Erg. **South African Journal of Geology**, 99: 77-87.

Besler, H. and Marker, M. E., 1979. Namib Sandstone, a distinct lithological unit. **Transactions of the Geological Society of South Africa**, 82: 155-160.

Birch, G. F., 1975. **Sediments on the Continental Margin off the West Coast of South Africa.** Unpublished PhD Thesis, University of Cape Town, 210pp.

Blom, L. W. R., 1976. Verslag oor die geohidrologie van die Koichabvallei en Anigab en die watervoorsiening aan Luderitz. **Internal Report, Department of Water Affairs**.

Boyd, A. J., 1983. Intensive study of the currents, winds and hydraulogy at a coastal site off central South West Africa, June/July 1978. **Investigative Report, Sea Fisheries Research Institute, South Africa**, 126: 1-47.

Bradley, W.C. and Griggs, G.B., 1976. Form, genesis and deformation of central Californian wave-cut platforms. **Geological Society of America Bulletin**, 87: 433-449.

Bremner, J. M., 1981. Surficial Sediments of the Continental Margin of South West Africa (Namibia). **Joint Geological Survey/University of Cape Town Marine Geoscience Unit Bulletin**, 10: 1-233.

Buckley, R., 1987. The effect of sparse vegetation on the transport of dune sand by wind. **Nature** 325: 426-428.

Burger, A. J. and Coertze, F. J., 1973. Radiometric age measurements on rocks from Southern Africa to the end of 1971. **Bulletin of the Geological Survey of South Africa**, 58: 46pp.

Clement C.R., Harris, J.W., Robinson, D.N. and Hawthorn, J.B., 1986. The De Beers kimberlite pipe - a historic South African mine. In: Anhaeusser, C.R and Maske, S. (Eds.), Mineral Deposits of Southern Africa. **Geol. Soc. of S. Afr.**, Vol II: 2193-2214.

Clifford,T.N., 1966. Tectono-metallogenic units and metallogenic provinces of Africa. **Earth and Planetory Science Letters**. Vol. 1: 421-434.

Cole, D.I., 1998. Diamonds in the SADC region. Mining Sector Co-ordinating Unit, Mineral Resources Survey Programme, No. 3 Project AAA 1.2, 36. In: Venter, L. J., 1998. **A Review of Southern African Kimberlites and Exploration Techniques.** Unpublished Masters Dissertation, Rhodes University 120pp.

Compton, J., Harris,C. and Thompson, S., 2001. Pleistocene dolomite from the Namibian shelf: High $^{87}Sr/^{86}Sr$ and $\sigma^{18}O$ values indicate and evaporative, mixed water origin. **Journal of Sedimentary Research,** Vol.71, September 2001: 800-808.

Cooper, G., 1990. Report on prospecting operations in Prospecting Grant Areas M46/3/1673 and M46/3/1674 during 1989. Tidal Diamonds (Pty) Ltd. **Report to Ministry of Mines and Energy, Windhoek, Namibia**, 25pp.

Corbett, I. B., 1989. The Sedimentology of Diamondiferous Deflation Deposits within the Sperrgebiet, Namibia. **Unpublished PhD Thesis, University of Cape Town**, 420pp.

Corbett, I. B., 1990. The modern and ancient pattern of sandflow through the southern Namib deflation basin. **Special Publication of the International Association of Sedimentologists**, 16: 45-60.

Corbett, I.B., 1993. The modern and ancient pattern of sandflow through the southern Namib deflation basin. **Special Publication of the International Association of Sedimentologists**, 16: 45-60.

Corbett, I. B., 1996. A review of the diamondiferous marine deposits of western southern Africa. **African Geoscience Reviews**, 3: 157-174.

Corbett, I. B., Ward, J., Pickford, M. and McMillan, I., 1995. Applications of sequence stratigraphy to the high-energy arid continental margin of south-western Africa. **Abstracts Centennial Geocongress (1995) Geological Society of South Africa**, Rand Afrikaans University, Johannesburg, South Africa, 871pp.

Cox, K. G., 1978. Kimberlite pipes. **Scientific American**, 238(4): 120-132.

Dalrymple, R. A., 1988. Model for refraction of water waves. **Journal of Waterway, Port, Coastal, and Ocean Engineering**, 114(4): 423-435.

Dauphin, Y., Pickford, M. and Senut, B., 1993. Des Oeufs géants en quête d'identitité. **La Recherche**, 24: 1408-1409. In: Corbett, I. B., 1996. A review of the diamondiferous marine deposits of western southern Africa. **African Geoscience Reviews**, 3: 157-174.

Dauphin, Y., Pickford, M. and Senut, B., 1993. Diagenetic changes in the mineral and organic phases of fossil avian eggshells from Namibia. **Applied Geochemistry**, 13: 243-256.

Day, R.W., Franzsen, A.J. and Rogers, J., 1992. Coast-parallel palaeochannels off southern Namibia. **Marine Geology**, 105: 299-304.

Dean, R. G and Dalrymple, R. A., 1984. **Water Wave Mechanics for Engineers and Scientists**, Prentice-Hall, Englewood Cliffs, N.J., 353pp.

De Beer, J.H., Blume, J. and Coetzee, V. D. A., 1986. Time-domain electromagnetic and direct current resistivity surveys in the Koichab and Anigab areas, South West Africa. **Internal Report, Department of Water Affairs of South West Africa/Namibia**. 38pp.

De Beers Geological Department, 1976. Diamonds. In: Coetzee, C.B. (Ed.), **Mineral Resources of the Republic of South Africa, 5th Edition**. South African Geological Survey 17-30.

De Decker, R.H., 1986. 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** 86: 1-99.

De Decker, R.H., 1993. The Diamond Potential of Prospecting Grant Areas M46/3/1946 and M46/3/1950 off the Coast of Namibia. **Unpubl. Internal report for Arena Mining (Pty) Ltd.** 19pp.

De Decker, R.H., 2001. An Independent Due Diligence Report on the Sea Diamond Project of Diamond Fields International. **Technical Report for OPIC.** 59pp.

De Decker, R.H., 2002. Technical report on the marine diamond properties of Namibian Minerals Corporation off the southern African west coast. **Technical Report for the Ontario and British Columbia Securities Commissions**, 1 - 92.

De Decker, R.H., and Woodborne M.W, 1996. Geological and Technical Aspects of Marine Diamond Exploration in Southern Africa. **Abstracts Offshore Technology Conference 8018, Houston Texas, USA, 6-9 May 1996**, 561-572.

De Villiers,J. and Söhnge, P.G, 1959. The Geology of the Richtersveld. **Memoirs of the Geological Society of South Africa**, 48: 1-266.

De Vriend, H., 1999. Sediment Transport and Morphodynamics. In: Mocke, P. (Ed)., **Fifth International Conference on Coastal and Port Engineering in Developing Countries, Cape Town 16 -17 April 1999**. COPEDEC V, 2.1 - 2.14.

De Wit, M.C.J, 1993. **Cainozoic Evolution of Drainage Systems in the North Western Cape.** Unpublished PhD Thesis, University of Cape Town, 371pp.

De Wit, M.C.J, 1996. The distribution and stratigraphy of inland diamond deposits in South Africa, In: Kogbe, C. A., (Ed.), **Diamond deposits in Africa: Special edition of Africa Geoscience Review**, 101-118.

De Wit, M.C.J, 1999. Post-Gondwana Drainage and the development of Diamond Placers in Western South Africa. **Economic Geology**, 94: 721-740.

De Wit, M.C.J., Marshall, T.R. and Partridge, T.C., 2000. Fluvial Deposits and Drainage Evolution. _*In:* Partridge, T.C. and Maud, R.R. (eds). **The Cenozoic of Southern Africa**. Oxford University Press, Inc (New York), 3-18.

Diester-Haas, L., meyers, P.A. and Rothe, P., 1990. Miocene history of the Benguela Current and Antarctic ice volumes: Evidence from rythmic sedimentation and current growth across the Walvis Ridge (Deep Sea Drilling Project Sites 362 and 532). **Paleoceanography**, 5(5): 685-707.

Dingle, R.V, 1973a. The Geology of the Continental Shelf between Lüderitz and Cape Town (South West Africa), with special reference to Tertiary Strata. **Journal of the geological Society of London**, 129: 337-363.

Dingle, R.V, 1983. Structural and sedimentological development of the continental margin off southwestern Africa. **Communications of the Geological Survey of Namibia**, 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**, 56: 13-26.

Dingle, R.V. and Scrutton, R.W., 1974. Continental breakup and the development of post-Palaeozoic sedimentary basins around southern Africa. **Bulletin of the Geological Society of America**, 85: 1467-1474.

