STRATIGRAPHY AND SEDIMENTOLOGY OF THE CAPE AND KAROO SEQUENCES IN THE EASTERN CAPE PROVINCE

by

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DECLARATION

All material contained in this thesis represents the original work of the author except where specific acknowledgement is made to the work of others.

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20th May 1976

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ABSTRACT

The Cape Supergroup (Sequence) comprises three groups, embracing a total of twenty-three formations, with a maximum combined thickness of approximately 8 km. The Table Mountain Group consists of medium-grained (occasionally fine- or coarse-grained), "clean", ultra-quartzose sandstone plus subordinate fine-grained, "dirty", subfeldspathic to feldspathic sandstone, mudrock, and rhythmitite. Average total thickness is about 3000 m. The Bokkeveld Group is composed of mudrock, rhythmitite and subordinate subfeldspathic to feldspathic sandstone (generally fine-grained and "dirty"), with a maximum total thickness of over 3000 m. The Witteberg Group comprises fine- to medium-grained ultra-quartzose sandstone, micaceous streaky rhythmitite, mudrock, and one thin diamictite unit; total thickness is about 1700 m.

The strata belonging to the Cape Supergroup appear to have been largely deposited under marine conditions in environments ranging from outer shelf to beach. Deltaic deposits are,however, common in the upper part of the Bokkeveld Group and the Witteberg Group, while the main sandstone units in the upper third of the Table Mountain Group may have accumulated on a coastal alluvial plain. Deposition took place in a basin elongated in an east-west direction, with the palaeoslope inclined towards the south. Palaeocurrents were generally directed down the palaeoslope, but westerly transport directions parallel to the palaeostrike and presumed shoreline are present in both the Table Mountain and Witteberg Groups.

The sedimentary rocks of the Karoo Sequence are subdivided into two groups (containing a total of eleven formations) and four ungrouped formations. Using the maximum thicknesses of the individual formations, a combined total thickness of about 12 km can be calculated. The sequence commences with the Dwyka Tillite, a 700-m-thick diamictite unit. The overlying Ecca Group consists of "varved" rhythmitite, dark, massive, fine- to very fine-grained ultra-lithofeldspathic sandstone and subordinate mudrock with a total thickness of 2000 - 3000 m. The Beaufort Group is composed of thick mudstone layers alternating with thinner fine-grained ultra-lithofeldspathic, lithofeldspathic and lithic sandstones, with the exception of the Katberg Formation which consists largely of sandstone. Fining-upward cycles are ubiquitous, while red mudstone is common, especially in the upper half of the group. A maximum thickness of about 6000 m was obtained in the East London area. The Molteno Formation

consists of up to 600 m of alternating fine- to coarse-grained sublithic sandstones (frequently pebbly) and grey mudstones, generally forming fining-upward cycles. The Elliot Formation (up to 500 m thick) consists of red and grey mudstones and subordinate fine-grained lithofeldspathic sandstones arranged in fining-upward cycles. The bulk of the Clarens Sandstone consists of very fine-grained massive (occasionally cross-bedded) sandstone, with a maximum thickness of 300 m.

The Drakensberg Group, consisting of up to 1200 m of basalt with some pyroclastic intercalations near the base, caps the Karoo sedimentary succession.

The deposition of the Dwyka Tillite by glacier action coincided with a major change from the generally shallow marine conditions which characterised the sedimentation of the Cape Supergroup (with the source area located on the craton to the north of the basin) to a deep linear trough receiving clastic sediments from a source area situated south and south-east of the basin. The Ecca Group, the lower half of which is characterised by the presence of "proximal" turbidite sandstones, records the gradual infilling of this basin, with deltaic conditions developing in the upper part of the group in the western half of the study area (i.e. in the Waterford Formation). The overlying strata were virtually all deposited under fluviatile conditions, the chief exceptions being a stratigraphic interval within the lower half of the Beaufort Group which appears to have formed in a large body of water, and the aeolian Clarens Sandstone. The fluviatile sediments were all deposited by rivers flowing towards the north and north-west, while the Clarens Sandstone was laid down by winds blowing from the west.

The Ecca and Beaufort Group sandstones are characterised by a high rock fragment content with "felsitic" grains being a prominent constituent. This, together with the relative abundance of quartz-feldspar porphyry pebbles in the Katberg Sandstone unit (Beaufort Group) near East London, indicates that volcanic material probably formed a prominent part of the post-Dwyka Karoo provenance.

PREFACE AND ACKNOWLEDGEMENTS

In general, the study of sedimentary rock sequences can be considered to embrace three distinct objectives:

(a) Description.- Describing the strata systematically and accurately, so that other geologists can readily visualise their appearance and recognise similar deposits in other areas (where similar genetic and economic factors would probably be involved).

(b) Interpretation.- Deciphering the genesis and history of the strata, and, where possible, relating these to contemporaneous geological events in adjacent areas.

(c) Economic evaluation.- Assessing the economic potential of the strata, and predicting subsurface occurrences of petroleum, coal or other mineral deposits.

The primary aim of this project was to provide a basic description and interpretation of the Cape and Karoo Sequences in the eastern Cape Province. Attention had to be confined to the first and second of the three above objectives, since the evaluation of petroleum, uranium and coal reserves (if and where present) can only be effectively undertaken by those possessing the requisite financial resources, exploration equipment and specialised technical skills.

Failure to keep the basic aims underlying sedimentary rock studies clearly in view has in the past often resulted in a disproportionate emphasis on certain relatively minor properties or features of sedimentary rocks which contributed very little really useful information as regards either description or interpretation. Moreover, as Elliot (1965, p.865) has remarked, "the situation is now familiar in which statistical manipulation of the data produces outwardly impressive but geologically meaningless results". The implications of these developments will be explored further in some of the introductory chapters.

The general lack of agreement among sedimentologists concerning both terminology and methodology as they apply to the measurement and description of a wide range of sedimentary rock features has resulted in a rather lengthy introductory section (Part A) in which certain of these aspects are fairly fully discussed. Part B contains the actual description and interpretation of the strata, presented in a fixed order for each group, followed by a synthesis in which the historical development of the depositional basin in terms of palaeogeography and sedimentary tectonics is reviewed. Photographic illustration has been limited to features which have not previously been depicted in any of the standard, generally available reference works, such as those by Pettijohn and Potter (1964), Pettijohn and others (1972) and Reineck and Singh (1973). Maps and diagrams too large to be incorporated in the text have been assigned to a map pocket.

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CHAPTER I

SYSTEMATISATION OF DATA PRESENTATION AND ANALYSIS IN SEDIMENTARY ROCK STUDIES

A. INTRODUCTION

In the past both published and unpublished descriptions of sedimentary rock sequences have generally suffered from two major deficiencies:

1. The actual description of individual properties has usually followed no logical, standard (and hence predictable) sequence. As a result much time may be wasted in locating - or searching in vain for - new information concerning a particular feature in which the reader is interested. Moreover, without a systematic approach most descriptions tend to end up being fragmentary and incomplete. While exhaustive descriptions will not always be feasible or necessary - we need to always evaluate critically the relative value of descriptive data, in order to avoid becoming bogged down in masses of trivial detail - nevertheless certain items of information may prove crucial for hypothesis-testing and comparative studies at a later date, and these could easily have been included in the original description if a complete, systematic approach had been adopted.

2. Most information has been presented in conventional language form, and the information is hence inaccessible to those who cannot read the particular language or who do not have the services of a translator.

The remaining portion of this section is devoted to exploring ways of overcoming the first of the above deficiencies. The second aspect mentioned above (the language barrier) can only be overcome through international agreement on a comprehensive set of symbols covering all aspects of sedimentary rock description. In addition, those intending to make use of symbolic and graphic modes of data presentation will be forced to adopt a rigorously quantitative approach at all levels of description. In practice this is not always possible or even desirable.

B. THE BASIC FRAMEWORK

As a first step in attempting to describe and interpret a sedimentary rock unit or a sequence of such units, it is necessary to establish a framework consisting of various descriptive categories which can act as a broad basis for the classification and grouping of information. Such a scheme is contained in Table I-1, which also illustrates the interrelationships between the various aspects involved. However, even at this elementary level problems are immediately presented by the arch-enemy of all theoretically ideal schemes, namely, "usage". Accordingly, having defined the terms used in Table I-1, a discussion of past and present usage as they affect the proposed classification and definitions will be attempted.

1. Definitions

In the scheme presented in Table I-1, stratigraphy is conceived of as that branch of sedimentary geology that is concerned primarily with the subdivision of sedimentary rock sequences into named, mappable units on the basis of lithology (lithostratigraphy), age considerations (chronostratigraphy) or - where specialised palaeontological help is available - fossil content (biostratigraphy), and the elucidation of the vertical and lateral relationships of these units. Sedimentology (sedimentary petrology) can be defined as "the scientific study of sedimentary rocks and of the processes by which they were formed; the description, classification, origin and interpretation of sediments" (AGI Glossary, 1972, p. 642). Two distinct aspects are involved, namely sedimentography (sedimentary petrography) which is "the description and classification of sedimentary rocks" (AGI Glossary, 1972, p. 642) and sedimentogenesis (sedimentary petrogenesis) which concerns the formation and origin of sediments and sedimentary rocks (cf. AGI Glossary, 1972, p. 642) and embraces the consideration of provenances, sedimentary processes and dispersal patterns, palaeoenviroments and palaeoclimates. Sedimentography in turn can be conveniently divided into macro-sedimentography, referring to those aspects that are normally studied in outcrop (colours, primary structures, sandstone geometry, etc.) and micro-sedimentography, which deals with those

Table I-1. A classification of the basic elements involved in sedimentary rock studies

	STRATIGRAPHY	SEDIMENTOLOGY	PALAEONTOLOGY
RAW MATERIALS	Potentially mappable assemblages of strata	Cycles, beds, structures, textures, minerals	Fossils
OBSERVATION + DESCRIPTION	Lithological columns, maps, cross-sections	Macro-sedimentography, micro-sedimentography	Fossil identification and description
ANALYSIS + INTERPRETATION	Lithostratigraphic classification and nomenclature Correlation Chronostratigraphy (Biostratigraphy)	Sedimentogenesis i.e. dispersal patterns, sedimentary processes, palaeoenvironments, palaeoclimates, provenances	Biostratigraphic zonation. Palaeoecology Evolutionary trends (Chronostratigraphy)
SYNTHESIS	↘	↙	↓
	Palaeogeography	→	Historical geology

aspects that are generally studied in the laboratory (texture, mineral composition, etc.). Finally, in historical geology all available stratigraphic, sedimentological and palaeontological information is integrated and utilised to reconstruct the biological and physical events constituting the past geological history of the earth.

2. Discussion

Having outlined a theoretical classification and defined the terms employed we can consider some of the difficulties which such a scheme raises.

Many statigraphers will probably object to the idea that stratigraphy should be regarded as just one branch or aspect of sedimentary geology. It would appear from a number of sources that stratigraphy is often regarded as a sort of "umbrella" under which all the other branches of sedimentary geology must shelter. This philosophy is best expressed by Krumbein and Sloss (1963, p.1) who claim that "it [i.e. stratigraphy] may now be considered as the integrating discipline which combines data from almost all other branches of earth science in a form from which historical geology emerges as a natural product." Their Table I-1, "Components of Stratigraphy" (p. 4) makes it clear that nothing is excluded from stratigraphy's embrace. In similar vein the International Subcommission on Stratigraphic Classification (ISSC) (1972, p.298) has stated that "stratigraphy is the descriptive science of strata. It deals with the form, arrangement, distribution, chronologic succession, classification and relationships of rock strata (and other associated rock bodies), in normal sequence, with respect to any or all of the characters, properties, and attributes which rocks may possess. It thus involves origin, composition, environment, age, history, relationship to organic evolution, and innumerable other features of rock strata" (cf. Hedberg, 1958, p. 1881).

It is apparent that in the above approach "stratigraphy" becomes virtually a synonym for "sedimentary geology", and we are left without a usable term to describe that aspect of sedimentary geology which concerns itself with the subdivision of the stratigraphic column into named, mappable units and the investigation and elucidation of the mutual relationships in space and time between the various units so defined. A more restricted definition of stratigraphy would seem to be far more useful, and the following comments by Pettijohn and Gignoux respectively lend support to this point of view:

"The primary task of stratigraphy is to ascertain the order of superposition of the strata at any given place and then to integrate the local geologic column thus constructed with the geologic columns of other places - places isolated or removed from one another. In short, the task of stratigraphy is to determine the temporal sequence of the strata the world over" (Pettijohn, 1957, p. 1).

"*Stratigraphy* studies the beds of the earth's crust, the rocks, from the point of view of their *chronological succession* and their *geographic distribution*. Its indispensable prerequisite is, then, the knowledge of these rocks themselves, a study that can be made up to a certain point outside of time and space, and, so to speak, in the drawers of collections. That is what petrographers and paleontologists do" (Gignoux, 1955, p. 1).

The true scope of stratigraphy is also clearly indicated by the contents of the various reports on stratigraphic classification and terminology drawn up by the International Subcommission on Stratigraphic Classification (ISSC). It is evident that *in practice* stratigraphic classification and terminology is concerned only with *stratigraphic units* as such, and does *not* embrace the classification and terminology of, for example, primary structures, sandstone, environments of deposition, geosynclines and fossils, to list just a few random examples of subjects that lie *outside* the field of stratigraphy proper. A careful study of the ISSC definition quoted earlier indicates that it is not necessarily incompatible with the more restricted view of stratigraphy, since it can be argued that origin, composition, environments, etc., are involved in stratigraphy *only* in so far as they may be of assistance in establishing, defining, or following stratigraphic units or elucidating mutual interrelationships between such units.

Finally, Dunbar and Rodgers (1957, p. xi) maintain that "The study of sedimentary rocks has three main aspects. The first is *sedimentary petrography*, the study of the rock material as such, its composition, texture and structure. The second is *sedimentation*, the study of the processes by which sediments are formed, transported, and deposited. The third is *stratigraphy* proper, which deals with the overall relations of the stratified rocks, areal and temporal, and with the history they record". Stratigraphy is here clearly conceived of as just one aspect of the study of sedimentary rocks; on the negative side, the definition of stratigraphy presented by Dunbar and Rodgers creates an overlap with historical geology.

Turning now to sedimentology (sedimentary petrology) and its relationship to sedimentography (sedimentary petrography) and sedimentogenesis (sedimentary petrogenesis), we first need to clarify the relationships between petrology, petrography and petrogenesis (petrogeny) in general. Two quotations, from Grout and Tyrrell respectively, express clearly the basic concepts involved:

"Petrography is here regarded as the systematic and descriptive side of the study of rocks, whereas petrology is more comprehensive, covering not only the description but also the theories of origin of rocks - petrogeny - and the interpretation of the facts in petrography". (Grout, 1932, p.1).

"The study of rocks as specimens may be properly designated petrography. Petrology is however a broader term which connotes the philosophical side of the study of rocks, and includes both petrography and petrogenesis, the study of origins. Petrography comprises the purely descriptive part of the science from the chemical, mineralogical and textural points of view" (Tyrrell, 1926, p.1).

Returning to the field of sedimentary rocks, Krumbein and Pettijohn (1938, p. 4) wrote that, "The scientific study of sediments may be divided into two broad divisions. The first of these is the field and laboratory investigation of sediments, which yields data that lead to their description and classification. The second part of the subject is concerned with the laws of sedimentation and the origin of sedimentary deposits. To the first aspect may be applied the term sedimentary petrography or sedimentography. The second division is properly designated as sedimentary petrology or sedimentology". However, Krumbein and Pettijohn had previously (p.3) stated that "the subject [i.e. sedimentary petrology/sedimentology] involves a complete study of sediments from the point of view and with the methods of pure science". The "second division" referred to in the first quotation should hence have been designated sedimentary petrogenesis or "sedimentogenesis", which together with sedimentary petrography (sedimentography) would constitute sedimentary petrology (sedimentology). The above quotations are, however, important as an early example of the use of "sedimentography" and "sedimentology" as synonyms of "sedimentary petrography" and "sedimentary petrology" respectively; the writers in fact expressed regret that the term "sedimentology" had not come into general use. However, the situation has changed and "sedimentology" now has a firmly established place in geological literature, used in the sense suggested by Krumbein and Pettijohn (as a comparison of the contents of the journal "Sedimentology" and the "Journal of Sedimentary Petrology" will show).

The distinction between macro-sedimentography and micro-sedimentography (as defined above) would seem to be an important one, since, for one thing, it highlights the fact that textbooks purporting to deal with sedimentary petrography (eg. Krumbein and Pettijohn, 1938; Milner, 1962) are normally devoted exclusively to micro-sedimentography. This same bias is seen in two recent textbooks entitled "Methods in Sedimentary Petrology" (Müller, 1967) and "Techniques in Sedimentary Petrology" (Carver, 1971), where the entire contents of the former and nine-tenths of the contents of the latter are devoted to micro-sedimentography. This emphasis is surprising in view of the far greater value of macro-sedimentographic information for interpreting the origin of sedimentary strata. An attempt has been made to preserve a correct balance in the descriptive scheme outlined later in this chapter, and in the process to indicate more clearly the full scope of macro-sedimentography.

The scope of palaeontology is fairly clearly defined, although trace fossils (burrows, tracks, etc.), are a borderline case between macro-sedimentography and palaeontology, sensu stricto, since they do not represent actual organic remains. However, the identification of the organisms responsible for these "hieroglyphics" can only be attempted by those possessing a sound knowledge of the habits of such organisms; trace fossils must therefore be considered to be within the domain of the palaeontologist.

In addition, although "biostratigraphy" is certainly an aspect of stratigraphy as such, in practice the biostratigraphic zonation of sedimentary sequences are carried out by palaeontologists and even the actual mapping of such zones can often only be carried out by a stratigrapher with specialist palaeontological training. It is thus not at all certain that biostratigraphy does not belong more with palaeontology than stratigraphy proper.

C. A STANDARD SCHEME FOR LITHOSTRATIGRAPHIC UNIT DESCRIPTIONS

The scheme that follows was devised primarily as a guide-line for fully quantitative descriptions, but can be simplified and adapted to less elaborate descriptions (as has been done in Part B of this project). Those items that can most readily be omitted without serious overall loss are marked with an asterisk.

1. Basic concepts

Stratigraphy

Data concerning lithostratigraphic units as such (i.e. viewed as a whole).

Palaeontology

Data concerning fossil remains.

Sedimentography

Data concerning lithosomes (individual lithological entities).

Macro-sedimentography

Data concerning sedimentary aggregates.

Micro-sedimentography

Data concerning sedimentary particles.

Sedimentogenesis

Interpretation and analysis of data.

2. Sedimentography: some general principles

1. The scheme outlined below has been drawn up with siliciclastic rocks primarily in view, but can readily be adapted and expanded to cover other rock types.
2. The "lithosome" represents a fundamental concept in macro-sedimentography, and following Krumbein and Sloss (1963, p. 301), is used here for "rock masses of essentially uniform lithologic character which have intertonguing relationships with adjacent masses of different lithology". Wheeler and Mallory (1956) first proposed the term.
3. If the thickness values of a particular lithology are bimodal or polymodal, the desirability of treating the various groupings separately should be considered, since two or more genetically distinct types may be present. Similarly, if "rhythmitites" (see Chapter III) can be clearly assigned to both "varved" (tabular-bedded) and "streaky" (lenticular-bedded) classes, these classes should be described separately where possible.
4. Complexity of description can vary enormously, depending on the purposes of the study, the nature of the exposures and the time available. Decision is required not only whether to adopt a simple qualitative or an elaborate quantitative approach (or something in between) but also whether the description will be based on an average

for the whole formation at one representative locality or will include a detailed analysis of vertical and lateral variation in properties. In general, a qualitative approach will normally be adequate for interpreting the genesis of a particular formation, but for comparing different formations (or the same formation at different localities) and for detailed exploration work some form of quantitative approach will be necessary.

5. The following values should always be quoted, where possible, in quantitative studies, arranged in the order in which they are given below:

(a) Mean ($\bar{x}$)
(b) Range of values (minimum and maximum)
(c) Standard deviation (s)
(d) Number of readings (n)

3. Outline of scheme

A. STRATIGRAPHY

A1 General stratigraphic interrelationships
A1.1 Lithostratigraphic relationships
* A1.2 Chronostratigraphic relationships
* A1.3 Biostratigraphic relationships
A2 Basic concept and distinguishing features
A3 Geographic distribution
A4 History and Nomenclature

History.- First reference (author and date) to the specific stratigraphic interval under discussion as a distinct and separate lithostratigraphic unit in the area under consideration. Other relevant historical developments.

Nomenclature.- Previous name(s), derivation and suitability of present name, and correlation problems that bear on nomenclature.

A5 Boundaries
A5.1 Lower boundary
A5.2 Upper boundary
A5.3 Lateral boundaries

Information required in each case:

(a) Adjacent lithology
(b) Nature of boundary (including thickness of transition zones, if present)
(c) Definition of boundary

A6 Overall lithology and facies changes

Relative abundance (percent) of each rock-type present. If this information is given for various localities, facies changes can be analysed and discussed.

A7 Dimensions and Shape

A7.1 Thickness (m)

*A7.2 Rate of thickness change (m/km)(cross-sectional shape)

*A7.3 Lateral extent (km)

A8 Stratotypes (Type and reference sections)

For each kind of stratotype recognised the following information should be provided:

(a) Nature of stratotype: nature of exposures, degree of tectonic disturbance, suitability of choice, alternatives, etc.
(b) Accessibility of stratotype: nature of roads, footpaths, etc. and distances involved.
(c) Location of stratotype.

B. PALAEONTOLOGY

B1 Vertebrate fossils

B2 Invertebrate fossils

B3 Plant fossils

B4 Trace fossils

B5 Microfauna

B6 Microflora (spores and pollen)

For each species (or larger category) encountered, the following information should be provided:

(a) Number of species present (in each major category)
(b) Average relative abundance (spec. $/m^2$)
(c) Maximum concentration (spec. $/m^2$)
(d) Dimensions of specimens
(e) Orientation data

C. MACRO-SEDIMENTOGRAPHY

C1 Cyclicity

Nature and extent of cyclic arrangement of lithological entities (if any).

Information required for each type of cycle present:

(a) Lithological composition

(b) Relative abundance of cycle (in relation to other kinds of cyclic or non-cyclic arrangements present).

(c) Thickness (of cycle or couplet)

(d) Lateral extent (width)

(e) Width/thickness ratio (cross-sectional shape)

C2 Lithosome dimensions and shape

C2.1 Thickness data

C2.2 Lateral extent (width)

C2.3 Width/thickness ratio (cross-sectional shape)

C3 Lithosome boundaries

C3.1 Lower boundaries

C3.2 Upper boundaries

C3.3 Lateral boundaries (if observed)

Information required in each case:

(a) Adjacent lithology

(b) Nature of boundary: relative abundance of boundary types present; thickness of transitional (or pinch-out) zones (if any); depth of erosion (if present)

C4 Colours

Information required for each colour-type present:

(a) Relative abundance

(b) Thickness of colour bands (in multi-coloured lithosomes)

(c) Lateral extent of colour bands (ditto)

(d) Width/thickness ratio (cross-sectional shape) of colour bands

(e) Nature of pigmentation (mineralogical data)

C5 Sedimentary structures

C5.1 General bedding characteristics

General external form (thickness and cross-sectional shape) of beds (sedimentation units or individual layers in lithologically "banded" sediments, e.g. rhythmitites).

C5.2 Pre-depositional (erosional) structures

C5.3 Syn-depositional current structures

C5.3.1 Internal syn-depositional structures (within beds)

C5.3.2 External syn-depositional structures (on upper bed surfaces)

C5.4 Deformational (post-depositional) structures

C5.5 Chemical structures

C5.6 Biogenic (organic) structures

Information required for each structure/bedding type present:

(a) Relative abundance

(b) Dimensions and shape, if significant

When describing syn-depositional structures, individual laminations, sedimentation units (sets) and cosets should be treated separately.
(c) Directional data

D. MICRO-SEDIMENTOGRAPHY

D1 Texture
D1.1 Grain size
D1.1.1 Percentage coarse component in visually bimodal lithologies
D1.1.2 Central tendency (mean size)
D1.1.3 Dispersion (spread of values, "sorting")
D1.1.4 Maximum size in samples
D1.1.5 Matrix percentage
*D1.1.6 Skewness
*D1.1.7 Kurtosis
D1.2 Roundness
*D1.3 Shape
*D1.4 Orientation data
*D1.5 Porosity
*D1.6 Permeability
D2 Composition
D2.1 Mineral composition
D2.1.1 Gravel and conglomerate. List rock-types present and their relative abundance.
D2.1.2 Sand and sandstone
D2.1.2.1 Framework fraction (allogenic)
*D2.1.2.2 "Matrix" (allogenic)
*D2.1.2.3 Authigenic minerals
For each category, list minerals present and their relative abundance.
*D2.1.3 Mud and mudrock.
List minerals present and their relative abundance.
*D2.2 Chemical composition
D2.2.1 Major elements
D2.2.2 Minor elements (trace elements)
List chemical components present and their relative abundance.

E. SEDIMENTOGENESIS

E1 Dispersal patterns (palaeocurrents)

E2 Sedimentary processes (transportation/deposition) and palaeoenvironments

E3. Provenances (nature and location of source areas)

*E4. Palaeoclimates.

*E5. Diagenesis

F. SYNTHESIS

F1. Tectonic framework of sedimentation

F2. Palaeogeography

F3. Historical geology.

CHAPTER II

STRATIGRAPHIC CLASSIFICATION AND TERMINOLOGY

A. GENERAL

The principles adopted in the naming and definition of the stratigraphic units covered by this study are, basically, those that have been embodied in the "South African Code of Stratigraphic Terminology and Nomenclature" (SACS, 1971). As stated in the introduction to this document, the compilers have drawn heavily on the recommendations of the International Subcommission on Stratigraphic Classification (ISSC) as well as on an article by Van Eysinga (1970). The "international" approach in turn owes much to developments in North America during the period 1930 to 1960, culminating in the production by the American Commission on Stratigraphic Nomenclature (ACSN) of a "Code of Stratigraphic Nomenclature" in 1961. Since stratigraphic knowledge is continually expanding, the South African Code will doubtless be modified with time and the compilers accordingly invite comments on it (p. iii). The most recent recommendations of the ISSC are contained in an unpublished draft of an "International Stratigraphic Guide" which appeared during 1974.

Useful historical and critical reviews covering the development of stratigraphic terminology in South Africa were given by Verwoerd (1965) and Truswell (1967). Reasons for adopting an internationally recognised terminology and abandoning traditional South African usage were advanced by the present writer (1966), A.C. Theron (1967), Rust (1967), Truswell (1967), Loock (1967), and J.N. Theron (1972); these writers all attempted to apply the "new" terminology to those parts of the Cape and Karoo "Systems" with which they were concerned. Further argumentation along these lines has been rendered unnecessary by the adoption of the present South African Code, and discussion can now centre around suggestions for improvements to the code itself.

B. ESTABLISHMENT OF FORMAL STRATIGRAPHIC UNITS

Section 8 of the South African Code ("Procedure for the Establishment of Formal Stratigraphic Units") does not appear to be completely satisfactory in its present form, for the following reasons:

1. No attempt has been made to indicate what is essential and what is not essential among the details which, according to the Code, should be included in the description of a new "stratigraphic unit and its stratotype". Many of the items listed are actually non-essential for the purposes of establishing a formal lithostratigraphic unit (e.g. palaeontology; mineralogy; structure; geomorphic expression; graphic profiles; photographs; columnar sections; structure sections; boundary-stratotypes; reference-stratotypes; discussion of origin; environmental facies; age). On the other hand, certain other items are indispensable, and must form part of any formal proposal of a new lithostratigraphic unit. Such a set of minimum requirements should have been more clearly indicated, as has been done for example by the ISSC (1970a, p. 19): "Establishing a formal lithostratigraphic unit requires publication in some recognized scientific medium, preferably with a reference system control, of a definition that includes: (i) statement of intention to designate a formal unit; (ii) selection of name, (iii) definition of unit in the type area, with specific location of the type section; (iv) distinguishing characteristics; (v) definition of boundaries and contact relationships; (vi) dimensions and shape; and, as far as possible, (vii) geologic age and correlation."

A comparison of Article 8 in the South African Code with the corresponding section (Article II c) in Report No. 4 of the ISSC (1970b, p. 8) - from which the former was apparently derived - indicates that much greater clarity could have been achieved by printing the key words in italics to show that they in fact represent the basic categories involved. The draft "International Stratigraphic Guide" (ISSC, 1974) uses an even clearer layout, with all items arranged under ten distinct, numbered headings.

The classification of boundary-stratotypes as non-essential probably requires some amplification. While the value of a type section in defining and illustrating in "concrete" terms the general concept of a stratigraphic unit cannot be questioned, it may legitimately be queried whether the additional selection of boundary stratotypes is generally necessary. For one thing, it is perfectly possible to compile a map showing the distribution of a number of different formations (selected on the basis of obvious differences in character and tied to definite type sections illustrating the basic concept of each unit) without ever having seen exposed the actual boundary between any of them. Even in areas where boundary stratotypes can be located, it is still uncertain whether the designation of specific boundary stratotypes is really necessary. If we have formation A (with sandstone predominant) overlain by formation B (shale predominant) and we decide to draw the base of formation B at the horizon above which the shale percentage is greater than 50%, a boundary stratotype showing this transition is not actually needed. Boundary stratotypes may in some situations make for a certain rigidity and inflexibility of approach in which a worker may insist on following a particular horizon as defined in such a stratotype rather than continuing to maintain the general concept of each formation, even if it means shifting the boundary up or down in the succession in order to keep pace with lateral facies changes.

In the light of the above arguments, and in view of the semi-reconnaisance nature of much stratigraphic mapping in South Africa, it is clear that proven mappability, plus the existence of suitable type sections (or even type localities) showing the characteristic features and lithology of a succession should be adequate prerequisites for the formal establishment of a new formation (even if exposure is incomplete and the top and bottom contacts are covered). This does not mean to say that situations will never arise in which boundary stratotypes can serve a useful purpose.

2. The order in which the various items are listed does not always form a logical sequence. Since it would be helpful if all proposals for new lithostratigraphic units could follow a similar (if not identical) pattern, more attention could have been devoted in the past to this particular aspect in the interests of consistency. In the descriptive scheme which was outlined in the previous chapter, an attempt was made in the "Stratigraphy" section to include all those items which are indispensable for the formal definition of lithostratigraphic units, and to arrange these items as far as possible in a definite order reflecting a natural progression of thought.

C. USE OF THE TERM "SHALE" IN LITHOSTRATIGRAPHY

According to the ISSC (1970 a, p. 16), "where a lithologic term is used in the name of a lithostratigraphic unit, the simplest generally acceptable term is recommended". In view of the widespread use of "shale" in lithostratigraphy to denote fine-grained sediments in general (i.e. mudrocks and argillaceous rhythmitites), this usage is retained here.

D. ACCESSIBLITY OF STRATOTYPES

Every stratotype description should contain some indication of the easiness (or otherwise) of access which is involved. It is suggested that accessibility may be rated as "excellent", "good", "fair" or "poor" according to the following criteria:

Excellent - Exposures adjoin a main road.

Good - Exposures commence within 1 km of any road readily negotiable with an ordinary vehicle.

Fair - Exposures commence within 3 km of a road negotiable with an ordinary vehicle.

Poor - Exposures relatively inaccessible, involving use of a special vehicle and/or more than 3 km walking.

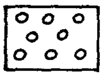
CHAPTER III

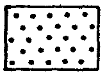
SEDIMENTARY ROCK NOMENCLATURE

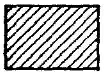
In this study an attempt has been made to adhere as far as possible to the basic field classification presented below. Though the emphasis falls on the siliciclastic rocks, the other major sedimentary rock groups have been included for the sake of completeness. Suggested lithological symbols suitable for graphic portrayal are also included.

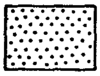
1. Siliciclastic rocks.(i.e. non-carbonate clastics)

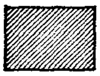
1a. Visually homogeneous rocks:


Conglomerate (Rudite)

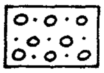

Sandstone (Arenite)

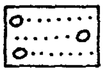

Mudrock (Lutite) (Undifferentiated)

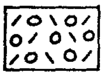

Siltrock


Clayrock

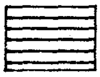
1b. Visually heterogeneous rocks(two or more distinct components)

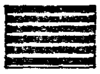

Sandy conglomerate

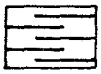

Conglomeratic sandstone


Diamictite (pebbly mudstone)


Rhythmitite (undifferentiated)

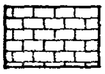

Arenaceous "varved" rhythmitite


Argillaceous "varved" rhythmitite


Arenaceous "streaky" rhythmitite


Argillaceous "streaky" rhythmitite

2. Carbonate rocks


Limestone


Dolomite

3. Non-carbonate chemical rocks

▩ Evaporites (rock salt in general)

▽ Chert

4. Volcaniclastic rocks

" Tuff

◠ Volcanic agglomerate

5. Miscellaneous rocks

■ Coal

The only terms used above which need to be discussed here are "mudrock" and "rhythmitite"; the remaining names are fairly clear and unambiguous, and are adequately defined in the 1972 edition of the AGI Glossary of Geology (Gary et al., eds.). The class limits and names proposed by Wentworth (1922) have been almost universally adopted as a standard of reference by sedimentologists, and are adhered to in this study.

Mudrock.- Since to many geologists the terms "shale" and "mudstone" imply the presence or absence of fissility respectively (see AGI Glossary, 1972), we are left without a suitable general term to describe the finer-than-sand sediments as a group. The term "mud" is now commonly used to cover silt plus clay (see Folk et al, 1970; Gary et al., 1972), and Ingram (1953, p. 870) proposed the scheme depicted in Table III-1, which, if adhered to, would solve most of the terminological difficulties associated with the fine-grained clastics. Although the compilers of the AGI Glossary (1972) regard "mudstone" and "mudrock" as synonyms, the distinction made by Ingram does enjoy considerable support (e.g. Dunbar and Rodgers, 1957, p. 166; Folk, 1968, p. 141; Blatt et al., 1972, p. 374), and was retained in this study. If a completely unambiguous term is considered necessary, "lutite" will probably have to be used.

Table III-1. Nomenclature of homogeneous sedimentary rocks containing more than 50 percent silt and/or clay. After Ingram, 1953.

	General Term	Massive	Fissile
General Term	Mudrock	Mudstone	Shale
Silt predominant over clay	Siltrock	Siltstone	Silt shale
Clay predominant over silt	Clayrock	Claystone	Clay shale

Rhythmitite. - Rhythmitite is here defined as a fine-grained siliclastic rock (very fine sand + silt + clay) showing alternation of coarser (relatively pale) and finer (relatively dark) material on a small scale (individual layers less than 10 cm thick), giving rise to a banded or streaky appearance. In practice two main types occur: "streaky" rhythmitites (individual layers discontinuous; flaser-bedding a characteristic feature) and "varved" rhythmitites (individual layers continuous and parallel; varve-like appearance). The name "laminite" was applied to certain rhythmically-bedded rocks in flysch sequences by Lombard (1963), while the term "rhythmite" has been used for the individual unit of a rhythmic succession (Gary et al., 1972).

Typical streaky rhythmitites are illustrated by Pettijohn and Potter (1964 Plate 17), De Raaf and others (1965 Figs. 9,10), and Reineck and Singh (1973, Figs. 151, 164-177), while "varved" rhythmitites are depicted by Pettijohn and Potter (Plates 5, 11A, 109) and De Raaf and others (Fig. 3).

The recognition of "rhythmitites" as a distinct lithological entity avoids the use of cumbersome expressions (e.g. "fine-grained alternation of sandy siltstone and silty shale") and focusses attention on the presence of a volumetrically important and genetically significant group of rocks which have not received adequate attention in the past.

CHAPTER IV

SIZE AND SHAPE DATA IN MACRO-SEDIMENTOGRAPHY

Information regarding "size" and "shape" is commonly presented at five different levels in sedimentological studies, namely, for lithostratigraphic units (formations, etc.), cycles, lithosomes, sedimentation units, and individual grains. In view of the considerable attention that has been devoted to the theoretical and practical problems associated with the measurement of grain size and shape, it is surprising that not much thought seems to have been given to the similar theoretical problems associated with obtaining meaningful "size" and "shape" data at other (macroscopic) levels. While measurement of the total thickness and lateral extent of a group, formation or member is fairly straightforward and unambiguous, the same does not necessarily apply in the case of cycles, lithosomes and sedimentation units.

A. SEDIMENTARY LAYER THICKNESS AND WIDTH

In three dimensions, sedimentary layers (cycles, lithosomes, sedimentation units) can be considered to possess maximum, intermediate and minimum dimensions, i.e. length, width and height (thickness). However, while it is possible to isolate pebbles or even individual sand-size grains and obtain their true maximum, intermediate and minimum dimensions, such a procedure is not possible with sedimentary layers. In practice we normally have to deal with random vertical sections through such layers, leading to measurements of apparent thickness and apparent width (length). Depending on the location of the section, the former value can lie anywhere between nil and the true thickness while the latter value can similarly vary from nil to the true length. The situation is analogous to the measurement of grain size in thin section, with one significant difference: whereas in thin section it is always possible to measure the maximum and minimum apparent dimensions of individual grains, due to incomplete exposure the measurement of maximum apparent dimensions is rarely possible when dealing with cycles and lithosomes, and not always possible even when dealing with sedimentation units.

Confining ourselves for the moment to a consideration of thickness, three fundamental decisions need to be made. The first concerns the use of number or volume frequencies in arriving at estimates of central tendency and dispersion (spread of values), the second concerns the choice of arithmetic or geometric means as the most suitable estimator of central tendency, and the third concerns the practical definition of "thickness" in random sections. In addition, some thought should be given to the relationship between the size measures obtained in random section and true size, as well as the choice of a suitable size scale.

1. Number versus volume frequencies

Concerning the use of number or volume frequencies, a true number frequency (percent by number of layers in each thickness class present in a lithostratigraphic unit) can never be obtained in a single random section unless such layers are absolutely tabular in shape. Since such a situation rarely occurs it means that in practice we can only obtain the relative volumes of material occurring in each size (thickness) class. The same situation is encountered in grain size analyses made in thin section (see later discussion). The procedure involved in measuring a detailed stratigraphic section in a road-cut or stream bed is in fact identical to that involved in carrying out a modal analysis using an integrating stage; in each case the length of the intercepts made by each component present along a straight-line traverse are noted (and tallied). In both cases the relative proportions obtained are directly proportional to the volume of the components encountered. This applies to lithological classes and thickness classes in the same way that it does to mineral classes and size classes in thin section (see Stauffer, 1966, p. 261), although of course the actual "size" values obtained will in both cases be less than the "true" size. In addition, we need to remember that even if we could actually arrive at the number of beds in each thickness class, a mean based purely on the number of beds in each thickness category will give undue prominence to very thin beds or lithosomes, out of all proportion to their contribution to the total volume of rock (see hypothetical example below).

2. Arithmetic versus geometric means

Although nearly all mean thicknesses quoted in the literature for lithosomes and sedimentation units are arithmetic means, this measure is probably not the most satisfactory estimator of central tendency in this case. The use of 0 units in grain-size analyses give rise to a geometric mean, and this procedure has become standard practice. Thus the mean size of a sample containing equal volumes of grains 1,2, and 4 mm in diameter respectively (0Ø, -1Ø and -2Ø) is generally taken to be 2 mm ($\sqrt[3]{1.2.4}$) and not 2,33 mm (i.e. (1+2+4)/3).