Dingle, R.V., Siesser, W.G. and Newton, A.R., 1983. **Mesozoic and Tertiary geology of southern Africa**. A.A. Balkema, Rotterdam, 375pp.

Dixey, F., 1938. Some observations on the physiographic development of central and southern Africa. **Trans. of the Geol. Soc. of S. Africa**, 41: 113-172.

Du Toit, A.L., 1910. The evolution of the river system of Griqualand West. **Transactions of the Royal Society of South Africa**, 1: 347-362.

Du Toit, A.L, 1952. Die diamanddraende gruis van Lichtenburg. **Memoirs of the Geological Survey of South Africa**, 44: 1-51.

Edwards, C.B. and Howkins, J.B., 1966. Kimberlites in Tanganyika with special reference to the Mwadui occurrence. **Economic Geology**, 61: 537-554.

Emery, K. O. and Garrison, I. E., 1967. Sea levels 7,000 to 20,000 years ago. **Science**, 7: 684-687.

Flemming, B.W., 1976. Rocky Bank, Evidence for a relict wave-cut platform. **Annals of the South African Museum**, 71: 33-48.

Flemming, B.W., 1977. Depositional processes in Saldanha Bay and Langebaan Lagoon. **Bull. joint Geol. Surv./Univ. Cape Town, Marine Geoscience.**, 26: 177-198

Flemming, N. C. and Roberts, D. G., 1973. Tectono-eustatic changes in sea-level and seafloor spreading. **Nature**, 243: 19-22.

Frans-Odendaal, 2002. Palaeopathology in the pliocene fossil record: an analysis of the dental pathologies in the herbivores of the Langebaanweg and palaeoenvironmental reassessment. Unpublished PhD thesis. UCT Department of Zoology. Cited In: Pether, J. 2002. **Report to NDC**. Internal Report. 17pp.

Gardiner, D.E., 1955. Beach-sand heavy mineral deposits of eastern Australia. **Austr. Bur. Min. Res. Geol. Geophys. Bull.**, 28.

Gevers, T. W, 1953. On the Occurrence of Diamonds in Area No.2, South West Africa. **Internal report for Industrial Diamonds of S.A. Ltd.**, 1-45.

Gobba, J. M., 1989. Kimberlite exploration in Tanzania. **Journal of Africa Earth Sciences**, 9, 565-578

Gómez-Pina, G., 1999. Beach Norishment. In: Mocke, P. (Ed)., **Fifth International Conference on Coastal and Port Engineering in Developing Countries, Cape Town 16 -17 April 1999**. COPEDEC V, 6.1 - 6.48.

Gurney, J.J., Levinson, A.A. and Smith, S.H., 1991. Marine mining od diamonds off the west coast of southern Africa. **Gems and Gemology**, Vol 27, 4: 206-219

Hallam, C.D, 1964. The geology of the coastal diamond deposits of Southern Africa **(1959)**. In: Haughton, S.A. (Ed.). **The Geology of Some Ore Deposits in Southern Africa**, **Publications of the Geological Society of South Africa**, 2: 671-728.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1987. Chronology of Fluctuating Sea Levels since the Triassic. **Science**, 235, 1156-1166.

Haughton, S. H, 1931. The Late Tertiary and Recent Deposits of the West Coast of South Africa. **Transactions of the Geological Society of South Africa**, 34: 19-58.

Hawthorne, S., 1975. Model of a kimberlite pipe. **Physics and chemistry of the earth**. Vol.9: 1-15.

Hendey, Q.B.,1984. Southern African Late Tertiary Vertebrates. In: Klein, R.G. (Ed.), **Southern African prehistory and palaeoenvironments**, 81-106.

Hendey, Q. B. and Volman, T. P., 1986. Last interglacial sea levels and coastal caves in the Cape Province, South Africa. **Quaternary Research**, 25: 189-198

Hinde, C. (unknown). A newspaper article entitled "NAMIBIAN DIAMONDS". **Archives of the Namibian Geological Survey**, 1-2.

Jackson, J. A., 1997. (Ed.) **Glossary of Geology**, Fourth Edition. American Geological Institute, Alexandria, Virginia, 1997.

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**, 94: 749-758.

Jacob, R.J., 2001. Late Proterozoic Bedrock Geology and its Influence on Neogene Littoral Marine Diamondiferous Trapsites, MA1 - Sperrgebiet, Namibia. **Unpublished MSc Thesis, University of Cape Town**, 134pp.

Janse, A.J.A. and Sheahan, P.A., 1995. Catalogue of world wide diamond and kimberlite occurrences: a selective and annotative approach. In: Griffin, W. L. (Ed.). **Diamond Exploration: Into the 21st Century. Journal of Geochemistry Exploration**, 53: 73-111.

Janse, A.J.A., 1985. Kimberlites - where and when. In: **Kimberlite occurrence and origin: A basis for conceptual models in exploration**. Glover, J.E and Harris, P.G. (Eds.) Geol. Dept./Univ. Ext, Univ. Of W.A., Publ: 8, 19-61

Joyce, P and Scannel, T, 1993. Diamonds in Southern Africa. **Struik Publishers**, 1-23.

Kaiser, E., 1926. Die Diamantenwüste Südwest-Afrikas. D. Reimer, Berlin. Vol I, 321pp and Vol II, 256pp. In: Pickford, M. and Senut, B., 1999. Geology and Palaeobiology of the central and southern Namib Desert southwestern Africa. **Memoir of the Geological Survey of Namibia**, 18: 1-155.

Kashabano, J.B., 1989. Ion probe U-Pb perovskite dating of the Bubiki kimberlite, Tanzania. **Report for the Geol. Surv. of Tanzania**.

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**, 54: 1-23.

Keyser, U., 1976. Diamonds - Marine (coastal) Deposits. In: Coetzee, C. B. (Ed). **Mineral Resources of the Republic of South Africa (5th edition)**. Government Printer, Pretoria 27-30.

Kilham, J. C. L., 1992. Sperrgebiet Excursion CDM Mining Area 1. **Unpublished Report, Consolidated Diamond Mining, Ore Reserves Department, Geology Section**, 8pp.

King, L.C., 1941. The Monoclinal coast of Natal, South Africa. **Journal of Geomorphology**, 3: 144-153.

King, L.C., 1944 Geomorphology of the Natal Drakensberg. **Transactions of the geological Society of South Africa**, 47: 255-282.

King, L.C., 1947. Landscape study in southern Africa. **Proceedings of the Geological Society of South Africa**, 50: xxiii-lii.

King, L.C., 1949. On the ages of African land-surfaces. **Quarterly Journal of the Geological Society of London**, 104(4): 439-453.

King, L.C., 1951. **South African Scenery, 2nd Edition**. Oliver and Boyd, Edinburgh, 379pp.

Kirkley, M. B., Gurney, J. J and Levenson, A. A., 1991. Age, Origin and Emplacement of Diamonds: Scientific Advances in the Last Decade. **Gems and Gemnology**, Vol. 27(1): 2-25.

Kleinhans, D., Dale, D. C., and McMillan, I. K., 1995. Core description and micropalaeontology results of the Spencer Bay Voyage 142. **Internal Report, De Beers Marine** 258, 1-44. In: Corbett, I. B., 1996. A review of the diamondiferous marine deposits of western southern Africa. **African Geoscience Reviews**, 3: 157-174.

Kocurek, G., Lancaster, N., Carr, M. and Frank, A., 1999. Tertiary Tsondap Sandstone Formation: preliminary bedform reconstruction and comparison to modern Namib Sand Sea dunes. **Journal of Earth Sciences**, Vol. 29, 4:629-642.

Komar, P. D., 1976. The transport of cohensionless sediments on continental shelves. In: Stanley, D.J., and Swift, D.J.P., (Eds.). **Marine Sediment Movement and Environmental Management**. New York, John Wiley, 107-125

Komar, P. D. and Miller, M. C., 1975. Sediment threshold under oscillatory waves. **Proceedings of the 14th Coastal Engineering Conference**, Copenhagen, Denmark 1974, 756-775.

Kröner, A. and Jackson, M.P.A, 1974. Geological reconnaissance of the coast between Lüderitz and Marble Point, South West Africa. In: Kröner, A., (Ed.). **Contributions to the Precambrian geology of southern Africa**. Bulletin of the Precambrian Research Unit, Dept. Of Geology, University of Cape Town. 15: 79-103.

Kuhns, R., 1995. Sedimentological and geomorphological environments of the western South African continental shelf and its control and distribution of alluvial/marine diamonds. **Proceedings of the Annual Meeting of the Society for Mining, Metallurgy and Exploration**, Denver, Colorado (March 6 - 9, 1995).

Lancaster, N., 1984. Palaeoenvironments in the Tsondab Valley, central Namib Desert. **Palaeoecology of Africa**, 16: 411-419.

Lavelle, M., 1995.Cenozoic palaeo-oceanography of the Benguela System, southeast Atlantic. Sedimentology, palaeontology and stratigraphy. **Unpublished PhD. Thesis**, University of Cape Town.

Lavelle, M. and Amstrong, R.A., 1993. Strontium dating of marine sediments along the west coast of southern Africa. **Jour. S. Afr. Sci.**, 89, 533-536.

Le Roux, D.M., 1986. Geostatistics on the alluvial diamond mine at Alexander Bay. **Internal Report, Alexcor.**

Levinson, A.A., Gurney, J.J. and Kirkley, M.B., 1992. Diamond sources and production: past, present and future. **Gems and Gemology**, Vol. 28, 4: 234-254.

Li, Z. and Komar, P. D., 1992a. Longshore grain sorting and beach placer formation adjacent to the Columbia River. **Journal of Sedimentary Petrology**, 62: 429-441.

Li, Z. and Komar, P. D., 1992b. Selective entrainment and transport of mixed size and density sands: flume experiments simulating the formation of black-sand placers.

Light, M., Maslanyj, M. and Banks, N., 1992. New geophysical evidence for extentional tectonics on the divergent margin offshore Namibia. In: Storey, B.C., Abalaster, T. and Pankhurst, R.J. (Eds). Magmatism and the causes of Continental Break-up. **Geological Society of London Special Publication**, 71: 163-191.

Lotz, H., 1909. Uber die Luderitzbuchter diamantvorkommen. **Zeitschr. F. Prackt. Geol**, 17: 142. In: Pickford, M. and Senut, B., 1999. Geology and Palaeobiology of the central and southern Namib Desert southwestern Africa. **Memoir of the Geological Survey of Namibia**, 18: 1-155.

Lyle, L., Schrandt, R. L. and Schneider, N. F., 1974. How aerodynamic roughness elements control sand movement. **Transactions of the American Society of Agricultural Engineers**, 17: 134-139.

Lynn, M.D., 1998. Diamonds. In: Wilson, M.G.C and Annhaeusser, C.R. (Eds.) **The Mineral Resources of South Africa, 6th Edition**. South African Council for Geoscience Handbook 16: 232-258.

Malherbe, S.J., Keyser, A.W., Botha, B.J.V., Cornelissen, A., Slabbert, M.J. and Prinsloo, M.C., 1986. The Tertiary Koa River and the development of the Orange River drainage. **Annals of the Geological Survey of South Africa**, 20: 12-23.

Maree, B.D, 1966. Die voorkoms van diamante op land en onder die see langs die weskus van Suidelike Afrika. **Tegnikon**, 15:149-159

Maree, B.D, 1987. De Afsetting en verspreiding van spoeldiamante in Suid-Afrika. **South African Journal of Geology**, 90(4): 428-447.

Marshall, T.R., 1986. The alluvial-diamond fields of the southwestern Transvaal, South Africa. **Econ. Geology Research Unit, Univ. of Witwatersrand, Information Circular**, 188, 13pp.

Marshall, T.R., 1990. The nature, origin and evolution of the diamondiferous gravels of the southwestern Transvaal, South Africa. **Unpublished PhD. Thesis**, University of Witwatersrand, 211pp.

Marshall, T.R., 1994. The diamondiferous gravels of the southwestern Transvaal, South Africa. In: Meyer, H. and Leonardes (Eds.), **CPRM, Spec. Publ.**, 1B, 187-201.

Martin, A.K, and Flemming, B.W., 1986. The Holocene shelf sediment wedge off the south and east coast of South Africa. In: Knight, R.J. and McLeaan, J.R. (Eds.). **Shelf sands and sandstones. Canadian Society of Petrolium Geologists**, Memoir II: 27-44.

Martin, H., 1973. The Atlantic margin of southern Africa between latitude 17° south and the Cape of Good Hope. In: Nairn, A.E.M. and Stehli, F.G. (eds). **The Ocean Basins and Margins, Volume 1: The South Atlantic**. Plenum Press, New York, 277-300.

Martin, H., 1975. Structural and palaeographical evidence for an Upper Palaeozoic sea between Southern Africa and South America. **Proc. Pap. IUGS, 3rd Gondwana Symposium**, Canberra, 37-51.

Martinez, P.A., 1987. WAVE: Program for simulating onshore-offshore transport in two dimensions using the Macintosh™ computer. **Computers and Geosciences**, 13(5): 513-540.

Martinez, P.A. and Harbuagh, J.W., 1993. **Simulating nearshore environments**. Pergamon Press, Oxford, 265pp.

Maud, R.R, 1968. Quaternary geomorphology and soil formation in coastal Natal. **Annals of Geomorphology**, 7: 155-199.

McCarthy, T.S., Moon, B.P. and Levin, M., 1985. Geomorphology of the western Bushmanland plateau, Namaqualand, South Africa. **South African Geographical Journal**, 67, 160-178.

McMillan, I.K., 1987. **Late Quaternary Foraminifera from the Southern part of offshore South West Africa/Namibia**. Unpublished PhD. Thesis, University College of Wales, Aberystwyth, Wales, 551pp.

McMillan, I.K., 1993. Foraminiferal biostratigraphy, sequence stratigraphy and interpreted chronostratigraphy of marine Quaternary sedimentation on the South African continental shelf. **South African Journal of Science**, 89: 83-89.

Merensky, H., 1909. The diamond deposits of Lüderitzland, German South-West Africa. **Transactions Geological Society of South Africa**, 12: 13-23.

Middleton, G. V. and Southard, J. B., 1984. Mechanics of sediment movement (2nd Ed.). **Society, Economic Palaeontology and Mineralogy, Short Course Lecture Notes No.3**.

Miller, R. McG. and Seely, M.K., 1976. Fluvio-marine deposits south-east of Swakopmund, South West Africa. **Madoqua,** 9(3): 23-26.

Moore, W. S., 1982. Late Pleistocene sea level history. In: Ivanovich, M. and Harmon, R. (Eds.), **Uranium Series Dis-equilibrium: Applications to Environmental Problems in the Earth Sciences**: Oxford Univ. Press, 481-496

Moore, A. E. and Dingle, R. V., 1998. Evidence for fluvial transport of the Kalahari sands in central Botswana. **South African Journal of Geology**, 101, 2: 143-153.

Moore, A.E. and Larkin, P.A., 2001. Drainage evolution in south-central Africa since the breakup of Gondwana. **South African Journal of Geology**, 104: 47-68.

Moore, J.M. and Moore, A.E. (in prep). The Roles of Primary Kimberlitic and Secondary Dwyka Glacial Sources in the Development of Alluvial and Marine Diamond Deposits in Southern Africa.

Murray, L.G., Joynt, R.H., O'Shea, D.O.C., Foster, R.W. and Kleinjan, L., 1970. The geological environment of some diamond deposits off the west coast of South West Africa. In: Delany, F.M. (Ed.), **SCOR/IUGS Symposium on East Atlantic Continental Margins, Working Party 31, Cambridge, U.K.. Institute of Geological Sciences Report**, 70(3): 110-141.

Nixon, P.H., 1973. Lesotho kimberlites. In: Nixon, P.H. (Ed), **Lesotho National Development Corporation, Cape and Transvaal Printers Ltd.**, Cape Town: South Africa. 300-312.

Nummendal, D. and Swift, D.J.P., 1987. Transgressive stratigraphy at sequence bounding unconformities: some principles derived from Holocene and Cretaceous examples. In: **Sea-level Fluctuation and Coastal Evolution**. Nummendal, D., Pilkey, O.H. and Howard, J.D. (Eds.). Soc. Econ. Pal. Min. Spec. Publ. 41, 241-260.

Ollier, C.D., 1977. Outline of the geological and geomorphic history of the Central Namib Desert. **Madoqua**, 10(3): 207-212.

Ollier, 1978. Inselbergs of the Namib Desert - processes and history. **Zeitschr. F. Geomorph. NF Suppl.**, 31: 161-176.

Oosterveld, M.M., 1972. Ore Reserve Estimation and Depletion Planning for a Beach Diamond Deposit. **Tenth International Symposium on the Application of Computer Methods in the Mineral Industry, S. Afr. Inst. Min. Metall.**, 65-71.