The geometric mean is normally obtained by finding the arithmetic mean of the sizes expressed as Ø units ($-\log_2 d_{mm}$), in this case $(0+(-1)+(-2))/3 = -1Ø = 2$ mm. Returning to the larger units under discussion, bed thickness measurements frequently show a close approximation to a log-normal frequency distribution (Blatt et al., 1972, p. 115) and the calculation of a geometric rather than arithmetic mean is hence required. In practice this would be most readily achieved by finding the antilog of the arithmetic mean of the logarithms of the individual thickness values.

3. Field measurement of thickness values

Finally, with regard to the actual measurements made in the field, the thickness itself can be taken as either the maximum apparent thickness visible along the full length of the bed or the thickness encountered at the point at which the line of section intersects the bed. The latter procedure would seem to be preferable, since not only is the maximum visible thickness in any case nearly always less than the true maximum thickness, but the maximum visible thickness will be arbitrarily governed by the nature and extent of the outcrops adjacent to the line of section.

4. Practical implications of techniques

In order to illustrate some of the principles discussed above, it may be helpful to consider a simple practical example. Let us assume that we are dealing with a formation composed of lenticular (but parallel-sided) sandstone layers 10 m and 1 m thick and shale. The diagram (Fig. IV-1) represents a "sample" isolated for study purposes, ABCD being equivalent to a random vertical section (e.g. a cliff face) and EF representing the line along which a columnar section is to be measured.

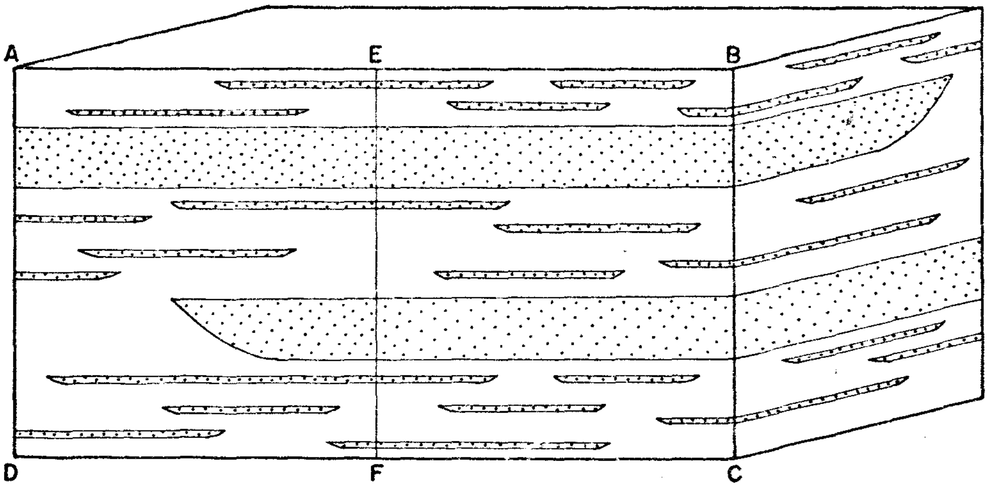


Fig. IV-1 "Sample" referred to in text.

The following observations can be made:

1. The ratio of the number of thin sandstone beds to the number of thick sandstone beds encountered along the section EF (2 : 1) bears no simple relation to actual ratio of thin to thick sandstone units present in the total sample (possibly 20 : 1).

2. There are at least six ways in which a value for mean thickness can be obtained (not taking into account other measures of central tendency such as the median and mode). Not all the thin layers present in the sample will have been intersected on the two visible sides of our sample and the true total number of thin layers is thus unknown; for ease of calculation a total number of 28 thin layers has been arbitrarily assumed to be present.

(i) True number frequency, arithmetic mean

$$\bar{x} = \frac{2\ (10)\ +\ 28\ (1)}{30}$$

$$= \frac{48}{30}$$

$$= 1{,}60 \text{ m}$$

(ii) True number frequency, geometric mean

$$\bar{x} = \text{Antilog} \left\{ \frac{2\ (\log 10)\ +\ 28\ (\log 1)}{30} \right\}$$

$$= \text{Antilog} \left\{ \frac{2\ (1)\ +\ 28\ (0)}{30} \right\}$$

$$= \text{Antilog}\ \frac{2}{30}$$

$$= \text{Antilog}\ 0{,}0666$$

$$= 1{,}17 \text{ m}$$

(iii) Apparent number frequency, arithmetic mean (Section EF)

$$\bar{x} = \frac{2\ (10)\ +\ 4\ (1)}{6}$$

$$= \frac{24}{6}$$

$$= 4 \text{ m}$$

(iv) Apparent number frequency, geometric mean (Section EF)

$$\bar{x} = \text{Antilog}\left\{\frac{2\ (\log 10) + 4\ (\log 1)}{6}\right\}$$

$$= \text{Antilog}\left\{\frac{2\ (1) + 4(0)}{6}\right\}$$

$$= \text{Antilog}\ \frac{2}{6}$$

$$= \text{Antilog}\ 0{,}333$$

$$= 2{,}15\ \text{m}$$

(v) Volume frequency, arithmetic mean (Section EF)

$$\bar{x} = \frac{20\ (10) + 4\ (1)}{24}$$

$$= \frac{204}{24}$$

$$= 8{,}50\ \text{m}$$

(vi) Volume frequency, geometric mean (Section EF)

$$\bar{x} = \text{Antilog}\left\{\frac{20\ (\text{Log}\ 10) + 4\ (\text{Log}\ 1)}{24}\right\}$$

$$= \text{Antilog}\left\{\frac{20\ (1) + 0}{24}\right\}$$

$$= \text{Antilog}\ \frac{20}{24}$$

$$= \text{Antilog}\ 0{,}833$$

$$= 6{,}81\ \text{m}$$

On the basis of our earlier discussion, the last value (6,81 m) probably represents the most "correct" estimate of mean size in this case. However, most geologists probably conceive of "average" values in terms of arithmetic means based on the number of beds (or other kinds of sedimentary layers) of various thicknesses actually encountered in a section, and, unless otherwise indicated, where the word "average" is used in this study it can be taken to represent the common usage (i.e. an arithmetic mean based on apparent number frequencies). In most cases this mean will represent a tolerably close approximation of the theoretically superior geometric mean based on volume frequencies.

It is also of course recognised that a bimodal distribution such as the one under discussion should normally be represented by the two modes; however, an extreme example was used for the sake of increased clarity in illustrating the significant differences in mean size that can be obtained using different methods of computation.

As regards the measurement of apparent width (length) the best procedure would seem to be to measure the width of those units intersected by the traverse, and to base calculation of means (where this is feasible) on volume-frequencies. Since unusually good laterally continuous exposures are required for this sort of operation, most workers will probably be content to quote approximate values for both lateral dimensions and shape factor (width/thickness).

5. Relationship between observed and true thickness

Concerning the relationship between thickness values obtained from columnar sections and true (i.e. maximum) thickness, it is clear that no universally applicable correction factor can be arrived at, since the shape of the lithosomes must be taken into account. Thus the difference between true and measured average thickness will be greatest when beds possess a triangular or wedge shape (i.e. where the bounding surfaces are straight but not parallel) and least where beds are rectangular in section. In the former case the average reduction in the thickness will be 50%. Plano-convex shapes will show intermediate reductions in apparent thickness. These situations are illustrated in Fig. IV-2 below. It is clear that in the case of a triangular or wedge-shaped bed the average thickness obtained from a series of equidistant vertical sections will be half the true thickness.

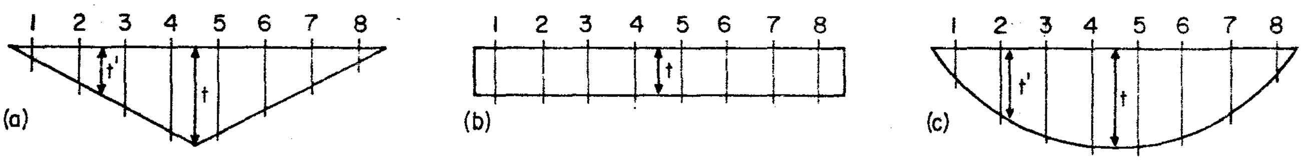


Fig. IV-2. Relationships between true thickness of beds and observed mean thickness obtained from 8 random vertical sections through triangular (a), rectangular (b), and plano-convex (c) beds. 1-8 = equidistant vertical sections; t = true thickness; t′ = observed mean thickness.

6. Choice of size scale

While the geometric grade scale proposed by Wentworth in 1922 (in which each size grade or class differs from adjacent classes by a constant ratio of 2) has been almost universally adopted for the description of sedimentary particles, no similar scale designed for larger sedimentary units has come into general use. Kelley (1956) used a semi-geometric scale (based on feet) to tabulate bed-thickness data, while Bokman (1957) proposed a geometric theta scale which was unfortunately based on inches and not metric units.

There would seem to be much to be said for adapting Wentworth's specific approach to the study of size in sedimentary rocks at all levels, including the study of vertical thicknesses of various kinds of sedimentary layers. In both cases the total size range involved is such that the size of the smallest unit encountered is about one millionth that of the largest; in the case of sedimentary particles the size ranges from clay particles smaller than one micron to boulders in excess of one metre, while in the case of sedimentary layers the variation is from paper-thin laminae less than one mm thick to stratigraphic units over 1 000 m thick.

It is clear from the above that whereas the grain size scale is based on fractions or multiples of one mm, if a similar scale is to be constructed for sedimentary units it will have to be based on multiples and fractions of a metre. Such a scale can be used as an aid in analyzing the thickness distribution of beds and lithosomes; the central tendency can be stated in terms of a modal class, while graphical portrayal of the distribution by means of a histogram can be readily accomplished. A total of 22 classes encompasses the entire range of thickness values encountered in macro-sedimentography. If desired, a scale analogous to the Ø scale can be drawn up and used in preference to the metre values indicated. The actual scale is presented in Table IV-1.

B. SHAPE DATA

The shape of sedimentary layers (lithosomes, sedimentation units, etc.) in plan view can rarely be ascertained except where exposures are unusually good or abundant subsurface data are available. On the other hand, some idea of the average cross-sectional shape can be much more readily obtained and information on this aspect should be included wherever possible in sedimentographical studies. Since cross-sectional shape normally varies with direction (due to the fact that both lithosomes and sedimentation units invariably show a preferred direction of elongation) the directions along which this property was measured should be clearly stated, unless values are based on a series of completely random cross-sections.

Table IV-1. A geometric size scale for use in macro-sedimentography

Category	Thickness (mm)	Category	Thickness (m)
1	< 1	12	1 - 2
2	1 - 2	13	2 - 4
3	2 - 4	14	4 - 8
4	4 - 8	15	8 - 16
5	8 - 16	16	16 - 32
6	16 - 31	17	32 - 64
7	31 - 62	18	64 - 128
8	62 - 125	19	128 - 256
9	125 - 250	20	256 - 512
10	250 - 500	21	512 - 1024
11	500 - 1000	22	> 1024

Cross-sectional shape is most commonly defined as the width/thickness ratio. Krynine (1948, Fig. 9) used the width-to-thickness ratios of lithosomes to establish a strictly geometric classification into blanket (greater than 1000 : 1), tabular (50 : 1 to 1000 : 1), prism (5 : 1 to 50 : 1), and shoestring (less than 5 : 1) shapes. However, the classes proposed by Krynine are far too large to be useful even in semi-quantitative studies. A series of classes based on an approximately geometric scale involving a ratio of about 3 will probably prove to be more useful in analysing cross-sectional shape, and the scheme presented in Table IV-2 was accordingly devised.

It was felt that the scheme in Table IV-2 adequately encompasses the full range of situations normally encountered. The verbal designations give due weight to the fact that while width : thickness ratios which differ by a factor of 3 are readily discernible and genetically significant in the more lenticular units, much larger differences can be encompassed by a single class in the case of tabular units.

Table IV-2. A classification of shape classes applicable to sedimentary layers.

Class	Width/thickness	Designation
1	> 100 000	Ultra-tabular
2	30 000 - 100 000	Highly tabular
3	10 000 - 30 000	
4	3 000 - 10 000	Moderately tabular
5	1 000 - 3 000	
6	300 - 1 000	Subtabular
7	100 - 300	Sublenticular
8	30 - 100	Moderately lenticular
9	10 - 30	Highly lenticular
10	< 10	Ultra-lenticular

CHAPTER V

SEDIMENTARY LAYERS: TERMINOLOGY AND DESCRIPTIVE ASPECTS

A. TERMINOLOGY

A set of basic definitions needs to be adopted and consistently applied in order to eliminate the ambiguities present in the nomenclature applied to the various kinds of layers or units encountered in sedimentary rock sequences. "Bed", for example, has been used without qualification for lithostratigraphic units, lithological units, sedimentation units and individual laminae greater than 1 cm in thickness (cf. AGI Glossary, 1972, p. 66); the term thus amounts to a synonym for a "stratum" or "layer" of any kind (although many writers have attempted to restrict its meaning). For more precise description the following hierarchy of terms should be adhered to:

Lithostratigraphic units: group, formation, member, bed.
The above terms are applied to formally recognised stratigraphic units.

Lithosomes

Sedimentary layers essentially uniform in lithologic character; differentiated from layers above and below by change in lithology (cf. Krumbein and Sloss, 1963, p. 301).

Sedimentation units

A layer or deposit resulting from one distinct act of sedimentation, defined by Otto (1938, p. 574) as "that thickness of sediment which was deposited under essentially constant physical conditions." It is distinguished from like units by changes in grain size and/or fabric (structure) indicating changes in velocity and/or direction of flow (cf. AGI Glossary, 1972, p. 642; Pettijohn and Potter, 1964, p. 338). In addition, "if sedimentation ceases locally or is replaced by erosion, the change records a sedimentation-unit boundary" (Otto, 1938, p. 578). Although Bokman (1956) and Campbell (1967) both wish to see the use of "beds" restricted to "sedimentation units", this is unlikely to happen and it is therefore preferable to retain "sedimentation unit" to avoid ambiguity, in spite of it being a more cumbersome expression.

Laminae

Smallest layers visible in sedimentary rocks, commonly a few mm to a few cm thick. "The thinnest or smallest recognisable unit layer of original deposition in a sediment or sedimentary rock, differing from other layers in colour, composition or particle size, and resulting from variations in the rate of supply or deposition of different material during a momentary or local fluctuation in the velocity of the depositing current" (AGI Glossary, 1972, p. 394; cf. Otto, 1938, p. 575; Bokman, 1956, p. 126; Pettijohn and Potter, 1964, p. 317; R.E. Elliot, 1965, p. 198; Campbell, 1967, p. 18). It must be added that laminae are very often only recognised because of the presence of distinct bedding planes between them, and that visible differences in colour, composition or grain size are not present in many, if not most, cases.

In addition to the above terms, we need to define two additional bedding terms proposed by McKee and Weir (1953) which have become fairly popular because of their usefulness, namely, set and coset.

Set

"A set is a group of essentially conformable strata or cross-strata [i.e. laminae as defined above], separated from other sedimentary units by surfaces of erosion, nondeposition, or abrupt change in character. It is the smallest and most basic group unit " (McKee and Weir, p. 382, 383). All sets would thus seem to constitute sedimentation units, but not all sedimentation units (eg. graded turbidite beds) are sets.

Coset

"The term coset is proposed for a sedimentary unit made up of two or more sets, either of strata or cross-strata [i.e. laminae], separated from other strata or cross-strata by original flat surfaces of erosion, non-deposition or abrupt change in character " (McKee and Weir, p. 384). A coset consists essentially of adjacent sets with the same internal structure, bounded above and below by sets or cosets characterised by different internal structures (or by a major break or discontinuity). These relationships are actually clearer in Fig. I (p. 383) than they are in the verbal definitions.

The whole of the above scheme is illustrated diagrammatically in Fig. V-1.

Campbell (1967) has recently discussed sedimentary layer terminology in some detail, but in this writer's opinion his paper serves to confuse rather than clarify the issues. Campbell (p. 7) regards "beds" as the "basic building blocks" of sedimentary bodies. He defines a bed as "the stratum that reveals the principal rock layering" (p. 8); another definition given is "a layer of sedimentary rocks or sediments bounded above and below by bedding surfaces" (p. 12). Bedding surfaces in turn are "depositional surfaces that reveal the principal rock layering or bedding" (p. 12). They are produced during periods of non-deposition

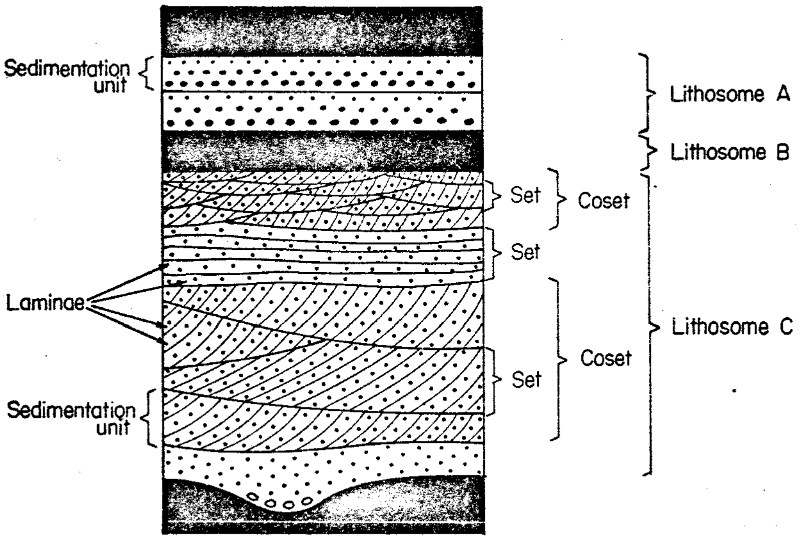


Fig. V-1. Sedimentary layer terminology.

or abrupt change in depositional conditions, and erosion commonly accompanies non-deposition. Distinction of beds depends upon recognition of bedding surfaces.

A lamina is defined by Campbell as "the smallest megascopic layer in a sedimentary sequence" (p. 18), which agrees with the definition adopted earlier in this section. Campbell then introduces two new terms: "laminaset", which consists of "a group or set of conformable laminae that compose distinct structures within a bed", and "bedset", which consists of "two or more superposed beds characterized by the same composition, texture, and sedimentary structures" (p. 20). Campbell states that the bedset of his paper in some examples corresponds to McKee and Weirs' coset.

Campbell is of the opinion that distinction between laminasets and bedsets is to be recommended in order to more precisely describe the internal structure of sedimentary bodies. However, the distinction which Campbell is attempting to maintain can be perfectly adequately coped with in terms of existing terminology, i.e. in terms of sets and cosets of micro-cross-lamination, wavy-bedding, etc. (for small-scale features), and sets and cosets of cross-bedding, flat-bedding, etc. (for large-scale features). There is no need to add to the confusion by introducing superfluous new terms.

B. DESCRIPTIVE ASPECTS

1. Lithosome boundaries

The nature of the upper, lower and lateral boundaries of lithosomes can be of considerable importance for the reconstruction of depositional environments, and a simple classification listing the various possibilities was attempted:

Upper and lower boundaries

a. Sharp, even (flat surface with abrupt change in lithology).
b. Sharp, uneven (irregular surface with abrupt change in lithology).
c. Gradational (progressive change in grain size).
d. Intertongued (intercalation of adjacent lithologies).

Lateral boundaries

a. Erosional (truncated).
b. Wedged (sharp sedimentary pinch-out).
c. Gradational (progressive grain-size change).
d. Intertongued (interfingering of adjacent lithologies).

2. Rock colours

The names and symbols embodied in the "Rock-Color Chart" distributed by the Geological Society of America (Goddard et al., 1963) have been used for the description of rock colours in this study.

CHAPTER VI

SEDIMENTARY STRUCTURES

A. GENERAL BEDDING CHARACTERISTICS

By "general bedding characteristics" is meant the general external form (thickness and shape) of individual beds (sedimentation units or individual layers in lithologically "banded" sediments e.g. rhythmitites). Pettijohn and Potter (1964, p. 4,5) suggest that the external form of beds can be most readily described by noting whether beds are equal, subequal or unequal in thickness, laterally uniform or variable, and continuous or discontinuous. For actual thicknesses the verbal categories proposed by Ingram (1954; cf. Dunbar and Rodgers, 1957, p. 97) can be used, while the shape classes and their designations suggested for lithosomes (see Chapter IV B) can also be employed in the case of sedimentation units.

B. CLASSIFICATION OF SEDIMENTARY STRUCTURES

Several writers have attempted to classify sedimentary structures on the basis of genesis and/or morphology (e.g. Pettijohn, 1957, p. 158; Krumbein and Sloss, 1963, p. 125; Pettijohn and Potter, 1964, p. 3 ff.; R.E. Elliot, 1965; Allen, 1968; Conybeare and Crook, 1968, p. 6-15; Allen, 1970, p. 238; Selley, 1970, p. 9 ff.; Pettijohn et al., 1972, p. 103; Blatt et al., 1972, p. 114). According to Allen (1970, p. 90) there is as yet no real agreement as to how sedimentary structures are best classified, as some writers prefer a purely descriptive approach, while others favour the genetic approach. The classification presented below is modelled largely on that given by Pettijohn and others (1972) and was intended mainly for use as a "check-list" in the description of sedimentary structures. An attempt was thus made to pigeon-hole all the more commonly-occurring structures found in the siliciclastic rocks.

1. Pre-depositional (erosional) structures

a. Current-produced structures

Channels, scours, runnels, cut-and-fill, flutes, current crescents, rill marks, etc.

b. Tool-produced markings

Slide marks, groove marks, striations, bounce, brush, skip and prod marks, chevron marks, etc.

Most of the above structures are normally preserved as casts on the lower surface of the overlying bed (i.e. as flute casts, groove casts, chevron casts, etc.), hence they are classified as pre-depositional; strictly speaking they are of course post-depositional with respect to the beds in which they were actually formed. Moreover, since the casts themselves were formed while the overlying sediment was being laid down, they can also be regarded as syn-depositional structures. "Erosional structures" is probably the preferred designation for this class, since it avoids to some extent the ambiguities which we have been considering. On the other hand, it is open to question whether tool marks can legitimately be termed "erosional" structures (although they are classified thus by Selley, 1970, Table 10.1, p. 186).

2. Syn-depositional current structures

a. Internal structures (occurring within sedimentation units)
Flat-bedding, parting lineation (current lineation; includes parting-plane lineation and parting-step lineation), inclined bedding, cross-bedding, micro-cross-lamination, wavy bedding, graded bedding, "massive bedding"

b. External structures (occurring on upper surfaces of sedimentation units)
Oscillation (wave) ripple marks (± symmetrical), current ripple marks (markedly asymmetrical), interference ripple marks

3. Deformational (post-depositional) structures

a. Impact structures
Rain prints, hail prints

b. Dessication structures
Mud cracks, mud crack casts

c. Foundering structures
Load casts, ball-and-pillow structures, sedimentary boudinages, flame structures (?)

d. Injection structures
Clastic dykes and sills

e. Drag structures
Convolute bedding, overturned (deformed) cross-bedding, flame structures (i.e. structures confined to a single bed which presumably did not suffer significant translation).

f. Slump structures
Contorted bedding (including all irregular (chaotic) disturbed bedding and recumbent folding involving a group of beds). Implies dislocation and translation of beds.

g. Disruption/transportation structures

Intraformational conglomerates and breccias (mud-pellet conglomerate, sandstone balls, etc.)

h. Eruption structures

Gas pits, sand volcanoes, mud volcanoes, etc.

4. Chemical Structures (mineral segregations)

Concretions, nodules, spherulites, rosettes, sand crystals, geodes, septaria, cone-in-cone. For definitions and distinctions between various terms, see Pettijohn, 1957a, p. 196-211.

5. Biogenic (organic) structures

All trace fossils (ichnofossils, lebensspuren, i.e. vertebrate and invertebrate tracks and trails, burrows, borings, animal tubes) root tubes, bioturbation, mottled structure.

Although classified here as organic structures, the detailed classification and description of trace fossils is a palaeontological problem.

C. DEFINITIONS

With the exception of those commented on below, all the structures mentioned in the preceding section are adequately defined in Pettijohn and Potter (1964) and/or the AGI Glossary of Geology (Gary et al., 1972). In the case of cross-bedding the differentiation and definition of sub-types also need some comment.

Flat-bedding

Sub-horizontal or horizontal lamination (often accompanied by parting lineation), common in fluviatile deposits. The term was apparently first used by Allen (1964) with reference to the "flat-bedded sandstone facies". Pettijohn and others (1972) refer to "parallel lamination" (p. 103), "horizontal lamination" (p. 105) and "laminated bedding" (p. 107).

Inclined bedding

Although usually regarded as a general term which includes cross-bedding, in this study "inclined bedding" is used for very low-angle inclined stratification which does not appear to have been formed by the same processes responsible for the formation of foresets in normal cross-bedding.

Cross-bedding

According to Pettijohn and others (1972, p. 108) cross-bedding is a structure confined to a single sedimentation unit characterised by internal bedding or laminations, called foreset bedding, inclined to the principal surface of accumulation. This definition specifically excludes, for example, the lower angle stratification related to deposition on a prograding beach, etc. Earlier Pettijohn (1962, p. 1471) had stated that true cross-bedding ("high-angle" cross-bedding) forms angles of 10° - 30° or more (average about 20°) with the true bedding, and that it is produced by the deposition of sand at or near the angle of repose, being formed by gravity sliding down a steep face.

Pettijohn and others (1972) also point out that there is some evidence of a deficiency in abundance of sand waves having heights between 3 and 7 cm, which may reflect a fundamental difference in origin. Sets smaller than 5 cm in height can accordingly be termed micro-cross-lamination, thus restricting the term cross-bedding to sets thicker than 5 cm, the former structure being formed by the migration of ripples (small sand waves) and the latter by the migration of dunes (large sand waves). This is consistent with the observation that thicknesses of cross-bed sets commonly show a distinctly bimodal distribution, with modal thicknesses at about 2 - 3 cm and 30 cm (Allen, 1968, p. 100).

McKee and Weir (1953) differentiated between cross-bedding (foreset layers greater than 1 cm thick) and cross-lamination (foresets less than 1 cm thick). However, since the average thickness of foreset layers is probably close to 1 cm, this distinction creates quite unnecessary complications in describing cross-bedded strata.

A number of classifications of types of cross-bedding have been proposed in the past, varying from McKee and Weir's simple but popular scheme (1953) to the elaborate and morphologically exhaustive scheme proposed by Allen (1963a). Pettijohn and others (1972, p. 108) have, however, pointed out that it is difficult to apply these classifications in practice owing to the fact that exposures are seldom adequate or complete enough to determine to which class a given cross-bed set belongs, and that it is even difficult in small outcrops to distinguish between planar and trough cross-bedding. The following simple two-fold classification (illustrated in Pettijohn et al., 1972, p. 109) is probably adequate for most routine investigations, especially in the light of Pettijohn's earlier (1962, p. 1471) conclusion that there are only two basic types of cross-bedding.

Tabular (planar) cross-bedding.- Lower bounding surfaces flat (straight); sets tabular in cross-section (upper and lower boundaries parallel or sub-parallel). The traces of the foreset laminae as seen in plan view are essentially straight.

Trough cross-bedding.- Lower bounding surfaces curved; sets lenticular in cross-section (upper and lower boundaries convergent). The traces of the foreset laminae as seen in plan view are invariably curved (concave).

Wavy bedding

This term is here used to describe all internal small-scale structures which reflect undulating irregularities on the original depositional interface (ripple marks of various kinds) which could not be clearly assigned to the micro-cross-lamination category, i.e. which did not show recognizable development of small-scale foresets (cf. Pettijohn and Potter, 1964, p. 352).

D. THE DESCRIPTION OF SEDIMENTARY STRUCTURES

The general principles involved in the description of the size and shape of sedimentary layers have already been dealt with (see Chapter IV). However, most primary structures show preferred orientations, and the special problems associated with the study of directional features, as well as the presentation of the results obtained, need to be briefly discussed.

1. Sampling procedure

The sampling technique adopted in any study will be governed by the purpose of the study. In the present case our object will presumably be to arrive at a reasonably reliable estimate of the general direction of sediment transport prevailing during the deposition of a particular stratigraphic unit; such a direction is usually either parallel to, or, less commonly, perpendicular to the regional palaeoslope (a knowledge of which is essential to palaeogeographic reconstruction). Since local current directions are often governed by ephemeral features such as river meanders and shoreline irregularities, it is clear that palaeoslope predictions at a particular locality can never be derived from directional data obtained from just a single lithosome. Measurements should accordingly be spread throughout a number of lithosomes (and preferably over an appreciable area) in order to average out the effect of local variation in direction; failure to do this may result in a chaotic scatter in the orientation of directional arrows plotted on palaeocurrent maps. The use of "moving averages" then has to be resorted to in an attempt to derive meaningful conclusions from this data. This technique, however, suffers from the disadvantage that directional arrows are plotted at the intersections of an arbitrary grid system rather than at the actual localities concerned.

The actual number of measurements required to satisfy specified confidence limits about the mean will be governed by the degree of variability (standard deviation) of the directional property being measured. For a 90% confidence limit, the following relationship holds (B.E. Lock, personal communication):

$$\bar{X} = \bar{x} \pm \frac{1{,}645\ s}{\sqrt{n-1}}$$

where $\bar{X}$ = population mean

$\bar{x}$ = sample mean

s = sample standard deviation

n = sample size (number of measurements)

Thus for a standard deviation of 50° (vector strength = 0,70), a fairly common figure for cross-bedding data and approximately mid-way between 0° and the standard deviation of a uniform distribution, namely 104°, we can calculate the following values:

$n = 5$; 90% confidence limit $\sim 40^{\circ}$

$n = 17$; 90% confidence limit $\sim 20^{\circ}$

$n = 65$; 90% confidence limit $\sim 10^{\circ}$

From the above it is clear that at least 17 readings will have to be taken if we want to be 90% certain that the mean direction obtained from our sample will lie within 20° of the true population mean and at least 65 measurements for the mean to lie with 10° of the true mean. This, however, does not take into account any bias that may be introduced by confining the measurements to a particular part of a lithosome which may have been deposited by currents flowing at an appreciable angle to the regional palaeoslope; the fundamental assumption made is that our measurements represent a random sample drawn from the whole population. Thus in order for 5 measurements to predict a regional palaeocurrent direction within 40^{o} with 90% confidence, these 5 readings should be randomly taken from 5 different lithosomes, otherwise we will simply obtain the local mean current direction within 40^{o}, a largely meaningless value as far as palaeogeographic reconstruction is concerned.

In the above discussion the writer has had in mind thick stratigraphic units such as the various formations belonging to the Beaufort Group which are composed of a large number of alternating sandstone and mudrock lithosomes (which presumably represent channel and floodplain deposits respectively). It is assumed that the local orientation of the stream depositing a particular sandstone bears no direct relation at any particular locality to the local orientation of the streams responsible for the deposition of the overlying and underlying sandstone lithosomes. Much of the discussion is hence not applicable to those situations where a single, thin, sandstone unit is being investigated on its own.

Finally, it is clear that sampling techniques will have a considerable bearing on the values obtained for standard deviation and vector strength. A set of measurements obtained from a single lithosome at a single locality will show a much lower dispersion than data collected over a large area from a number of different lithosomes. Similarly, a group of measurements of foreset dip directions obtained from points located at random within a number of trough-cross-bedding sets will show much greater dispersion than a group of measurements based on the orientation of the trough axes of the same cross-bed sets, assuming the common situation where foresets are concave in plan view and hence vary in dip direction along their length. Since it is in most cases not feasible to base directional studies of cross-bedding entirely on measurements of trough axes, and since there are many situations in which trough axes cannot be measured at all, e.g. where strata are steeply dipping, or where measurements have to be confined to road cuttings or vertical cliffs, for the purpose of vector strength and standard deviation calculations trough axes and cross-bedding should be treated as two quite distinct subjects. The distinction between trough-axis studies and cross-bedding studies has not always been consistently maintained in the past and has resulted in values being obtained for standard deviation and vector strength which cannot legitimately be compared with one another or with results obtained by other workers. It is suggested that where cross-bedding is well displayed in plan view, representative readings of foreset dip directions should be taken at two or three random points within each set, thus simulating the situation encountered in small exposures or vertical sections and making the spread of values obtained in the two situations comparable. This policy was generally adhered to in this study. It should also be remembered that the nature of the final distribution will be influenced by the nature of the cross-bedding (trough or tabular), as well as by the variability of the actual depositing currents and that it will be difficult in practice to ascertain the relative contributions of these influences to the directional scatter obtained.

2. Statistical treatment of orientation data

(a) Central tendency.

It is generally agreed that the vector mean (see Potter and Pettijohn 1963, p. 264) represents the most satisfactory estimator of central tendency in the case of directional data. Details of the calculation of vector means for both circular (360°) and semicircular (180°) normal distributions are given in Curray (1956) and Jones (1968). However, there seems to be little agreement as to the most satisfactory symbol to use for this quantity. The following are some of the designations used in the past:

θ_m = mean angle of azimuth (Krumbein, 1939, p. 689)

$\bar{\alpha}$ = mean angle (direction of the mean vector) (Pincus, 1953, p. 496)

$\bar{\theta}$ = azimuth of resultant vector (Curray, 1956, p. 119)

$\bar{x}$ = azimuth of the resultant vector (Potter and Pettijohn, 1963, p. 264)

$\bar{x}_v$ = vector mean (Potter and Pettijohn, 1963, p. 265)

$\hat{\gamma}$ = maximum likelihood estimator of γ, the central value (Jones, 1968, p. 63) = vector mean (Jones, p. 64).

The symbol $\bar{x}_v$ has been arbitrarily adopted in this study.

(b) Dispersion.

Dispersion (concentration of the data) has been most commonly represented by the standard deviation or by the use of the vector magnitude divided by n (number of measurements). The latter value is probably most correctly referred to as the vector strength, $\bar{a}$ (Pincus, 1953, p. 496). It is not strictly equivalent to the "consistency ratio" introduced by Reiche (1938), as some writers have assumed, since the calculation of the vector resultant and consistency ratio by Reiche involved a system of weighting which reduced the effect of cross-beds with low dip angles on the final results. The consistency ratio is thus a weighted measure of the degree of grouping. By multiplying the vector strength by 100, Curray (1956) arrived at a nameless quantity designated "L" which is equivalent to the magnitude of the resultant vector in terms of percent (p. 119). Computational details for the vector strength (or "L") are given by Pincus (1953), Curray (1956), Potter and Pettijohn (1964) and Jones (1968); Curray and Jones deal with 180° distributions as well as 360° distributions.

Curray presents a graph (Fig. 3, p. 123) showing the relationship between "vector magnitude L in percent" and standard deviation (for both 0° to 360° and 0° to 180° distributions). In order to confirm that the graph could be used to obtain standard deviations directly from calculated values for the vector strength (or vector magnitude in percent) standard deviations were calculated from the raw data for a number of samples, and the values obtained were compared with those read off from the graph. The results obtained are listed in Table VI-1, and indicate a satisfactory measure of agreement.

Table VI-1. A comparison of calculated standard deviations with the corresponding values derived from Fig.3 of Curray (1956).

Formation	Locality	Structure	n	L(%)	S_{true}	S_{graph}
Balfour	Bf 50	cross-bedding	101	58	60,63°	60°
Witpoort	W 20	cross-bedding	50	89	27,75°	28°
Kouga	T 18	cross-bedding	52	90	26,70°	27°
Kouga	T 17	cross-bedding	40	95,5	17,65°	16,50°

n = number of readings; L = vector strength in percent; S_{true} = calculated standard deviation; S_{graph} = standard deviation derived from Curray (1956, Fig. 3). Locality numbers refer to Folder 3.

The good agreement between the true and graphically-derived standard deviations for the first example given above is especially significant in view of the much greater deviation from the theoretical curves of Curray's own empirical data in the L = 45% to L = 65% range. Curray's graph was used to obtain the standard deviation of all samples with $\bar{a}$ less than 0,90. In view of the steepness of the curve beyond this point (i.e. beyond L = 90%), rendering the graphical method less reliable, standard deviations were calculated directly from the raw data.

Although the vector strength represents the most commonly quoted, and probably most "correct", measure of dispersion for vector data, it suffers from the serious disadvantage that the values obtained are not in fact directly proportional to the actual spread of values. Thus while a standard deviation of 0° corresponds to a vector strength value of 1, and a standard deviation of 104° (representing a uniform distribution - see Griffiths and Rosenfeld, 1953) corresponds to a vector strength of 0, a standard deviation of 52° (midway between 0° and 104°) is eqiuvalent to a vector strength of about 0,70 and not 0,50 as might be expected. Similarly, a standard deviation of 10°, representing about one-tenth of the maximum standard deviation (104°) is equivalent to a vector strength of about 0,98 (and not 0,90).

3. Correction for tectonic tilt

In all cases where the strata have been tectonically tilted by more than about 5°, the dip of the foreset plane and that of the "true" bedding were both recorded and a correction made using a Wulff stereonet. Rust (1967) and Theron (1972) used a computer programme to perform this operation, in the process obtaining contoured plots on an equal area projection of the line of maximum dip of cross-bedding foresets ,as well as the vector mean and vector strength. However, an examination of some of the stereographic plots obtained by these authors using this method reveal certain peculiarities which will have to be accounted for before general use can be made of this particular technique. Thus, for example, in some diagrams the contours cross the circumference and reappear surrounding a secondary peak on the opposite side of the diagram. Although bimodal cross-bedding patterns with opposing peaks are not uncommon in nature (especially in tidal deposits), in this case the "bimodality" usually appears to have been generated by the technique itself. These anomalous 180° repetition of peaks (as well as peculiar mirror-image relationships) are generally most conspicuous in diagrams based on a relatively small number of readings (cf. Rust, 1967, Fig. 87F; Theron, 1972, Fig. 17B,C; Fig. 20B, H; Fig. 21A,G,H; Fig 24A; Fig. 27A; Fig. 30A,B,C,E,F; Fig. 33A,B,D,H).

Theron's Fig. 30H is especially interesting, not only because it illustrates rather well the strange distributions encountered, but also because the directions obtained by correcting for tilt on a Wulff stereonet using the original raw data for this locality (kindly supplied by J.N. Theron)do not substantiate the plotted pattern of peaks. In addition, a number of the readings correspond to cross-bedding dip angles of 10° or less. In fact, in many of the diagrams the contours seem to indicate that a significant proportion of the actual points must have fallen near the circumference of the diagrams (thus representing cross-bedding dipping at angles approaching zero). Such readings would normally be rejected on the grounds that they either do not represent true cross-bedding or that measuring errors were involved.

Finally, some of the diagrams presented by Theron (1972, Fig. 7a; Fig. 9b; Fig. 17E; Fig. 20C,F) show cross-bedding dip angles varying from 0° to 90°. Fig. 7a (composite cross-bed diagram for the Hex River Formation) is especially peculiar, since the contours form an irregular pattern extending right across the whole diagram, and most of the other composite diagrams (Figs. 6-11) show the same sort of anomalies, although not always to quite such a marked degree. However, since this particular phenomenon seems to be absent from Rust's diagrams, it may represent incorrect application of the technique by Theron rather than any actual shortcoming of the technique itself.

4. Presentation of results

It is generally not feasible or necessary to tabulate each individual directional measurement; normally it is adequate to summarize the data by using 30° (or smaller) class intervals in a frequency table, each row corresponding to a different formation or a different geographic area. For every summary we also need to include the vector mean, vector strength and/or standard deviation, and the number of measurements (n). In addition,the tabulated data should, where appropriate, be used to construct a current rose (rose diagram) which, apart from its value as a visual aid, represents the most suitable device for the detection and presentation of bimodal or polymodal distributions. Finally, the palaeocurrent data obtained can be represented on a map by means of directional arrows, each arrow being accompanied by some indication of the number of readings on which it was based, as well as an indication of the spread of the values.