O'Shea, D. O'C., 1971. **An Outline of the Inshore Submarine Geology of Southern S.W.A and Namaqualand**. Unpublished M.Sc Thesis, University of Cape Town, 102pp.

Partridge, T.C. and Maud, R.R., 1987. Geomorphic evolution of southern Africa since the Mesozoic. **South African Journal of Geology**, 90(2): 179-208.

Partridge, T.C., 1997/98. Cainozoic environmental change in southern Africa, with special emphasis on the last 200,000 years. **Progress in Physical Geography** 21: 3-22.

Partridge, T. C., 1998. Of diamonds, dinosaurs and diastrophism: 150 million years of landscape evolution in southern Africa. **South African Journal of Geology**, 101 (3), 167-184.

Partridge, T.C. and Maud, R.R., 2000. Macro-Scale Geomorphic Evolution of Southern Africa. *In:* Partridge, T.C. and Maud, R.R. (eds). **The Cenozoic of Southern Africa**. Oxford University Press, Inc (New York), 3-18.

Pether, J., 1994a. The sedimentology, palaeontology and stratigraphy of the coastal-plain deposits at Hondeklip Bay, Namaqualand, South Africa. **Unpublished MSc Thesis**, University of Cape Town, 313pp.

Pether, J., 1994b. Molluscan evidence for enhanced deglacial advection of Agulhas waters in the Benguela current, off Southwestern Africa. **Palaeogeography, Palaeoclimatology, Palaeoecology**, 111: 99-117.

Pether, J., Roberts, D.L. and Ward, J.D., 2000. Deposits of the West Coast. In: Partridge, T.C. and Maud, R.R. (eds). **The Cenozoic of Southern Africa**. Oxford University Press, Inc (New York), 33-54.

Pethick, J., 1984. **An Introduction to Coastal Geomorphology**. Pethick, J. (Ed.). Edward Arnold Publishers Ltd. 257pp.

Phillips, D., Kiviets, G. B., Barton, E. S., Smith, C. B., Viljoen, K. S. and Fourie, L. F., 1999. 40Ar/39Ar dating of kimberlites and related rocks: Problems and solutions. **Proceedings of the VIIth International Kimberlite Conference**, 2, 677-688.

Pickford, M., 1987. Miocene Suidae from Arris Drift, South West Africa/Namibia. **Annals of the South African Museum** 97: 283-295.

Pickford, M., 1995. Palaeontology. In: Pallet, J. (Ed). **The Sperrgebiet: Namibia's least known wilderness**. DRFN and Namdeb, Windhoek, 33-37.

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**, 94 (1), 5-8.

Pickford, M., 2000. Neogene and Quaternary vertebrate biochronology of the Sperrgebiet and Otavi Mountainland, Namibia. **Communications of the Geological Survey of Namibia**, 12, 359-365.

Pickford, M. and Dauphin, Y., 1993. *Diamantornis wardi* nov. gen., nov. sp., giant extinct bird from Rooilepel, Lower Miocene, Namibia. **C. R. Acad. Sci. Paris**, 316: 1643-1650.

Pickford, M., Senut, B. and Dauphin, Y., 1995. Biostratigraphy of the Tsondab Sandstone (Namibia) based on gigantic avian eggshells. **Geobios**, 28 (1): 85-98.

Pickford, M., Senut, B., Mein, P., Morales, J., Soria, D., Nieto, M., Ward, J. and Bamford, M., 1995. The discovery of lower and middle Miocene vertebrates at Auchas, southern Namibia. **C. R. Acad. Sci. Paris**, 322: 901-906.

Pickford, M. and Senut, B., 1999. Geology and Palaeobiology of the central and southern Namib Desert southwestern Africa. **Memoir of the Geological Survey of Namibia**, 18: 1-155.

Pickford, M., Eisenmann, V. and Senut, B., 1999. Timing of landscape development and calcrete genesis in northern Namaqualand, South Africa. **South African Journal of Science**, 95 (8), 357-359.

Quilty, P.G., 1977. Cenozoic sedimentation cycles in Western Australia. **Geology**, 5: 336-340.

Rau, G., 1995. Grant M46/3/1950, Hottentot Bay - Saddle Hill Prospect: Submarine terraces and palaeoshoreline sediment dynamics. **Unpublished internal report for NAMCO**, 13pp.

Rau, G., 1996. Grant M46/3/1946, Lüderitz Bay - Koichab Prospect: A detailed investigation of submarine terraces. **Unpublished internal report for NAMCO**, 12pp.

Rau, G., 1999. Hottentot Bay Grant - Sediment Dynamics Study: A detailed investigation of the submarine terraces and sediment dynamics in Hottentot Bay Grant for the delineation and prioritisation of high potential prospecting areas. **Unpublished internal report for NAMCO**, 18pp.

Rau, G., 2000. Geological Report - EPL 1950 (Hottentot Bay Grant). **Unpublished internal report for NAMCO**, 42pp.

Rau, G., 2002. Evaluation of the Lower Orange River Gravels in Blocks 1, 3, 4 and 6, Namibia. **Unpublished internal report for IMI**, 37pp.

Rau, G., 2002. Synopsis of the NDC Prospecting Programme on the farms Geelwal Karoo, Klipvley Karoo Kop and Graauw Duinen on the west coast of South Africa as of August 2002. **Unpublished internal report for NDC**, 11pp.

Reunert, T, 1886. History, Productions and Resources of the Cape of Good Hope, In: **Official Handbook: History, productions and resources of the Cape of Good Hope**. Noble, J.,(Ed)., W. A. Richards and Sons, Government Printers, 178-219.

Rogers, J., 1977. Sedimentation on the Continental Margins off the Orange River and Namib Desert. **Joint Geological Survey/Univ. Cape Town Marine Geoscience Unit Bulletin**, 7: 1-212.

Ross, F. and Rau, G., 1999. Geotechnical investigations within Feature HBG022. **Unpublished internal report for NAMCO**, 23pp.

Roussouw, J., Coetzee, L.W. and Visser, C. J., 1982. South African wave climate study. **Proc. 18th Coastal Engineering Conference**. 1: 87-107.

Rubey, W.W., 1933. The size distribution of heavy minerals within a water-laid sandstone. **Journal of Sedimentary Petrology**, 3(1): 3-29.

Schneider, G. I. C. and Miller, R. McG., 1993. Diamonds. In: Miller, R. McG. (Ed.) **The Mineral Resources of Namibia - Ministry of Mines and Energy, Geological Survey**, 1992.

Seely, M. K., 1987. **The Namib. Natural History of an Ancient Desert**. Windhoek, Shell Oil, South West Africa, 104pp.

Seggie, A. G., Hannweg, G. W., Colgan, E. A. and Smith, C. B.,1999. The geology and geochemistry of the Venetia kimberlite cluster, Northern Province, South Africa. **Proceedings of the VIIth International Kimberlite Conference**, 2, 750-756.

Selby, M. J., 1977b. Palaeowind directions in the central Namib Desert, as indicated by ventifacts. **Madoqua**, 10: 195-198.

Selby, M. J., Hendey, C. H. and Seely, M. K., 1979. A late Quaternary lake in the central Namib Desert, southern Africa, and some implications. **Palaeogeography, Palaeoclimatology, Palaeoecology**, 26: 37-41.

Senut, B., Pickford, M. and Ward, J. D., 1994. Biostratigraphie des eolianites néogènes du Sud de la Sperrgebiet (Desert de Namib, Namibie). **C. R. Acad. Sci. Paris, Sér II**, 318: 1001-1007. In: Pickford, M. and Senut, B., 1999. Geology and Palaeobiology of the central and southern Namib Desert southwestern Africa. **Memoir of the Geological Survey of Namibia**, 18: 1-155.

Senut, B. and Pickford, M., 1995. Fossil eggs and Cenozoic continental biostratigraphy of Namibia. **Palaeont. Afr.** 32: 33-37.

Senut, B., Pickford, M., Ward, J., De Wit, M. Spaggiari, R. and Morales, J., 1996. Biochronology of the Cainozoic sediments at Bosluis Pan, Northern Cape Province, South Africa. **South African Journal of Science, 92 (5)**, 249-251

Shackelton J. N. and Kennett, J. P., 1975. Palaeotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analyses in DSDP sites 277, 279 and 281. In: Kennett, J. P., (Ed.), **Initial Report of the Deep Sea Drilling Project**, US Government Printing Office, Washington, 29: 743-755.

Shepard, F. P., 1963. **Submarine Geology**, Harper and Row, N. Y., 557pp.

Sichel, H.S., 1966. The Estimation of means and associated confidence limits for small samples from lognormal populations. **Journal of the South African Institute of Mining and Metallurgy**, March 1966: 106-122.