CHAPTER VII

SANDSTONE GRAIN-SIZE DATA

A. INTRODUCTION

Before embarking on the measurement of grain size in sedimentary rocks, and the presentation of the results obtained, we need to clarify the basic objectives involved in such a study, define our concept of "size", choose a suitable measurement technique, and select a set of descriptive measures which will convey to the reader an adequate and correct picture of the texture of the rocks. In addition, we need to discuss the practical methodology involved in the measurement technique selected, as well as the relation between the "size" data generated by the said technique and the true size of the grains. Finally, it may prove useful to draw up a standard recording sheet on which the actual results obtained in the course of a grain-size analysis can be entered in a form that will facilitate reworking of the raw data at a later stage.

The argillaceous rocks of the Cape and Karoo Supergroups are generally well indurated and thus incapable of yielding meaningful grain-size data. Hence in the discussion which follows attention will be confined to problems related to obtaining grain-size data in sandstones.

B. BASIC OBJECTIVES IN GRAIN-SIZE STUDIES

"Two of the most discussed yet most poorly understood topics in this day of quantitative geology are the concepts of grain size and sorting of sediments. Countless values have been published ... yet the meaning of all these figures and their ultimate geological significance (if any) are still quite obscure .... If this vagueness is true of fairly simple ideas such as mean size or sorting, the situation with regard to more complex parameters like skewness or kurtosis is even worse .... One begins to wonder if all these lengthy computations are not wasted effort - do they show us anything of real value, or are they merely a deceptively impressive shell of figures surrounding a vacuum of geologic meaning" (Folk and Ward, 1957, p. 3).

In the light of the above comments, it is pertinent to ask whether subsequent research has significantly clarified matters and rendered Folk and Ward's assessment out of date. According to Griffiths (1967, p. 46) the purpose of measuring grain size in sediments is to understand the processes which result in the formation of sedimentary rocks; consequently frequent attempts have been made to reconstruct the environment of sediment formation from measurement of grain size of the constituent particles. However, Griffiths points out that the results obtained thus far have been disappointing. "It is quite evident that despite a large investment of time and money the size data generally collected admit of very little unequivocal interpretive petrology" (p. 104). Griffiths adds that, to date, the main function of size frequency data has been their use as a descriptive, petrographic, rather than an analytic, petrologic tool (p. 104). Selley (1970, p. 6) concludes that "statistical textural studies of ancient sediments have largely proved an unsatisfactory method of environmental diagnosis", and goes on to outline some of the reasons why this should be so.

Blatt and others (1972, p. 61,62) have pointed out that most of the studies making use of size distribution to discriminate environments have been on recent sediments, and that the methods have been little tested on ancient sediments, while Reineck and Singh (1973, p. 115) state that the numerous attempts to relate statistical parameters calculated from grain-size distributions to different environments of deposition have had only a limited success in environmental interpretation. Finally, after claiming that "plots of skewness against kurtosis for suites of samples are a powerful tool in interpreting the genesis of sediments", Folk (1966, p. 86) goes on to quote a number of published examples, all of which refer to work done on modern sediments! According to Pettijohn, Potter and Siever (1972, p. 87), "attempts to relate the size distribution of a sandstone to its environment of deposition have had but limited success even with modern sands where results have not always been consistent, some finding distinctions between environments where others failed".

Even where success has apparently been achieved in differentiating between depositional environments among modern sediments on the basis of textural attributes, no consensus has arisen as to which parameters (or combinations of parameters) are most effective in achieving this objective. To judge from the variety of techniques employed to squeeze detectable differences out of the size data obtained ("statistical gymnastics" - Selley, 1970), it would seem that no particular combination of parameters have been found to be <u>universally</u> effective even in modern sediments.

Furthermore, data presented by Friedman and Sevon for beach, dune and river sands from North America and New Zealand respectively (Sevon, 1966), demonstrate that quite appreciable textural differences can occur between suites of samples collected from identical environments on different continents, even where these suites are large and consist of samples from a variety of localities. One cannot help wondering if many of the textural differences noted have not been due to factors other than those related directly to the local depositional environment. At the same time, since the same or similar hydrodynamic factors may be operative in different environments, similar grain-size distributions may be encountered in these environments (Reineck and Singh, 1973, p. 118).

It would also appear that the influence of primary structures (and the depositional processes responsible for their formation) on textural parameters has not been adequately evaluated or controlled in most studies on modern sediments. One would expect, for example, that there would be certain basic textural similarities between sedimentation units characterised by a specific type of bed form (internal primary structure), regardless of the particular depositional environment in which such sedimentation units are found. Considerations such as these do in fact feature prominently in a fairly recent study by Visher (1969, p. 1074 ff.) in which the author has attempted to recognise log-normal sub-populations within individual grain-size distributions (plotted on probability paper), and to relate these sub-populations to different modes of sediment transport (suspension, saltation and surface creep or rolling).

Finally, all attempts made thus far to extract genetically significant information from grain-size data (including Visher's) suffer from the disadvantage that they are based on sieve analyses and hence offer limited assistance for the interpretation of indurated sediments where grain size data has to be obtained from thin sections.

To conclude, it is clear that since grain size is one of the fundamental properties characterising an aggregate (Griffiths, 1967, p. 104), grain-size data (specifically, mean size and "sorting") are needed to characterise sedimentary rocks. However, the value of such data in deducing specific depositional environments appears to be strictly limited. On the other hand, when combined with other petrographic data, grain size information can offer appreciable assistance in analysing the broad tectonic and depositional history of a group of strata. More specifically, the grain size of a sediment is an important indicator of the energy level of a depositional environment. "The coarser the grain size, the higher the energy level of the depositing current and the better the sorting the more prolonged its action" (Selley, 1970, p. 6).

C. THE CONCEPT OF "SIZE"

What exactly is meant by the "size" of a sedimentary particle? Since different concepts of "size" are involved in the various techniques which have been used in the past to obtain information on the dimensions of grains, it is necessary to briefly explore the basic concepts involved before considering the actual techniques themselves.

It is generally agreed that the concept of size should be related to volume (see Wadell, 1932, p. 444; Conner and Ferm, 1966, p. 397; Griffiths, 1967, p. 43; Blatt, et al., 1972, p. 44). However, since it is only in the case of pebbles that one can measure volume "directly" by displacement of a fluid, it has become standard practice to represent "size" by means of "diameters". In practice no sedimentary particles are perfect spheres and ideally they possess long, short and intermediate diameters. Theoretically, the most satisfactory measure of size will be the "true nominal diameter", this being the diameter of a sphere having the same volume as the particle under consideration (Wadell, 1932, p. 444; Sahu, 1965a, p. 969).

According to Sahu (1965b, p. 753) the intermediate diameter (b) may be used as the best estimator of the true nominal diameters of sedimentary grains; in theory this corresponds to the short diameter of loose grains resting on a flat surface when viewed from above. Wadell, (1935, p. 258) has, however, also defined the "nominal sectional diameter" as the diameter of a circle equal in size to the area of the non-magnified reproduction of a quartz particle in the plane of the largest and intermediate diameters i.e. of the projected area of loose grains. This value will lie approximately mid-way between the longest and intermediate diameters.

Wadell's concept can be extended to thin-section studies by defining the "nominal thin-section diameter" as the diameter of a circle equal in size to the area of a particle as seen in thin section. This "size" measure possesses the powerful theoretical advantage that it is the only measure which is independent of grain shape and hence the only measure which can be used in thin section studies to obtain the actual mean size (defined as the average true nominal diameter of the grains). The latter value can be arrived at merely by applying a simple correction factor to the mean nominal thin-section diameter which will compensate exactly for the reduction in mean size due to the sectioning effect (i.e. the effect of measuring random sections through grains rather than sections which all pass through grain centres). However, since the measurement of "nominal diameters" is a time-consuming process (involving the measurement of individual grain areas) this measure is unsuitable for the routine size analysis of sedimentary rocks (although it can be approximated by measuring the long and short diameters of grains from which the approximate nominal thin-section diameters can be calculated, assuming an elliptical shape for the grains).

In practice, grain size in thin section is probably most often conceived in terms of the maximum diameter (length of "a" axis) of particles. At first sight this procedure would seem unsatisfactory, since grain shape is disregarded. However, differences in average quartz grain shape (defined as b axis / a axis, as measured in thin section) between various sedimentary formations appear to be small (Griffiths, 1967, p. 123, 124). Consequently, the average lengths of the "a axis" of quartz grains in thin section will in general bear a direct and predictable relationship to the true size (i.e. volume) and the corresponding true nominal diameter. This relationship will be discussed more fully at a later stage.

Turning to size measurements obtained by sieving techniques, Krumbein and Pettijohn (1938, p. 124) point out that "sieves sort grains on the basis of the least cross-sectional area, which may or may not have any fixed relation to the volume of the particles" and that if size is defined in terms of the nominal diameter (that is, based on volume), the sieving process does not sort according to size . It is clear that the sieve aperture will always be less than the intermediate diameter (b) of a particle passing through the sieve except in those cases where the least cross-sectional area is circular (b=c). Thus sieving will in theory consistently underestimate the intermediate diameter which, according to Sahu (see above), closely corresponds to the true nominal diameter. Since the average b/c ratio for quartz grains is unknown, the amount of error involved cannot be calculated. However, Ludwick and Henderson (1968, p. 233) estimate that sieving underestimates modal intermediate diameters of particles by 10% to 20% (grain size in mm).

D. CHOICE OF TECHNIQUE: SIEVING, LOOSE GRAIN OR THIN SECTION

Traditionally it has been standard practice to measure grain "size" by passing a disaggregated sample through a set of standard sieves. However this technique suffers from a number of disadvantages.

1. The relationship between "size" measures ("diameters") obtained by sieving (i.e. by bouncing grains on a square wire mesh) and the true size (related to volume) is still somewhat obscure (see earlier discussion). According to Blatt and others (1972, p. 47), "it is not clear exactly what property of the grain is measured by sieving." "Large areas remain to be explored and the findings quantified before a wholly satisfactory means is developed for measuring particle size accurately by sieving" (Ludwick and Henderson, 1968, p. 233).
2. Many rocks cannot be disaggregated without breaking the component grains, and in such cases size measurement by sieving (and/or pipette sedimentation) of the disaggregated residue is really a measure of the efficiency of the disaggregation procedure (Griffiths 1967, p. 64). Even slightly consolidated rocks are bound to be affected by disaggregation procedures, especially if they contain an appreciable proportion of soft lithic fragments.
3. In mineralogically heterogeneous sediments it is impossible to evaluate whether any distinctive characteristic of the grain size distribution can be attributed to peculiarities in the composition of the sediment.
4. Very fine sand/coarse silt mixtures are not amenable to sieve analysis, since the finest sieves generally available are 300 mesh (0,050 mm), which is near the sand/silt boundary.

It is also possible to measure the size of loose grains in a grain mount, but with this technique the total number of grains in each size class have to be counted; this becomes impractical for the finest sizes. In addition, this method suffers from the same main disadvantage as sieving, in that samples must be completely disaggregated. Also, the number frequencies obtained have to be converted to volume frequencies whereas thin-section size analyses yield volume frequencies directly (provided some form of point counting is used for selecting grains to be measured).

In the light of all the above considerations, a strong case can be made out for measuring grain size in thin sections even in those cases where a sieve analysis or loose grain study is possible. "Such a procedure has much to recommend it for all sediments, and adopting a single technique, if it were possible, would in itself be of very considerable advantage " (Griffiths, 1967, p. 64).

E. PRESENTATION OF DATA: CHOICE OF DESCRIPTIVE MEASURES

Various measures have been used in the past to express the four main attributes of grain-size distributions. These attributes are central tendency (expressed as the mean, median or mode), dispersion (expressed as the variance, standard deviation, mean deviation or sorting coefficient), asymmetry (expressed as skewness) and "peakedness" (expressed as kurtosis). In view of the poorly understood genetic significance of skewness and kurtosis values, the lack of correlation between values obtained for these parameters by sieving and thin-section techniques respectively (Friedman, 1962) and the limited usefulness of these measures for visualising the physical nature of a sediment (in contrast to mean size and standard (or mean) deviation), they are omitted from further consideration in this study.

In the past most of these measures have been derived from grain-size distribution curves. However, the measures obtained from such curves are unsatisfactory in that, being based on intercepts read off the curves at certain selected points, they do not express all the information represented by the raw data which was used to construct the curve (although in most cases they are fairly reasonable approximations). On the other hand, measures based on statistical moments take into account the entire sediment distribution, including the tails, and therefore represent the most suitable parameters for describing the textural characteristics of sedimentary rocks. An additional advantage is that errors introduced in the drawing of curves to fit the plotted cumulative frequency points are eliminated (Rogers, 1965, p. 731, 732). It is also worth noting that Cadigan (1954, p. 124) found large differences between moment standard deviations and standard deviations determined graphically (by using the formula ($\phi 84$ - $\phi 16$)/2) for the same samples and attributed this to a failure of the graphic method to respond to moderate skewness.

Previously the main disadvantage of moment measures has been the tedious computation necessary to obtain some of the measures (Friedman, 1962, p. 16; Rogers, 1965, p. 732). However, with the general availability of electronic desk-type calculators capable of reading out means, variance and standard deviations without special programming this is no longer a drawback. In actual practice, using one-tenth phi classes and 50-100 grains per sample, the data can be fed in and the mean and standard deviation obtained in less that three minutes. This is certainly far quicker than any method which involves plotting a size distribution curve.

To conclude, mean size and dispersion of size values are fundamental attributes of all populations, including sedimentary particles. Since it is advantageous to adopt a procedure for expressing these concepts which is generally applicable to all frequency distributions, the dispersion is best expressed as either the mean deviation or the standard deviation, while the mean deviation and standard deviation should be defined in the normal statistical sense. From these measures an acceptable mental image of the sediment can be formed.

Certain arguments have been advanced by Folk (1966, p. 77 -80) against the use of moment measures ("cranking out parameters" on a computer, as he terms it) and the omission of cumulative curves ("hasty sloppiness", in his opinion), and these must be briefly considered. Examination of Folk's objections shows that most of them are either trivial, equally applicable to other techniques or not valid for the techniques actually proposed in this study (thin-section analysis using one-tenth ø intervals). For example, Folk takes great pains to point out (quite correctly) that in computation it is assumed that the particles within a given class interval have a centre of gravity at the halfway mark of that class, and that this can be quite erroneous. However, exactly the same assumption is normally made when using graphical techniques, so that this is hardly a serious objection to the use of non-graphical methods involving moment measures. Folk also points out the difficulties involved in applying the method of moments to "open-ended" distributions. In the writer's experience very few thin-section analyses of the non-matrix fraction of sandstones proved to be "open-ended" to any significant degree, especially when the analyses were continued down to 0,02 mm. All-in-all, moment measures remain the most accurate, quickest, easiest and most elegant means of obtaining values for central tendency and dispersion.

Although the standard deviation is far more commonly used than the mean deviation by both statisticians and sedimentologists, the former is actually influenced to a much greater extent by abnormally small or large grains in a sample that the latter, since it is based on the square of the deviation from the mean rather than on the actual deviation. This can be a disadvantage where small samples ($<$ 100 grains) are being used, since a few large or small grains can have an unduly large influence on the final result. In such cases the mean deviation will be a more consistent estimator of dispersion.

In addition to the mean and standard deviation, there may be some value in the relatively simple operation of noting the maximum size visible in the thin section, especially in view of Passega's use of "CM patterns" (1957, 1964). Passega defined "C" as the one percentile value, and plotted values of C vs. M (median), utilising a number of samples with different means from each of a number of specific environments, giving rise to distribution patterns which he felt were diagnostic for those environments. Quite apart from such considerations, however, the ratio C : M does give a crude idea of sorting and provides some additional information for a minimum expenditure of time. Highly elongated grains can be avoided by stipulating a minimum b/a ratio of 0,5.

F. METHODOLOGY (THIN SECTION SIZE ANALYSIS)

In outlining the practical procedure to be followed in measuring grain size in thin section, the following factors must be considered:

1. Choice of grade scale.
2. Choice of mineral components.
3. Upper size limit of "matrix".
4. Dimension(s) to be measured.
5. Selection of grains.
6. Number of grains to be measured.

1. Choice of grade scale

The so-called phi (ø) scale, first proposed by Krumbein in 1934, has become generally accepted as the most satisfactory scale for the measurement and presentation of grain size data. The SEPM Grain Size Study Committee has produced a report listing 11 specific advantages of the phi-scale (Tanner, 1969, p. 809). No other scale comes even close to matching this list.

2. Choice of mineral components

Griffiths (1967, p. 64) and others have proposed confining size measurement in thin section to the quartz grains, in an attempt to reduce the number of variables influencing particle size, since in theory "size" measurements in thin section are a function of mineral composition, size, shape, orientation and packing (Griffiths, p. 32). However, this procedure does not seem satisfactory for those rocks in which quartz forms only a small percentage of the total rock composition (which is the case with the sandstones of the Ecca and Beaufort Groups in this study). The aim in sedimentography should be to provide a description of the texture of the rock as a whole, not just of one minor component. On the other hand, it is clearly unsatisfactory to attempt to base size distribution data on <u>all</u> the detrital particles present since many of the lithic particles tend to be highly distorted, often being squeezed into the spaces between other grains. In addition lithic fragments are often difficult to distinguish from matrix. These considerations seem to suggest that the utilisation of quartz plus feldspar represents the most satisfactory compromise. This procedure is also less time-consuming, since no time is wasted in distinguishing quartz from feldspar and less time is required to hit the required total number of particles during point counting. Faced with a similar situation, Barret (1966, p. 795), measured size on "quartzofeldspathic" grains.

3. Upper size limit of "matrix"

This has been variously placed at 0,030 mm (the dividing line between coarse and medium silt) or 0,020 mm. Okada (1971, Table 2, p. 514) lists six authors who adopt 0,02 mm (20 microns) as the upper size limit of matrix, and three who favour 0,03 mm. In actual practice very few grains with sizes between 0,02 and 0,03 mm were encountered, so that the question is largely an academic one. In very fine-grained sandstones it may be wise to extend measurements down to 0,02 mm in order to ensure that the final distribution obtained is not a truncated (open-ended) one.

4. Dimension(s) to be measured

Ideally, if size is to be related to volume, then the most meaningful size measure obtainable in thin section would be the nominal thin-section diameter (see earlier discussion). Since such an operation on individual grains would be unrealistic in practice, it has become customary to measure a particular diameter or intercept across the grain, either directly under the microscope by means of a micrometer eyepiece or indirectly on the projected image of the grain. Although some workers have utilised the shortest diameter (short axis) of grains, more frequently the longest intercept through the grain is chosen. As Griffiths points out (1967, p. 64), a number of definitions exist which achieve this objective; the one favoured by Griffiths depends on the selection of the shortest intercept through the projected image and the subsequent measurement of the longest intercept perpendicular to the shortest. However, there would appear to be no a priori reasons why one intercept should be better than another as long as the definition results in the selection of a unique axis (Griffiths, p. 64). In the present study the longest intercept across grains was chosen in view of the popularity of this approach and the fact that it is the least time-consuming. If sufficient time is available, it would be advantageous to measure both long and short axes and average these to obtain an "intermediate" diameter, thus minimizing the effect of grain shape on the final size values obtained.

5. Selection of grains

The oft-repeated assertion (or implication) that size measurements made in thin section give rise to a number-frequency distribution (Friedman, 1958, p. 411; Rogers 1965, p. 730; Sahu, 1966; Griffiths, 1967, p. 64; McBride, 1971, p. 110; Textoris, 1971, p. 99) needs to be challenged afresh, although Stauffer (1966) has effectively exposed this fallacy (see also Blatt, et al., 1972, p. 56). Stauffer (p. 261) pointed out that criticisms by Van der Plas (1962) of thin-section point counting (i.e. grid sampling) as a method of size analysis appear to be based on confusion between number percent and volume percent. "Points are samples of volume, and point counts yield volume percents. This is as much true of size classes as of other types of constituents, though distortions are caused in the distribution by the sectioning effect". If measurements are confined to quartz grains (as Griffiths advocates), then the volume percentages obtained will be equal to weight percentages. In order to establish point counting as the only valid technique for grain selection in thin-section size analyses, it is important to note (as Stauffer fails to do), that all other methods suggested for selecting grains yield neither volume/weight frequencies, nor number frequencies. Such other methods include measuring all the grains in a slide or field of view ("Fleet" of "Area" method) measuring all the grains intersected by a straight-line traverse ("Line" method) or measuring all the grains encountered between two parallel lines ("ribbon" method, Van der Plas, 1962). In order to demonstrate this it is helpful to consider a practical example. Let us take a hypothetical aggregate composed of equal quantities by volume (weight) of square blocks 1,0 mm and 0,25 mm in diameter respectively. A small portion of this aggregate can be represented diagrammatically as in Fig. VII-1.

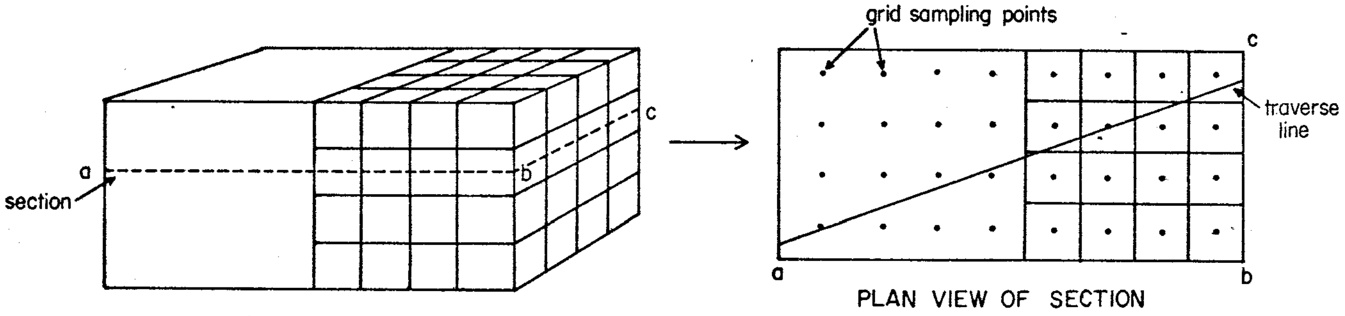


Fig. VII-1. Hypothetical sample illustrating principles involved in grain selection for size-distribution studies.

If a section is cut as indicated in Fig. VII-1, the percentages given in Table VII-1 will be obtained using the various possible techniques.

Table VII-1. Relative percentages of 1 mm and 0,25 mm "grains", using various grain-selection methods.

Technique	1 mm grains		0,25 mm grains	
	Frequency	Percentage	Frequency	Percentage
1. True number percent	1	± 1,5	64	± 98,5
2. True volume percent		50		50
3. Point counting (grid)	16	50	16	50
4. Field-of-view	1	± 6	16	± 94
5. Line method	1	± 14-20	4-6	± 80-86
6. "Ribbon" method	1	[1] ± 6-20	[1] 4-16	[1] ± 80-94

[1] Depends on width of "ribbon".

It is quite clear that a true number percent can only be obtained if loose grains from a disaggregated sediment are studied and <u>all the grains are counted</u>; it can <u>never</u> be obtained <u>directly</u> from a thin-section study nor can it in fact be obtained by the use of a "line" method on loose grains. It may be possible to obtain the true number frequency <u>indirectly</u> by multiplying "field-of-view" frequencies by their square roots (i.e. in the above case, multiplying 16 by 4 to give 64) thus restoring the third dimension. In terms of the frequencies obtained, it is also clear that relative to the true volume percentages, all techniques other than point counting manifest a bias towards the smaller grains in thin-section studies; this effect is most pronounced when grains in the whole field of view are counted, and least when line counting is used. "Ribbon" techniques fall somewhere between line counting and area counting, the actual result obtained depending on the width of the "ribbon". From all this it can be concluded that point counting represents the only valid technique for selecting grains for measurement in thin-section size distribution studies, and that results obtained by using different techniques cannot be directly compared with one another. A brief but helpful discussion on the number-frequency problem as it affects loose-grain studies has been presented by Galehouse (1969).

6. Number of grains to be measured.

Thin-section size analyses which have depended on the construction of size distribution curves for obtaining grain-size parameters have involved the measurement of 100 to 500 grains per sample (Rosenfeld, et al., 1953; Friedman, 1958, p. 398; Barrett, 1966, p. 795). However, if it is simply desired to obtain the mean and standard deviation, then the minimum number of grains required to satisfy specified confidence limits can be calculated using standard statistical techniques.

According to Mulholland and Jones (1968, p. 157) a 90% confidence interval for the mean (implying that an average of 9 samples out of 10 will fall within the given range) is denoted by the following expression:

$$\bar{x} \pm z_{5\%} \frac{s}{\sqrt{n}} \qquad (1)$$

where $\bar{x}$ = sample mean

z = standardized variate ($z_{5\%}$ = 1,645)

s = sample standard deviation

n = sample size (number of grains measured)

In the case of the variance the following relationship holds (Mulholland and Jones, p. 184):

$$\frac{(n-1)s^2}{\chi^2_{5\%\,(n-1)}} \leqslant \sigma^2 \leqslant \frac{(n-1)s^2}{\chi^2_{95\%\,(n-1)}} \qquad (2)$$

where n = sample size (number of grains)
s^2 = sample variance
σ^2 = population variance
χ^2 = chi-squared value

For the standard deviation (2) can be adapted as follows:

$$s\sqrt{\frac{(n-1)}{\chi^2_{5\%\,(n-1)}}} \leqslant \sigma \leqslant s\sqrt{\frac{(n-1)}{\chi^2_{95\%\,(n-1)}}}$$

where σ = population standard deviation
s = sample standard deviation

Using the above relationships we can calculate the confidence limits around the mean and standard deviation for 10, 25, 50 and 100 grains (Tables VII-2, VII-3).

Table VII-2. 90% confidence limits for mean grain size (ø units). Values given are added to $\bar{x}$ to give upper limit and subtracted to give lower limit.

n	s = 0,30	s = 0,60	s = 1,00
10	0,156	0,312	0,520
25	0,099	0,197	0,329
50	0,070	0,140	0,233
100	0,049	0,099	0,165

n = number of grains, s = standard deviation.

Table VII-3. 90% confidence limits for standard deviations.

$n = 25$: $1{,}316\,s > \sigma > 0{,}812\,s$
$n = 51$: $1{,}200\,s > \sigma > 0{,}861\,s$
$n = 101$: $1{,}132\,s > \sigma > 0{,}897\,s$

n = number of grains, s = sample standard deviation, σ = population standard deviation.

Sample standard deviations of 0,30 ø, 0,60 ø and 1,00 ø were chosen for the calculations in Table VII-2 since nearly all sandstones are encompassed in the range s = 0,30 ø to s = 1,00 ø, while 0,60 ø is probably close to an average value. Depending on the sorting of the sediment and the degree of accuracy required, 10-25 grains would appear to be adequate for determining mean size in most studies. With regard to standard deviations, Griffiths (1967, p. 345) stated in the light of similar calculations that 30 to 50 grains (length measurements) are ample for standard deviations below $\sigma = 0,75\phi$, but that considerably more are required for higher standard deviations. However, it does not follow that because larger standard deviations show wider confidence limits in absolute numerical terms one needs to measure more grains. If the upper and lower confidence limits are expressed as fractions (or percentages) of the standard deviation obtained (as has been done above), rather than as numerical values around a series of standard deviation values (as Griffiths does, Table 17-1, p. 344 - which incidentally gives values of confidence limits for the variance and not the standard deviation as the caption indicates) it should at once be apparent that the number of grains required to satisfy specified confidence limits is independent of the actual standard deviation.

For the data tabulated above it is apparent that the gain in precision achieved in going from 50 to 100 grains is probably not worth the extra effort involved. Fifty grains were accordingly utilised in this study.

G. RELATING THIN-SECTION DATA TO TRUE DIMENSIONS AND SIEVING DATA

Before commencing this discussion, we need to decide whether there is in fact any necessity for considering the whole question of "correcting" grain-size data obtained from thin sections. If the whole object of the exercise is the comparison of various samples (or the populations from which they were taken), it is clear that any technique, suitably standardised and consistently applied, is capable of yielding meaningful data. While this is true, it is generally accepted that a satisfactory petrographic technique must be capable of describing a rock correctly and accurately. In other words, we ought to know as precisely as possible what the relationship is between the values obtained by our chosen technique and the actual dimensions of the grains in the rock which is being described.

1. Previous Work

A number of writers have considered the problem of applying a "correction" to the size data obtained from thin-section measurements which would compensate for the errors resulting from measuring "size" on random sections through grains rather than sections containing the maximum and intermediate dimensions (e.g. Krumbein, 1935; Greenman, 1951; Rosenfeld et al., 1953; Packham, 1955; Friedman, 1958, 1962; Sahu, 1966; Kellerhals et al., 1975). Several alternative methods of "correcting" thin-section data have been arrived at in the process, resulting from the employment of various combinations of the following fundamental differences of approach:

1. Use of "number" frequencies or volume frequencies.
2. Use of mm or ∅ units.
3. Use of graphical reconstructions or moment measures.
4. Restoration to true dimensions or sieve-equivalent dimensions.
5. Use of empirical solutions or mathematically-derived solutions.

Having previously established that the ∅ scale is superior to a mm scale, and that volume frequencies (obtained by point counting) are superior to psuedo - number - frequencies (obtained in all other methods), we can eliminate all those "correction" techniques and equations which were arrived at using a mm scale and/or number frequencies. In view of the tedious and time-consuming nature of the operation we can also eliminate those methods that involve the reconstruction of a grain-size distribution curve.

The uncertainty surrounding the relationship between "size" measures obtained by sieving, and true size, indicates that there is no point in attempting to bring thin-section data into line with sieving results rather than true size. Finally, mathematically-derived (theoretically-derived) correction factors must of necessity be superior to empirically-derived ones, in view of the many factors militating against the possibility of arriving at a universally applicable correction by means of the latter course.

Since the writer is not aware of any study in which all the above requirements were complied with, the bulk of this section will be devoted to an exploration of the differences between mean size and standard deviation obtained in thin section, and the true mean and standard deviation. However, before doing this it may be instructive to take a closer look at a popular empirically-derived method for equating thin-section size analyses with sieve analyses developed by Friedman (1958, 1962) as well as a comparison between thin-section and loose-grain size data given by Smith (1966) and an attempt by Sahu (1965a) to derive equations for transforming arithmetic moments to phi-moments.

(a) Friedman (1958, 1962)

Friedman's work has been given prominent treatment in two recent textbooks (Müller, 1967, p. 58-60; Carver, 1971, p. 103 - 105), and his results have been used by numerous research workers. Pettijohn and others

(1972, p. 70) go so far as to say that "since Friedman (1958 and 1962) resolved the problem of correlating thin section and sieve size estimates, direct measurement in thin section is more widely used", while Blatt and others (1972, p. 56) also recommend the use of Friedman's correction factors. However, a closer inspection of the results which he has presented will show that they do not appear to justify the confidence which has been placed in them. For the purpose of the present study we can confine ourselves to a discussion of the relationships between sieving and observed thin-section mean and standard deviation which Friedman analyzed in his 1962 paper (Figs. 1 and 5 respectively).

From a plot of "mean (ø units) sieving" against "mean (ø units) thin-section (observed)" for the 38 samples which he studied, Friedman obtained a regression line with the following equation (Table 5, p. 20):

$$\text{Mean (sieving)} = 1{,}0550 \text{ mean (thin-section)} - 0{,}3602$$

However it is clear from the graph that the above equation should in fact read as follows:-

$$\text{Mean (sieving)} = \frac{1}{1{,}0550} \text{ mean (thin-section)} + 0{,}3602$$

If the implications of this equation are thought through, it should at once be apparent that the relationship expressed cannot be a valid one in any general sense at all (although it may be approximately true for Friedman's actual samples). On the basis of the corrected equation it can be readily demonstrated that sieving mean will equal thin-section mean at about 7 ø; the same result is obtained if the regression line is extrapolated to 7 ø. For ø values smaller or larger than 7 ø, the difference between sieving and thin-section means will (according to the equation) increase at a constant rate. This is clearly absurb, since it implies that if we were to measure the apparent size of large boulders in a conglomerate in a vertical road-cutting (which procedure is analogous to measuring sand grains in thin section) the average diameters obtained will, according to Friedman's formula, be nearly double the true diameters and that with extremely small particles, assuming that these could be sectioned and measured by some or other technique , the effect would be reversed and the measured diameters should, according to Friedman, be considerably smaller than the true diameters.

Turning now to Friedman's plot of "standard deviation (ø units) sieving" against "standard deviation (ø units) thin-section (observed)" (Fig. 5, p. 21), the following observations can be made:

1. The equation for the plotted regression line is incorrectly given in Table 5 as

$$\sigma \text{ (sieving)} = 0{,}7177\ \sigma \text{ (thin-section)} + 0{,}1356$$

The true regression equation, roughly calculated from the graph, is

$$\sigma \text{ (sieving)} = 1{,}37\ \sigma \text{ (thin-section)} - 0{,}175.$$

2. As in the case of the mean, predictions based on the (corrected) regression equation give rise to theoretically impossible results. Thus both the graph and the corrected regression equation predict that sieving and thin-section standard deviations equal each other at about 0,46 ø and that for standard deviation values greater than 0,46 ø sieving will give rise to larger standard deviations than thin-section size analyses, with the difference increasing at a constant rate. However, one would expect that the difference between the two techniques will be greatest for extremely well-sorted sediments (true standard deviation approaching 0 ø) and that for progressively more poorly sorted sediments the results from the two techniques should converge (since a sandstone composed of identical grains will, in thin section, show a complete range of apparent sizes, while in the case of a poorly sorted sandstone, in which a wide range of sizes is already present, the overall spread of sizes will be little affected). The actual regression line will theoretically be a curved one, having the basic form shown in Fig. VII-2 (assuming that sieving is capable of approximating the true standard deviation in very well-sorted sediments).

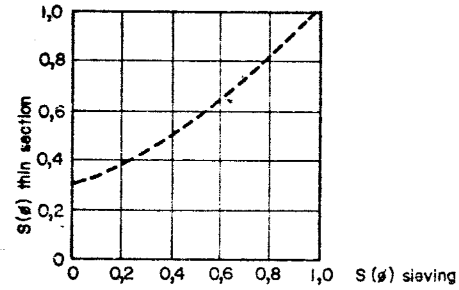


Fig. VII-2. Approximate relation between sieving and thin-section standard deviations.

3. Inspection of the actual points on Friedman's graph (as well as the actual standard deviation values contained in his Table 2c, p. 18) indicated that, contrary to all expectations, considerably higher standard deviation values were obtained from the sieving results compared with the thin-section results for a number of samples.

In the light of the above discrepancies the raw data presented by Friedman in his 1958 paper (Table 3, p. 400, 401) were re-examined;

the following facts emerged:

1. In all the samples a significantly larger "pan fraction" (> 4,00 ø) was obtained from the sieve analyses compared with the thin-section analyses. In theory the effect of measuring size in thin section would be to increase the relative number of very fine grains, and a sieve analysis, if correctly performed, should never result in a higher percentage of fines than a comparable thin-section size analysis. Two possible explanations for this deviation from the expected pattern come to mind:

(a) A significant quantity of fines are produced by crushing during disaggregation procedures prior to sieving.
(b) The very fine material was ignored in the thin-section analyses.

In either case the results obtained from the two techniques cannot be directly compared with each other unless this anomalous feature is taken into account.

2. It was noted that in many cases a large pan fraction (finer than 4 ø) was obtained, while a few samples showed a significant percentage of undifferentiated coarse material (coarser than 0,25 ø). Since purely arbitrary size values have to be assigned to the coarser than 0,25 ø and finer than 4,00 ø groups, such open-ended distributions should not be used in a study of this sort where a high level of accuracy is essential. Where the pan fractions are very large (in excess of 20% - e.g. samples 17, 29, 30, 31) the calculated moment measures will be virtually meaningless..

3. Standard deviations obtained from sieving data for at least the four samples showing the widest divergence from the expected results (5, 21, 23, 26) appear to have been incorrectly calculated.

4. A peculiar deficiency in the 3,75 - 4,00 ø class for all the sieving results seem to indicate that a faulty (over-sized) 0,062 mm sieve was used.

In view of all the above facts, the writer re-calculated means and standard deviations for 22 of Friedman's original 38 samples, omitting those for which the fine or coarse "pan fractions" exceeded 5% for thin-section data or 10% for sieving data, as well as those for which 0,50 ø intervals were used instead of 0,25 ø intervals. In addition, an attempt was made to eliminate the effect of anomalous relative percentages in the fine pan fraction by making the sieve percentage equal to the thin-section percentage; an arbitrary size of 4,50 ø was assigned to the fine pan fraction. Finally, all percentages were rounded off to the nearest whole number and the calculations performed on an electronic calculator. The results are contained in Table VII-4, and a plot of sieving standard deviation (ø units) against thin-section standard deviation (ø units) is presented in Fig. VII-3. The following conclusions can be drawn:

1. The average difference between means obtained by sieving and by measuring long axes in thin section for the 22 samples utilised is 0,103 ø i.e.

$$\text{Mean}_{\text{(sieving)}} = \text{Mean}_{\text{(thin section)}} + 0{,}103\ ø$$

<u>Table VII-4.</u> Recalculated means and standard deviations based on data supplied by Friedman (1958, Table 3).

Sample	Mean		Standard Deviation	
	Sieving	Thin-section	Sieving	Thin-section
1	2,640	2,540	0,308	0,428
3	2,701	2,563	0,298	0,430
4	2,574	2,387	0,294	0,402
5	2,759	2,555	0,305	0,383
6	2,888	2,763	0,390	0,518
7	2,767	2,660	0,451	0,570
8	2,836	2,686	0,456	0,546
9	2,816	2,723	0,445	0,538
10	2,924	2,795	0,511	0,606
11	1,136	0,950	0,709	0,687
16	2,679	2,478	0,475	0,571
20	2,784	2,848	0,392	0,482
21	2,174	2,202	0,299	0,379
22	2,076	2,113	0,475	0,568
23	2,258	2,293	0,455	0,541
24	2,665	2,641	0,385	0,477
25	2,098	2,048	0,357	0,433
26	1,788	1,700	0,427	0,495
34	2,867	2,730	0,446	0,579
35	2,366	2,193	0,421	0,520
36	2,305	2,089	0,692	0,718
37	2,320	2,203	0,596	0,651

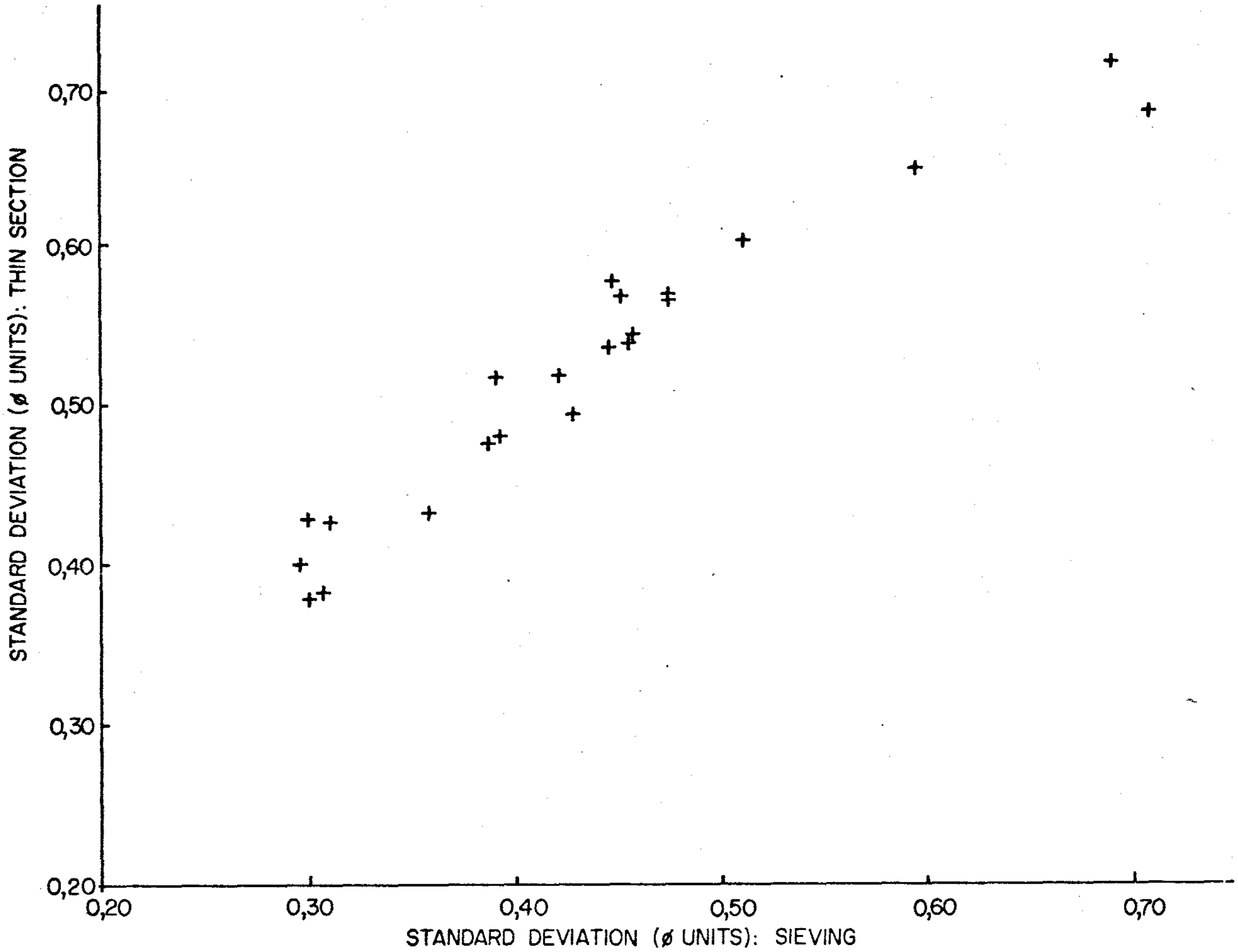


Fig. VII-3. Plot of sieving vs. thin-section standard deviations for recalculated data from Table 3 of Friedman (1958).

Friedman (1962, Table 3) shows a difference of 0,21 ø for his results.

2. The correlation between standard deviations obtained by sieving and in thin section are much better than Friedman's original results had led us to believe (compare Fig. VII-3 with Friedman's Fig. 5 , 1962).

3. As expected, thin-section standard deviations are now in nearly all cases larger than sieving standard deviations (by an average amount of 0,088 ø). Friedman, contrary to expectation, had found thin-section standard deviations to be smaller than sieving standard deviations (by an average amount of 0,05; see Table 3 , p. 19).

4. Comparisons made by Friedman (1962) between values obtained for skewness and kurtosis using the two techniques, although not investigated in this study, will also have to be queried in the light of the facts presented in this discussion. The same also applies to the regression lines obtained for medians and quartiles in Friedman's earlier paper (1958). Since these form the basis of Friedman's conversion graph

for determining sieve-size distributions from thin-section data (1958, Fig. 9, p. 414), this too must be rejected as invalid.

(b) <u>Smith (1966)</u>

Turning now to the paper by Smith (1966, p. 841 ff.), interest centres on Fig. 3 : "Scatter diagram of the length of the 'a' axis, as measured in grain mount, vs. the 'a' axis, as measured in thin section, of quartz grains from thirteen grain mounts and thirteen thin sections". Smith uses the thirteen points plotted to draw a regression line with the equation Y = 0,719 + 0,791 X. Smith states that the slope of the regression line (Fig 3) is not significantly different from the slope of the one to one line when tested by a 't' test (although a simple inspection of the scatter diagram makes one wonder why it was necessary to use a 't' test to prove the obvious) and summarises his results as follows:

"Since these two lines (i.e. the regression line and the 1:1 line) are essentially parallel, and the intercept of the regression line is significantly different from zero, one may conclude that the two techniques of measurement are significantly different, and the difference is a constant (in phi units). On the basis of these data, the thin section measurement will generally underestimate true grain size (in these samples the difference is 0,719 phi units) and the difference gets larger as the grains become coarser" (p. 843). The following observations are in order:

1. The figure of 0,719 phi units is based on extrapolation of the original regression line, and, as an inspection of the graph points will show, such extrapolation is completely inadmissable, since the data available hardly warrant the drawing of <u>any</u> regression line at all, let alone one which is capable of yielding a constant to three decimal places. In actual fact all that can be deduced from the data given on the graph is that the two techniques yield results which differ from each other by amounts that vary from 0 ø to 0,8 ø, and that the average difference is about 0,4 ø. An unusual feature of the results is that the points are clustered at the extremities of the range (i.e. around differences of 0,8 ø and 0 ø); only three out of the thirteen points correspond to intermediate values. Some explanation needs to be given for this peculiarity before the results can be accepted. In any case, it is hard to believe that the two techniques will normally show such highly variable differences in adequately controlled experiments. It is probable

that more samples are needed, that more grains per sample than the 40 that Smith used should be measured, and that the psuedo - number - frequency obtained in grain mount (line counting was used) should first be converted to volume frequency so as to be comparable to the volume frequencies obtained in thin section (assuming point counting was used).

2. Smith's statement that "the difference gets larger as the grains become coarser" stands in direct contradiction to the statement in the preceding sentence that "the difference is a constant (in phi units)". The first statement would be true of measurements in mm, but only ø units are considered in the paper and some reference to mm should have been given to avoid confusion (if this is in fact what was meant).

(c) Sahu (1965a)

Sahu (1965a, p. 969 ff.) "develops the theory of transformation of arithmetic to phi-moments and vice versa for any method of size analysis and where the frequency is recorded as weight (in percentage) or as number (in percentage)".

The following relationships are derived (p. 970):

$$\sigma^2 = \frac{(\lg (Mx^2) - 2 \lg (Mx^1))}{(\lg 2) \cdot (\ln 2)} \qquad (1)$$

$$\mu = \frac{(\frac{1}{2} \lg (Mx^2) - 2 \lg (Mx^1))}{\lg 2} \qquad (2)$$

where σ^2 = phi-variance
μ = phi-mean
Mx^1 = first arithmetic moment
Mx^2 = second arithmetic moment
lg = $\log_{10}$
ln = $\log_e$

Equations for "correcting" the arithmetic size distribution moments obtained from thin sections were presented later by Sahu (1966), and, in theory, the use of equations (1) and (2) above should enable one to calculate the true phi-mean and phi-variance from the corrected arithmetic moments. However, using a hypothetical sample with a known size distribution the above equations proved incapable of predicting the phi-mean and phi-variance from the first and second arithmetic moments. The example used is presented in Table VII-5.

Table VII-5. Hypothetical sample used to test validity of equations (1) and (2).

f	d_{mm}	$d_{mm}f$	d_{mm}^2	$d_{mm}^2 f$	d_{ϕ}	$d_{\phi}f$
10	0,1	1,0	0,01	0,1	3,322	33,22
20	0,2	4,0	0,04	0,8	2,322	46,44
40	0,3	12,0	0,09	3,6	1,737	69,48
20	0,4	8,0	0,16	3,2	1,322	26,44
10	0,5	5,0	0,25	2,5	1	10,00
Totals 100		30,0		10,2		185,58

f = frequency; d = grain diameter (class mid-point)

From the data in Table VII-5, Mx^1 (first arithmetic moment), Mx^2 (second arithmetic moment) and $\bar{x}_{\phi}$ (phi-mean) were calculated:

$$Mx^1 = \frac{30,0}{100}$$

$$= 0,30 \text{ mm}$$

$$Mx^2 = \frac{10,2}{100}$$

$$= 0,102 \text{ mm}$$

$$\bar{x}_{\phi} = \frac{185,58}{100}$$

$$= 1,8558\ \phi$$

Using equations (1) and (2) above, the following values were obtained for phi-mean (μ), phi-variance (σ^2) and phi-deviation (σ), with the true values, derived directly from Table VII-5, in brackets:

$$\mu = 1,8276\ \phi \quad (1,8558\ \phi)$$
$$\sigma^2 = 0,2608\ \phi \quad (0,3983\ \phi)$$
$$\sigma = 0,5107\ \phi \quad (0,6311\ \phi).$$

Other hypothetical and actual distributions were also tested with similar results. Unfortunately, the present writer was unable to establish the reason for the non-viability of Sahu's equations.

2. Present Investigation

In the light of the failure of the literature to provide satisfactory clarity on the relationships between means and standard deviations measured in ϕ units in thin section, and true means and standard deviations, this problem will now be discussed in some detail.

(a) Mean grain size

Krumbein and Pettijohn (1938, p. 132) using mm and number frequencies, and assuming spherical particles, derived mathematically the following relationships between thin-section mean and true mean:

$$n_{x,1} = (\pi/4)\, n_{r,1} = 0{,}7854\, n_{r,1}$$

or $$n_{r,1} = (4/\pi)\, n_{x,1} = 1{,}275\, n_{x,1}$$

where $n_{x,1}$ = observed number frequency arithmetic mean

$n_{r,1}$ = actual (true) number frequency arithmetic mean.

Sahu (1966, p. 258) using mm and volume (weight) frequency arrived at the following relationship via a mathematical treatment (spherical grains assumed):

$$w_{x,1} = (9\pi/32)\, w_{r,1} = 0{,}8836\, w_{r,1}$$

or $$w_{r,1} = (32/9\pi)\, w_{x,1} = 1{,}132\, w_{x,1}$$

where $w_{x,1}$ = observed weight frequency arithmetic mean (thin section)

$w_{r,1}$ = actual (true) weight frequency arithmetic mean.

We now need to arrive at a solution for the problem of obtaining the true size from thin section data using ø units and volume frequencies.

The approach adopted is based on the fact that the size distribution obtained by randomly sectioning a spherical grain an infinite number of times can be closely approximated by means of a finite series of closely-spaced equidistant parallel sections through the sphere; in two dimensions this can be represented by a circle cut by a series of parallel equidistant lines. In each case the length of the chord will be equivalent to the apparent diameter of the circle as seen in section, and the area of this circle will be directly proportional to the frequency accorded to that particular size (diameter) in the final size distribution (if a point-counting technique is being simulated). From such a size distribution the mean size obtained can readily be calculated, and compared with the true diameter of the original sphere.

In this study a 191 mm circle was superimposed on a series of equidistant parallel lines spaced about 0,8 cm apart; a total of 22 lines were found to pass through the circle. The chords corresponding to each of these lines were measured and the corresponding areas (= frequencies) calculated. The above operation was done in both mm and ϕ units, the former enabling the results to be checked against Sahu's mathematically-derived equation. From the data obtained (Table VII-6) the following relationships were derived:

$$\bar{x}_{mm\ (observed)} = \frac{71253500}{422229}\ mm$$

$$= 168{,}75\ mm$$

Since the true diameter of the sphere is 191 mm,

$$\bar{x}_{mm\ (true)} = \frac{191}{168{,}75}\ \bar{x}\ _{mm\ (obs.)}$$

$$= 1{,}132\ \bar{x}\ _{mm\ (obs.)}$$

$$\bar{x}_{mm\ (obs.)} = \frac{168{,}75}{191}\ \bar{x}\ _{mm\ (true)}$$

$$= 0{,}8835\ \bar{x}\ _{mm\ (true)}$$

If these results are compared with Sahu's theoretically derived equation (see above) it is clear that the results are virtually identical, and that the model can legitimately be used to derive the correction factor for the ϕ mean.

The tabulated results show that the difference between the ϕ mean obtained from the observed frequency distribution (-7,3755 ϕ) and the actual diameter of the original sphere (-7,5780 ϕ) amounts to o,2025 ϕ. This relationship can be expressed as follows:

$$\bar{x}_{\phi\ (obs.)} = \bar{x}_{\phi\ (true)} + 0{,}2025\ \phi$$

$$\bar{x}_{\phi\ (true)} = \bar{x}_{\phi\ (obs.)} - 0{,}2025\ \phi$$

For practical purposes this correction factor can be taken as 0,20 ϕ and we can write

$$\bar{x}_{\phi\ (true)} = \bar{x}_{\phi\ (obs.)} - 0{,}20\ \phi.$$

Table VII-6. Data derived from 22 equidistant sectionsthrough a 191-mm-diameter sphere.

$f(=\pi r^2)$	d_{mm}	fd_{mm}	d_ϕ	fd_ϕ	d_ϕ^2	fd_ϕ^2
1810	48	86900	-5,585	10110	31,192	56400
6505	91	592000	-6,508	42330	42,354	275500
10937	118	1290600	-6,883	75280	47,376	518200
14743	137	2019800	-7,099	104660	50,396	743000
18148	152	2758500	-7,249	131550	52,548	953600
21127	164	3464800	-7,358	155450	54,140	1143800
23509	173	067100	-7,435	174790	55,279	1299500
25450	180	4581000	-7,493	190700	56,145	1428900
26884	185	4973500	-7,532	202490	56,731	1525200
28059	189	5303200	-7,563	212210	57,199	1604900
28356	190	5387600	-7,571	214680	57,320	1625400
28656	191	5473300	-7,578	217160	57,426	1645600
28356	190	5387600	-7,571	214680	75,320	1625400
27468	187	5136500	-7,548	207330	56,972	1564900
26019	182	4735500	-7,509	195380	56,385	1467100
24332	176	4282400	-7,460	181520	55,652	1354100
22170	168	3724600	-7,393	163900	54,656	1211700
19362	157	3039800	-7,295	141250	53,217	1030400
16063	143	2297000	-7,160	115010	51,266	823500
12471	126	1571300	-6,978	87020	48,692	607200
8172	102	833500	-6,673	54530	44,529	363900
3632	68	247000	-6,088	22110	37,064	134600
422229		71253500		3114140		23002800

f = frequency; d = diameter of section.

Since the correction was based on a consideration of the effects of sectioning a sphere it is clear that with non-spherical grains the correction factor obtained can in theory only be utilised to obtain the average true nominal diameter from the average measured nominal thin-section diameter. However, Griffiths (1967, p. 123, 124) has shown that the ratio of the observed short "b" axis to the observed long "a" axis of quartz grains <u>in thin section</u> shows little variation among various sandstones. He gives two sets of data (Tables 6.6, 6.7) displaying average b/a ratios of 0,685 and 0,663 respectively; a mid-way figure of 0,675 is probably a satisfactory overall ratio.

If the figures given by Griffiths are, as he believes, representative of most sandstones, then the ratio of the long "a" axis in thin section to the nominal diameter can be calculated, and should be reasonably constant in all sandstones. This calculation can be carried out as follows:-

Let a = 1 mm, b = 0,675 mm (i.e. b/a = 0,675) where a and b are long and short axes <u>observed in thin section</u> and measured in mm. Assume an elliptical shape.

$$\text{Area} = (\pi \frac{a.b}{4})\ \text{mm}^2$$

$$= 3{,}1416\ (\frac{0{,}675}{4})\ \text{mm}^2$$

$$= 0{,}53015\ \text{mm}^2.$$

To find the diameter of a circle having the above area (i.e. the nominal thin-section diameter, d):

$$\pi r^2 = 0{,}53015\ \text{mm}^2$$

$$r^2 = \frac{0{,}53015}{3{,}1416}\ \text{mm}^2$$

$$= 0{,}16875\ \text{mm}^2$$

$$r = 0{,}41085\ \text{mm}$$

$$\text{and} \quad d = 0{,}8217\ \text{mm}$$

$$\text{Thus} \quad d = 0{,}8217\ a\ (\text{since } a = 1\ \text{mm})$$

$$\text{and} \quad a = 1{,}217\ d$$

Reverting to ø units, the above relationships can be expressed thus:

$$d_{\phi}\ (\text{obs.}) = a_{\phi} + 0{,}283\ \phi \quad (\text{since } 0{,}8217\ \text{mm} = 0{,}283\ \phi)$$

$$\text{and} \quad a_{\phi} = d_{\phi}\ (\text{obs.}) - 0{,}283\ \phi$$

$$\begin{aligned} \text{Since}\quad d_{\phi}\,(\text{true}) &= d_{\phi}\,(\text{obs.}) - 0{,}203\,\phi \quad (\text{p. } 71) \\ \text{and}\quad d_{\phi}\,(\text{obs.}) &= a_{\phi} + 0{,}283\,\phi \\ \therefore\quad d_{\phi}\,(\text{true}) &= (a_{\phi} + 0{,}283\,\phi) - 0{,}203\,\phi \\ &= a_{\phi} + 0{,}080\,\phi \\ \text{and}\quad a_{\phi} &= d_{\phi}\,(\text{true}) - 0{,}080\,\phi \end{aligned}$$

From the above, we can conclude that the means obtained by measuring the "a" axes in thin section will, on the average, overestimate the true mean (conceived of in terms of the nominal diameter) by an amount of 0,080 ϕ. However, for most purposes means based on long axes measured in thin section are probably satisfactory estimators of the true nominal diameter means. Provided we have made a mental note of the actual difference between the observed and the true data, it will not be necessary in most sedimentological studies to actually apply a correction factor to all the results.

Returning to Friedman's recalculated data (Table VII-4) it was found that observed thin-section means (based on long axes) overestimated sieving means by an average amount of 0,103 ϕ. In view of the relationship established above between a_{ϕ} and $d_{\phi\,(\text{true})}$, it would appear that sieving means will only slightly underestimate nominal cross-sectional means (the actual difference being 0,023 ϕ). In the light of our earlier discussion on the significance of "size" measures obtained by sieving (see p. 50 above), and in view of the opinion expressed by Ludwick and Henderson (1968, p. 233), who stated that "if no assumption about particle shape is made, and if nominal screen opening is equated with particle size, the modal intermediate diameter of particles in each sieved fraction will often be underestimated by 10 - 20%," this result is somewhat unexpected. However, the suite of 22 samples used to obtain the relationship between sieving and thin-section means is probably too small to be used for accurate generalisations, especially if we bear in mind that the actual differences varied from +0,216 ϕ to -0,064 ϕ . On the other hand the available evidence does indicate that both sieving analysis and the measurement of long axes of quartz grains in thin section are capable, under ideal conditions, of yielding means that are within 0,10 ϕ of the true mean size (true nominal diameter).

(b) Standard deviation/mean deviation.

Arriving at a correction factor (or factors) for standard deviations obtained from long axes of particles in thin section is likely to prove an involved and tedious operation, if it is possible at all. This conclusion is based on the following facts: (1) As a result of measuring the diameter of random sections through grains, the total size distribution is distorted (with the coarsest classes suffering reductions in frequency and the intermediate and finer classes being augmented). (2) The individual grains (which in practice all vary in shape) are orientated at various angles to the plane of section, with the result that even where the section passes through the centre of a grain, the value obtained for the apparent maximum diameter will generally lie somewhere between the true maximum diameter and the true intermediate diameter (the maximum diameter at right angles to the a axis) further increasing the spread of the values obtained. (3) As noted earlier (p.63 above) a plot of thin-section standard deviation against true standard deviation will give rise to a curved line and not a straight one; the relationship cannot therefore be expressed as a simple linear function.

The effect of shape and orientation could be mimimised by using nominal cross-sectional diameters instead of the longest diameters, but this involves spending considerably more time on each sample. The gains will in any case be of dubious value since we still have the sectioning effect to contend with.

There would seem to be no reason why the apparent standard deviation obtained from the long "a" axes as seen in thin section should not be used as a universal standard of comparison and measure of "sorting" in sedimentological studies. The minimum standard deviation obtainable in thin section can be calculated and this figure will equal a true standard deviation of 0 ø.

Minimum value for standard and mean deviation in thin section.- From the above considerations it is clear that a perfectly sorted sediment, where all the grains possess identical size and shape, will, when sectioned, appear to possess a far from negligible standard deviation. Taking the simplest possible case, that of a sediment composed of same-sized spherical grains, it is possible to calculate the standard deviation that would be obtained if a thin section was made of this sediment, using the same model that was employed to calculate the effect of sectioning on the mean. The value thus obtained represents the minimum standard deviation that can normally be encountered in thin section, and is equivalent to a true standard deviation of 0 ø. Using the data of Table VII-6, the calculation can be carried out as follows:

$$\begin{aligned} s^2 &= \frac{1}{N}\sum_{i=1}^{N} x_i^{\,2} - \left(\frac{1}{N}\sum_{i=1}^{N} x_i\right)^2 \\ &= \frac{23002800}{422229} - \left(\frac{-3114140}{422229}\right)^2 \\ &= 54{,}4794 - (-7{,}37547)^2 \\ &= 54{,}4794 - 54{,}3976 \\ &= 0{,}0818 \\ s &= \sqrt{0{,}0818} \\ &= 0{,}286 \end{aligned}$$

By adding 7,578 to all the values in the fourth column of Table VII-6, a similar table can be set up corresponding to a sphere 0 ø (1 mm) in diameter. This was done, and the above calculation repeated to confirm that the value obtained for s is independent of size. Identical values for s^2 and s were obtained.

An inspection of the above calculation shows that the final result can be substantially affected by rounding-off errors if only four figures are used throughout. Hence four-figure tables should not be used to calculate standard deviations for very coarse or very fine sediments (involving high numerical values for ø) if more than a moderate degree of accuracy is required.

As regards the mean deviation, a similar calculation using the data of Table VII-6 was performed, and the following result was obtained:

Minimum mean deviation $_{\text{(thin section)}}$ = 0,196 ø.

Friedman (1962, p. 22) suggests that a standard deviation of 0,50 or less characterises a very well-sorted sandstone; a standard deviation of 0,50 to 0,80 a well-sorted sandstone; and a standard deviation of 0,80 to 1,30 a moderately sorted sandstone. Results obtained by the writer, by Griffiths (1967, p. 96) and by Friedman himself (recalculated data in Table VII-4) indicate that only the most poorly sorted sandstones will give standard deviation values in excess of 1,0 ø in thin section. The following classification is felt to be much more realistic and practical:

< 0,45 ø	Very well sorted
0,45 - 0,55 ø	Well sorted
0,55 - 0,70 ø	Moderately sorted
0,70 - 0,90 ø	Poorly sorted
> 0,90 ø	Very poorly sorted

H. CONCLUSIONS

For the sake of uniformity in sedimentary rock descriptions and in view of some powerful theoretical and practical advantages, it is not too much to hope that the measurement of maximum size, mean,and standard (or mean) deviation based on long axes of quartz (or quartz plus feldspar) grains in thin sections will become standard practice in the not-too-distant future. It is neither necessary nor desirable to convert the measures thus obtained to "true" size or sieve-equivalent size.

In addition, in the course of developing the theme there have been a number of opportunities for illustrating our earlier observation that wrong basic concepts can sometimes lurk beneath impressive-looking statistical manipulations in the published literature.

CHAPTER VIII

SANDSTONE MINERALOGY

Since the identification of gravel clasts is usually straightforward and the study of mudrock composition involves the use of specialised non-microscopic techniques, we can confine ourselves to a discussion of sandstone composition. The following five aspects are involved:

Point-counting methodology.
Classification of common sandstone-forming components.
Distinguishing between mineralogical components.
Sandstone classifications and terminology.
The place of accessory-mineral studies.

A. MODAL ANALYSIS: POINT-COUNTING METHODOLOGY

The theoretical considerations underlying the use of point counting for modal analyses have been adequately dealt with in the literature (e.g. Chayes, 1956) and are sufficiently well known not to require further comment here. However, a decision has to be made regarding the level of accuracy required, and in the light of this to decide on the number of grains (points) to be counted in each sample.

According to Krumbein and Pettijohn (1938, p. 471) counts of 300 grains will be satisfactory for most work, while Galehouse (1971, p. 396) is also of the opinion that 300 points or grains is a "good number" to count in order to get the maximum accuracy for a minimum investment of time. However, according to Potter and Pettijohn (1963, p. 193) most commonly 200 point counts per thin section have been used to estimate modal composition. Galehouse (1971, Fig. 5, p. 398) presents a series of graphs on which the estimate of probable error in percent at the 95,4 percent confidence level is plotted against number of points counted for various mineral percentages. Inflection points on most of the curves occur between 200 and 300 points, indicating that a figure somewhere between 200 and 300 represents an optimum number of points to be counted. Beyond 300 points the increase in accuracy achieved will rarely justify the additional expenditure of time, especially if a large number of samples are being used. Accordingly all the analyses in this study are based on counts of between 200 and 300 grains.

B. CLASSIFICATION OF COMMON SANDSTONE-FORMING COMPONENTS

Griffiths (1967, p. 179) suggests that "As a first step all the constituents in sediments can be embraced by a fourfold classification which fulfills the essential requirements of being mutually exclusive and exhaustive. The criterion forming the basis of this classification is the morphology or habit of the constituents as seen in thin section - essentially the nature of the internal and external bounding surfaces".

The four classes recognised by Griffiths (and illustrated in his Fig. 9.1, p. 182) are:

Class AB: Internally homogeneous or continuous, externally homogeneous or continuous (quartz, feldspar, etc.)
Class $A\bar{B}$: Internally heterogeneous or discontinuous, externally homogeneous or continuous (rock fragments).
Class $\bar{A}B$: Internally homogeneous or continuous, externally heterogeneous or discontinuous (cement, overgrowths).
Class $\overline{AB}$: Internally heterogeneous or discontinuous, externally heterogeneous or discontinuous (matrix).

Griffiths (1967, p. 183 ff) discusses some of the problems associated with distinguishing the various elements belonging to each of the above classes (as well as those involved in differentiating between the classes themselves).

The scheme proposed by Griffiths was intended to reduce to a minimum the subjective element responsible for operator bias in modal analyses. However, Pettijohn and others (1972, p. 27) have pointed out that the interpretation of the mineralogy of a sandstone is dependent on a proper assignment of mineral species present to meaningful genetic categories. Thus a single list of minerals present is virtually meaningless and we need instead several lists by categories, such as primary detrital, precipitated cement, and post-depositional alteration products. These writers add that the distinctions between detrital and chemical categories (for example) are mainly based on the geometry of a particular grain; Griffith's scheme can thus act as an aid in assigning points to genetically meaningful categories, rather than being simply an end in itself. In this study an attempt was made to adhere to the classification outlined below. Listed are the mineral varieties actually recognised and noted during point counting even where these were not included in the final tabulations of the data.

H. CONCLUSIONS

For the sake of uniformity in sedimentary rock descriptions and in view of some powerful theoretical and practical advantages, it is not too much to hope that the measurement of maximum size, mean, and standard (or mean) deviation based on long axes of quartz (or quartz plus feldspar) grains in thin sections will become standard practice in the not-too-distant future. It is neither necessary nor desirable to convert the measures thus obtained to "true" size or sieve-equivalent size.

In addition, in the course of developing the theme there have been a number of opportunities for illustrating our earlier observation that wrong basic concepts can sometimes lurk beneath impressive-looking statistical manipulations in the published literature.

CHAPTER VIII

SANDSTONE MINERALOGY

Since the identification of gravel clasts is usually straightforward and the study of mudrock composition involves the use of specialised non-microscopic techniques, we can confine ourselves to a discussion of sandstone composition. The following five aspects are involved:

Point-counting methodology.
Classification of common sandstone-forming components.
Distinguishing between mineralogical components.
Sandstone classifications and terminology.
The place of accessory-mineral studies.

A. MODAL ANALYSIS: POINT-COUNTING METHODOLOGY

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The scheme proposed by Griffiths was intended to reduce to a minimum the subjective element responsible for operator bias in modal analyses. However, Pettijohn and others (1972, p. 27) have pointed out that the interpretation of the mineralogy of a sandstone is dependent on a proper assignment of mineral species present to meaningful genetic categories. Thus a single list of minerals present is virtually meaningless and we need instead several lists by categories, such as primary detrital, precipitated cement, and post-depositional alteration products. These writers add that the distinctions between detrital and chemical categories (for example) are mainly based on the geometry of a particular grain; Griffith's scheme can thus act as an aid in assigning points to genetically meaningful categories, rather than being simply an end in itself. In this study an attempt was made to adhere to the classification outlined below. Listed are the mineral varieties actually recognised and noted during point counting even where these were not included in the final tabulations of the data.

1. Primary (allogenic) minerals

1.1 Framework minerals

1.1.1 Quartz

1.1.2 Feldspar

1.1.2.1 Microcline

1.1.2.2 Orthoclase

1.1.2.3 Plagioclase

Plagioclase varieties can be distinguished by means of the symmetrical extinction angle using a universal stage.

1.1.3 Rock Fragments

Six classes and a number of sub-classes were recognised on the basis of the mineral combinations present. The first three classes embrace all fragments presumed to be derived from sedimentary and metamorphic source rocks, while the remaining three are presumed to represent igneous rocks, although an unknown amount of highly altered igneous fragments has probably been assigned to the first and second categories.

1.1.3.1 Clay minerals + fine-grained mica (sericite) + chlorite (=claystone, fine-grained slate and phyllite, highly altered igneous rocks or feldspar)

Two sub-classes can be recognised on the basis of whether or not the individual flakes show a sub-parallel orientation.

1.1.3.2 Quartz (and feldspar ?) + clay minerals + fine-grained mica (sericite) + chlorite (=mudrock, slate, phyllite, schist)

Four sub-classes can be recognised depending on whether quartz plus feldspar are predominant or subordinate, and whether or not the grains display a sub-parallel orientation .

1.1.3.3 Polycrystalline quartz grains (= chert, quartzite)

Two sub-classes exist : very fine-grained microcrystalline quartz mosaic, probably chert, and coarser-grained mosaics, presumably representing very fine-grained quartzite (or recrystallised chert).

1.1.3.4 Microcrystalline quartz-feldspar mosaic + chlorite, etc. (= non-porphyritic "felsite")

1.1.3.5 Distinct feldspar microlites or crystals (plus quartz, etc.) (= pilotaxitic and porphyritic igneous rocks)
Two sub-classes exist : porphyritic and non-porphyritic.

1.1.3.6 Quartz plus feldspar aggregates (= phaneritic acid igneous rocks or arkose)

1.1.4 Accessory minerals
Muscovite, biotite, opaque minerals (magnetite, etc.), others.

1.2 "Matrix" minerals
Carbonaceous material, quartz/feldspar, kaolinite/montmorillonite/illite/sericite, chlorite, others.

2. Secondary (authigenic) minerals
Silica (quartz, chalcedony, opal), calcite/dolomite, feldspar, prehnite, laumontite, analcime, epidote, pumpellyite, sericite, chlorite, clay minerals, etc.

C. DISTINCTION BETWEEN MINERAL COMPONENTS

Differentiating between the various mineralogical elements present in many sandstones is less simple than the corresponding task in igneous and metamorphic rocks. This is largely due to the comparatively fine-grained nature of the rocks, the heterogeneous assemblage of components brought together at depositional sites by depositing currents, and the presence of authigenic minerals filling the interstitial cavities originally present in the rock. In the writer's experience the greatest difficulty in assigning mineralogical components to the correct class was experienced in the following situations:

1. Distinguishing between quartz and feldspar.
2. Distinguishing between orthoclase and plagioclase.
3. Distinguishing between coarse-grained rock fragments and monomineralic grains.
4. Distinguishing between fine-grained rock fragments and matrix.
5. Distinguishing between different types of rock fragments.
6. Distinguishing between primary and secondary quartz.

At the commencement of this study an attempt was made to utilise standard staining techniques in order to simplify the first and second of the above operations. However, the very fine-grained nature of most of the rocks, as well as the presence of significant amounts of feldspathic igneous rock fragments in the Karoo sandstones which tended to become stained along with the feldspar, rendered the results unsatisfactory. Furthermore, Theron (1970, p. 104) could not succeed in staining the plagioclase in Beaufort sandstones from the Orange Free State area when attempting to differentiate between orthoclase and plagioclase. It was accordingly decided to rely mainly on optical properties to differentiate between quartz and feldspar, since experience had shown that the interference figures produced by uniaxial quartz grains could in most cases be readily distinguished from those produced by feldspar grains regardless of the orientation of the grains with respect to the plane of section, and to abandon the possibility of subdividing the feldspar category. The common presence of untwinned, unaltered feldspar in certain formations meant that it was advisable to examine the interference figure of every quartz/feldspar grain; failure to do this has undoubtedly resulted in feldspar being underestimated in many petrographical studies of sandstone. Unfortunately, this technique cannot be applied to very small grains with the result that quartz : feldspar ratios obtained in the very fine-grained sandstones are much less reliable than those quoted for relatively coarser sandstones.

As regards the third and fourth of the problems enumerated above, no completely satisfactory criteria seem to exist for establishing classes which are truly mutually exclusive. Pettijohn et al. (1972, p. 207) also draw attention to this problem and point out that great difficulty can be experienced in distinguishing between somewhat altered rock fragments and recrystallised sericitic and chloritic matrix, as well as between the softer pelitic rock fragments, which may be deformed and squeezed into pores between more durable quartz grains, and true matrix. The latter process gives rise to a false or psuedomatrix. De Booy (1966, p. 280) believes that the amount of matrix present in graywackes in particular has often been grossly overestimated in the past, and that a great deal of what is called matrix is in fact made up of grains of rock fragments and minerals larger than 20 microns.

In the present study all interstitial material which seemed to represent flattened or distorted remains of lithic grains were assigned to the rock fragment category. Identification was normally based on the internal homogeneity and external continuity (in contrast to the heterogeneous and discontinuous nature of the true matrix), as well as similarity to undoubted rock fragment grains present in the sample. However, the criteria become progressively more difficult to apply consistently as the grain size of the sandstone decreases, with the result that in dealing with very fine-grained sandstones the whole operation becomes highly subjective, and large operator-to-operator variation would undoubtedly occur if other workers were to study the same samples.

Like the above, the fifth problem (distinguishing between different kinds of rock fragments) also involves a large number of borderline decisions which become more frequent and more difficult as the grain size decreases. The writer would not pretend that the original definitions applied to the six categories recognised were always consistently adhered to, and the subjective element again featured far too prominently for comfort.

One of the main difficulties encountered involved the distinction between microcrystalline quartz (chert) and microcrystalline quartz plus feldspar ("felsite"). In practice the latter category could often be identified by the slight difference in refractive index between the quartz and feldspar microcrystals as well as the presence of alteration products (cloudiness) in the feldspar microlites; in the case of the former (chert) class, no such differences exist since only a single mineral species is present. In the present study the very immature nature of most of the Karoo sandstones make it unlikely that chert will constitute more than a few percent of the rock fragments.

Finally, the complete absence of original grain outlines or other diagnostic differences between primary and secondary quartz in virtually all the samples studied meant that no separation could be effected between these two components. All quartz, regardless of origin, has accordingly been assigned to the detrital quartz category, with the result that this category will probably have been inflated by an unknown amount in all the silica-cemented sandstones. On the other hand, it is quite possible, if not probable, that most of the secondary quartz was not introduced from outside, but was derived from the pre-existing detrital grains by pressure solution, a process which Carozzi (1960, p. 24) refers to as "welding" and Waldschmidt (1941) as "autocementation". This means that the procedure adopted here could conceivably give rise to quartz percentages fairly close to the original percentage of detrital quartz, and that if the secondary overgrowths were to be classed separately as cement, the original quartz percentage would be significantly underestimated. However, Bissel (1959) believes that 90-95% of the introduced silica cement in the orthoquartzites of the Cordilleran geosyncline is syngenetic and in the discussion appended to his paper Krynine stated that his own studies of orthoquartzites in the Appalachian region also indicated that 95% of the silica cement was syngenetic.

D. SANDSTONE CLASSIFICATION AND TERMINOLOGY

No doubt the first reaction of many sedimentologists on encountering yet another "contribution" to the vexed question of sandstone terminology is one of dismay. So much has been written on the subject, and so many proposals made, that it would seem impossible not to add to the confusion even while attempting to evolve some order out of the chaos. In actual fact, however, the situation is not as chaotic as it sometimes appears, and there are signs of some measure of basic agreement as to what constitutes the best approach to the whole subject.

1. Basic features of previous classifications

Comprehensive reviews of sandstone classifications proposed up to 1960 and 1963 respectively have been given by Klein (1963) and McBride (1963) while Okada (1971) covers subsequent developments. Klein and Okada both pointed out that the classifications which they were reviewing could be divided into two broad classes - those in which texture ("matrix") is ignored in naming sandstones and those in which it plays an essential role in nomenclature. Unlike McBride, Klein did not present his own scheme, but did express a preference for those schemes in which texture and mineralogy are treated separately (i.e. as independent properties), a preference which seems to have been shared by most of those who have contributed to the discussion in subsequent years. Two notable and very recent exceptions have been Okada (1971) and Pettijohn, Potter and Siever (1972) who, while considerably modifying Pettijohn's earlier (1957a) scheme, continue to make a fundamental distinction between "arenites" (less than 15% matrix) and "wackes" (more than 15% matrix).

Although Odada has noted that nearly fifty classifications have been proposed up to 1971, there are at present only about seven or eight classifications in existence which are of sufficient importance to merit consideration in a discussion of this kind. They are those which have been proposed by Crook (1960), McBride (1963), Moore (1964), Folk (1968), Chen (1968), Folk et al. (1970), Okada (1971), and Pettijohn et al. (1972). The actual classifications are reproduced in Folder 5. It is immediately apparent that all the diagrams show a certain basic similarity, reflecting a fairly good measure of agreement as to the essential features of a sound classification. These features can be summarised as follows:

1. Sandstones are best classified on the basis of the proportions of three end-members, i.e. utilising a triangular composition diagram.
2. Quartz (+ quartzite and chert?), feldspar, and rock fragments (+ mica?) are universally recognised as the end-members in terms of which most commonly-occurring sandstones are best classified and named.
3. Although there are differences in the actual terminology and the precise boundaries between classes, three major sandstone types (and two intermediate ones) are recognised in nearly all the classifications:

    (a) The quartz-rich sandstones (quartzose sandstone, quartzose arenite, quartz sandstone, quartz arenite).
    (b) The feldspar-rich sandstones (arkose, arkosic arenite, feldspathic sandstone, feldspathic arenite, feldsarenite).
    (c) The rock fragment-rich sandstones (lithic sandstone, lithic arenite, litharenite).
    (d) Intermediate feldspathic sandstones (subarkose, subfeldspathic sandstone, subfeldsarenite, sublabile feldspathic arenite).
    (e) Intermediate lithic sandstones (sub-lithic sandstone, sublitharenite, sublabile lithic arenite).

4. Major divisions of the triangle have generally been made along lines corresponding to 90 - 95% quartz and 65 - 75% quartz.

Having defined the areas of agreement, we are now in a position to examine some of the more important differences between the various systems. These differences concern the use of textural criteria (matrix percentage) to separate major sandstone clans (Okada, 1971; Pettijohn et al., 1972), the subdivison of the triangle (including the definition of class boundaries), and the actual terminology used.

2. The use of matrix in sandstone classifications

Most recent writers have rejected the approach to sandstone nomenclature exemplified by Okada and Pettijohn - an approach in which a fundamental distinction is made between two basic sandstone types ("arenites" and "wackes") on the basis of whether more or less than 15% fine-grained matrix is present. The present writer feels that Okada's and Pettijohn's systems (involving the use of two sets of names rather than a single set of terms) is more cumbersome and less logical than those in which matrix is treated as an aspect of texture, and therefore irrelevant in a compositional classification. In the latter approach matrix-rich sandstones are simply designated by the prefix "muddy" or "dirty".