Siesser, W.G., 1980. Late Miocene origin of the Benguella upwelling system. **Science**, 208: 283-285.

Siesser, W.G. and Dingle, R.V., 1981. Tertiary sea-level movements around southern Africa. **Journal of Geology**, 89: 83-96.

Siesser and Salmon, 1979. Eocene marine sediments in the Sperrgebiet, South West Africa. **Annals of the South African Museum**, 79: 9-34.

Skelton, P. H., 1986. Fish from the Orange-Vaal system. In Davies, B.R and Walker, K. F., (Eds.), **The Ecology of River Systems**: Dordrecht, Netherlands, Junk Publishers: 143-161.

South African Committee for Stratigraphy, 1980. Stratigraphy of South Africa, Part 1. In: Kent, L. E., (Ed.), **Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Rebublics of Bophuthatswana, Transkei and Venda: Handbook of the Geological Survey of South Africa**, 8: 690pp.

Stocklemayer, V. R., 1981. Diamonds in Zimbabwe. **Annals of the Zimbabwe Geological Survey**. Vol. 6: 27-34.

Stöcken, 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. Geological Department**, 1-33 and maps 1-4.

Stuut, J.-B.W, Prins, M.A., Schneider, R.R., Weltje, G.J., Jansen, J.H.F. and Postma, G., 2002. A 300-Kyr record of aridity and wind strength in southwestern Africa: Inference from grain-size distributions of sediments on the Walvis ridge, S.E. Atlantic. **Marine Geology**, 180: 221-234.

Sullivan, D., 1966. Report on the prospecting operations carried out during the twelve months ending 31st December 1965, as requested in clause 6 of the Deed of Grant. **Unpublished internal report for Tidal Diamonds South West Africa (Pty) Ltd.**

Sutherland, D.G., 1982. The transport and sorting of diamonds by fluvial and marine processes. **Economic Geology and the Bulletin of the Society of Economic Geologists**, 77(7): 1613-1620.

Swart, D. H., 1983. Physical aspects of sandy beaches - a review. In: McLachlan, A and Erasmus, T., (Eds.), **Sandy beaches as ecosystems**. Junk, the Hague

Tankard, A. J., 1976. Cenozoic sea-level changes: a discussion. **Annals of the South African Museum**, 71: 1-14

Tankard, A. J. and Rogers, J., 1978. Late Cenozoic palaeoenvironments on the west coast of Southern Africa. **Journal of Biogeography**, 5: 319-337.

Thompson, S., 1996. **The Petrogenesis and Associated Sedimentology of Authigenic Dolomite in Hottentot Bay, Namibia**. Unpublished Honours Project, Department of Geological Sciences, University of Cape Town, 39pp

Thurston, M., 2001. Diamond Fields International. Sea Diamonds Project: Feasibility Study Report. Internal Report to DFI. In:De Decker, R.H., 2001. An Independent Due Diligence Report on the Sea Diamond Project of Diamond Fields International. **Technical Report for OPIC.** 59pp.

Tija, H. D., 1970. Quaternary shore lines of the Sunda Land, South East Asia. **Geologie en Mijnbouw,** 49(2): 135-144.

Turner, B. R. and Minter, W. E. L., 1985. Diamond-bearing upper Karoo fluvial sediments in NE Swaziland. **Journal of the Geological Society of London**, Vol. 142: 765-776.

Vail, P. R., Mitchum, R. M. and Thompson, S., 1977. Seismic stratigraphy and global changes in sea level, part 4: global cycles of relative changes in sea level. In: Payton, C. E. (Ed.), **Seismic stratigraphy - applications to hydrocarbon exploration**. AAPG Memoir 26, 83-97.

Vail, P.R. and Hardenbol, J., 1979. Sea-level changes during the Tertiary. **Oceanus**, 22: 71-79.

Valentine and Moores, 1970. Cited In: Pethick, J., 1984. **An Introduction to Coastal Geomorphology**. Pethick, J. (Ed.). Edward Arnold Publishers Ltd. 257pp.

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**, 2: 2309-2321.

Venter, L. J., 1998. **A Review of Southern African Kimberlites and Exploration Techniques.** Unpublished Masters Dissertation, Rhodes University 103pp.

Visser, J. N. J, van Niekerk, B. N. and van der Merwe, S. W., 1997. Sediment transport of the Late Proterozoic glacial Dwyka Group in the southwestern Karoo Basin. **South African Journal of Geology**, 100: 223-236.

Vogel, J.C., 1982. The age of the Kuiseb river silt terrace at Homeb. **Palaeoecology of Africa**, 15: 201-209.

Vogel, J.C., 1989. Evidence of past climatic change in the Namib Desert. **Palaeogeography, Palaeoclimatology, Palaeoecology**, 70: 5-355-366.

Wagner, P.A, 1914. The Diamond Fields of Southern Africa. **The Transvaal Leader,** Johannesburg, 347pp.

Wagner, P.A and Merensky, H, 1928. The Diamond Deposits on the coast of Little Namaqualand. **Transactions of the Geological Society of South Africa**, 31: 1-41.

Ward, J.D., 1982. Aspects of a suite of Quaternary conglomeratic sediments in the Kuiseb River Valley, Namibia. **Proceedings of the Vith SASQUA Conference. Palaeoecology of Africa**, 15: 211-216.

Ward, J. D., 1987a. Tsondab Sandstone - extensive tertiary desert deposits in the Central Namib. **South African Journal of Science**, 83: 507.

Ward, J. D., 1987b. The Cenozoic succession in the Kuiseb Valley, Central Namib Desert. **Memoirs of the Geological Survey of South West Africa/Namibia**, 9: 1-124.

Ward, J. D., 1988. Eolian, fluvial and pan (playa) facies of the Tertiary Tsondap Formation in the central Namib Desert, Namibia. **Sedimentary Geology** 55, 143-162.

Ward, J. D. and Corbett, I. B., 1990. Towards an age for the Namib. In: M. Seely (Ed.). Namib Ecology: 25 years of Namib Research. **Transvaal Museum Monographs**, 7: 17-26.

Ward, J. D. and Martin, H., 1987. A terrestrial conglomerate of Cretaceous age - a new record from the Skeleton Coast, Namib Desert. **Communications of the Geological Survey of South West Africa/Namibia**, 3: 57-58.

Ward, J. D. and Seely, M. K., 1990. Dune sands, ocean currents and man: Namibia's dynamic coastline. **Rössing Magazine**, Oct. 1990: 12-17.

Ward J. D. and von Brunn, V., 1985. Sand dynamics along the lower Kuiseb River. In: Huntley, B.J. (Ed.), The Kuiseb Environment: The Development of a Monitoring Baseline. **South African National Science Programme Report 106**: 51-72.

Ward, J. D., Seely, M. K. and Lancaster, N., 1983. On the antiquity of the Namib. **South African Journal of Science**, 79: 175-183.

Wijnberg, A. R., 1995. Regional Refraction Model - User Guideline. **Internal report for Marine and Coastal Geoscience**, 9pp.

Williams, R., 1996. **King of Sea Diamonds; The Sage of Sam Collins**, W.J . Flesch and Partners (Pty) Ltd, 20 - 28.

Williams, C. M. and Robey, J. V. A., 1999. Petrography and mineral chemistry of the Mwenezi-01 Kimberlite, Zimbabwe. **Proceedings of the VIIth International Kimberlite Conference**, 2, 896-903.

Wilson, A. N., 1972. The missing 3 000 000 000 carats of diamonds. In: Wilson, A. N. (Ed.), **Diamond Annual 2: Johannesburg. South Africa**. Diamond Annual (Pty) Ltd: 57-59.

Woodborne, M. W., 1987. Acoustic Stratigraphy and Bedrock Morphology of the Namaqualand Inner Shelf immediately North of the Buffels River Mouth, Kleinzee (Diamond Concession Area No. 4). **Technical Report of the Joint Geological Survey/Univ. Cape Town Marine Geoscience Unit Bulletin**, 17: 51-60.

Woodborne, M. W., De Decker, R. H., Gurney, J. J. and Smith, H. S., 1991. New information on wave-cut terraces and the importance in relation to diamond deposits on the west coast of South Africa. **Abstract, Mineral Exploration 93,** 18-20 August, Cape Town: 2pp

Wright, J, A, 1964. Gully Pattern and Development of Wave-Cut Bedrock Shelves North of the Orange River Mouth. **Transactions of the Geological Society of South Africa**, 67: 163-171.