3. Subdivision of the compositional triangle

While McBride and Pettijohn base the initial subdivision of the triangle on the feldspar and rock fragment percentages, the remainder base their initial subdivision on the quartz percentage. The latter approach seems to represent the more elegant solution, although both methods are of course purely arbitrary.

As regards the actual number of categories to be established, and the location of the boundaries between them, care must be taken not to establish either too few categories (in which case too large a range of composition is represented by one compositional name, which then becomes meaningless) or too many categories (in which case one might as well quote the actual composition). Three of the schemes under consideration (those by Pettijohn, Okada, and Moore) include sandstone classes which are so large as to be virtually useless in sedimentary rock descriptions, while with one exception (Chen) none of the schemes make provision for naming the very quartz-poor sediments, which are often common in geosynclinal belts (although in fairness to Folk and others (1970), these writers do make provision for such sandstones in the text accompanying their classification diagram). On the other hand, there would seem to be little justification for establishing <u>four</u> distinct classes on the basis of feldspar: rock fragment ratios; <u>one</u> class covering those sandstones composed of subequal proportions of feldspar and lithic fragments would seem to be quite adequate for descriptive purposes. As regards the quartzose sandstones no real provision has hitherto been made for naming the pure quartz sandstones (i.e. those consisting entirely of quartz).

The precise location of boundaries between classes (in the absence of any clearly defined natural groupings) will always be a largely arbitrary business. As pointed out earlier, certain trends are apparent in current schemes, and these have been kept in mind in establishing the boundaries of the scheme presented in Folder 5.

4. Choice of names

With one exception (Moore), all the schemes discussed use the term "arenite" rather than "sandstone". However, in view of the fact that

Gilbert (1954), Krumbein and Sloss (1963) and more recently Okada (1971) as well as Pettijohn and others (1972) have used this term in a restricted sense (for "clean" sandstones, in contrast to the "dirty" wackes), this trend is an unfortunate one. Use of the general term "sandstone" would seem to be advisable in order to avoid confusion.

Having ruled out Pettijohn's two-fold classification, the much-discussed term "graywacke" no longer poses a threat to the smooth flow of this discussion (although it remains a useful field term to describe indurated lithic or sublithic sandstones containing appreciable amounts of dark, chloritic/sericitic matrix). We are left, then, with the need to make a decision on the place of the term "arkose" in a compositional classification. This term appears in three of the schemes being considered, while in addition Pettijohn uses the term "arkosic arenite". Folk and others (1970) reject "arkose" because of the existing diversity in both descriptive and genetic connotations, as well as the implications of a granitic source area. Moore (1964) classifies arkose as a "special rock type" (greywacke suffers a similar fate) and defines it as a "feldspathic sandstone with evidence of granitoid derivation". Apart from the arguments presented by Folk and others, the use of feldspathic sandstone (arenite) parallels the use of lithic sandstone (arenite) and is therefore preferable in the interests of consistency.

Because of the shortcomings present in the existing classifications, a scheme was devised which would hopefully eliminate some of the more serious deficiencies, and yet preserve the basic measure of consensus which has been achieved thus far. This scheme is presented in Folder 5. Unless otherwise stated, all sandstone names used in this study are defined by the diagram depicted in Folder 5.

E. THE PLACE OF ACCESSORY-MINERAL STUDIES

Griffiths (1967) gives a historical review of accessory-mineral investigations, and concludes that after the early 1940s accessory-mineral studies continued to be used but with much reduced enthusiasm and only for certain very specific problems. It also became recognised that while accessory-mineral studies contributed to the reconstruction of the broad regional picture, and while correlation of broad stratigraphic zones over large areas was quite feasible, local variation tended to be haphazard, and the effectiveness of the tool in detailed studies was questionable (p. 203). In general, in near-source sediments and in the younger, particularly Tertiary, sedimentary rocks the accessory minerals have proved very useful. In sediments far from their source, in which the accessories may have suffered several cycles of sedimentation, and also in the progressively older sediments, in which diagenesis has reduced the variety of accessories, the amount of information supplied may be very meagre (p. 201).

Pettijohn and others (1972, p. 43) have pointed out that to the extent that the heavy minerals survive the hazards of weathering, transportand diagenesis and to the degree that they occur in a restricted range of provenance types, they are most useful for source rock interpretation. The use of heavy minerals for correlation purposes, on the other hand, involves the assumption that the source areas surrounding a sedimentary basin simultaneously underwent virtually identical changes in lithological character, and that these changes will be simultaneously reflected in the sediments accumulating in the basin. Since such a situation is unlikely to have been at all common, it can be concluded that heavy minerals are not of great use for ordinary detailed time-stratigraphic correlation, just as lithologic facies in general are not useful as time-stratigraphic markers.

The study of accessory minerals (the so-called "heavy minerals") has in the past formed part of most South African theses dealing with sedimentary rock sequences. Has the time and space devoted to this aspect been justified by the results obtained? A consideration of the actual use to which the results obtained from heavy-mineral studies have been put in the past, leads us to answer this question in the negative. In general, very little reliable information on source rocks has been extracted from the data, and, as pointed out by Pettijohn and others, stratigraphic correlations based on heavy minerals must be regarded as suspect. Since accessory minerals in any case rarely constitute more than one percent of the total volume of sedimentary rocks, they do not represent a fundamental property of such rocks, and their study is not essential for the routine description of these rocks. Hoffman (1973, p. 178) refers to the "discovery" of Recent sediments having rescued sedimentology from "at best unsung decades of sieving and heavy minerals".

CHAPTER IX

SEDIMENTOGENESIS

Having given a complete description of each formation, the significance of this information must be assessed and interpreted in terms of one of our original objectives, namely, that of deducing the genesis of the sedimentary succession studied. In order to do this effectively the concept of "genesis" or "origin" first needs to be broken down into its constituent elements, each of which should be considered separately before attempting a final synthesis in the form of a palaeographic reconstruction. These different elements can be listed as follows:

Dispersal patterns (palaeocurrents)
Sedimentary processes (transportation and deposition) and palaeoenvironments (environments of deposition)
Provenances (nature and location fo source areas)
Palaeoclimates
Diagenesis

Since palaeoclimatology and diagenesis are specialised fields beyond the scope of routine sedimentological studies, they will not be considered further.

A. DISPERSAL PATTERNS

Klein (1967) and Selley (1968) have reviewed and summarised the various possible palaeocurrent patterns that are encountered in practice and their models have formed the basis for relating palaeocurrents to environments in this study. Selley and Klein appear to disagree, however, on the important issue of whether unimodal downslope palaeocurrent patterns are possible in a shallow marine environment.

According to Klein (1967, Table 1), the tidal flat channel environment would appear to be the only situation in which a unimodal downslope dispersal pattern could be encountered under coastal or shallow marine conditions (apart, that is, from fluvial processes extending into the sea in a delta environment). Selley, on the other hand, postulates a model (Fig. 6,F) in which fluviatile currents are absent, and net transport is offshore. However, he cites only one example in support of this model, namely a study by Pelletier (1965). Pelletier, however, does not supply any proof of unimodality, for example in the form of rose diagrams, nor does he give any indication of the vector strengths (or standard deviations) relating to his data. Neither Selley nor Pelletier attempt to explain the downslope direction in terms of depositional processes, although Pelletier does suggest that his sandstone constituted ancient offshore bars. However, Reineck and Singh (1973, p. 305) point out that cross-bedding dip directions in the upper shoreface (i.e. the zone of longshore bars) shows a maximum toward the land, with another maximum present parallel to the shoreline and much dispersion in the values (cf. Masters, 1967, p. 2039).

Similar arguments apply to the papers cited by Potter and Pettijohn (1963, p. 84, 85) and Hobday and Mathew (1974, p. 227) in support of offshore-directed marine palaeocurrents. In fact, in order to establish the existence of marine palaeocurrent systems indistinguishable from those encountered in the fluviatile regime, the following criteria would have to be satisfied:

1. The marine origin of the sandstone must be established on the basis of sound internal evidence.
2. The shoreline direction must have been correctly deduced.
3. Clear evidence of unimodality must be presented.
4. Standard deviations should be less than about 70° for foreset dip direction data (i.e. low to moderate), and less than about 50° for trough axis data.
5. An adequate hypothesis accounting for the generation of the structures on which the measurements were made should be advanced.

The activity of rip currents would appear to be the only process capable of generating unimodal palaeocurrent patterns directed seaward in a shallow marine environment. Rip-current deposits have not often been reported in the literature (see Masters, 1967, Fig. 11 and Gietelink, 1973, p. 130 for examples), and it seems highly unlikely that a thick succession of sandstones could be formed solely by rip-currents. Since this condition would have to be met if a sandstone formation displaying a well-developed unimodal downslope dispersal pattern is to be interpreted as a marine deposit, we can conclude that Selley's model F will very rarely (if ever) be encountered in practice. Thus all sandstone units displaying unimodal palaeocurrents directed downslope at right angles to the shoreline should be interpreted as fluviatile, unless there is absolutely convincing evidence for a marine origin such as the presence of abundant glauconite or marine fossils <u>within the sandstones themselves</u>. It is possible that many sandstone units have been considered to be marine merely on the grounds that they occur interbedded with marine shale or limestone. Since non-marine sands can extend into an essentially marine environment during periods of regression (or marine shales extend into essentially terrestrial deposits during transgression), it is clear that the sandstones must be treated on their own merits before any definite pronouncement as to environment can be made.

Finally, published data reviewed by Potter and Pettijohn (p. 88, 89) suggest that standard deviations of cross-bed dip directions in fluvial-deltaic deposits are generally less than about 78°, while those of marine deposits are generally greater than 78°.

B. SEDIMENTARY PROCESSES AND PALAEOENVIRONMENTS

A major aim in the interpretation of sedimentary rock sequences has generally been deduction of the "sedimentary environment". According to Reading (1969, p. 580), "Sedimentological interpretation requires acute observation, an understanding of processes and a wide experience of ancient and recent sediments, together with common sense, imagination, and intuition", while Blatt and others (1972, p. 211) aver that "Skill in the recognition and interpretation of sedimentary facies is achieved only by long experience in the field with ancient and modern examples, and by careful study of the world literature of sedimentology and stratigraphy". At first sight these sentiments seem to preclude the possiblity of successful environmental interpretations being achieved by all but a select few sedimentologists! However, a survey of the literature, especially some of the recent syntheses by writers such as Visher (1965), Selley (1970), Allen (1970), Pettijohn and others (1972) and Reineck and Singh (1973) indicate that there are a limited number of commonly occurring basic sedimentary facies in nature, and that these can in most cases be readily related to the correct sedimentary environment (cf. Visher, 1965, p. 42).

Before we can proceed with an environmental analysis we need to decide on the meaning we are going to attach to the word "environment", define the environments to which we are going to refer, and adopt a suitable basis for classifying these environments. "Review of environmental literature suggests that, at this time, it is especially important for each writer to define his use of terms and to keep his discussions consistent with his own definitions" (Crosby, 1972, p. 9).

Regarding the term environment itself, there seems to be general agreement that it represents a "geographically restricted complex where a sediment accumulates, described in geomorphic terms and characterised by physical, chemical, and biological conditions, influences, or forces; e.g. a lake, swamp, or flood plain" (AGI Glossary, 1972, p. 231; cf. Krumbein and Sloss, 1963, p. 234; Selley 1970, p. 1; Gould, 1972, p. 1; Pettijohn and others, 1972, p. 450). According to Pettijohn and others (1972, p. 450), environmental analysis turns out to be essentially palaeogeomorphology, and in making an environmental reconstruction, the sedimentologist becomes, in effect, a geomorphologist. If this approach is correct, it means that one cannot speak of "turbidite" and "aeolian" environments (as Selley, 1970, p. 3, does, for example) since these terms refer not to the place of deposition, but to the processes involved. On the other hand, there are many situations where it is in fact the process (e.g. turbidity currents) rather than the place of deposition (e.g. a continental rise) that leaves a dominant impress on the resultant sediments. As a result it is often easier to first deduce the physical/chemical/biological process(es) responsible for the formation of a group of strata (since this can generally be inferred more directly from the sediments themselves than can the geomorphic environment) and then, if possible, to go on from there to reconstruct the local palaeogeomorphology. For this reason physical processes and palaeoenvironments are discussed under a single head in part B of this study.

1. Sedimentary Processes

A careful perusal of several recent syntheses (especially those of Swift, 1969 a,b, Allen, 1970, and Reineck and Singh, 1973) indicated that the following list embraces all the more important agents responsible for the creation of sedimentary deposits. Except where otherwise indicated, the terms listed are adequately defined in the AGI Glossary of Geology (1972).

1. Physical processes

1.1 Wind

Two main processes are involved: traction (surface creep + saltation), responsible for moving sand and gravel, and suspension, responsible for the transport and deposition of dust (silt + clay) and eventually forming loess blankets as well as tuff blankets (ash fall deposits - Pettijohn et al., 1972, p. 274).

1.2 Ice (Glaciers)

Reineck and Singh (1973, p. 170) distinguish between basal deposits (unstratified, completely unsorted) laid down directly by ice at the bottom of the glacier and representing essentially the basal moraine, and ablation deposits (stratified, somewhat sorted) representing englacial and surface moraines laid down by rapid melting of the ice. The latter class includes fluvio-glacial and glacio-marine deposits.

1.3 Water

As in the case of wind transport, two main modes of transport occur in water, namely traction and suspension (cf. Krumbein and Sloss, 1963, p. 211). The former process (operative in the higher energy processes) is responsible for the transport and deposition of sand and gravel, while the latter is responsible for the transport and deposition of mud (silt + clay).

1.3.1 River flow

1.3.1.1 Channel flow

1.3.1.2 Overbank flow (Reineck and Singh, 1973, p. 250)

1.3.2 Swash - backwash

1.3.3 Longshore currents (see Allen, 1970, Fig. 5.7)

1.3.4 Rip currents (see Allen, 1970, Fig. 5.7)

1.3.5 Wind-wave drift

Allen (1970 p. 149) refers to wind-wave currents, but intended this term to cover longshore and rip currents as well as areally extensive wave-induced bottom currents. Swift (1969a, Fig. 4 - 16) differentiates between the "residual components" of "wave surge" (ie. nett mass transport by waves - see Fig. 4 - 19) and "surface wind drift currents" (p. DS - 4 - 15), both of which form part of the "wind-induced velocity field" (p. DS - 4 - 15) and which together also are ultimately responsible for longshore drift and rip currents. The term "wind-wave drift" is used here to cover the currents produced in the wind-induced velocity field seaward of the breaker zone, including storm generated wave drift (Pettijohn, et al., 1972, p. 354), but excluding longshore and rip currents. Wind-wave drift currents combined with tidal currents and oceanic circulatory currents give rise to the so-called "coastal currents" (Swift, 1969a, Fig. 4 - 19; Reineck and Singh, 1973, p. 286) which characterise the offshore region and trend roughly parallel to the coast.

1.3.6 Oscillatory wave currents (= orbital wave currents - Swift, 1969a, p. DS - 4 - 14)

1.3.7 Storm surge reflux (ebb currents) (Swift, 1969a, p. DS - 4 - 18)

1.3.8 Tidal currents

Swift (1969a, p. DS - 4 - 19) groups tidal currents into three categories: rotary currents of the open shelf, rectilinear reversing currents in coastal water bodies (with cyclic and residual components - Fig. 4 - 16) and hydraulic currents generated at restricted entrances such as tidal inlets.

1.3.9 Oceanic circulatory currents (Allen, 1970, p. 149, 166)

1.3.10 Contour currents (Reineck and Singh, 1973, p. 388, 389)

1.4 Turbity currents

1.5 Gravity

Gravity-induced mass movements are discussed by Blatt and others (1972, p. 159 - 164), who recognise and define the following main types:

1.5.1 Debris flows (embracing sandflows and mudflows).

1.5.2 Gravity sliding/slumping

1.5.3 Grain flows

2. Chemical processes

The main chemical process responsible for sedimentary rock formation is precipitation resulting from excessive evaporation or other influences.

3. Biological processes

The main biological process producing significant thicknesses of sedimentary rocks is the formation and accumulation of calcareous and siliceous exoskeletons produced by marine organisms.

2. Palaeoenvironments

Having listed the agents and processes responsible for the formation of sedimentary strata, we can now list and define the various geomorphic features which commonly act as accumulation sites for sediments. Where terms are listed without further comment, the definition given in the AGI Glossary of Geology (1972) is accepted or the name is self-explanatory.

1. Terrestrial (supratidal) environments
    1.1 Dunes
    1.2 Loess plains
    1.3 Alluvial fans
    1.4 Rivers
        1.4.1 Braided streams (deposition on channel (braid) bars)
        1.4.2 Meandering streams
            1.4.2.1 Channels (deposition on point bars)
            1.4.2.2 Floodplains

According to Reineck and Singh (1973, p. 230) in most fluvial regimes the floodplain can be further subdivided into bank (levee, etc.) and flood basin. In humid climates flood basins develop as backswamps (p. 251).

    1.5 Lakes
    1.6 Glaciers

2. Marginal (shore-related) environments
    2.1 The beach (incl. barrier island beaches)
        2 1.1 Backshore (above tidal range)
        2.1.2 Foreshore (inter-tidal)

Following Dunbar and Rodgers (1957, p. 68), Kukal (1971, p. 209), Dickinson and others (1972, p. 194) and the AGI Glossary of Geology (1972), the mean tidal low water level is here regarded as the outer limit of the beach proper. This differs from Reineck and Singh (1972, p. 285) who include the shoreface (see below) with the beach.

2.2 The sheltered shelf

The terms "sheltered shelf" (cf. Kukal, 1971, p. 225, 235) is used here to embrace a variety of near-shore (shore-related) environments characterised by being sheltered in various ways and to varying degrees from the full effect of normal high energy coastal marine processes and which therefore form sites of deposition for relatively fine-grained sediments which cannot be readily distinguished from each other. Thus Kukal (p. 237) does not attempt to distinguish between bays and lagoons, on the grounds that they are sedimentologically similar and difficult to separate on a geomorphological basis, while Reineck and Singh (1973, p. 354) state that coastal lagoons and tidal flats are in turn geomorphologically intimately associated and are therefore often difficult to differentiate (cf. p. 350).

The following are the more important sub-environments:

2.2.1 Marsh
2.2.2 Tidal flat
2.2.3 Lagoon
2.2.4 Bay
2.2.5 Estuary

3. Open sea environments

3.1 Epicontinental shelves (continental shelf proper + intracratonic basins).

The term "epicontinental sea" is used here to denote "shallow marine" in general whether deposition takes place on the continental shelf proper or in a shallow sea on the craton. This usage conforms to that of the AGI Glossary (1972), but differs from that of Heckel (1972, p. 227) who differentiates between "epicontinental" and "pericontinental" seas, confining the former to shallow seas other than those on the continental shelf (the "pericontinental" seas).

On the modern continental shelf, the following sub-environments can generally be recognised (Reineck and Singh, 1973, fig. 410; p. 286).

3.1.1 Shoreface ("Inshore Zone" of Allen, 1970, p. 168)

Generally characterised by submerged longshore (barrier) bars.

3.1.2 Transition zone

3.1.3 Offshore zone

3.2 Distributary (river) mouth bars

3.3 Organic reefs

3.4 Closed shallow basins (evaporite basins)

3.5 The continental slope

3.6 Submarine valleys (including submarine canyons, fan valleys, shelf channels, etc. - see Reineck and Singh, 1973, p. 377)

3.7 The continental rise

3.8 Submarine fans

3.9 Abyssal plains

3.10 Deep-sea basins/trenches

This term is used to cover those cases where a well-developed continental shelf is absent and the land-mass is bordered directly by a deep basin.

4. Compound environments

4.1 Deltas

Following Blatt and others (1970, p. 195) deltas are not included in the above threefold classification of environments since they not only embrace environments from all three major categories but also occur in both lakes and the open sea. However, there are two environments which, since they are dependent on the overall geomorphic form of the delta, are peculiar to the delta environment.

4.1.1 Delta-front platform (subaqueous delta platform - Selley, 1970, Fig. 5.1).

Reineck and Singh (1973, p. 269) list the following sub-environments: distributary channel, distributary mouth bar, distal bar and inter-distributary bay. Bar finger sands and delta-front sheet sands are the two most characteristic deposits.

4.1.2 Pro-delta slope

According to Selley (1970, Fig. 5.1; p. 77) the subaqueous delta platform is separated from the pro-delta (bottomset) environment by the delta slope. However, Curray (1969, p. JC-III-27) identifies the pro-delta muds with the foreset beds, while Kukal (1971, p. 186, 189), Reineck and Singh (1973, p. 273) and the AGI Glossary (1973) all regard the pro-delta environment as occurring directly beyond the delta-front environment.

The compound term "pro-delta slope" (cf. Kukal, 1971, p.189; Crosby, 1972, p.10) would seem to be the most unambiguous designation. According to Reineck and Singh (1973, p.273) "delta-front slope" is also sometimes used for this environment.

Lithologically and biologically pro-delta muds may be indistinguishable from offshore shelf muds (Reineck and Singh, 1973, p. 273; cf. Selley, 1970, p. 106, 107).

C. PROVENANCES

The only evidence normally available for the lithologic composition of the source areas is the mineralogy of the sediments derived from them; palaeocurrent data and the regional palaeogeography can give some idea of the approximate location of such areas.

CHAPTER X

GENERAL INTRODUCTION TO DESCRIPTIVE DATA

A. BASIC OBJECTIVES

As mentioned in the preface, the primary aim of this project was to provide a basic description of the Cape and Karoo strata as they occur in the eastern Cape Province and to decipher the broad outlines of the geological history which they represent. Attention has been focussed on the vertical succession of strata - the stratigraphic column seen as a whole - and emphasis was placed on tracing variations in a vertical sense, rather than on synchronous lateral facies variations within formations. Accordingly, stratigraphic and facies maps (isopach, isolith, etc.) have not been constructed, and lateral stratigraphic variation has been discussed only where marked lateral variation is present. Nevertheless, an attempt has been made to give a true picture of the general features of each formation within the study area. In any case, in view of the largely linear nature of the outcrop belts, the three-dimensional control needed for the compilation of stratigraphic maps is generally lacking and the amount of additional insights gained from the time-consuming process of constructing these maps would be disproportionately small.

B. THE STRATA: DISTRIBUTION AND NOMENCLATURE

The Cape and Karoo Sequences embrace two generally conformable successions which between them represent an almost unbroken record of deposition extending from Late Cambrian (?) to Early Jurassic. Outcrops of the Cape Supergroup are confined to the south-western and southern Cape Province and Natal, but the Karoo Sequence occurs in a basin which extends across a large part of South Africa and adjacent territories. Schenk (1888, p.227) introduced the name "Kapformation" ("Cape formation"), while Bain (1856, p.178) first used "Karoo" as a stratigraphic name in the form of a "Karoo Series". Rogers (1902) proposed a stratigraphic scheme which formally established the idea of Cape and Karoo "Systems", each divided into a number of "series". The present writer (1966) suggested that the "supergroup" designation would be more appropriate.

Although the names Cape Supergroup and Karoo Supergroup have passed into general use, the application of the term "supergroup" to the old

Karroo "System" does raise certain serious problems. Thus in areas remote from the main Karoo basin the continued use of the name Karoo Supergroup for strata of roughly equivalent age and stratigraphic position will generally not be valid since the succession at these localities will in most cases be composed of an appreciably different assemblage of lithological units (with different formation names). In addition, even within the main basin there are not all that many unifying lithological features which could justify the use of the term "supergroup". The absence of quartzose sandstone and limestone, and the abundance of sand-sized "rock fragments" within the Karoo sandstones, would seem to be the main, if not only, unifying features.

Sloss (1963) developed the idea of "sequences" embracing major stratigraphic units of greater than group or supergroup rank, traceable over large areas of a continent and bounded by unconformities of interregional scope. A "Karoo Sequence" would avoid most of the problems associated with the use of "supergroup", since lithology does not, strictly speaking, enter into the picture. As the South African Stratigraphic Code (SACS, 1971, p.117) points out, "sequence" does not form part of a formal lithostratigraphic hierarchy of terms; it expresses a basically different concept, and its use therefore gives added scope and flexibility in an overall system of stratigraphic terminology.

The expression "Cape Supergroup" is more acceptable than "Karoo Supergroup", since in the former case there is a considerably greater degree of internal lithologic homogeneity. However, the Cape Supergroup also constitutes a distinct sequence, and it is therefore legitimate to refer to the "Cape and Karoo Sequences" as has been done in the title of this project. "Sequence" has been capitalised to indicate that it refers to a formally recognised, defined and named stratigraphic unit, thereby distinguishing it from the ordinary use of the term where it is employed for any specific interval of strata to which reference is being made. Thus the Karoo Sequence is equivalent to the old Karroo System, but the Karoo sequence would refer to the local succession of Karoo strata encountered in the Great Karoo geographic area (in contrast to, say, the Natal sequence or the Lebombo sequence).

The historical development of stratigraphic classification and terminology for the Cape and Karoo Sequences is depicted on Folder 2. Corstorphine (1904) presented a chart containing virtually all the schemes that had been proposed prior to 1903. The accompanying scheme (Folder 2) while showing only the more significant developments, does serve to relate the older classifications to the one used in this study, as well as showing more clearly than did Corstorphine's chart the way in which the various lithological entities were named and classified at different periods.

C. POST-DEPOSITIONAL TECTONISM

Subsequent to their deposition the Cape Supergroup and the lower part of the Karoo Sequence became involved in an episode of folding and faulting generally known as the Cape orogeny. As a result the strata lying south of 33°S (and just north of this line in places) have become involved in a series of roughly east-west trending synclines and anticlines, with the degree of deformation increasing southwards and decreasing fairly rapidly northwards. The most intense deformation involves the Table Mountain Group in the mountain ranges west of Uitenhage and Port Elizabeth where overfolding is common and at least one large-scale thrust-fault occurs. The age of this orogenic episode has been given as early to middle Triassic (De Villiers, 1944, p.200).

Along the south-east coast north of 33°20'S the Karoo strata have been affected by a number of generally east-west trending faults having large throws (up to 3 000 m) near the coast and dying out rapidly inland. A mid-Cretaceous age can be tentatively assigned to this faulting (Du Toit, 1954, p.571) which may in some way be linked with fracturing associated with the break-up of Gondwanaland.

D. POST-DEPOSITIONAL IGNEOUS ACTIVITY

The deposition of the Karoo strata terminated during the Jurassic with the pouring out of over 1 200 m of basic lavas. Only remnants of the original complex of lava sheets, which must have covered an extensive area, now remain, forming a capping to the older strata in the Drakensberg range. A number of volcanic plugs and diatremes are present in the area north of 31°30'S and appear to be associated with the effusion of these lavas. An associated intrusive phase is represented by numerous dykes and sills of dolerite which have extensively penetrated strata belonging to the Beaufort Group and the Molteno and Elliot Formations throughout the study area.

E. AREA STUDIED

The choice of study area was largely influenced by "accidents of history" and practical considerations, rather than straightforward scientific factors. This research project had its origin in a series of detailed stratigraphic investigations carried out in the eastern Cape Province for the South African Geological Survey while the writer was stationed at the Survey's regional office in Grahamstown. These stratigraphic studies were conducted in connection with an extensive search for petroleum which took place in the southern Karoo area between 1964 and 1970, the responsibility for which rested largely with the state-sponsored Southern Oil Exploration Corporation (SOEKOR). A number of deep boreholes were drilled in the area covered by this thesis, but in view of the negative results obtained from these and the unpromising nature of the strata themselves, this search has been abandoned.

The actual study area is rather ill-defined, and, since none of the formations was exhaustively studied or mapped, the idea of a study area is perhaps in this case a rather meaningless concept. However, the descriptions and interpretations which are given for the various formations probably hold good for an area lying between the 23°E and 29°E lines of longitude, and bounded on the north-west and north by a line which passes through Rietbron, Middelburg and Aliwal North and then follows the Orange River and the Cape Province - Lesotho boundary (see Folder 3).

F. FOLDERS

The data contained in the text has been used to construct a number of diagrams in an attempt to elucidate relationships and patterns which are not otherwise easily visualised. These include the following aspects:

1. Stratigraphic interrelationships (Folder 1).
2. Historical developments (Folder 2).
3. Areal distribution of palaeocurrent directions (Folder 3).
4. Palaeocurrent rose diagrams (Folders 4a, 4b).
5. Sandstone composition (on a triangular Q F R diagram)(Folder 6).
6. Vertical trends in lithology, texture and sandstone mineralogy (Folder 7).

It is assumed throughout that the reader is aware of the existence of these diagrams, and they are not therefore mentioned on every occasion where reference to them would be appropriate. In addition, Folder 3 also constitutes a locality map to which reference is constantly made throughout the text by means of locality symbols (indicated by a letter, or letters, plus a number, e.g. T8, Bf15).

CHAPTER XI

TABLE MOUNTAIN GROUP

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1 Lithostratigraphic relationships

The stratigraphic setting of this group, and the sequence of stratigraphic units within it, are shown on Folder 1.

A 1.2 Chronostratigraphic relationships

Within the Table Mountain Group only the Cedarberg Shale (in the western Cape Province) and the sandstone lying immediately below the overlying fossiliferous Bokkeveld Group are known to contain identifiable fossils (brachiopods in both cases). According to Cocks and others (1969, p. 599) an uppermost Ordovician (Ashgill) age can tentatively be assigned to the Cedarberg Shale fauna (although a lowermost Silurian age cannot be ruled out). Since the lower part of the overlying Bokkeveld Group would appear to be Early Devonian in age (Theron, 1972, p. 121) a Silurian age can be fairly safely inferred for the Tchando and Kouga Formations (i.e. Nardouw Subgroup of the western Cape Province). In addition, if the Cedarberg Shale lies close to the Ordovician - Silurian boundary, an Ordovician age can probably be assigned to the Peninsula Sandstone with reasonable confidence. Using a Lower Silurian age for the Cedarberg Shale and making certain assumptions as to rates of sedimentation, Rust (1967, p. 94) has in fact suggested that deposition of Table Mountain Group strata commenced as early as the Late Cambrian.

A 2. Basic concepts and distinguishing features

Table Mountain Group

Pale, medium-grained, "clean", ultra-quartzose sandstone plus very subordinate amounts of "shale" and feldspathic sandstone (generally "dirty").

Peninsula Sandstone

Pale, medium-grained, siliceous, ultra-quartzose sandstone plus very subordinate "shale". The general absence of true cross-bedding is a distinctive and characteristic feature.

Cedarberg Shale

Mudrock, fine-grained near base (with occasional small isolated pebbles) but grading upwards into coarser, silty material.

Tchando Sandstone

Grey (brownish-weathering), fine- to medium-grained, siliceous, slightly feldspathic sandstone plus subordinate "shale". Cross-bedding is fairly common, but beds are often massive in appearance.

Kouga Sandstone

Light grey (whitish-weathering), siliceous, medium- to coarse-grained ultra-quartzose sandstone plus very subordinate "shale". Cross-bedding is abundant and constitutes a characteristic feature.

Baviaanskloof Formation (excluding Kareedouw Sandstone Member)

Dark, very fine-grained, "dirty", feldspathic sandstone plus dark grey mudrock and streaky rhythmitite. Sandstones are generally massive or bioturbated.

Kareedouw Sandstone Member

Pale, fine- to medium-grained, siliceous, feldspathic sandstone plus very subordinate "shale".

A 3. Geographic distribution

Although the various formations that have been recognised in this study have thus far only been mapped west of 24° 30'E (by D.K. Toerien), there is no reason for believing that they are not present in the remaining areas covered by the Table Mountain Group in the study area. The distribution of the whole group is adequately depicted on the geological map of South Africa (1:1 000 000) published by the South African Geological Survey (1970).

A 4. History and nomenclature

Table Mountain Group

Wyley (1859) introduced the name "Table Mountain sandstone" while Rogers (1902) applied the term "series" to the Table Mountain strata.

Peninsula Sandstone

The separate existence of this formation as a mappable unit in the eastern Cape Province was first established by De Villiers (1941) in the course of mapping the Baviaanskloof area. This unit was termed the "Lower Sandstone" by De Villiers. In the western Cape Province Rust (1967, p. 16) applied the name "Peninsula Formation" to what was previously known as the "Lower Sandstone" (cf. Du Toit 1954, p. 240) or "Main Sandstone" (Haughton, 1969 p.331). The choice of name was based on the abundance of typical exposures in the Cape Peninsula area. The legitimacy of the name "Peninsula" has been questioned by some on the grounds that the word by itself does not actually represent a geographical place name. However, in South Africa "The Peninsula" (capitalised) ranks as a conventional place name, and the objection is therefore not all that serious.

The use of the name "Peninsula" in the eastern Cape Province is only legitimate if we can be reasonably certain that Rust's Peninsula Formation can be correlated with the formation under consideration. The upper boundary of this formation (at the base of the overlying Cedarberg Formation, which can with almost complete certainty be followed through from the western Cape to the eastern Cape) is clearly the same as that defined by Rust (1967) in the western Cape, if one allows for the wedge-out of the glacial Pakhuis Formation. The lower boundary is, however, more problematical, since the equivalents of Rust's Piekenier Formation (basal conglomerate and sandstone) and Graafwater Formation (lower shales and sandstone) have not been recognised in the eastern Cape. There are two possibilities: these formations were either not deposited here at all, or else they have undergone lateral facies changes, giving rise to deposits which are no longer distinguishable from the bulk of the Peninsula Sandstone. The lack of detailed work in the intervening areas at this stage makes it uncertain which of these possibilities is the correct one. However, in view of the rather restricted development of significant thicknesses of Piekenier and Graafwater sediments even in the western Cape Province, it is quite possible that they are not present even in modified form in this area (or, if present, that their thicknesses are not significant). In any case, since we are correlating on a lithostratigraphic basis, neither possibility is incompatible with the application of the name "Peninsula Formation" to the whole succession between the "Pre-Cape" strata and the Cedarberg Shale.

Cedarberg Shale

This unit was first described and mapped in the eastern Cape Province by De Villiers (1941) working in the Baviaanskloof area. He correlated it with the "Upper Shales" (Du Toit, 1954, p. 240) of the western Cape Province, a correlation which has never been seriously disputed, subsequent work in intervening areas supporting his conclusion. Rust (1967, p. 16), working in the western Cape, assigned the name Cedarberg Formation to the Upper Shales, the name being derived from the Cedarberg mountain range. There appear to be no sound reasons for not using the name "Cedarberg" in the eastern Cape as well.

Tchando Sandstone

This formation was first recognised and mapped by D.K. Toerien (personal communication) in 1971 in the area between 23°30'E and 24°30'E.

From the description given by Rust (1967, p. 49 - 51) of his Goudini Member, which immediately overlies the Cedarberg Formation in the western Cape Province and forms the lowermost member of his Nardouw

Formation, it would seem that certain lithological similarities exist between it and the Tchando Sandstone. However, the exact stratigraphic relationships between these two units is at present unkown; in addition the thickness of the Tchando Sandstone (as defined here) is between five and ten times that of the Goudini Member. In view of these facts it seemed advisable to adopt a new name for this formation; the name chosen by Toerien was derived from the Tchandokloof ravine in which the type section is situated. The type section itself is located just south of the southern boundary of the farm Tchando.

Kouga Sandstone

This unit was first recognised as a separate mappable unit (and mapped as such) by D.K. Toerien (personal communication) during 1971 in the area between 23°30'E and 24°30'E.

Lithologically there would appear to be a fairly close resemblance between the formation under discussion and Rust's Skurweberg Member (see Rust, 1967, p. 51ff.). However, the exact relationships between these two units have not been worked out, and it seemed advisable at present to assign a different name to the formation under discussion. The name "Kouga" is derived from the location of the type section flanking the Kouga River at the site of the Kouga (Paul Sauer)Dam (Toerien, pers. comm.).

Baviaanskloof Formation

This unit was first regarded as a separate formation and mapped by D.K. Toerien in the Baviaanskloof area (between 23°30'E and 24°30'E) in 1971 (personal communication).

Although the middle "arkose" member may be in part equivalent to Rust's Rietvlei Member (since both are feldspathic - see Rust, 1967, p. 52), the formation as a whole has no equivalent in the western Cape Province. This formation is probably also partly equivalent to the "passage beds" (about 120 m thick) which Rossouw and others (1964, p. 23) describe from the Prince Albert area. The name "Baviaanskloof" was assigned to this unit in view of the fact that typical exposures are present at many localities in the Baviaanskloof valley. The actual stratotype is located near the Paul Sauer Dam on the Kouga River, but the name "Kouga" had already been assigned to the underlying formation, and no other suitable name exists at the type locality. The name was proposed by Toerien (personal communication).

Kareedouw Sandstone Member

This unit was first recognised as a potentially mappable member of the Baviaanskloof Formation by D.K. Toerien (personal communication), although it has never actually been mapped as such. Strictly speaking, in view of the marked lithological differences between the unit under discussion and the rest of the Baviaanskloof Formation (of which it comprises about one-third), the Kareedouw Sandstone should have been accorded formation status. This would have involved the creation of two additional formations (to take care of the argillaceous units underlying and overlying this unit). However, the introduction of three new formation names for a rather insignificant portion of the Table Mountain succession seemed undesirable at this stage; a single formation with one clearly defined and named member seemed a more practical and elegant proposal, and one best suited to normal mapping operations.

As was pointed out above, this member is possibly partly equivalent to Rust's Rietvlei Member, since both are feldspathic. However, the exact relationship between these units will only be elucidated once the intervening areas have been studied in some detail. The name "Kareedouw" was obtained from the town Kareedouw in the Langkloof, and was assigned to this member on the strength of a number of outcrops which occur in road cuttings both east and west of the town (Toerien, pers. comm.).

A 5. Boundaries

Peninsula Sandstone: lower boundary

Underlying lithology.- Grey, siliceous, slightly feldspathic sandstone plus subordinate phyllitic shale.

Nature of boundary.- Uncertain due to intensity of folding and structural complications, as well as basic similarity of overall lithology on both sides of boundary. May be conformable or unconformable. However, the fact that very similar strata underlie the Peninsula Sandstone at all points where the base is exposed indicates a generally conformable contact with a transitional zone approximately 50 m thick. There is no unequivocal evidence anywhere of an angular unconformity; if an unconformity is present it is probably in the nature of a disconformity or paraconformity.

Definition of boundary.- Considerable uncertainty has prevailed in the past concerning the line of demarcation between "Pre-Cape" and Table Mountain strata in the eastern Cape Province. Thus J.A.H. Marais, when measuring a stratigraphic section across the Table Mountain strata north of Uitenhage, was left with 1 200 m of "indeterminate" material (Marais, unpublished section,1963).Subsequently, in the course of obtaining a thickness measurement in the Groot River area, the present writer included in the Table Mountain Group nearly 600 m of strata which probably belong to the Pre-Cape formations.

In the light of recent mapping carried out by D.K. Toerien and petrographic studies done by the writer, it would seem that the following combination of criteria best serve to differentiate Table Mountain and Pre-Cape strata:

1. Sandstone : shale ratio is significantly higher in the Peninsula Sandstone than in the underlying Pre-Cape rocks.

2. Sandstones become appreciably thicker-bedded in the Peninsula Sandstone.

3. Overturned cross-bedding is common in the Pre-Cape strata, and rare or absent in the Peninsula sandstones. In fact, cross-bedding of any sort is rare in the Peninsula Sandstone.

4. Peninsula Formation sandstones do not appear to contain any feldspar whatsoever; the underlying Pre-Cape sandstones are consistently slightly feldspathic, containing 3% to 11% (average 7%) feldspar in the samples examined.

5. The shales in the Pre-Cape give the appearance of being more phyllitic than those in the Peninsula Sandstone.

6. A reddish colour is common in the Peninsula sandstones near water, and rare or absent in the Pre-Cape rocks.

Peninsula - Cedarberg boundary

Nature of boundary.- Generally sharp and conformable. In places a quartzitic sandstone unit (up to about 5 m thick) occurs intercalated near the base of the Cedarberg Shale.

Definition of boundary.- Level at which sandstone passes upwards into mudrock.

Cedarberg - Tchando boundary

Nature of boundary.- Conformable: intertongued/gradational. Transition zone 3 - 15 m thick. The Cedarberg Shale seems to pass upwards into the Tchando Sandstone through a combination of intertonguing and progressive increase in grain size.

Definition of boundary.- Point at which sandstone becomes more abundant than mudrock.

Tchando - Kouga boundary

Nature of boundary.- Conformable: intertongued/gradational. Transition zone less than 50 m. In places the boundary is fairly sharp.

Definition of boundary.- Point at which paler, white-weathering sandstones (typical of the Kouga Formation) become more abundant than darker, reddish-weathering sandstones (typical of the Tchando Formation). Kouga Formation sandstones are also more prominently cross-bedded and are generally thicker-bedded than Tchando sandstones.

Kouga-Baviaanskloof boundary

Nature of boundary.- (a) Paul Sauer Dam (T 18). Conformable: intertongued/gradational; transition zone: ± 5 m. (b) Hottentotspoort (T 16). Boundary is sharp, regionally flat and locally uneven. The underlying quartzitic sandstone is bioturbated and reddish over a thickness of 15 - 30 cm.

Definition of boundary.- Point at which dark sandstone and "shale" become more abundant than pale sandstone.

Kareedouw Sandstone Member

Lower boundary

Nature of boundary.- Conformable: sharp (?).

Definition of boundary.- Contact between pale sandstone and darker underlying material.

Upper boundary

Nature of boundary.- Conformable: gradational. Thickness of transition zone: ± 1 m (?).

Definition of boundary.- Horizon above which light-coloured siliceous sandstone is no longer present.

A 6. Overall lithology

Peninsula Sandstone

Sandstone (occasionally conglomeratic):	> 95%
Mudrock/streaky rhythmitite:	< 95%

Mudrock percentages may be higher near the coast, but the highly weathered nature of the outcrops have made it difficult to establish the exact nature of the softer-weathering zones between more resistant quartzite zones.

Cedarberg Shale

Sandstone:	< 10%
Mudrock/rhythmitite:	> 90%

This unit commences at its base with relatively fine-grained mudrock containing several thin gritty layers (less than 1 cm thick) and isolated small pebbles (less than 1 cm in diameter). The grain size increases progressively upwards, through argillaceous streaky rhythmitites (micaceous) to arenaceous streaky rhythmitites with interbedded, somewhat massive, fine-grained argillaceous sandstone.

Tchando Sandstone

Baviaanskloof

Sandstone:	90 - 95%
Mudrock/rhythmitite:	5 - 10%

Tsitsikama coast

Sandstone: 60% (estimated)

Mudrock/rhythmitite: 40% (estimated)

Kouga Sandstone

North of Langkloof

Sandstone: > 98%

Mudrock/rhythmitite: < 2%

Tsitsikama coast

Sandstone: 80 - 90% (estimated)

Mudrock/rhythmitite: 10 - 20% (estimated)

Baviaanskloof Formation.

Paul Sauer Dam (T 18)

Upper (transitional) member:

Dirty, fine-grained feldspathic sandstone: ± 75%

Mudrock/rhythmitite: ± 25%

Kareedouw Sandstone Member:

Sandstone: 94%

Rhythmitite: 6%

Lower (basal) member:

Dirty, fine-grained feldspathic sandstone: ± 75%

Mudrock/rhythmitite: ± 25%

Hottentotspoort (T 16)

Although not measured accurately, the sandstone:"shale" ratio appears to be lower here. Both upper and lower members may contain as much as 50% mudrock/rhythmitite.

A 7. Dimensions and shape

A 7.1 Thickness

Peninsula Sandstone

Tsitsikama coast (T 3): 1480 m (± 50 m)

Sipree River (T 4): 2700 m (± 150 m) (max. 2850 m)

Cedarberg Shale

Baviaanskloof area (approx. average): 45 m (± 7 m)

Tsitsikama coast (approx. average): 40 m (± 10 m)

Tchando Sandstone

Baviaanskloof area (average): 230 m (± 30 m)

Tsiksikama coast (average): 280 m (± 30 m)

Kouga Sandstone

Paul Sauer Dam (T 18): 380 m (± 30 m)
Tsitsikama coast: 300 m (± 30 m)

Baviaanskloof Formation

Thickness data are summarised in Table XI-1.

Table XI-1. Baviaanskloof Formation thickness data (m)

	Locality				
Member	T6	T16	T21	T18	Coast
Upper (transitional) member	6	38 (± 5)	38	55 (± 5)	-
Middle (Kareedouw) member	15	35 (± 5)	62	53 (± 3)	-
Lower (basal) member	30	50 (± 5)	90	85 (± 5)	-
	51	123 (± 10)	190	193 (± 10)	200 (± 20)

A 7.2 Rate of thickness change (m/km)

Peninsula Sandstone

Tsitsikama coast (T 3) to Sipree River section (T 4): 40m/km.

The above figure is based on a reduction of 1 200 m in the total thickness over a distance of 30 km; the original, pre-folding rate of change must have been considerably less than the above figure, since the initial distance separating the strata at the two points where the thickness measurements were obtained has been considerably reduced (perhaps as much as 50%) by the folding of the intervening area.

By way of comparison the isopach map presented by Rust (1967, Fig. 112) made it possible to calculate the following rates for the western Cape area:

1. North flank of trough, average rate: 900 m/37 km = 24 m/km
2. South flank of trough, average rate: 900 m/55 km = 16 m/km
3. South flank of trough, maximum rate: 900 m/40 km = 23 m/km

If a correction factor to eliminate the effect of folding were to be applied to the figure of 40 m/km obtained in the study area, a value not very different from those obtained in the western Cape Province could conceivably be arrived at. This indicates that the large difference in thickness obtained at the Sipree River section on the one hand and the

Tsitsikama coast on the other are not necessarily due to measuring errors.

Cedarberg Shale

Maximum thickness difference between Baviaanskloof and the coastal areas is probably 25m, corresponding to a rate of 0,2 m/km in a north-south direction. Rust (1967, Fig. 115) gives general thickness values varying from 60 m to 120 m for the western Cape Province (450 km west of the Baviaanskloof/Tsitsikama area). This corresponds to a thickness change rate of less than 0,2 m/km in an east-west direction. It is clear that the Cedarberg Formation is a remarkably tabular unit.

Tchando Sandstone

Thickness measurements are not precise enough for a reliable calculation of thickness change rate: a figure of 1 - 2 m/km is probably reasonably close to the true figure.

Kouga Sandstone

A north-south thickness change rate of about 2 m/km was calculated.

Baviaanskloof Formation

The thickness of this formation seems to increase rapidly eastwards and southwards from 50 m near Willowmore (T6) to nearly 200 m at Groot River Poort(T21) and the coastal area (± 1,5 m/km). In addition, a significant (approximately 50%) increase in thickness also appears to have taken place between Hottentotspoort (T16) and the Paul Sauer Dam (T18). This change is reflected in the thickness of each of the members, as well as in the total thickness, and corresponds to a thickness change rate of 3 m/km. Across the rest of the area this formation appears to maintain a fairly constant thickness, with a thickness change rate considerably less than 1 m/km. The unit can thus be regarded as tabular.

A 7.3 Lateral extent

Peninsula Formation

Maximum known lateral extent (east-west) is about 600 km.

Cedarberg Shale

Maximum known lateral extent (east-west) is about 600 km.

Tchando Sandstone

This formation has at present only been mapped between 23°30'E and 24°30'E (by D.K. Toerien) and its full lateral extent is therefore unknown (minimum : 100 km).

Kouga Sandstone

As in the case of the Tchando Sandstone, maximum lateral extent has not yet been established (mimimum : 100 km).

Baviaanskloof Formation

This formation (with its three members) probably extends along the entire Bokkeveld - Table Mountain boundary in the study area (200 km +).

A 8. Stratotypes

Peninsula Sandstone

Type locality.- Rust (1967, p.16, 36) states that the type area is between Piekenierskloof Pass, Citrusdal, and Dasklip Pass, Porterville in the western Cape Province, but no actual type section is suggested. In view of the great distance separating the two areas, the establishment of reference stratotypes for the eastern Cape Province is clearly desirable.

Reference stratotype 1.- Sipree River (T 4).

Nature of stratotype: A series of natural exposures flanking a stream, moderately complete, through the full thickness of the formation. Angle of dip is close to 90° throughout the section.

Accessibility: Poor. Access is via Forestry Department tracks, and this section is hence rather inaccessible.

Location: See Fig. XI-1a.

Reference stratotype 2.- Goede Hoop (T 19).

Nature of stratotype: Representatives exposures through the lower half of the formation in the form of vertical cliffs and shallow exposures adjacent to the Groot River. Strata are overfolded (dip 60°).

Accessibility: Fair/Poor. Access is via farm roads which are not usable when the Groot River is flowing strongly, while part of the section cannot be reached by motor car.

Location: See Fig. XI-1b.

Reference stratotype 3.- Zuur Anys Outspan (T 11).

Nature of stratotype: Representative exposures in road-cuttings through central part of formation. Strata are approximately vertical.

Accessibility: Good. Exposures adjoin road.

Location: See Fig. XI-1c.

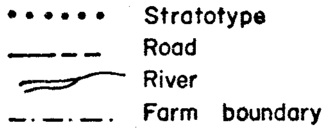
Cedarberg Shale

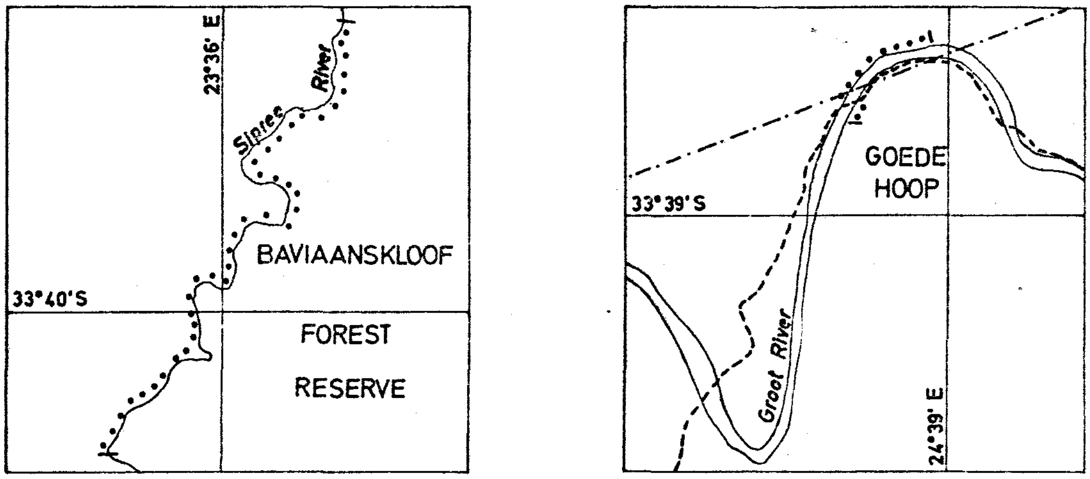
Unit-stratotype.- Rust (1967, p.47 and Fig. 63) has designated a type section near Porterville in the Western Cape Province. The exact geographic location remains to be precisely described.

FIG XI - I

STRATOTYPES : TABLE MOUNTAIN GROUP

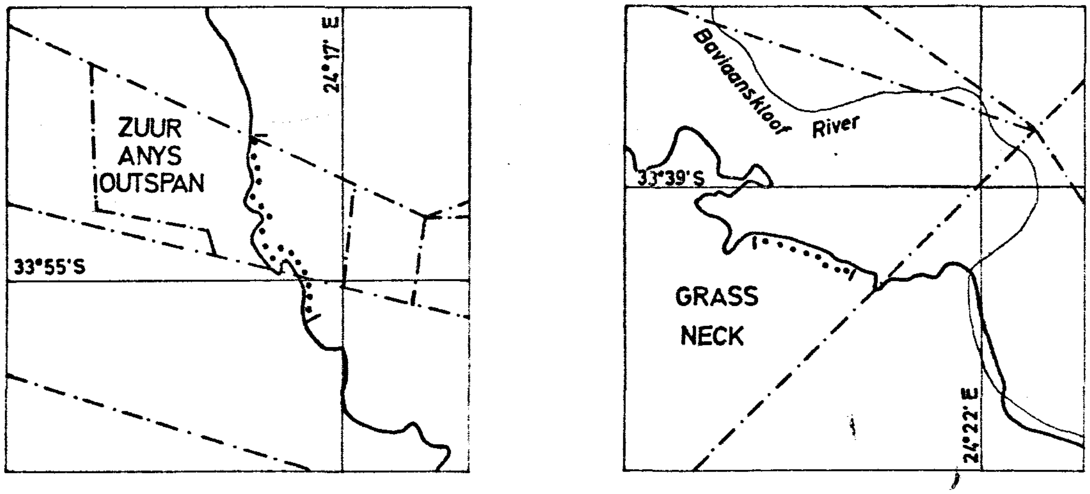
SCALE OF MAPS : 1 : 50000





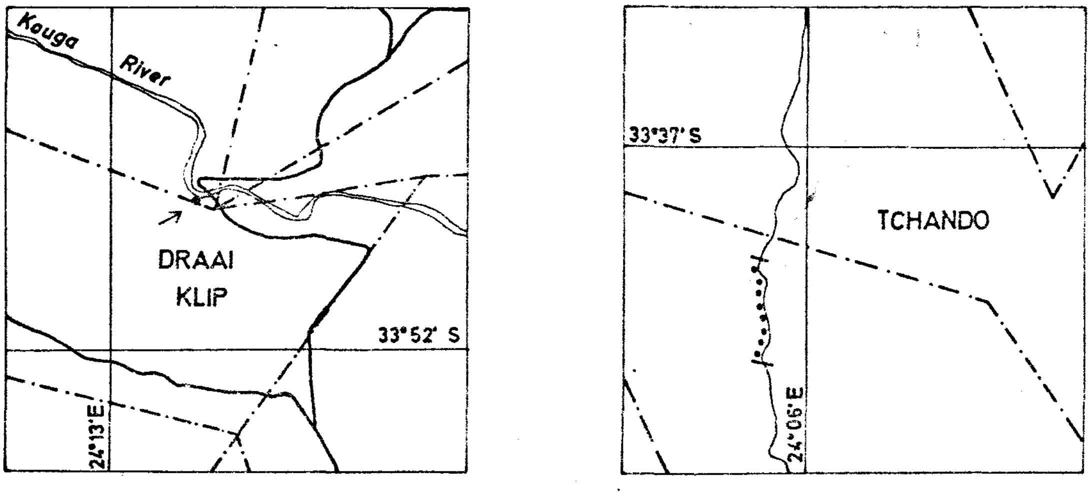
a. Peninsula Formation.
Reference stratotype 1
Map ref. : 3323 DA

b. Peninsula Formation.
Reference stratotype 2
Map ref. : 3324 DA



c. Peninsula Formation
Reference stratotype 3
Map ref. : 3324 CD

d. Cedarberg Formation.
Reference stratotype 1
Map ref. : 3324 CB



e. Cedarberg Formation
Reference stratotype 2
Map ref. : 3324 CC

f. Tchando Formation.
Unit-stratotype
Map ref. : 3324 CA

Reference stratotype 1.- Droëepoort/Grass Neck (Baviaanskloof) (T 14).

Nature of stratotype: Good exposures of the basal contact and the lower half of the formation in road-cuttings. Upper part of the formation is largely covered. Strata are almost flat-lying.

Accessibility: Good. However, access route is slow due to tortuous mountain passes that must be negotiated.

Location: See Fig. XI-1d.

Reference stratotype 2.- Kouga River bridge, north of Kareedouw (T 10).

Nature of stratotype: Incomplete but reasonably adequate exposures of the upper half and the top contact of the Cedarberg Formation occur near the southern end of the bridge across the Kouga River on the above farm. The strata dip at about 30°.

Accessibility: Good.

Location: See Fig. XI-1e.

Tchando Sandstone

Unit-stratotype.- Tchandokloof (T 9).

Nature of stratotype: Steep-sided ravine about 300 m deep. Virtually continuous exposures of near-vertical strata on flanks of ravine (not easily accessible) showing typical field appearance. Accessible exposures along edges of ravine floor are limited due to talus and bush cover, but a number of representative outcrops do occur. Actual base of formation is covered, while upper boundary is not sharply defined.

Accessibility: Poor (cannot be reached by motor car).

Location: See Fig. XI-1f.

Reference stratotype 1.- Langkop (Baviaanskloof) (T 15).

Nature of stratotype: Generally fresh exposures occur in a continuous road-cutting through a major portion of the formation, although the actual top and base are covered. Intense tectonic disturbance has obscured internal primary structures and rendered this locality unsuitable as a unit-stratotype. Strata are overfolded (dip angle: 50° - 60°).

Accessibility: Good, but Baviaanskloof road is slow and time-consuming.

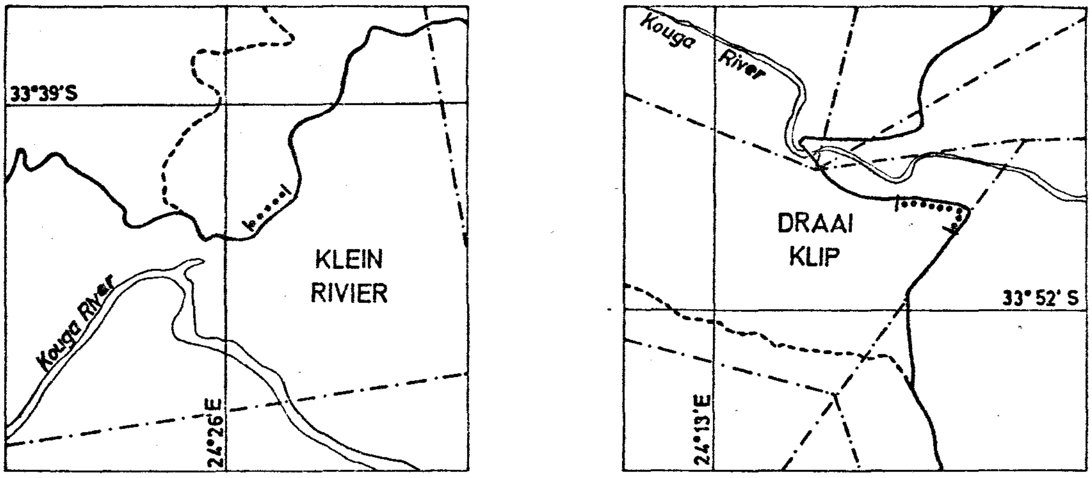
Location: See Fig. XI-2a.

FIG XI-2

STRATOTYPES: TABLE MOUNTAIN GROUP

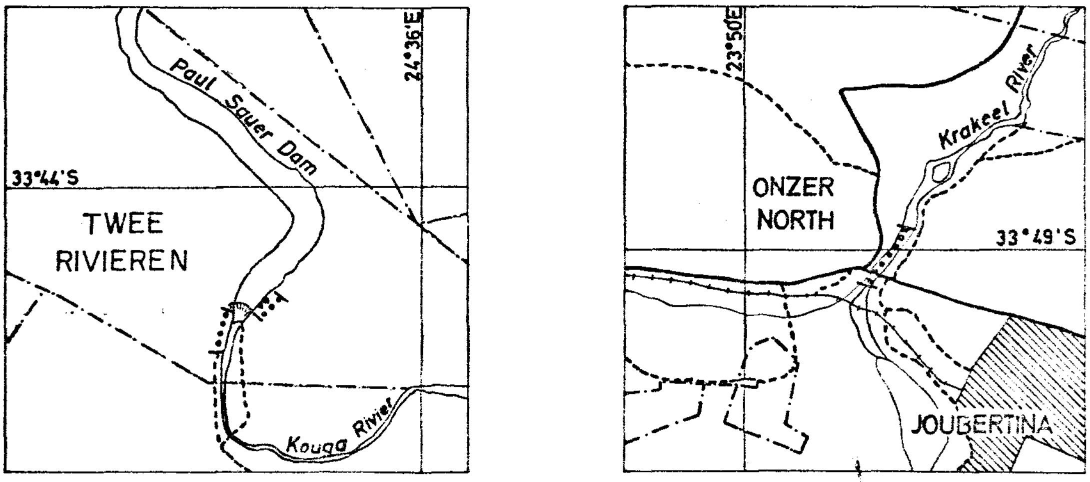
SCALE OF MAPS: 1:50000

••••••	Stratotype
— —	Road
═	River
—·—·—	Farm boundary



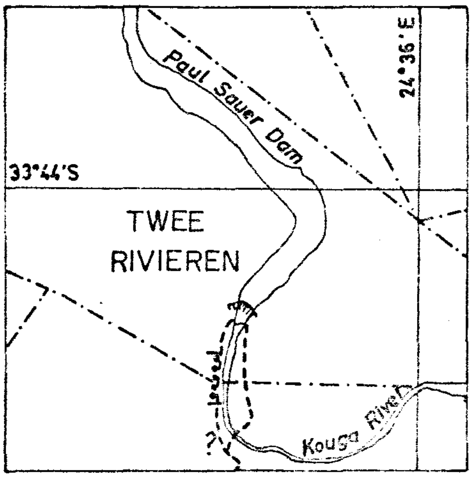
a. Tchando Formation.
Reference stratotype 1
Map ref.: 3324 CB

b. Tchando Formation.
Reference stratotype 2
Map ref.: 3324 CC



c. Kouga Formation.
Unit-stratotype
Map ref.: 3324 DA

d. Kouga Formation.
Reference stratotype
Map ref.: 3323 DD



e. Baviaanskloof Formation.
Unit stratotype
Map ref.: 3324 DA

Reference stratotype 2.- Draai Klip (north of Kareedouw) (T 10).

Nature of stratotype: Excellent continuous exposures through about 100 m of this formation occur in shallow road-cuttings. Primary structures and nature of bedding are particularly well displayed. Strata dip normally at about 30°.

Accessibility: Good.

Location: See Fig. XI-2b.

Kouga Sandstone

Unit-stratotype.- Paul Sauer Dam (T 18).

Nature of stratotype: Exposures are in the form of vertical artificial sections showing the complete succession (except possibly for a small portion near the base) in unweathered form. The section is not unduly affected by tectonism (general dip is 50° south).

Accessibility: Good.

Location: See Fig. XI-2c.

The stratotype consists of two parts:

(a) The lower half of the formation is exposed along the disused roadway leading from the public parking area at the eastern end of the dam wall down to the "boathouse" at the water's edge north of the parking area.

(b) The upper half of the formation is exposed adjacent to the road leading to the canal inlet at the western end of the dam wall, and extends from the wall southwards to the point where the dark argillaceous material of the Baviaanskloof Formation commences.

Reference stratotype.- Joubertina (T 8).

Nature of stratotype: Fresh natural exposures in the bed and banks of the Krakeel River. Strata are steeply dipping.

Accessibility: Excellent.

Location : See Fig. XI-2d.

Baviaanskloof Formation

Unit-stratotype.- Paul Sauer Dam (T 18).

Nature of stratotype: Vertical artificial exposures showing almost the complete succession in unweathered form. Tectonic disturbance is only moderate (general dip 50°).

Accessibility: Good.

Location: See Fig. XI-2e.

The section in question occurs alongside the roadway on the west bank of the Kouga River below the Paul Sauer Dam. The section commences at the point where the thick succession of white quartzitic sandstones belonging to the Kouga Formation gives way to dark sandstones and mudrock, and ends where the thick, continuous mudrock succession belonging to the Gydo Formation (Bokkeveld Group) commences.

B. PALAEONTOLOGY

No fossils have been recorded from the main mass of Table Mountain Group strata in the study area. Numerous specimens of a small brachiopod species were seen in the uppermost prominent dirty sandstone lithosome of the Baviaanskloof Formation (i.e. just underneath the top boundary of the Table Mountain Group). Theron (1972, p. 30) has also noted the occurrence of these fossils along this horizon at a number of localities.

C. MACRO-SEDIMENTOGRAPHY

C 1-3. Lithosome data

None of the formations belonging to the Table Mountain Group are characterised by the presence of distinct alternating lithosomes; lithologically all are relatively homogeneous units. Although thin mudrock/rhythmitite lithosomes occur sporadically throughout the Peninsula, Tchando and Kouga Formations, they are generally poorly exposed and invariably show evidence of intense tectonic disturbance, with the result that the relationships between such units and the adjacent sandstone units are usually obscure. It was therefore difficult to establish whether or not these argillaceous layers form part of coarsening-upward or fining-upward cycles. Thickness varies from a few cm to a few metres, 5 m rarely being exceeded.

The basal member of the Baviaanskloof Formation at Hottentotspoort (T 16) displays about seven crudely-developed coarsening-upward cycles; average thickness is very roughly 7 m. This cyclic development is not particularly evident at the Paul Sauer Dam (T 18).

C 4. Colours

Sandstones belonging to this group are generally light grey (N 7), but range from medium dark grey (N 4) or medium grey (N 5) (Baviaanskloof Formation) through medium light grey (N 6) (Kareedouw Sandstone Member) to very light grey (N 8) (some samples from the Peninsula Formation). Mudrocks are generally dark grey (N 3) when fresh.

C 5. Sedimentary structures

Peninsula Sandstone

Beds generally appear to be fairly persistent laterally with sub-parallel margins. However, the fractured and jointed nature of strata and the general lack of marked discontinuity between adjacent sedimentation units made it difficult to estimate the thickness and shape of these units. Major visible breaks (defining the visible bedding in outcrops) are generally spaced between 0,3 m and 2 m apart; the average (estimated visually) is probably about 0,7 m.

Initially the available natural exposures of Peninsula strata failed to reveal the presence of clearly-defined internal structures apart from occasional sets of cross-bedding and it appeared that this formation was characterised by massive bedding. However, a series of recent road-cuttings through partially-weathered strata north of Kareedouw altered this impression considerably and most beds were seen to display internal laminations. Four main types of syn-depositional structures could be identified: flat-bedding (or sub-horizontal bedding), inclined bedding, small-scale low-angle "cross-bedding" (10 - 20 cm thick) in cosets up to one metre thick, and occasional cross-bedding. Because of the contorted and fractured nature of the strata, it proved difficult to obtain meaningful directional information from the cross-bedding; visual inspection indicated a general southerly transport direction.

Cedarberg Shale

Overall bedding characteristics are generally not well displayed in outcrops.

The more silty and sandy upper portions of this formation appear to be characterised by wavy bedding, flaser-bedding and related structures.

Tchando Sandstone

Beds are generally discontinuous in the northern part of area. In the coastal area at least part of the Tchando Formation has an evenly-bedded appearance, due to the finer-grained, non-cross-bedded character of the sandstone and the increase in rhythmitite interbeds.

Although superficially massive-bedded in many exposures in the northern area, under favourable conditions this formation can be seen to be largely, if not entirely, trough-cross-bedded. Maximum thickness of sets is about one metre, average thicknesses of 20 cm and about 35 cm being obtained near the base in Commandokloof (T9) and in the upper half north of Kareedouw (T10) respectively. Thin wavy-bedded or micro-cross-laminated cosets up to 20 cm thick also occur sporadically.

In the coastal area only one isolated exposure of the topmost 100 m or so of this formation was available for study. Cross-bed sets are both rare and thin, and micro-cross-lamination is also uncommon. The sandstone is characterised by wavy bedding and smooth laminations representing "streaked-out" wavy bedding (and hence has a general flat-bedded appearance). In the interbedded rhythmitites the individual layers are generally continuous and only slightly lenticular.

Kouga Sandstone

This formation is nearly everywhere conspicuously cross-bedded, regardless of the nature of the exposures. In the type area cross-bedding (generally of the trough type) is by far the predominant structure present, and occurs throughout the formation. Maximum thickness of sets is nearly 2 m, an average of 45 cm (n = 47) being obtained for the whole formation. The sets are generally thickest in the lower part of the upper half of the formation where the grain size is also coarser than average.

In the coastal area examination of two sets of exposures (T 13 and T 17) showed that, especially in the lower half, cross-bedding is not as ubiquitously developed as elsewhere, being almost absent from some zones. Wavy bedding, cosets of low-angle cross-bedding, inclined bedding and bioturbation are fairly common in the lower half, giving rise to an evenly-bedded appearance.

Baviaanskloof Formation

General.- The upper and lower members are fairly evenly-bedded, but the Kareedouw Sandstone Member shows lensing of sedimentation units. In the upper and lower members the overall bedding appearance is a function of subtle lithological changes (variation in grain size) and concomitant changes in small-scale structures (if present) rather than a reflection of superimposed sedimentation units. As such, it is difficult to describe objectively. However, in the upper member beds are typically 10 - 30 cm thick.

Basal member.- Internally, the sandstone in the type section (T 18) is generally massive (structureless), less commonly being bioturbated, horizontally-laminated or wavy-bedded , while it normally is bioturbated, massive, wavy-bedded, micro-cross-laminated and horizontally-laminated in the Hottentotspoort area (T 16). Bioturbation is common in the mudrock/rhythmitite layers. Wave-ripple-marked surfaces are fairly common in the type area (i.e. the Paul Sauer Dam area).

Kareedouw Sandstone Member.- Low-angle inclined bedding is more common than true cross-bedding. Cross-bed sets vary from 8 cm to one metre (average 40 cm for 8 sets) in thickness. Inclined-bedding sets are generally thicker.

Transitional member.- Sandstone displays wavy bedding, bioturbation and massive bedding. Mudrock/rhythmitite is generally characterised by wavy bedding and bioturbation.

Table XI-2. Statistical measures calculated from cross-bedding orientation data for the Table Mountain Group.

Unit/locality	n	$\bar{x}_v$	$\bar{a}$	s
Kareedouw (T 18)	11	192°	0,79	41°
Kouga (T 2)	56	147°	0,72	47°
Kouga (T 3)	14	152°	0,85	34°
Kouga (T 5)	18	170°		
Kouga (T 8)	72	170°	0,75	45°
Kouga (T 12)	10	191°	0,97	15°
Kouga (T 17)	40	182°	0,95	18°
Kouga (T 18)	52	200°	0,90	27°
Kouga (T 20)	31	191°	0,87	31°
Tchando (middle) (T 9)	11	199°	0,95	19°
Tchando (base) (T 9)	15	255°	0,69	50°
Tchando (combined) (T 9)	26	227°	0,71	48°
Tchando (T 10)	38	201°	0,88	30°
Peninsula (T 7)	5	161°		

n = number of measurements

$\bar{x}_v$ = vector mean

$\bar{a}$ = vector strength

s = standard deviation

Table XI-3. Orientation of cross-bedding dip directions in the Table Mountain Group: number of readings per 30° class interval .

	Class mid-points (°)											
Unit/locality	15	45	75	105	135	165	195	225	255	285	315	345
Kareedouw (T 18)					2	3	2	1½	2½			
Kouga (T 2)	1½	1½	2	4	18½	19½	5	1		1	½	1½
Kouga (T 3)	½	½			6	6	1					
Kouga (T 5)					3	10	5					
Kouga (T 8)		1	3½	7	5	29½	16	7	1	1½	½	
Kouga (T 12)						2½	7½					
Kouga (T 17)					2	15	21	2				
Kouga (T 18)					2	9½	19½	20	1			
Kouga (T 20)					3	8½	11½	5½	2½			
Tchando (m)(T 9)					1½	7	2	½				
Tchando (b)(T 9)					1	1	1	2	4½	3½	2	
Tchando (c)(T 9)					1	2½	8	4	5	3½	2	
Tchando (T 10)				1	½	6½	15	13½	1½			
Peninsula (T 7)					2	2	1					

b = base, m = middle, c = combined

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Study of texture in Table Mountain Group sandstones was rendered difficult as a result of dynamic metamorphism. Most of the Peninsula Sandstone samples showed extensive development of "mortar texture", which meant that only a rough idea of mean grain size could be formed, while standard deviation values obtained from these samples would be meaningless. At Meirings Poort the grains were found to be affected to a lesser degree with the result that the figures obtained for standard and mean deviations are probably not too wide of the mark.

Since it proved possible to sample the younger formations in less highly disturbed areas, mortar texture was only slightly developed and values were obtained for dispersion which, although still unreliable, do give some indication of the nature of the original size distribution. Only rarely could original grain outlines be observed, and hence all size measurements are based on the outlines of the secondarily enlarged grains, while roundness and shape studies were rendered impossible.

Table XI-4. Sandstone grain size data, Table Mountain Group.

Unit/locality	n	$\bar{x}(\phi)$		$s(\phi)$	$MD(\phi)$	$d(\phi)$	$\bar{x} - d$	M(%)
Baviaanskloof (T18) (excl. K'douw Mb.)	3	3,40		0,59	0,47	1,66	1,74	[1]21,5
Kareedouw (T3, 18)	5	2,09	(1,83/2,39)	0,42	0,33	1,00	1,09	6,5
Kouga (T18)	4	1,18	(0,32/2,30)	0,47	0,37	0,01	1,17	[2]5
Tchando (T15)	2	2,20		0,56	0,42	0,41	1,79	9,5
Peninsula (Mp)	5	1,39	(1,09/2,01)	0,52	0,40	0,05	1,34	7
Peninsula (T7)	11	1,56	(0,97/2,18)			0,30	1,26	3,5
Peninsula (T19)	5	1,42	(0,60/2,16)			0,25	1,17	4

[1] Range: 12 - 28%

[2] Range: 0 - 13%

n = number of samples (50 grains per sample), $\bar{x}$ = mean size (range in brackets), s = standard deviation, MD = mean deviation, d = maximum thin-section diameter, M = matrix content, Mb. = member, Mp = Meiringspoort (22½°E)

D 2. Composition

Results of modal analyses of Table Mountain Group sandstones are contained in Table XI -5.

Table XI-5. Mineral composition, Table Mountain Group sandstones.

Unit/locality	n	Q	F	R	Acc.	Cem.	M	Q	:	F	:	R
Baviaanskloof(T18) (excl. Kdw. Mb.)	3	50,5	[1]22	0,5	[2]3	[3]2,5	21,5	69	:	30	:	1
Kareedouw (T3, 18)	5	69	23,5	0,5	0,5	-	6,5	74	:	25,5	:	0,5
Kouga (T18)	3	91	[4]4	-	tr.	-	5	96	:	4	:	0
Tchando (T15)	2	87,5	3	-	-	-	9,5	96,5	:	3,5	:	0
Peninsula (Mp)	5	93	-	-	tr.	-	7	100	:	0	:	0
Peninsula (T7)	12	96,5	-	-	tr.	-	3,5	100	:	0	:	0
Peninsula(T19)	5	96	-	-	-	-	4	100	:	0	:	0

[1] Range: 12 - 37%

[2] Consists largely of mica flakes

[3] Largely reflects the 6,5% calcite encountered in one sample.

[4] Feldspar (12%) only occurred in one sample (near upper formation boundary).

n = number of samples (200 - 300 points per sample), Q = quartz (including secondary quartz), F = feldspar, R = rock fragments, Acc. = accessory minerals (incl. mica flakes), Cem. = cement and secondary minerals (excluding secondary quartz), M = matrix, Kdw.Mb. = Kareedouw Member, Mp = Meiringspoort ($22\frac{1}{2}^{o}$E).

E. SEDIMENTOGENESIS

E 1. Palaeocurrents

In view of the paucity of cross-bedding in the Peninsula Formation, palaeocurrent data are only available for the formations occurring above the Cedarberg Shale.

Measurements obtained from the base of the Tchando Sandstone point to a westward transport direction; however, the bulk of this formation appears to be characterised by southward directions. The Kouga Sandstone is everywhere characterised by unimodal south-directed palaeocurrent patterns with very high vector strengths. There is evidence that tectonic deformation may be partly responsible for the strong concentration of readings, since oversteepening of cross-beds is fairly common on the northern flanks of anticlines. Due to this factor, as well as the neglect of plunge in untilting the cross-beds, the mean directions obtained may possibly deviate by up to 30° from the true sample means. The few measurements obtained from the Kareedouw Sandstone Member (Baviaanskloof Formation) also point to a southerly transport trend.

E 2. Sedimentary processes and palaeoenvironments

The sedimentary history of the Table Mountain Group has been discussed in some detail by Rust (1967, 1973) and Visser (1974) while Hobday and Mathew (1974) have described the thick quartzose sandstone succession of Pondoland in the Transkei (which has in the past been correlated with the Table Mountain Group, although it may in fact be equally well correlated with the Witpoort Formation of the Witteberg Group - see Lock, 1973a). All these authors favour a marine environment of deposition, although they do so for various reasons. Since serious problems are associated with a marine interpretation when applied to some of the formations concerned, all the relevant arguments need to be carefully reassessed. There are, however, certain formations which are undoubtedly marine, and others that are probably marine, and these can first be dealt with.

a. Marine units

The argillaceous character and large areal extent (in relation to thickness) of the Cedarberg Shale points to deposition in a single extensive body of water under fairly quiet conditions (offshore zone of the shelf, grading upwards into the transition zone). The discovery of marine invertebrates (brachiopods) in this formation in the western Cape Province (Rust, 1967, p. 48) has confirmed the marine character of the environment.

The Cedarberg Shale appears to reflect a fairly sudden increase in water depth, presumably associated with a major regional transgression. The onset of glacial conditions in the western Cape Province slightly prior to the deposition of the Cedarberg (Rust, 1973, p. 256 - 258) - some evidence of which is preserved in the study area in the form of isolated tiny pebbles embedded in the fine-grained mudrock at the base of this unit in at least one locality - may have been largely responsible for a sudden cessation of sediment supply to the basin, thus upsetting the relationship between supply and subsidence and indirectly causing the transgression.

The argillaceous sandstones, mudrocks, and rhythmitites, which characterise the bulk of the Baviaanskloof Formation, signify a second general episode of quiet-water, low-energy conditions. The overall lithology indicates that accumulation probably took place in the transition zone of the shelf, but presence of sheltered shelf environments (e.g. tidal flats) cannot be excluded. The presence of oscillation ripple marks at a number of horizons also points to relatively shallow-water environments (above wave base), while the occurrence of brachiopods in the uppermost dark sandstone establishes the marine character of the environment.