Yates, R. J.,1986. A late mid-Holocene high sea-level: a preliminary report on geoarchaeology at Elands Bay, western Cape Province, South Africa. **South African Journal of Science**. Vol 82, 164-165

Yokoyama et al

Zeuner, F. E., 1958. Dating the past, Fourth Edition. Methuen and Co., London. In: O'Shea, D. O'C., 1971. **An Outline of the Inshore Submarine Geology of Southern S.W.A and Namaqualand**. Unpublished M.Sc Thesis, University of Cape Town, 102pp.

Zweistra, P., Jarvis, W. and McGeorge, I. B., 1998. The geology of micaceous kimberlite intrusives, Khutse, Botswana. **Abstracts, Seventh International Kimberlite Conference**, University of Cape Town, 1037-1038.

APPENDIX 1

BRIEF REVIEW OF WAVE REFRACTION AND SEDIMENT DYNAMIC MODELLING

RCPWAVE is a programme developed to compute the wave heights, directions and effects of wave shoaling, refraction and wave current interaction and non-linearity, given certain wave front direction (angle), wave amplitude, and wave period input parameters for a defined digital terrain model surface. The two central principles are the irrotationality of the wave number, which for planar bathymetry reduces according to Snell's Law, and the conservation of wave action, that, in the absence of currents becomes wave energy. In the version of RCPWAVE used in this study the finite difference method has been reduced to a two step Lax Weadroff procedure to minimise directional bias inherent in previous versions of the programme. The fundamental principles and equations used by the software are summarised from Wijnberg (1995), below:

Waves propagating across variable bathymetry change direction due to differences in wave speed along the wave crest. If a co-ordinate system is chosen with *x* onshore and *y* alongshore, then a wave train can be described by:

$$\eta(x, y, t) = a(x, y) \cos (k \cos\theta x + k \sin\theta y - \sigma t) \qquad (1)$$

Where:

k = the wave number (=2Π/L, where L = wave length)
σ = the angular frequency of the wave (=2Π/T, where T = wave period)
θ = the angle made by the wave propagation direction and the x axis

The wave number satisfies the following dispersion relationship, from linear wave theory (Dean and Dalrymple, 1984).

$$\sigma^2 = gk \tanh kh \qquad (2)$$

which relates to the wave frequency, wave number and water depth, *h*

The wave number, k, is irrotational, which leads to a general form of Snell's Law for refraction

$$\frac{\partial k \sin\theta}{\partial x} - \frac{\partial k \cos\theta}{\partial y} = 0 \qquad (3)$$

This equation relates changes in wave direction to changes in wave speed, through wave number change. This equation can be written as:

$$\frac{\partial A}{\partial x} - \frac{\partial B}{\partial y} \qquad (4)$$

where B is defined as

$$B = k\cos\theta = \sqrt{k^2 - A^2} \quad (5)$$

If the x axis is divided into segments, $x = i\Delta x$, $i = 0, 1, 2, 3, \ldots\ldots\ldots, m$, and if the y axis is subdivided as $y = j\Delta y$, $j = 0, 1, 2, 3, \ldots\ldots, n$, then finite difference methods can be used to solve the above equation for $A(x, y) \rightarrow A_{i,j}$, given that θ is known on the offshore grid row ($i = 0$). The solution is incrementally determined from this offshore row in the increasing i direction. Dalrymple, (1988) solved the equation using a second order accurate scheme that was asymmetric, leading to minor errors in symmetric problems. This asymmetry led to the adoption of a new algorithm, based on the two-step Lax-Wendroff method.

The procedure first involves resolving the determination of a mid-grid value of $A_{i+1/2,\, j+1/2}$ from the governing equation,

$$\frac{A_{i+1/2,\, j+1/2} - (A_{i,\, j+1} + A_{i,j})/2}{\Delta x/2} - \frac{(B_{i,\, j+1} - B_{i,j})}{\Delta y} = 0 \quad (5)$$

Solving for Ai+1/2, j+1/2,

$$A_{i+1/2,\, j+1/2} = \frac{(A_{i,\, j+1} + A_{i,j})}{2} + \frac{\Delta x}{2\Delta y}(B_{i,\, j+1} - B_{i,j}) \quad (6)$$

From $A_{i+1/2,\, j+1/2}$, $B_{i+1/2,\, j+1/2}$ is determined. Then a second step is made to find $A_{i+1,\, j}$,

$$\frac{(A_{i+1,\, j} - A_{i,j})}{\Delta x} - \frac{(B_{i+1/2,\, j+1/2} - B_{i+1/2,\, j-1/2})}{\Delta y} = 0 \quad (7)$$

Finally, the following is obtained,

$$\underline{A_{i+1,\, j} = A_{i,j} + \Delta x\, (B_{i+1/2,\, j+1/2} - B_{i+1/2,\, j-1/2})}_{\Delta y} \quad (8)$$

The two-step method is also second order accurate.

RCP wave requires two input parameter files to run, namely; 1) INDAT.dat which contains wave data, and 2) REF-DAT.dat that contains the bathymetric data. These files need to be constructed in specific formats in order for the programme to run. Further information on the specifics of this software can be obtained from the US Corps of Engineers. The version of the programme used in this study was compiled in FORTRAN and runs on a UNIX workstation. Wijnberg (1995), modified the programme to include orbital velocity on the seabed under waves (Komar and Miller, 1975) using the equation:

$$U_d = \frac{\Pi H}{T \sinh (2\Pi d)/L} \quad (9)$$

Where:

Ud = the orbital velocity under waves
H = wave height
d = grain diameter
L = wave length
T = wave period

Strictly speaking this equation is an oversimplification in that it predicts unidirectional movement in what in reality is a highly complex oscillatory flow with a shorter, stronger shoreward velocity under the peak of the wave and weaker, longer offshore flow under the trough of the wave (Martinez, 1987). The result is that if the entrainment velocity of hydraulically "heavy" grains is such that it is only transported during the more powerful forward motion and not moved or not transported back as far as on the forward movement, nett forward motion results. The longer but weaker offshore orbital velocity under the trough results in the nett transport of the hydraulically "light" grains offshore. This non-uniform orbital beneath waves results in winnowing and ultimately in placer formation in gravel bodies that occupy the foreshore and upper shoreface.

Childs (pers. Comm.), believes that there may be some inaccuracies associated with RCPWAVE's steady state approximation, finite difference schemes and/or a inadequate modelling equations. However, it should be mentioned that his studies in this field led to him creating a programme that tried to incorporate so many parameters that it "hung" UCT Oceanography server on numerous occasions (S. Courtney - UCT IT Manager, Oceanography, pers. Comm). Many of these sedimentological and oceanographical parameters cannot be measured accurately over a large enough area, and therefore while admirable the practicality of his methodology is questionable. RCPWAVE cannot model the wave once it has broken as this motion is far too chaotic. Should the wave reform RCPWAVE can model it once again. Most of the wave energy is dissipated once the wave breaks but the programme cannot accurately reflect the processes in the highly active littoral zone where much of the winnowing and placer formation takes place. Nevertheless, a good indication of where high and low velocity zones exist are easily identified and can be extrapolated shoreward during interpretation.