The laterally uniform and areally extensive nature of the Kareedouw Sandstone Member can again only be explained in terms of a marine (shelf) environment, while the lithology and internal structures (chiefly inclined bedding in thick sets) are fully consistent with deposition in the shoreface (innermost shelf) and foreshore (lower beach) sub-environments. The overall thickness (up to 60 m) and non-linear outcrop pattern imply considerable shifts in the position of the shoreline during the deposition of this unit. The inclined bedding is analogous to the "beach accretion bedding" of Ball (1967) and the "welded beach face" lamination (with an offshore dip of 5 - 15°) depicted by Davis and others (1972, p. 420), while McKee (1957) and many other researchers have pointed out that beach stratification can be readily recognised by the low angles and the long even surfaces of the foreshore laminae. According to Selley (1970, p. 97) regular bedding dipping gently seawards is also the typical internal structure of barrier islands and offshore (longshore) bars, with rare trough and tabular cross-bedding generally dipping landwards.

b. Probable marine units

The lack of true cross-bedding in the Peninsula Formation in the study area rules out the river and dune environments, while the lithology (medium-grained sandstone) eliminates all other environments except the foreshore (beach) and shoreface. As pointed out above (in the Kareedouw Sandstone Member discussion) gently dipping bedding is characteristic of the beach and near-shore zones; since the Peninsula appears to be characterised by gently dipping sub-parallel lamination, the case for a foreshore-shoreface environment is considerably strengthened. However, beach deposits generally have a low preservation potential and virtually all beach deposits that have been recognised elsewhere in the past are relatively thin sheet or shoestring sandstones (the former recording a major transgression and the latter representing barrier island deposits). Assuming shelf currents and processes similar to those occurring at present, the deposition of about 2 000 m of beach and offshore bar sand over a shelf area which was originally (prior to folding) at least 100 km wide, must have involved 100 - 200 transgressions and regressions of the shoreline (assuming deposition of a 10 - 20 m thickness of sand with each transgression). However, the sediments display no convincing evidence of such a cyclic pattern of sedimentation, and the absence of the transition and offshore zone sediments which would normally be deposited in deeper water simultaneously with the beach deposits along the shoreline is difficult to explain. The only other alternative would seem to be to postulate a non-uniformitarian situation (i.e. one with no modern analogy) in which currents capable of moving medium sand and forming offshore bars or similar features extended 100 km or more beyond the shoreline.

c. Possible non-marine units

The Kouga Sandstone and the bulk of the Tchando Sandstone in the study area display palaeocurrent patterns which seem to be explicable only in terms of a fluviatile environment. Since similar situations are encountered in the case of the Peninsula Formation in the western Cape Province (Rust, 1967, 1973) and the Pondoland sandstones described by Hobday and Mathew (1974) we need to consider carefully the reasons advanced by these writers, as well as by Visser (1974), for rejecting non-marine environmental interpretations. These reasons include palaeontological evidence, the supermature, largely feldspar-free character of the sandstones, and the presence of sheet-sandstone units (in the Pondoland area).

(i) Palaeontological data.- According to Rust (1973, p. 256) fossil evidence indicates a marine environment for the Peninsula Formation. However, since the Peninsula Formation itself is unfossiliferous, it would appear that Rust is in fact assuming that the presence of marine trace fossils in the underlying Graafwater Formation and marine brachiopods in the overlying Cedarberg Shale imply a marine origin for the Peninsula itself. In this writer's opinion such an assumption is not valid. However, the various trace fossils described and illustrated by Hobday and Mathew (p. 224, 225), which occur on the upper surfaces of both sheet and lenticular sandstone units, seem to afford a much more convincing argument for marine influence in the Pondoland sandstones.

(ii) Petrographic data.- According to Visser (p. 235), the deposition of mature quartz arenites is only possible on beaches and in an aeolian environment. Many writers have, however, expressed the opinion that texture is not environmentally diagnostic (see Chapter VII for a review of the problem). Comparable sorting and matrix content values to those measured in the Tchando and Kouga Formations can be encountered in fluviatile sands, while no quantitative roundness data has yet been supplied for Table Mountain Group sandstones.

Turning to the problem of feldspar content, no empirical evidence bearing on the ability of marine processes to remove significant quantities of feldspar from a feldspathic sand has been presented by any of the above authors. A review of the relevant literature indicates that in both beach and river systems abrasion is ineffective as a means of eliminating feldspar. Thus Koldewijn (1955, p. 45) in a study of the provenance, transport and deposition of Rhine sediments, concluded that loss of feldspar through attrition has little effect on the composition of the sand. Referring to the South Canadian River (southern USA) Pollack (1961) states that mineralogical composition of the river channel sands remain essentially constant over 650 miles of river distance; the removal of feldspar by abrasion or weathering is a slow, if operative, process. Hsu (1960) investigated Recent beach sands of the Gulf of Mexico and concluded that although losses of feldspar by abrasion and solution during longshore transport and deposition cannot be evaluated quantitatively, they are probably minor. In an experimental study of abrasion effects on arkose mixtures, Morris and Fan (1962) found that while large grains of feldspar suffered a high rate of abrasion, once equality of grain size between quartz and feldspar is reached, size reduction by abrasion may be disregarded (p. 229). Although data collected by Martens (1931) indicated a definite decrease in the ratio of potash feldspar to quartz with increasing distance from the source of the sand over an interval of more than 500 miles (800 km) along the beach on the Atlantic coast of the southeastern states of the USA, his Fig. 1 and Table 1 show that the decrease is very erratic. Thus the quartz: feldspar ratios at points 80 miles and 422 miles from the source are actually identical.

It would seem that the formation of pure quartz sandstones is more readily explained in terms of extraordinary chemical weathering in the source area than abrasion in the beach zone (cf. Pettijohn, et al., 1972, p. 227). Moreover, relief rather than climate is generally the chief factor determining the feldspar content of a sand (Pettijohn, 1957a, p. 639). "Low relief leads to complete destruction of the feldspar and the formation of residues capable of yielding orthoquartzite sands."

(iii) Sheet sandstones.- The sheet sandstones described by Hobday and Mathew (p. 224) could not have been formed in a non-marine environment, and, together with the trace fossil evidence, offer fairly convincing proof of marine conditions for parts of the Pondoland succession at least.

In addition to the arguments advanced by the authors referred to above, the general absence of flat-bedding (and its accompanying parting lineation) militates against a fluviatile interpretation, since this structure is normally ubiquitous in river deposits.

Having considered the arguments favouring a marine interpretation, we must now consider one apparently insuperable difficulty faced by such an interpretation, namely, the lack of a suitable mechanism to account for the presence of unimodal palaeocurrents displaying high vector strengths and directed consistently southwards down the presumed palaeoslope and at right angles to the probable shoreline. This situation is true of the Peninsula Formation in the western Cape Province (Rust, 1973, p. 254; compare his Figs. 2 and 6), the Kouga and middle Tchando Formations in the study area (Folder 3) and the Pondoland sandstones (Hobday and Mathew, Fig 3; p. 226). Although Hobday and Mathew postulate a NW - SE trending shoreline (at right angles to the south-westerly current direction) it should be pointed out that the regional isopach lines and pinch-out trend (Visser, 1974 Figs. 3,4) are in fact more or less parallel to the palaeocurrent direction. In all three cases the cross-bedding appears to be conventional(i.e. not particularly low-angle), and the beach (foreshore) environment can hence be eliminated. Deposition must thus have taken place either landward or seaward of the beach. The presence of coarse sandstone, and occasional pebbles (in the western Cape and Pondoland) rules out an aeolian origin, which leaves the shoreface and braided river environments as the only possibilities.

It has previously been argued (Chapter IX) that unless there is convincing internal evidence for marine conditions, the existence of unimodal, low disperson, downslope palaeocurrents point unequivocally to a river environment, and there is no need to repeat the same arguments here. Rust (1973, p. 254 - 256) acknowledges the problems raised by the marine hypothesis, and indirectly concedes that he can see no way out of the impasse. Visser (1974, Fig. 2) postulates a wave-dominated open beach environment for the bulk of the Table Mountain Group in the western and southern Cape Province, and a shallow neritic (offshore bar) environment for the Kouga Formation and the Pondoland facies. He appeals to descriptions of modern sediments presented by Clifton and others (1971, p. 656) and Davis and others (1972, p. 420) in support of his hypothesis, but a careful study of the relevant data given by these authors failed to reveal any close resemblance to the Table Mountain sandstones under discussion. Both Visser (p. 235) and Hobday and Mathew (1974, p. 225) suggest that tidal currents were mainly (if not entirely) responsible for transporting the sand across the shelf. However, if this were the case the currents would have been directed more or less parallel to the shoreline, with at least some evidence of bipolarity (Allen, 1963b, p. 226).

It is concluded on the grounds of the available data that the Kouga Sandstone and the bulk of the Tchando Sandstone represent braided stream deposits, while the basal part of the Tchando Sandstone (displaying westward current directions) was deposited by longshore currents in the shoreface environment, thus forming a natural upward gradation from the transition zone deposits of the upper Cedarberg Shale. The occasional presence of fining-upward cycles (thick-bedded sandstone grading upwards into thin-bedded silty sandstone) reported by Visser (p. 231) lends some support to a fluviatile hypothesis, while the absence of thick overbank deposits favours a braided rather than meandering river system (Allen, 1970, p. 140 - 143).

Some general observations

Although the available evidence favours the creation of ultra-quartzose sandstones through the removal of feldspar by chemical weathering in a source area of low relief rather than mechanical weathering in the depositional area, the sudden increase in feldspar percentage at the top of the Kouga Formation - an increase which persists throughout the overlying Baviaanskloof Formation and the lower half of the Bokkeveld Group - is difficult to explain on any hypothesis. The fact that the Kareedouw Sandstone Member - the most convincing example of a beach sandstone in the whole succession - contains 24% feldspar means that a change to a lower-energy environment cannot be invoked to explain this change. It also seems unlikely that the whole character of the source area could change with the required rapidity. A relatively sudden change to an arid climate may be the most likely explanation. A rapid increase in the rate of uplift of a nearby source area could also have been involved.

The general interpretation given for the upper half of the Table Mountain Group is corroborated by the description presented by Pettijohn (1957b,p. 470 ff.) of a remarkably similar Precambrian succession in the Lake Superior region. The Lorrain Quartzite, 6500 ft (2000 m) thick, consists of medium- to coarse-grained, strongly cross-bedded, generally highly quartzose sandstone. The cross-bedding has a marked preferred orientation, and this orientation is uniform over a very large region and through a long period of time (p. 479). The Lorrain Quartzite overlies a thinly varved argillite (the Gowganda Formation). "The transition beds between the Gowganda and Lorrain...... clearly record a progressive shoaling of the waters and a probable transition from subaqueous (probably lacustrine) to subaerial (fluvial) environment" (p. 478). The presence of glacial beds (varved argillite) is especially interesting, in view of the close association of the Cedarberg Formation with glacial deposits in the western Cape Province.

E 3. Provenance(s)

The super-mature nature of the bulk of the Table Mountain Group sediments make it difficult to hazard a guess as to the nature of the source area(s), except that the contributing rocks must have been quartz-rich. However, the highly feldspathic nature of the sandstones in the uppermost few hundred metres points to the presence of significant areas of igneous or metamorphic rocks (gneiss, granite) in the source area. If the absence of feldspar in the older strata is explained in terms of destruction of feldspar present in the source area, then such granitic rocks could have formed a major part of the source area throughout the deposition of the Table Mountain Group. A combination of arenaceous sedimentary rocks and varying amounts of quartz-rich igneous and metamorphic rocks (gneiss, granite, etc.) represents the most likely provenance.

According to Visser (1974, p. 235) possible source areas of the Table Mountain Group consisted largely of metamorphic (gneissose) rocks (± 60% of the area), with subordinate medium- to fine-grained clastic rocks (± 25% of the area), non-clastic rocks (5 - 10% of the area) and volcanic rocks (5 - 10% of the area).

The uniformly southward-directed palaeocurrents indicate that the source areas lay to the north of the present Table Mountain Group outcrops, probably north of 32°S (cf. Visser, 1974, Fig. 4).

CHAPTER XII

THE BOKKEVELD GROUP

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1 Lithostratigraphic interrelationships

The general lithostratigraphy of the Bokkeveld Group is shown on Folder 1. Since this scheme contains a number of changes compared with an earlier scheme presented by the writer (1966) as well as the scheme put forward by Theron (1972), a few general explanatory remarks are necessary.

The subdivision of the Bokkeveld Group into two subgroups (Ceres and Traka) by Theron (1970, 1972) is accepted and retained here, since it introduces a useful distinction between the six lower units (three sandstones and three shales) which can be followed throughout most of the basin, and the material above these units which lacks a laterally persistent sandstone-shale alternation (except in the far west, where the Bidouw Subgroup takes the place of the Traka Subgroup). In addition, the Ceres Subgroup is everywhere fossiliferous while the Traka Subgroup is generally unfossiliferous except in the extreme west.

Although the present writer had proposed geographic names for each of the formations within Theron's Ceres Subgroup (Johnson, 1966), Theron introduced new names selected almost exclusively from the western Cape, largely on the grounds that the formations (especially the shale units) have been far less affected by folding and tectonic disturbance in the western area than they are in the Steytlerville area (where a prominent slaty cleavage is a characteristic feature). In addition, fossils are more plentiful and better preserved (less distorted) in the west. In the light of these considerations it was decided to adopt Theron's terminology for the Ceres Subgroup formations even though these units actually attain their maximum thicknesses in the eastern Cape Province.

As regards the Traka Subgroup, the three informal members of the writer's original Adolphs Kraal Formation ("argillaceous shale", "silt shale", and "red shale" members - Johnson, 1966, p. 18ff.) are probably sufficiently distinct to constitute mappable units, and have hence been accorded formation status (cf. Csàky et al., 1969, p. 25, 37). In fact, from the point of view of theoretical lithostratigraphy there are sound reasons for regarding the top of the "silt shale member" (Adolphspoort Siltstone in the new scheme) as the most "correct" Bokkeveld - Witteberg boundary, since all the strata above it - right up to the base of the main Witteberg sandstone mass - are characterized by a number of features which serve to unify them and distinguish them collectively from the material below. These features include the ubiquitous presence of coarsening-upward cycles, the reddish colouration in the rhythmitites, the abundance of trace fossils (including "Spirophyton"), the micaceous nature of the sediments, the presence of thin quartzitic sandstone beds, the common occurrence of yellow-weathering calcareous lenses and, finally, the presence of plant stems. In addition, the Adolphspoort Siltstone, being fairly resistant, tends to crop out in a series of low hills which are readily recognisable on aerial photographs or even topographic maps. Csåky and others (1969, p. 37) state that the "Red Shale Formation" (Sandpoort Shale) may be considered as transitional between the upper Bokkeveld Group and the lower Witteberg beds. The Adolphs Kraal Formation (Johnson, 1966; Theron, 1972) now falls away; it is in any case equivalent in scope to the redefined Traka Subgroup.

The Driekuilen Sandstone and overlying Erekroons Shale of Johnson (1966) have now been placed in the Witteberg Group since recent field work undertaken by members of the SACS Cape working group (J.C. Loock, J.N. Theron and the writer) has established that the Driekuilen Sandstone is in fact the lateral equivalent of the basal Witteberg quartzite unit of the western Cape Province and is also the same unit that was mapped as the base of the Witteberg by Rossouw and others in the Prince Albert area (Geological Survey, Sheets 3321B and 3322A).

A 1.2 Chronostratigraphic relationships

According to Theron (1972, p. 121), the invertebrate fossils from the lower Bokkeveld Group generally indicate an Early Devonian age. In addition "a Lower Carboniferous age for the Upper Witteberg sequence makes an Upper Devonian age for the Witteberg - Bokkeveld boundary quite tenable" (Theron, p. 121). It is thus fairly safe to infer an Early to Middle Devonian age for the whole Bokkeveld Group.

A 2. Basic concepts and distinguishing features

Bokkeveld Group

Mudrock, rhythmitite and subordinate sandstone, unified with respect to overlying and underlying groups by the universally feldspathic and generally "dirty" nature of the sandstones, as well as by the overall predominance of fine-grained material. Additional characteristic features are the presence of marine invertebrates and the generally dark colour of the rocks.

Ceres Subgroup

Alternating dark grey mudrock lithosomes and dark, very fine-grained, muddy sandstone plus subordinate paler grey fine- to medium-grained feldspathic sandstone lithosomes. Marine invertebrate fossils occur.

Gydo Shale

Dark mudrock with occasional invertebrate fossils.

Gamka Sandstone

Dark, muddy, fine-grained subfeldspathic sandstone plus paler feldspathic sandstone (proportion variable) plus subordinate mudrock.

Swartkrans Shale

Dark mudrock with occasional invertebrate fossils.

Hex River Sandstone

Dark, very fine-grained, muddy subfeldspathic sandstone becoming paler, coarser, less muddy and less feldspathic near the western edge of the area.

Tra-Tra Shale

Dark mudrock

Boplaas Sandstone

Grey, fine- to medium-grained subfeldspathic sandstone.

Traka Subgroup

Mudrock, rhythmitite and very subordinate sandstone. A thick, largely sandstone-free unit.

Karies Shale

Dark "varved" rhythmitite plus shale (both fine-grained) grading into streaky rhythmitite. Three thin sandstone members are present in the eastern part of the main outcrop (B7, B8).

Adolphspoort Siltstone

Dark streaky rhythmitite (silty/sandy) grading locally into mudrock or very fine-grained sandstone. Distinguished from the underlying formation by its coarser grain and more pronounced topographic relief.

Sandpoort Shale

Essentially streaky rhythmitite and mudrock. Distinguished from the underlying formation by the common development of coarsening-upward cycles, the common reddish colouration of the rhythmitite, the abundance of trace fossils (including "Spirophyton"), the very micaceous nature of the sediments, the presence of quartzitic sandstone interbeds and yellow-weathering calcareous concretions, and lower topographic relief.

A 3. Geographic distribution

The general geographic distribution of the Bokkeveld Group as a whole as shown on the geological map of the Republic of South Africa (Geological Survey, 1970) is reproduced on Folder 3. Since the same criteria have not always been used by different workers for drawing the boundary between Bokkeveld and Witteberg strata it is probable that some of the uppermost "Bokkeveld" outcrops in the eastern part of the area may belong to the Weltevrede Formation of the Witteberg Group.

All the Bokkeveld formations, with the possible exception of the uppermost part of the Traka Subgroup (which is partly covered by Cretaceous strata) can be followed throughout the main (western) outcrop area. In the easternmost outcrop areas both the Ceres and Traka Subgroups have been identified by the writer (working in collaboration with R.S. Hill). In the Ceres Subgroup, the Gamka Sandstone is well exposed at two localities along the coast (B10 on Folder 3), while a richly fossiliferous mudrock outcrop west of Alexandria (B9) indicates the presence of either Gydo (First) or Swartkrans (Second) Shale. In addition, a 100 m-thick predominantly arenaceous outcrop west of Alexandria was tentatively correlated with the Boplaas (Third) Sandstone. Poor exposures are responsible for failure to positively identify the remaining Ceres Subgroup formations. Lack of Boplaas Sandstone exposures will probably make it impossible to map even the boundary between the Ceres and Traka Subgroups in this area.

All three formations comprising the Traka Subgroup could also be recognised with a fair degree of certainty, although no distinction could be established between Sandpoort Formation and Weltevrede Formation (Witteberg Group) strata.

A 4. History and nomenclature

Bokkeveld Group

The Bokkeveld Group (previously the Bokkeveld "Series"), as currently defined, was apparently first recognised and mapped in this area by Haughton (1928). Although earlier workers had no doubt recognised the presence of fossiliferous Bokkeveld strata, no differentiation of the Bokkeveld Series (Group) as such was previously undertaken. The name "Bokkeveld" was originally derived from the Cold Bokkeveld area in the western Cape Province and was first used by Wyley (1859), who referred to both "Bokkeveld Shales" and "Bokkeveld Beds".

Ceres Subgroup

The Ceres Subgroup was introduced by Theron (1970) and embraces the three lowermost shale and sandstone units of the Bokkeveld which appear to persist throughout the whole sedimentary basin. Earlier Csáky and others (1969) has used the expression "Lower Bokkeveld Subgroup" for the same strata. The name "Ceres" was given because of the typical development of the Subgroup north of the town of Ceres in the western Cape Province.

Gydo Shale

First reference to unit (study area).- Haughton (1928, p. 11).

Derivation of name.- Gydo Pass north of Ceres in the western Cape Province (Theron, 1970).

Synonyms.- First Shale; Lower shales (Schwarz, 1899, p. 49); First Shales (Haughton, 1928, p. 11); Hottentotspoort Shale (Johnson, 1966, p. 15).

Gamka Sandstone

First reference (study area).- Haughton, (1928, p. 11).

Derivation of name.- Gamkapoort (nearly 40 km west of Prince Albert) (Theron, 1970).

Synonyms.- First Sandstone (Corstorphine, 1897, p. 16; Schwarz, 1905, p. 275); Fossiliferous Sandstone (Corstorphine, 1897, p. 16); Lower Sandstone (Schwarz, 1899, p. 37); First Fossiliferous Sandstone (Haughton, 1928, p. 11); Groot River Sandstone (Johnson, 1966, p. 16).

Swartkrans Shale

First reference (study area).- Haughton (1928, p. 11).

Derivation of name.- Swartkrans, about 8 km south of Wuppertal (Clanwilliam district) in the western Cape Province (Theron, 1970).

Synonyms.- Second Shale; Second Shales (Haughton, 1928, p. 12); Tretyre Shale (Johnson 1966, p. 17).

Hex River Sandstone

First reference (study area).- Johnson (1966).

Derivation of name.- Hex River Valley in the western Cape Province (Theron, 1970).

Synonyms.- Second Sandstone (Corstorphine, 1897, p. 16); Schwarz, 1905, p. 275); First Upper Sandstone (Schwarz, 1899, p. 38); First White Sandstone (Schwarz, 1905, p. 274); Tygerhoek Sandstone (Johnson, 1966, p. 18).

Remarks.- In the type area (western Cape Province) this formation consists of "light-grey, medium-grained, thick-bedded protosandstone and quartz wacke with trough and planar cross-bedding"(Theron, 1972, p.39). In the area under discussion, on the other hand, it consists of fine- to very fine-grained, dark grey, muddy sandstones. Although a radical change in appearance has taken place, the basic lithology remains a sandstone, so that a change in name is probably not justified. Perhaps the distinction can best be maintained by referring to the "arenite" and "wacke" facies (as Theron does in the case of the Gamka Formation - 1972, p. 34) or the "clean" and "dirty" sandstone facies.

Tra-Tra Shale

First reference (study area).- Johnson (1966).

Derivation of name.- Tra-Tra River near Wuppertal in the western Cape Province (Theron, 1970).

Synonyms.- Third Shale; Bucklands Shale (Johnson, 1966, p. 18).

Boplaas Sandstone

First reference (study area).- Johnson (1966).

Derivation of name.- The farm Boplaas in the Cold Bokkeveld area of the western Cape Province (Theron, 1970).

Synonyms.- Third Sandstone (Corstorphine, 1897, p. 16); Second Upper Sandstone (Schwarz, 1899, p. 40); Second White Sandstone (Schwarz, 1905, p. 275); Krompoort Sandstone (Johnson, 1966, p. 18).

Traka Subgroup

As far as the eastern Cape Province is concerned this name was assigned by Theron (1970) to certain formations that had been proposed earlier by the present writer (1966). The name was derived from the Traka River which crosses the Bokkeveld Group west of Willowmore (B1). Previously Csàky and others (1969) had used the term "Upper Bokkeveld Subgroup" for the same succession.

Karies Shale

This unit was first recognised and described by the present writer (1966) as the "argillaceous shale member" of the "Adolphs Kraal Shale". The present name (proposed here for the first time) is derived from the farm Karies (B16) on which the type section occurs. Csàky and others (1969) refer to the Karies Shale as the "Argillaceous Shale Formation".

Adolphspoort Siltstone

First recognised by the present writer (1966) and named the "silt shale member" of the Adolphs Kraal Shale, the new name proposed here is obtained from Adolphspoort near the type section (B7). Csåky and others (1969) refer to the "Silt-Shale Formation".

Sandpoort Shale

The present writer (1966) first recognised this formation as a separate mappable entity, and referred to it informally as the "red shale member" of the Adolphs Kraal Shale. The name Sandpoort, proposed here, is derived from the farm Sandpoort (B6) on which typical exposures occur. Csåky and others (1969) used the term "Red Shale Formation".

A 5. Boundaries

Ceres and Traka Subgroups

Each of these subgroups is bounded by the top contact of the uppermost formation within it and the bottom contact of the lowermost formation. There is thus no need to define the subgroup boundaries separately.

Baviaanskloof Formation-Gydo Shale

Nature of Boundary.- Conformable: intercalated/gradational. Transition zone: ± 10 m.

Definition of boundary.- According to Theron (1972, p. 23), "The criteria used in the past to draw the contact between the Ceres Subgroup and the underlying Table Mountain Group are: (i) change in colour from white to dark grey or blue-black; (ii) change in lithology: The uppermost fine- to medium-grained ortho- or protosandstone unit of the Table Mountain Group, as opposed to the overlying thin alternations of carbon-bearing shale, mudstone, siltstone and quartz wacke of the Bokkeveld Group". However, although Theron describes in some detail a number of actual Table Mountain - Bokkeveld transitions, he himself never actually supplies us with his own criteria for pin-pointing the exact boundary. Consequently we must assume that he attempted to apply the rather vaguely-defined traditional criteria mentioned in the above quotation.

How satisfactory are these criteria in actual fact? The main problem is presented by the invariable presence of transitional arenaceous material between the top of the last white Table Mountain sandstone and the main mass of dark grey Gydo mudrocks. On the basis of the above definition it would appear that these transitional strata should be included with the

Bokkeveld. Theron seems to be of this opinion when he mentions that "Exposures at Towerwaterpoort, Dassiesfontein and Grootrivierpoort indicate that a three-fold subdivision [of the Gydo Formation] is feasible, i.e. a basal and an upper silty to arenaceous sequence, separated by a dark-grey carbonaceous shale zone" (1972, p. 31). However, if the Gydo Formation is conceived of as a unit composed essentially of mudrock, then it would seem correct to take the base as the point above which mudrock is the dominant lithology. This is the approach adopted recently by D.K. Toerien in mapping the Bokkeveld-Table Mountain boundary between 23°30'E and 24°30'E, and for the sake of maintaining a consistent boundary in future mapping, it was decided to follow this procedure in the present text. On this basis the basal "silty to arenaceous sequence" of the Gydo Formation which Theron mentions (see quote above) probably represents the uppermost member of the Baviaanskloof Formation (Table Mountain Group).

Gydo Shale-Gamka Sandstone - Swartkrans Shale - Hex River Sandstone - Tra-Tra Shale - Boplaas Sandstone - Karies Shale

In view of their similarity, the boundaries between the above formations can be described and defined collectively. Theron (1972) nowhere provides explicit criteria for locating the limits of the formations which he had proposed, nor does he discuss the actual nature of the contact relationships (at least not directly). However, the situation is generally fairly straightforward, and in every case it will probably be satisfactory to define the contact as the horizon above which the lithology of the overlying formation predominates. Since the sandstone formations are known to become more argillaceous (even predominantly argillaceous) southwards (Csàky et al., 1969; Theron, 1972), it may be necessary in some cases to choose the contacts of the three sandstone units in such a way that they simply embrace relatively arenaceous zones, even though the criterion of sandstone predominance may no longer be fully satisfied.

As regards the nature of the boundaries, Csàky and others (1969, p. 8ff.) maintain that they are conformable and transitional in every case (generally representing a combination of interfingering and progressive change in grain size). The thicknesses of the transition zones are variable; in the case of the Gydo-Gamka transition a figure of 60 - 100 m is quoted, but in most cases it will be considerably less (say 30 m for the base of sandstone units, 10 m or less for the top).

Karies Shale - Adolphspoort Siltstone - Sandpoort Shale

Both the upper and lower boundaries of the Adolphspoort Formation are conformable (intertongued/gradational) with thick transition zones

(50 m or more). The boundaries are defined as the horizons above or below which the general concept and distinguishing features of the adjacent formation predominate.

A 6. Overall lithology and facies changes

Ceres Subgroup

Average lithological composition of the Ceres Subgroup at various localities is summari ed in Table XII-1. The close similarity in the sandstone-shale ratio obtaining at all the eastern localities (Steytlerville and eastwards) made the calculation of an average value for this whole area possible. In the Vondeling area (B1) the large discrepancy between the percentages obtained using Theron's data on the one hand and SOEKOR'S data (Csâky et al., 1969) on the other, must in part be due to the use of different criteria for establishing formation boundaries.

Table XII-1. Overall lithology, Ceres Subgroup.

Unit/locality/author(s)	Sandstone	Mudrock, rhythmitite, etc.
Vondeling area (B1) (Theron, 1972)	50%	50%
Vondeling area (B1) (Csàky, et al., 1969)	16%	84%
East of Willowmore (B3) (Csàky et al., 1969; Hill, unpub. data, 1969; writer)	35%	65%
Steytlerville - Krompoort (B4 - B8) (Csàky et al., 1969; Theron 1972; writer)	20%	80%

Traka Subgroup

In the areas studied sandstone constitutes less than 5 percent of the whole succession. The remainder consists predominantly of "streaky" rhythmitite. However, "varved" rhythmitite is characteristic of the lower portion of the Karies Shale, while mudrock is also present throughout the succession.

A 7. Dimensions and shape

A 7.1 Thickness data

All available thickness data for the Bokkeveld Group and its subdivisions in the study area are contained in Table XII-2.

Table XII-2. Bokkeveld Group thickness data (metres).

Unit	B1 (Theron, 1972)	B1 (Csåky et al., 1969)	B3 (Av. Csåky et al., 1969; Hill, 1969; writer)	B4 (Csåky et al., 1969)	B6 (Theron, 1972)	B6 (Csåky et al., 1969)	B6 (Johnson, 1966)	B7 (Johnson, 1966)	B8 (Csåky et al., 1969)
Sandpoort Shale				575*		425	425	(425)	
Adolphspoort Siltstone				190		620	395+	620	315*
Karies Shale				495		1145	945	1280	415*
Traka Subgroup total	525*	1000*	1000*	1260	1420	2190	1765	2325	
Boplaas Sandstone	60	50	90	170*	60	122	75	60	110*
Tra-Tra Shale	60	80	105	550*	610*	340	305	330	420
Hex River Sandstone	30	12	60	90	45	73	40	45	110*
Swartkrans Shale	90	243*	125	280	305	340	275	245	200
Gamka Sandstone	230?	60?	115	150	150	220	200	200	230
Gydo Shale	150?	305?	270	400	595	550	455	455	670
Ceres Subgroup total	620	750	765	1640	1765	1645	1350	1335	1740
Bokkeveld Group total	1145	1750	1765	2900	3185	3835	3115	3660	

* Values considered to be unreliable.

Reliability of data

The highly folded and contorted nature of the strata, coupled with the lack of bedding and extensive development of slaty cleavage in the argillaceous units, made it difficult to obtain reliable thickness values, especially for the shale units. Different opinions as regards the degree of undetected folding within a section, as well as differences of opinion as to the exact position of contacts between formations, no doubt accounts for some of the relatively large thickness differences obtained by different workers at the same localities. The considerable difference in the thicknesses obtained by Theron (1972) and Csáky and others (1969) for the Gydo and Gamka Formations at Vondeling (B1) was almost certainly due to selection of different contacts (Theron, personal communication).

Values considered by the writer to be unreasonably large or small have been marked with an asterisk in Table XII-2. With the exception of the first two figures in the last column, all the indicated values are considered to be excessively large. The figures of 315 m and 415m quoted by Csáky and others (1969) for the Adolphspoort and Karies Formations respectively are almost certainly too small, since the figures obtained by the writer (620 m and 1280 m) are both based on an average of two fairly reliable estimates (which agreed reasonably well with each other).

The most reliable thicknesses are probably those given for the area east of Willowmore (B 3) where the total thickness for the Ceres Subgroup is probably within 10% of the true value. Most other figures in the table (except where otherwise indicated) are probably within about ± 20% of the actual thicknesses although many sandstone thicknesses will be within 10% of the true values while shale unit thicknesses may in a number of cases be up to 30% or more out.

A 7.2. Rate of thickness change (cross-sectional shape)

Since the axis of the depositional basin appears to extend roughly east-west (cf. isopach maps presented by Csáky and others, 1969, and Theron, 1972), it is clear that the most rapid changes in thickness of the Bokkeveld Group and its component formations will take place in a north-south direction. However, unlike the Table Mountain Group, the available exposures do not in general permit a study of north-south changes in thickness.

As regards east-west changes in thickness, the available evidence indicates that the thickness of both the Traka and Ceres Subgroups (and thus the thickness of the whole Bokkeveld Group) increases markedly from west to east. From Vondeling (B 1) to the Adolphs Kraal area (B 7) a three-fold increase in Traka Subgroup thickness takes place (assuming a thickness of 750 m at Vondeling), while the Ceres Subgroup approximately doubles its thickness from the area east of Willowmore (B 3) to the area east of Steytlerville. Expressed as a rate of thickness change, the Traka Subgroup thickens eastwards at approximately 10m/km while the Ceres Subgroup thickens at about 7,5 m/km between the section east of Willowmore (B 3) and the Groot River section (B 6). Changes in shale unit thicknesses are largely responsible for the change in thickness of both the Traka and Ceres Subgroups, since the sandstone units (in the Ceres Subgroup at any rate) are remarkably tabular, maximum rate of change being 1 m/km for the Gamka Sandstone between the area east of Willowmore and the Groot River section.

Ignoring local variations, the remaining sandstone units are also exceptionally tabular, with thickness change rates approaching zero, and even the Gamka Sandstone, which has a thickness of 135 m at its type section on the Gamka River 170 km west of Willowmore and possibly 230 m at Vondeling (B 1) (Theron, 1972), can be regarded as essentially tabular when viewed regionally with an overall zero thickness change rate. Individually the shale formations within the Ceres Subgroup are also reasonably tabular, maximum rates of thickness change being about 2 - 3 m/km between the Willowmore area (B 3) and the Groot River Section (B 6).

Although the thickness changes discussed above have been represented as taking place roughly along an east-west direction, it should be borne in mind that the changes noted could simply be due to the fact that the eastern outcrop areas are further south than the western outcrops. In other words, if the basin axis is assumed to be aligned slightly north of east, similar thicknesses to those measured in the Willowmore area could have been obtained 20 - 30 km <u>north</u> of the eastern areas, while considerably larger thicknesses could also have orginally been present 20 - 30 km <u>south</u> of the Willowmore area. The cleaner nature of the sandstone, and the higher total sandstone content in the Willowmore sections indicates closer proximity to the source area and affords supporting evidence for the above idea. Isopach maps presented by Theron (1972, Figs. 56, 57) are based on a similar interpretation, and the isopach lines given correspond to north-south thickness change rates of 13,5 m/km and 23,5 m/km for the Ceres and Traka Subgroups respectively in the Steytlerville region.

A 7.3. Lateral extent

All the Ceres Subgroup formations extend from the westernmost Bokkeveld Group exposures to at least as far as a point north of Uitenhage (600 km total distance), and probably continue eastwards to the Alexandria area (an additional 100 km). The three Traka Subgroup formations can still be recognised at 22°30'E (Klaarstroom area) in the west, and disappear under the Cretaceous strata north of Uitenhage in the east, giving a lateral extent of at least 250 km.

A 8. Stratotypes

Gydo Shale

Unit-Stratotype.- Gydo Pass, north of Ceres (western Cape Province) (Theron, 1970, p. 203; 1972, p. 20).

Reference stratotype.- Hottentots Poort (B 5).

Nature of stratotype : Sporadic natural exposures through lower part of formation. Angle of dip moderate (30°+).

Accessibility : Good.

Location : See Fig. XII - 1a.

Gamka Sandstone

Unit-stratotype.- Gamkapoort, 37 km west of Prince Albert (Theron, 1970, p. 203; 1972, p. 20).

Reference stratotype 1.- Groot River (B 6)

Nature of stratotype : Almost complete section along banks of Groot River. Strata sub-vertical. Bottom contact visible.

Accessibility : Fair/poor. Last few km of road may not be negotiable by motor car.

Location : See Fig. XII - 1b.

Reference stratotype 2.- Bosch Nek (B 3).

Nature of stratotype : Almost complete section in the form of natural outcrops adjoining stream. Strata are steeply dipping.

Accessibility : Good

Location : See Fig. XII - 1c.

Reference stratotype 3.- Cannon Rocks (B 10).

Nature of stratotype : Partial section consisting of fresh exposures along coast. Angle of dip moderately high.

Accessibility : Good

Location : See Fig. XII - 1d

Swartkrans Shale

Unit -stratotype.- Cliff at Swartkrans ± 8 km south of Wuppertal in Clanwilliam district in the western Cape Province (Theron, 1970, p. 203; 1972, p. 20)

Reference stratotype 1.- Karies (B 6).

Nature of stratotype : Representative, but weathered, sporadic natural exposures showing part of succession. Steeply dipping.

Accessibility : Fair.

Location : See Fig. XII - 1e

Reference stratotype 2.- Olsta (B 3)

Nature of stratotype : Sporadic weathered natural exposures across parts of succession. Steeply dipping.

Accessibility : Good

Location : See Fig. XII - 1f.

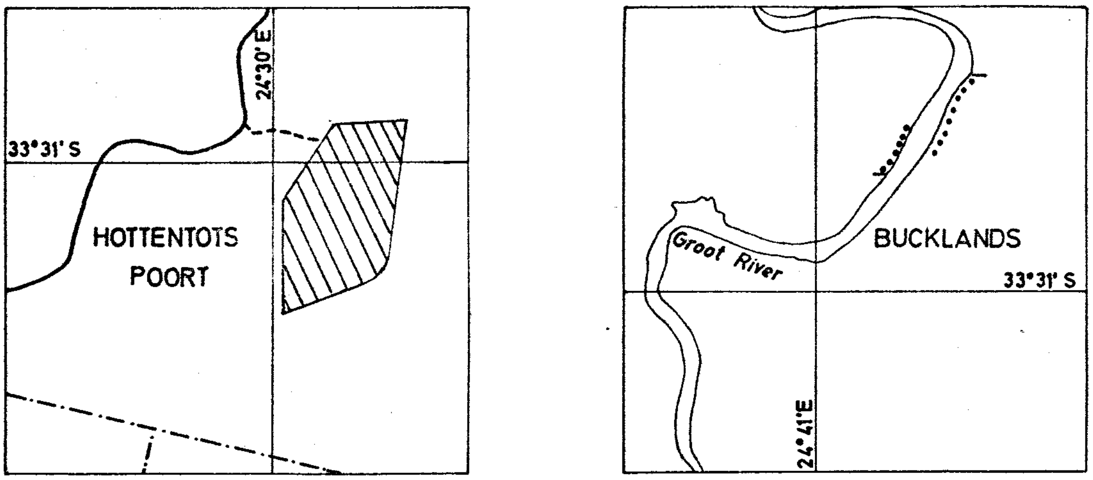
Hex River Sandstone

Unit-stratotype.- Oudekraalkop due east of De Doorns in the western Cape Province (Theron, 1970, p. 203; 1972, p. 20).

Reference stratotype 1.- Tygerhoek (B 7)

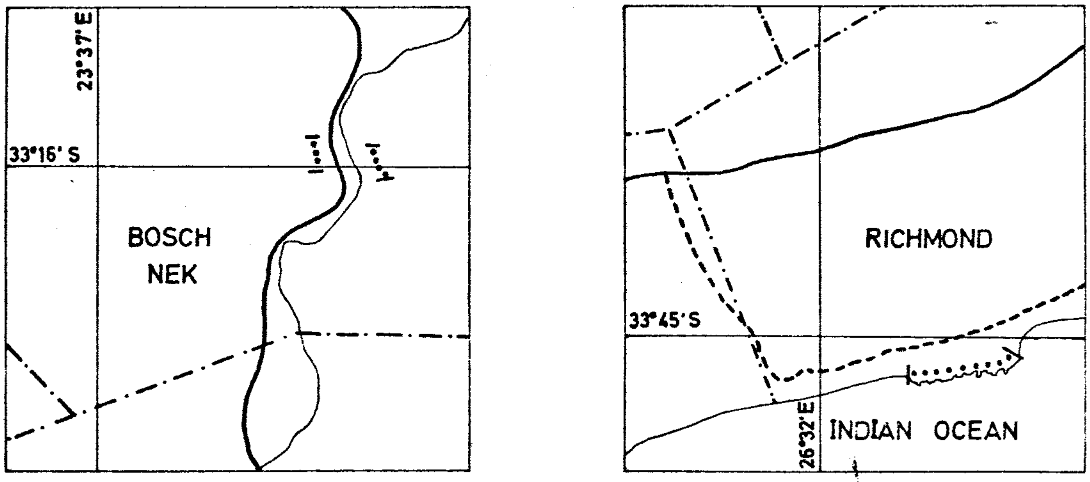
Nature of stratotype : Partial section across central and upper portion of formation in stream bed. Steeply dipping.