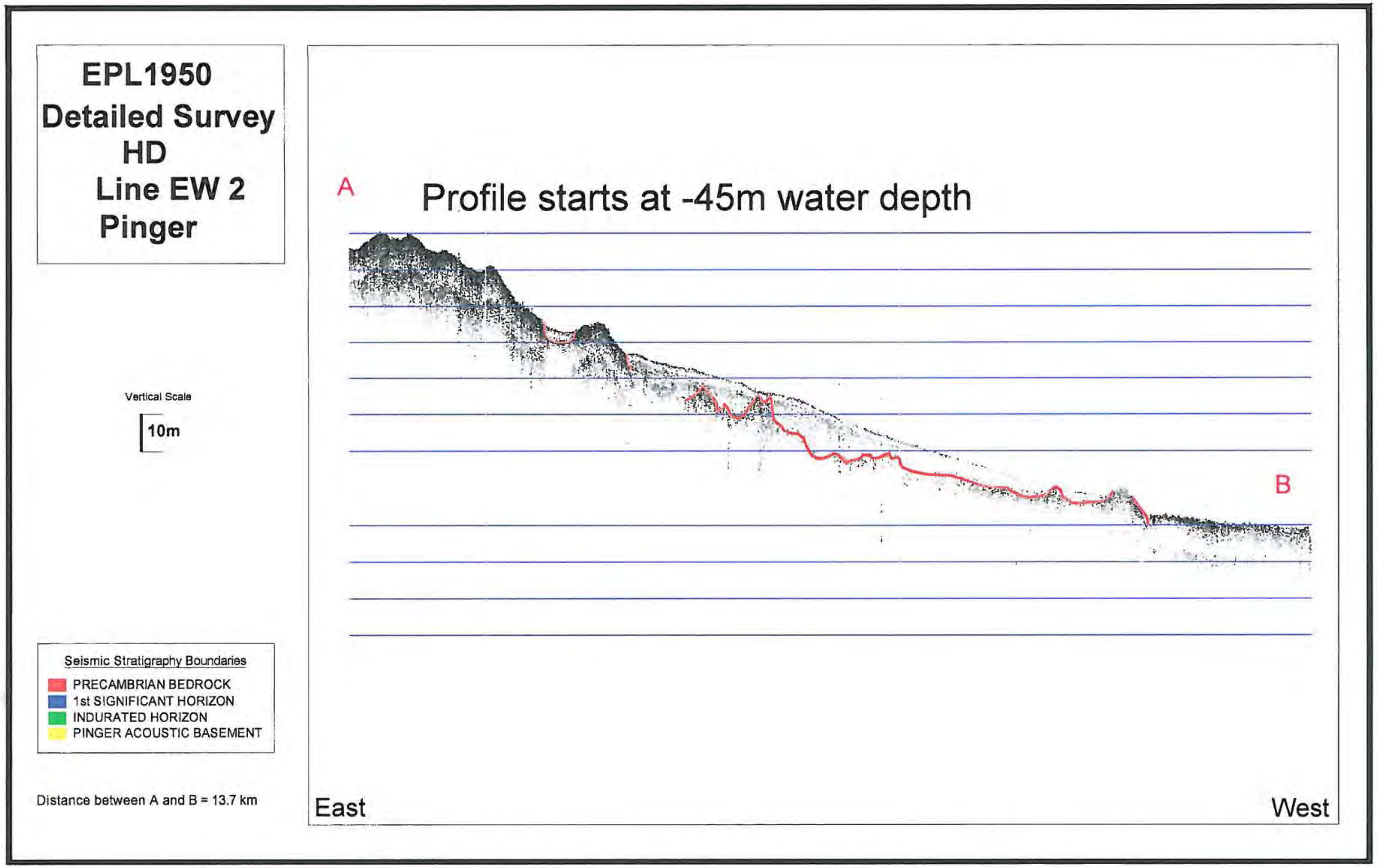
The complex nature and interaction of particle shape, bed roughness, imbrication and orbital velocity needs to be carefully considered. That is, on a smooth bedrock surface, covered with rounded quartz particles an orbital velocity of 0.1 m/s may transport the bedload, while over a rough, imbricated bedrock surface velocities of 0.6 m/s or greater may be required. Furthermore the bedrock may change character on a sub-metre scale in places, particularly on the west coast of southern Africa where intense shearing has produced thin, alternating, north-south trending bands of mylonite, schist and gneiss. The concept of hydraulic equivalence (Rubey, 1933), states that grains of different densities, if deposited together, should have the same settling velocities. Deviations from hydraulic equivalence among minerals may result from selective entrainment and transport of grains according to size, shape and density and/or limitations on available grain sizes (Li and Komar, 1992a & b). Diamonds with their high specific gravity (3.52) are hydraulically equivalent to the pebble sized gravel fraction and are deposited in the same environment. Due the order of magnitude difference between the heavy mineral sands and diamonds for typical populations of these materials on the west coast, the distribution of diamond placers should only be loosely correlated with the occurrence of heavy mineral deposits.

Theoretically if one converts a 0.1 ct and 0.5 ct diamond into a diameter using the equation:

$$\text{Weight in carats} = (d/6.42)^3 \qquad (10)$$

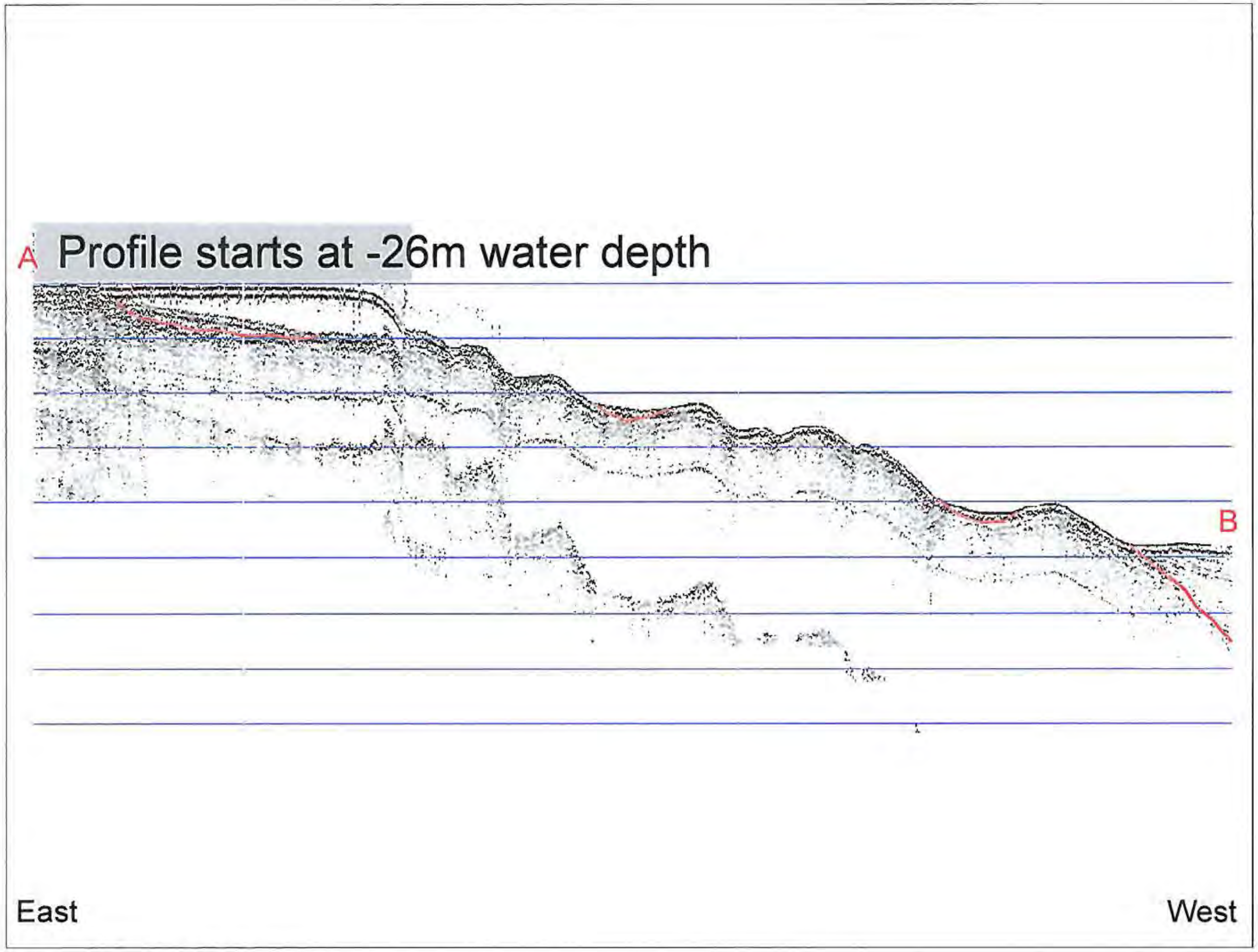
And then uses equation (9) to convert the diameter (2.98 mm and 5.09 mm) to a threshold velocity one gets 0.75 m/s to 0.99 m/s respectively if a long period storm wave is assumed. That is, this range of velocities are required to mobilise and transport a diamond along the seabed. Velocities required for mobilisation will vary considerably depending on the seabed friction, imbrication, bedload particle size, shape, cementation/induration and clay content amongst others. Therefore the most logical technique is to model the area and then, using sampling and diamond results, adjust the velocities until they best replicate the actual results. These velocities are then maintained and high potential targets delineated throughout the remainder of the area. This technique is analogous to calibration velocities of acoustic equipment using known depth datums. Given the constraints of the modelling the author simulates marine recessions based on terrace level studies (identified"nick points") in the area and known sea-levels of high diamond recovery (Refer: Section 8.4). Generally 4 or 5 sea-levels, using 3 wave front directions are modelled for long period storm conditions type waves as is the case in Section 8.5 in this study.

APPENDIX 2



Coast-perpendicular profile at 7147500N from 470000E to 480400E

EPL1950
Detailed Survey
Blue Mountain
Line 103
Airgun



Vertical Scale

20m

Seismic Stratigraphy Boundaries

🟥 PRECAMBRIAN BEDROCK
🟦 1st SIGNIFICANT HORIZON
🟩 INDURATED HORIZON
🟨 PINGER ACOUSTIC BASEMENT

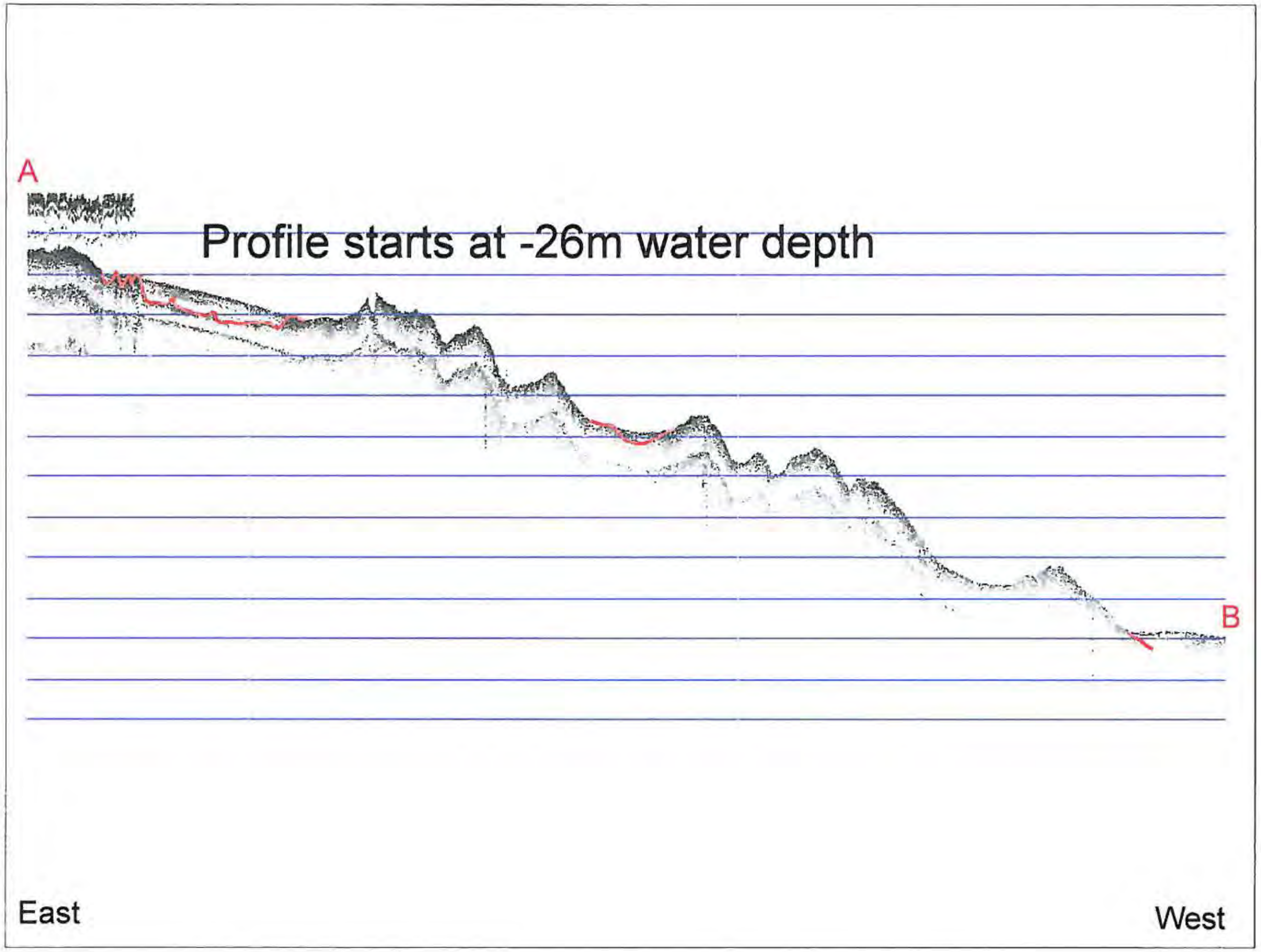
Distance between A and B = 15.4 km

Coast-perpendicular profile at 7113500N from 480000E to 495000E

EPL1950
Detailed Survey
Blue Mountain
Line 103
Pinger

Vertical Scale

10m

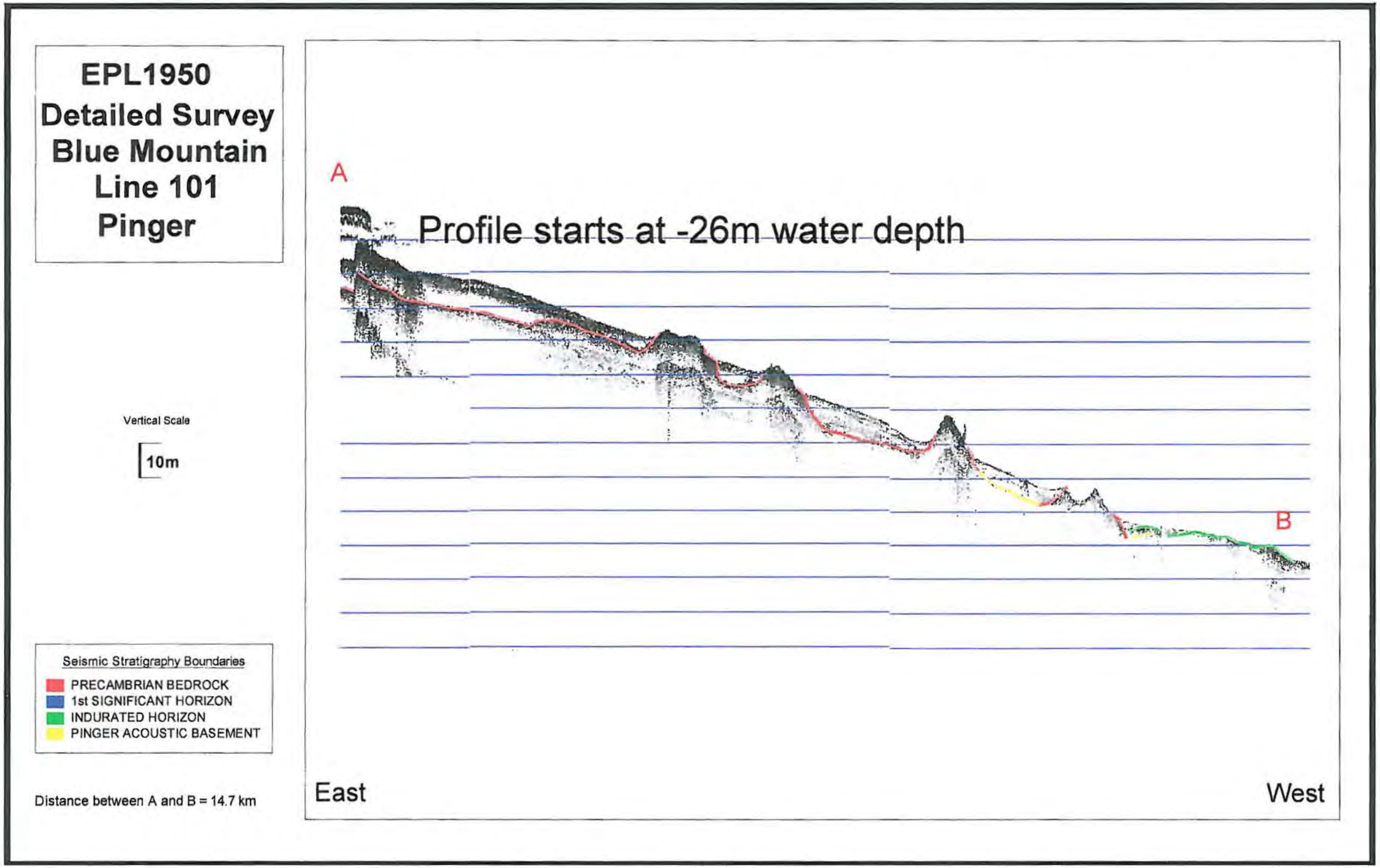


Seismic Stratigraphy Boundaries

- 🟥 PRECAMBRIAN BEDROCK
- 🟦 1st SIGNIFICANT HORIZON
- 🟩 INDURATED HORIZON
- 🟨 PINGER ACOUSTIC BASEMENT

Distance between A and B = 15.4 km

Coast-perpendicular profile at 7113500N from 480000E to 495000E



Coast-perpendicular profile at 7115050N from 480000E to 495000E