FIG XII-1
STRATOTYPES: BOKKEVELD GROUP
SCALE OF MAPS: 1:50000



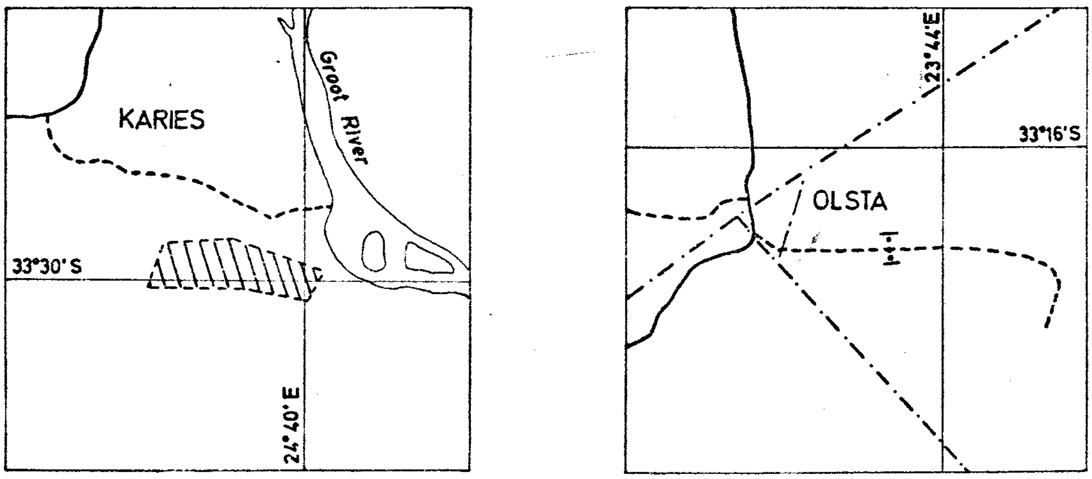
a. Gydo Shale
Reference stratotype (approx.)
Map ref.: 3324 CB/3324 DA

b. Gamka Sandstone
Reference stratotype 1 (approx.)
Map ref.: 3324 DA



c. Gamka Sandstone
Reference stratotype 2
Map ref.: 3323 BC

d. Gamka Sandstone
Reference stratotype 3
Map ref.: 3326 DA



e. Swartkrans Shale
Reference stratotype 1 (approx.)
Map ref.: 3324 BC/3324 DA

f. Swartkrans Shale
Reference stratotype 2 (approx.)
Map ref.: 3323 BC

Accessiblity : Fair/good

Location : See Fig. XII - 2a

Reference stratotype 2.- Bosch Nek (B 3)

Nature of stratotype : Natural exposures of upper half of formation in small hill. Strata are steeply dipping.

Accessibility : Fair/good

Location : See Fig. XII - 2b

Tra-Tra Shale

Unit-stratotype.- Along flank of Vaalheuningsberg Range south of Wuppertal in the western Cape Province (Theron, 1970, p. 203; 1972, p. 20).

Reference stratotype 1.- Tygerhoek (B 7)

Nature of stratotype : Weathered, incomplete, natural exposures of lower half of formation in dry stream bed plus isolated exposures of upper half. Steeply dipping.

Accessibility : Fair/good

Location : See Fig. XII - 2c

Reference stratotype 2.- Near Olsta (B 3)

Nature of stratotype : Partial section across formation in the form of weathered natural exposures.

Accessibility : Good

Location : See Fig. XII - 2d

Boplaas Sandstone

Unit-stratotype.- Eastern slope of Tafelberg about 5 km north of Boplaas in the Cold Bokkeveld (western Cape Province) (Theron, 1970, p. 203; 1972, p. 21).

Reference stratotype 1.- Krompoort (B 8)

Nature of stratotype : Natural exposures in cliff adjoining stream, constituting a complete section through most of the formation (top and base not exposed). Strata sub-vertical.

Accessibility : Excellent.

Location : See Fig. XII - 2e

Reference stratotype 2.- Bosch Nek (B 3)

Nature of stratotype : Complete natural exposures of upper clean sandstone member in small hill. Strata sub-vertical.

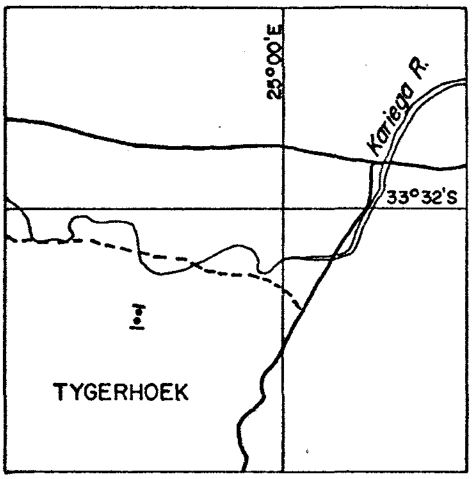
Accessibility : Good

Location : See Fig. XII - 2f.

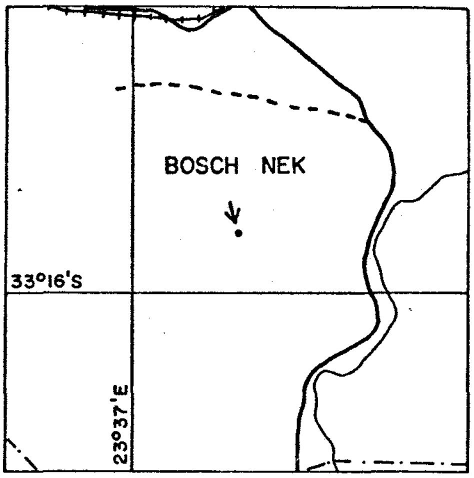
FIG XII-2
STRATOTYPES: BOKKEVELD GROUP

SCALE OF MAPS: 1:50000

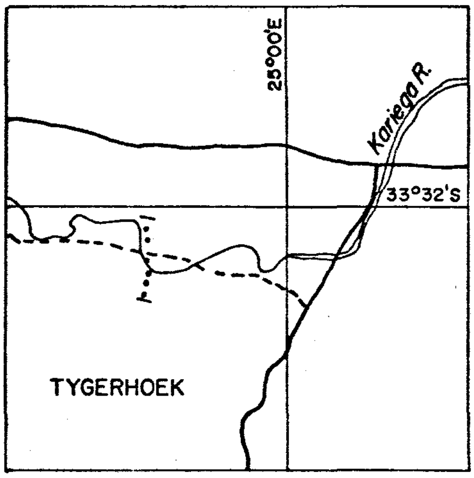
••••••	Stratotype
——–	Road
═	River
–·–·–	Farm boundary



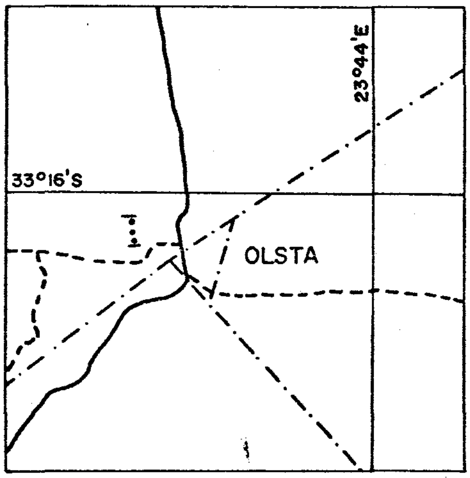
a. Hex River Sandstone
Reference stratotype 1
Map ref: 3324 DB / 3325 CA



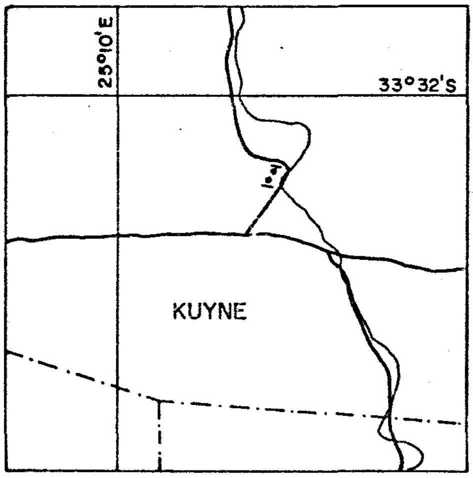
b. Hex River Sandstone
Reference stratotype 2
Map ref.: 3323 BC



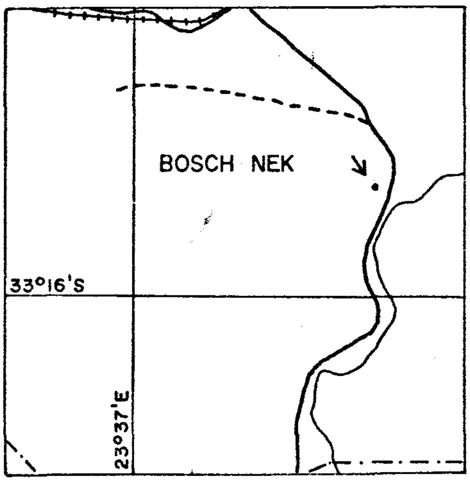
c. Tra-Tra Shale
Reference stratotype 1
Map ref.: 3324 DB / 3325 CA



d. Tra-Tra Shale
Reference stratotype 2
Map ref.: 3323 BC



e. Boplaas Sandstone
Reference stratotype 1
Map ref.: 3325 CA



f. Boplaas Sandstone
Reference stratotype 2
Map ref.: 3323 BC

Karies Shale

Unit-stratotype.- Karies (Groot River) (B 6)

Nature of stratotype : Partially weathered, fairly complete natural exposures in gully. Strata steeply dipping.

Accessibility: Fair

Location : See Fig. XII - 3a

Adolphspoort Siltstone

Unit-stratotype.- Adolphs Kraal (B 7)

Nature of stratotype : Virtually complete exposure of entire unit in road cuttings. Strata sub-vertical.

Accessibility : Good

Location : See Fig. XII - 3b

Sandpoort Formation

Unit-stratotype.- Erekroons River (B 6)

Nature of stratotype : Exposures are in the form of fairly fresh outcrops in the bed and bank of the Erekroons stream. The basal part of the unit is absent. The strata are steeply-dipping throughout.

Accessibility : Good

Location : See Fig. XII - 3c

B. PALAEONTOLOGY

The following list summarises the known distribution of organic remains within the Bokkeveld Group in the study area. Ceres Subgroup fossils come mainly from the area east of Steytlerville (B 6 - 8) and a small area near Alexandria (B 9).

(a) Western outcrop area

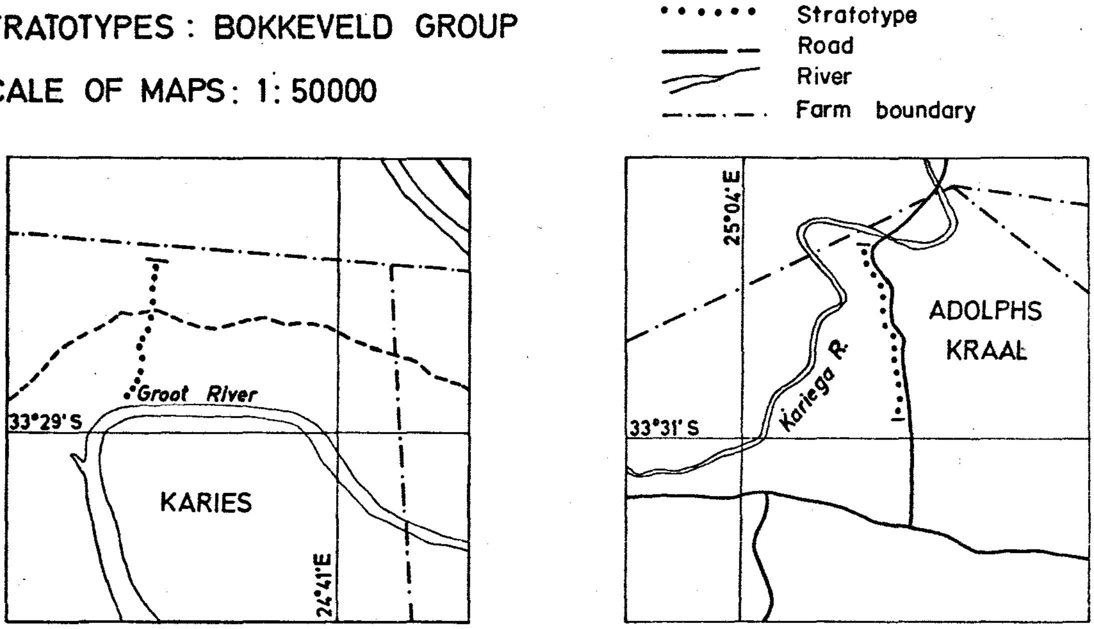
Except where otherwise stated the description which follows refers to the area east of Steytlerville (B 6 - 8).

Gydo Shale

Invertebrate fossils.- Brachiopods : ± 10 species; pelecyods : ± 5 species; gastropods : 2 species ; trilobites : 2 species ; pteropods : 1 species; crinoids : fragmentary stem remains.

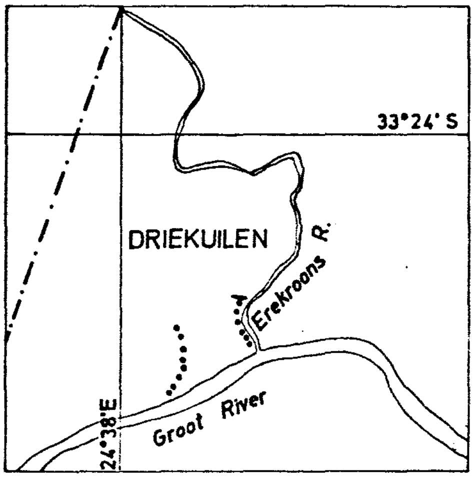
FIG XII-3
STRATOTYPES : BOKKEVELD GROUP

SCALE OF MAPS: 1: 50000



a. Karies Shale
Unit-stratotype
Map ref.: 3324 BC

b. Adolphspoort Siltstone
Unit-stratotype
Map ref.: 3325 CA



c. Sandpoort Formation
Unit-stratotype
Map ref.: 3324 BC

Gamka Sandstone

Invertebrate fossils.– Brachiopods : 3 species (Theron, 1972, p. 119).

Swartkrans Shale

Invertebrate fossils.– Brachiopods : 1 + species; pelecyods: ± 4 species; trilobites: 1 species; pteropods: 1 species; crinoids: fragmentary stem remains.

Hex River Sandstone

Invertebrate fossils.– Hill (1969) reports the presence of brachiopod and pteropod species from the area east of Willowmore (B 3).

Trace fossils .– Tracks and trails are common (Theron, 1972, p. 41).

Plant fossils.– Fragmentary plant remains occur (Csáky, et al., 1969, p. 19).

Tra-Tra Shale

Invertebrate fossils.– Some poorly preserved brachiopod, trilobite and crinoid impressions occur.

Boplaas Sandstone

Trace fossils.– Bioturbated zones occur in the western area.

Plant fossils.– Psilophytes : One species. Indeterminate stem fragments also occur. These plant fossils were reported from the Suidwaaikraal (B 3) area by Hill (1969).

Sandpoort Formation

Trace fossils.– Zoophycus (" Spirophyton ") impressions occur throughout this formation. Tracks, trails and burrows are also abundant.

Plant fossils .– Specimens of one or more proto-lycopod species (stem fragments) have been recovered from near the base of the Sandpoort Formation.

General observations

In general, invertebrate remains in the Ceres Subgroup only occur at certain horizons within each formation (where they may be comparatively abundant), the rest of the formation being practically barren. In addition, fossil remains become progressively less abundant upwards, the Tra-Tra Shale being practically unfossiliferous, while no invertebrate fossils have as far as is known been discovered in the Traka Subgroup.

Plant remains and Zoophycus (Spirophyton) impressions appear to be confined largely to the upper part of the Traka Subgroup (i.e. the Sandpoort Formation).

(h) Alexandria area (B 9)

Invertebrate fossils.- In this area brachiopods (± 5 species), pelecypods (2 species), gastropods (2 species), trilobites (1 species), cephalopods (1 species) and crinoid remains have been found in a shale unit which may be correlated with either the Gydo or Swartkrans Formations. Theron (1972, p. 39) favours the latter possibility. Brachiopod fossils and crinoid stems also occur in what is probably the equivalent of the Gamka Sandstone.

Plant fossils.- Some fragmentary, indeterminate plant remains occur in the Adolphspoort Siltstone.

C. MACRO-SEDIMENTOGRAPHY

C 1. Cyclicity

Only the Sandpoort Formation shows the development of distinct alternating lithosomes, although the Ceres Subgroup as a whole can be considered to consist of "an alternating sequence of 3 shale and 3 sandstone formations, forming 3 shale-sandstone cycles" (Csáky et al., 1969, p. 5).

As far as can be ascertained, the various lithologies present in the Sandpoort Formation (mudrock, argillaceous streaky rhythmitite, arenaceous streaky rhythmitite, sandstone), generally seem to occur in the form of incomplete or complete coarsening-upward cycles. According to Csáky and others (1969, p. 38) "cyclic sedimentation predominated, with thicknesses of cycles usually varying between 25 and 40 feet (7,5 - 12 m)". Range of thickness is from about 2,5 m to about 25 m. Lateral extent of cycles is unknown.

C 2. Lithosome dimensions and shape

Sandpoort Formation .-"Individual sandstone beds vary in thickness from a fraction of a foot (0,3 m) to 15 feet (4,5 m), while the lateral extent of each sandstone is limited" (Csáky et al., 1969, p. 38).

Average sandstone thickness is probably about 1 - 2 m. "The thickness of shales vary between 20 and 200 feet (6 - 60 m)" (op. cit.). The average in this case is probably in the region of 10 m.

C 3. Lithosome boundaries

Sandpoort Formation.- Sandstone lithosomes generally tend to display sharp (flat) upper contacts and gradational/intertongued lower boundaries, being overlain by dark mudrock or argillaceous streaky rhythmitite and underlain by arenaceous streaky rhythmitite.

C 4. Colours

Ceres Subgroup

Mudrock is normally dark grey (N3) but varies from medium dark grey (N4) to greyish black (N2). Weathered outcrops are light olive grey (5Y6/1).

Sandstones belonging to the dirty "wacke facies" vary from medium dark grey (N4) to medium grey (N5), while those belonging to the clean "arenite facies" vary from medium grey (N5) to medium light grey (N6) in the case of the Gamka Sandstone and medium light grey (N6) to light grey (N7) in the case of the Boplaas Sandstone.

In general, reddish colours are very rare in the Ceres Subgroup.

Traka Subgroup

Karies Shale.- Dark grey (N3) to medium dark grey (N4).

Adolphs Poort Siltstone.- Medium dark grey (N4) to medium grey (N5).

Sandpoort Formation.- Sandstone is medium grey (N5) to medium light grey (N6). Mudrock is grey or greyish red purple (5RP4/2). Rhythmitite is generally greyish red purple (5RP4/2) or some shade of grey in outcrop. However, there is evidence that all the argillaceous rocks (including the reddish varieties) are dark grey (N3) or greyish black (N2) and carbonaceous when fresh and unweathered.

C 5. Sedimentary structures

General bedding characteristics (Bokkeveld Group)

Rhythmitites and associated thin sandstones are generally evenly-bedded, while sedimentation units within the major sandstones show varying degrees of lenticularity.

Ceres Subgroup

The three argillaceous formations (Gydo, Swartkrans, Tra-Tra) are generally massive and structureless, but wavy bedding and occasional micro-cross-lamination are present in the more silty and sandy portions. Lebensspuren and bioturbated zones are also occasionally present, while Theron (1972, p.31) reports the presence of graded bedding (presumably micrograding) in the basal and upper portions of the Gydo Shale at Grootrivierpoort (B6).

Gamka Sandstone

Clean ("arenite") facies.- At Suidwaaikraal (B3) east of Willowmore, flat-bedding, cross-bedding and massive bedding are about equally represented. Cross-bedding is generally of the trough type, and sets average about 0,5 m (max. 1,4 m) in thickness. Inclined bedding is also fairly common in the finer-grained, more argillaceous sandstone, while bioturbated zones up to 30 cm thick are occasionally present. At Groot River (B6), where the "arenite" facies forms about 5% of the total Gamka thickness, the cross-bedding includes both planar and trough varieties, the latter in sets up to 1,2 m thick characterised by long, sweeping, gently curved foresets. At Cannon Rocks (B10) flat-bedding (in sets up to 1,2 m thick) is more abundant than cross-bedding (in sets up to 0,75 m). Micro-cross-lamination (0,3 m set) also occurs.

Dirty ("wacke") facies.- Massive bedding (?), inclined bedding, flat-bedding and bioturbation are all common. Superficially massive-bedded sedimentation units may in fact be inclined-bedded or flat-bedded. In the Groot River (B6) and Cannon Rocks (B10) sections it was found that apparently massive-bedded sandstones usually proved to be flat-bedded or inclined-bedded on closer inspection, while rocks subjected to the etching effect of wind and/or sea invariably revealed the presence of internal laminations (flat or inclined). Laminations are often aligned parallel to the sides of shallow, rather flat hollows (up to 30 cm deep) eroded into the underlying material.

Hex River Sandstone

Suidwaaikraal (B3).- The upper half of this formation (consisting of moderately clean "arenite" facies sandstone) is characterised by well-developed flat-bedding (30 - 60 cm sets) and minor cross-bedding, inclined bedding and micro-cross-lamination. Superficially massive beds also occur.

Dirty ("wacke" facies) sandstone constitutes the lower half of the formation, and displays flat-bedding, inclined bedding and occasional bioturbation. Current and oscillation ripple marks occur, as well as invertebrate trails.

East of Steytlerville (B5 - B8).- Structures are highly varied; massive bedding, "flat-bedding", inclined bedding (small-scale), mottled bedding, wavy bedding, micro-cross-lamination and small-scale graded bedding all occur. According to Theron (1972, p.41), current, interference and wave ripple marks of varying wave length and amplitude, as well as scour-and-fill structures are also common. Invertebrate trails are abundant in the argillaceous zones.

Boplaas Sandstone

Suidwaaikraal area (B3).- The upper clean ("arenite" facies) member is trough-cross-bedded throughout. In the upper half of this member the cross-bedding foresets meet the underlying depositional surface at high angles, but in the lower half the foresets are in the form of long "festoons" gently tangential to the lower boundaries of the sets. These two kinds of cross-bedding are associated with different palaeocurrent directions (see Table XII-3). Average thickness of sets is about 0,3 m (maximum one metre). Massive-bedded and flat-bedded sedimentation units (the latter showing primary current lineation) are occasionally present.

The lower dirty ("wacke" facies) member is characterised by massive bedding, "flat-bedding", bioturbation, inclined bedding and occasional oscillation ripple marks. Small-scale cut-and-fill structures are fairly common, (Theron, 1972, p. 44).

East of Steytlerville (B8).- Trough cross-bedding, massive bedding and flat-bedding (?) are all common.

Traka Subgroup

The streaky rhythmitites are, as usual, characterised by wavy bedding and occasional micro-cross-lamination, while mudrock layers are essentially massive (except in the Karies Formation, where thinly-laminated shale occurs). The "varved" rhythmitites which are common in parts of the Karies Shale generally display micro-grading in the individual couplets. Load-casting, small-scale ball-and-pillow structures and slump phenomena occur in the Adolphspoort Siltstone. Biogenic structures (bioturbated layers and "lebensspuren" of various kinds) while especially abundant in the Sandpoort Formation occur throughout the Traka Subgroup. According to Theron (1972, p.51), current, oscillation and interference ripple marks are ubiquitous.

The interbedded sandstone units are characterised by wavy bedding, flat-bedding (horizontal and sub-horizontal), micro-cross-lamination, and inclined bedding. Shallow cut-and-fill structures occur, but beds are generally parallel-sided and continuous.

Orientation data

Cross-bed dip direction data obtained by the writer are summarised in Tables XII-3 and XII-4. Theron (1972, Figs.18, 25) measured cross-bed dip directions in the Gamka and Boplaas Sandstones at both Vondeling (B1) and Groot River (B6); his map indicates vector means of 135° and 176° for the Gamka Sandstone at Vondeling and Groot River respectively (30 readings each) and 134° and 145° for the Boplaas Sandstone at the same localities (20 and 25 readings respectively). These directions have been plotted on the palaeocurrent map (Folder 3).

Table XII-3. Statistical measures calculated from orientation data for cross-bedding in the Bokkeveld Group.

Unit/locality	n	$\bar{x}_v$	$\bar{a}$	s
Boplaas (B3) (Upper member)	64	140°	0,63	56°
Boplaas (B3) (Lower member)	31	231°	0,86	33°
Gamka (B2 + B3)	30	157°	0,55	64°
Gamka (B10)	17	112°	0,54	63°

n = Number of measurements
s = standard deviation
$\bar{x}_v$ = vector mean
$\bar{a}$ = vector strength

Table XII-4. Cross-bedding dip directions in the Bokkeveld Group: number of readings per 30° class interval.

	Class mid-points (°)											
Unit/locality	15	45	75	105	135	165	195	225	255	285	315	345
Boplaas (B3) (Upper member)		2½	6½	12	18	10	6	2	5	2		
Boplaas (B3) (Lower member)						2	6½	9½	10½	2½		
Gamka (B2 + B3)			2½	5	6	5½	4	2½	1½	2		1
Gamka (B10)	1	1	2	3½	3½	4					1	1

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

All size measurements in Table XII-5 are based on the outlines of the original grains plus quartz cement. Figures obtained by Theron (1972, Table VI, p.160) in the eastern Cape Province have been included for comparison. Theron's figures were based on the measurement of apparent maximum diameters of 300 quartz grains per sample.

Table XII-5. Grain-size data for Bokkeveld Group sandstones.

Unit/locality	n	$\bar{x}$(Ø)	S(Ø)	MD(Ø)	d(Ø)	$\bar{x}$ - d	M(%)
Sandpoort (B8)	1	3,26	0,67	0,52	1,74	1,52	23
Boplaas (Upper member)(B2,B3)	6	1,93 (1,57/2,10)	0,52	0,39	0,79	1,14	3,5
Boplaas (Lower member)(B2)	2	4,18	0,55		2,33	1,85	36,5
[1]Boplaas (B6)	2	2,36 (1,49/3,22)	0,62				
Boplaas (B8)	5	2,81 (2,09/3,49)	0,54	0,41	1,40	1,41	18,5
Hex River (B3)	2	2,76 (1,83/3,69)	0,50	0,38	1,16	1,60	18,5
[1]Hex River (B6)	1	3,29	0,45				
Hex River (B7)	2	3,29	0,62	0,45	1,83	1,46	26,5
[1]Gamka (B1)	2	2,49	0,78				
Gamka ("arenite facies")(B3)	5	2,42 (1,78/3,19)	0,59	0,45	0,58	1,84	12,5 (5/17)
Gamka ("wacke facies")(B3)	4	3,14 (2,23/3,64)	0,59	0,44	1,15	1,99	32,5 (20/43)
[1]Gamka (undifferentiated)(B3)	6	2,73 (1,98/3,14)	0,57				
Gamka ("arenite facies")(B6)	2	2,70	0,52	0,38	1,11	1,59	8
Gamka ("wacke facies")(B6)	4	3,42 (3,01/3,91)	0,59	0,48	1,80	1,62	27 (19/41)
[1]Gamka (undifferentiated)(B6)	2	2,75	0,55				
Gamka (B7)	3	3,47	0,66	0,51	1,57	1,90	32
Gamka (unimodal) (B10)	4	2,90 (2,26/3,18)	0,49	0,39	1,75	1,15	13,5 (9/19)

Table XII-5 (contd.)

Unit/locality	n	$\bar{x}(\phi)$	S(ø)	MD(ø)	d(ø)	$\bar{x}$ - d	M(%)
Gamka (bimodal) (B10)	2	2,91	0,92	0,64	0,24	2,67	19

[1] Theron (1972, Table VI)

n = number of samples (50 grains per sample)

S = standard deviation

M = matrix content (range in brackets)

$\bar{x}$ = mean size (range in brackets)

MD = mean deviation

d = maximum thin-section diameter

D 2. Composition

Results of modal analyses on Bokkeveld sandstones are summarised in Table XII-6.

Remarks:

1. In the Gamka Sandstone the quartz : feldspar ratio appears to be higher in samples with a high matrix percentage (i.e. in "wacke facies" sandstones). It would be expected that feldspar content would also vary with grain size, but this does not appear to be the case.
2. A decrease in feldspar content towards the top of the Bokkeveld Group is evident from the table.
3. Rock fragments are generally microcrystalline quartz (chert?).
4. Muscovite appears to be the most common accessory mineral.
5. Material included under the heading "cement" is exclusively calcite. Distribution is erratic, calcite being absent from many sandstones.
6. Chlorite and fine-grained brown biotite (?) appear to be the most common matrix minerals in the darker "wacke facies" sandstones, while "vermicular" sericite is common in the paler "arenite facies" rocks.

Table XII-6. Overall mineral composition of Bokkeveld Group sandstones.

Unit/locality	n	Q	F	R	Acc.	Cem.	M	Q : F : R
Sandpoort (B8)	1	61,5	8	0,5?	2	5	23	88 : 11,5 : 0,5?
Adolphspoort (B7)	1	47,5	11,5	-	2	15	24	80,5 : 19,5 : 0

Table XII-6 (contd.)

Unit/locality	n	Q	F	R	Acc.	Cem.	M	Q : F : R
Karies (B8)	1	60	14	-	3	5,5	17,5	81 : 19 : 0
Boplaas (Upper member) (B2,B3)	6	88	7	1	0,5	-	3,5	92,5 : 7,5 : 0
Boplaas (Lower member) (B2)	2	53	6	1,5	2	1	36,5	87,5 : 10 : 2,5
Boplaas (B8)	4	63,5	14,5	0,5?	3	-	18,5	81 : 18,5 : 0,5?
Hex River (B3)	2	57	22	1	1,5	-	[1]18,5	71,5 : 27,5 : 1
Hex River (B7)	2	48,5	14	2?	1	8	26,5	75 : 22 : 3?
Gamka ("arenite") (B3)	5	60	26	0,5	0,5	0,5	12,5	69,5 : 30 : 0,5
Gamka ("wacke") (B3)	4	48	13	2	2	2,5	32,5	76 : 21 : 3
Gamka ("arenite") (B6)	2	48,5	39	1	1	2,5	8	55 : 44 : 1
Gamka ("wacke") (B6)	4	48,5	19	2	2,5	1	27	70 : 27 : 3
Gamka ("wacke") (B7)	3	51	14	0,5?	1,5	1	32	78 : 21,5 : 0,5?
Gamka (B10)	6	53	29	1	1	1	15	64 : 35 : 1

n = number of samples

Q = quartz (including secondary quartz)

F = feldspar

R = rock fragments (chert)

Acc. = accessory minerals (including mica flakes)

Cem. = cement and secondary minerals (excluding secondary quartz)

M = matrix (all allogenic material smaller than 20 - 30 μ)

[1] Average is based on one "arenite" facies sandstone (8%) and one "wacke" facies sandstone (29%)

E. SEDIMENTOGENESIS

Introduction

An interpretation of the depositional conditions prevailing during Bokkeveld times has been presented in concise form by Csåky and others (1969). Subsequently the same issue was discussed at greater length by Theron (1972, p. 132 ff.). Since the broader aspects of Bokkeveld sedimentation are relatively straightforward, it is not surprising that Theron's interpretations do not in general differ significantly from those of Csåky and others; such differences as there are concern mainly the nature of the locally developed subenvironments that abound in the near-shore area. Except in those instances where the present writer disagrees with either Csåky and others or Theron, the interpretations which follow will not be discussed in detail.

E 1. Palaeocurrents

Theron (1972, p.56 ff.) includes an extended discussion on palaeocurrent data from the Bokkeveld Group. However, as pointed out earlier (Chapter VI) most of this data was unfortunately processed by means of a computer technique which gave rise to plots on equal area projections which are in many cases obviously incorrect (and thus suspect even in those cases where they are not obviously wrong-looking). Therefore, although the vector means obtained from the computed data may be roughly correct in most cases, the details displayed by the various cross-bedding diagrams cannot be used to obtain diagnostic information regarding palaeocurrent patterns and trends (at least not as far as the eastern Cape is concerned).

In the discussion which follows cross-bedding is the only structure under consideration.

Gamka Sandstone

According to Csåky and others (1969, p.12), palaeocurrent directions (in the basin as a whole) indicate a main source area to the north.

Theron (1972, p.62; Figs. 7E, F,18) obtained unimodal patterns and vector means directed south-east and south at Vondeling (B 1) and Groot River (B 6) respectively, based on 30 measurements in both cases, and a high vector strength ($\bar{a}$ = 0,62) for the combined data from this eastern area.

The present writer obtained a SSE direction in the Willowmore area (B2, B5) and an ESE direction at Cannon Rocks (B10). In both cases unimodal patterns and intermediate vector strengths (0,54, 0,55) were obtained.

Hex River Sandstone

The only available information on palaeocurrents in this formation is a SSE direction (based on 9 readings) obtained by Theron (Fig. 19, 20H) at Vondeling (B 1). This situation reflects the paucity of true cross-bedding in this formation.

Boplaas Sandstone

Csåky and others (1969, p.24) state that the main palaeocurrent direction in this formation was to the south and south-east, and refer to Groot River (B 6) as one of the localities sampled. Theron (Fig. 24 G,H; Fig. 25) obtained vector means directed approximately south-east at both Vondeling (B 1) and Groot River (B 6) (20 and 25 readings respectively).

East of Willowmore (B3) the present writer also obtained a south-east transport direction (unimodal pattern with moderately high vector strength) for the upper half of the formation, but a south-westerly direction (unimodal, very high vector strength) in the lower half.

E 2. Depositional processes and environments

Ceres Subgroup : shale units

In view of their virtually identical dimensions and lithology, and the basic similarity of their fossil assemblages, the Gydo, Swartkrans and Tra-Tra Formations can be discussed collectively. The following three features, when considered together, can only be explained in terms of a moderately shallow marine environment (offshore zone of an epicontinental shelf or pro-delta slope):

a. Mudrock lithology with vertical thickness measured in hundreds of metres.
b. Lateral extent of about 700 km.
c. Varied benthonic invertebrate fossil assemblage.

Selley (1970, p.106, cf. Fig. 6.5) points out that both the lower marine sections and the transitional zone (interlaminated rippled and burrowed silt and very fine sand) are essentially identical in sedimentary sections produced by prograding deltas and prograding non-deltaic shorelines. Reineck and Singh (1973, p.273) also mention that it may prove difficult to distinguish the prodelta and shelf-mud (offshore zone) environments.

Ceres Subgroup : sandstone units

Although the inter-formational differences are greater than in the case of the shale units, the differences in the same formation at different localities are as great as those between the various formations at the same locality. The following combination of features should prove to be environmentally diagnostic:

1. Tabular nature of lithosomes.
2. Presence of two distinct sandstone types:
   a. Pale, relatively clean, fine-grained (occasionally medium-grained) cross-bedded sandstone.
   b. Dark, relatively dirty, very fine-grained non-cross-bedded sandstone.
3. Transitional (coarsening-upwards) lower boundaries to the "dirty" sandstone zones.

4. Unimodal palaeocurrent patterns, generally directed southwards, in the "clean" sandstones.
5. Occasional presence of marine invertebrate fossils in the dark sandstones.

The great lateral extent and very low regional rates of thickness change displayed by all three these formations can only be explained in terms of deposition within or along the margins of a single large body of water, presumably an epicontinental sea. The fossils which are occasionally encountered, as well as the abundant marine life present in the associated shale units, confirm this interpretation.

The poor sorting, very fine grain, abundant argillaceous matrix and presence of horizontal lamination and inclined bedding rather than cross-bedding in the dark sandstones points to deposition by relatively weak currents (wind-wave drift?) in the lower shoreface or transition zones. According to Reineck and Singh (1973, p.307), the sediments of the transition zone are usually clayey silt to silty sand. The lack of separation into distinct finer and coarser layers which normally characterises the transition zone (Allen, 1970, p.173; Reineck and Singh 1973, p.285) is probably due to rapid deposition which did not permit textural differentiation.

Csáky and others (1969, p.43) postulate rapid deposition for these argillaceous sandstones. According to them these sands were brought into an even shelf area by fairly competent rivers and distributed by gentle longshore currents.

The paler, cleaner, cross-bedded sandstones were clearly deposited under higher energy conditions closer to the shore, either on the upper shoreface or as coalescent distributary mouth bars and distributary channels. The unimodal, southward palaeocurrents obtained in the Gamka Formation seem to favour the latter possibility, since Reineck and Singh (1973, p.305) note that the cross-bedding of the upper shoreface shows a maximum toward the land, with a second maximum parallel to the shoreline. In addition there is much dispersion in the values. Furthermore, cross-bedding is very rare toward the deeper part of the shoreface (Reineck and Singh, op.cit.). The two distinct palaeocurrent modes encountered in the Boplaas Sandstone east of Willowmore may represent a combination of longshore drift in the upper shoreface zone and deposition in distributary channels aligned at right angles to the shore. Alternatively, the second mode may have been produced by rip currents in the shoreface zone (cf. Masters, 1967, Fig.11).

According to Csáky and others (1969, p.43), the clean sandstones include sequences deposited by streams in a deltaic or tidal environment. They also refer to sands deposited in a beach or offshore bar environment, but would appear to restrict these to the northern outcrops in the western Cape Province. No good examples of the "beach accretion bedding" (Ball, 1967, Fig.36) characteristic of the foreshore were found in the study area.

The Traka Subgroup

At first sight the succession Karies Shale- Adolphspoort Siltstone-Sandpoort Shale could be taken to signify a progressive decrease in water depth, and hence a transition from the pro-delta (shelf) environment, through the pro-delta slope to the outer delta-front platform (cf. Theron, 1972, p.151). However, the three distinct, laterally extensive, sandstone lithosomes in the upper half of the Karies Shale must have been deposited near the shore (lower shoreface or transition zone); there would be no way of accounting for them in the pro-delta environment short of transport by turbidity currents (for which there is no direct evidence). This means that the associated mudrocks must in fact represent deposition in the adjacent offshore area, with the general fineness of grain and presence of micrograding indicating fairly deep, quiet water in the outer offshore area. The writer is unable to agree with Csáky and others (1969, p.26) that these strata are unfossiliferous as a result of being deposited in high energy shallow water depositional environments.

If the above line of reasoning is correct, it would seem to follow that the Adolphspoort Siltstone was largely deposited under transitional zone conditions in shallower water than the bulk of the underlying formation. It is, however, more likely that it represents the pro-delta slope deposits of an advancing delta being built up over "conventional" epicontinental sea deposits, represented by the Karies Shale. This interpretation is supported by the strong contrast between the homogeneous Adolphspoort Siltstone and the heterogeneous Sandpoort Shale (characterised by the presence of coarsening-upward cycles, with the lithology ranging from dark, relatively fine-grained mudrock through reddish streaky rhythmitite to fine-grained sandstone). A definite change in depositional environment is implied by the contrast between the Karies and Adolphspoort Formations, which is difficult to account for if both formations were deposited in or near the transitional zone of an epicontinental sea. The substantial thickness of the Adolphspoort Siltstone also supports a deltaic hypothesis.

From the above discussion it would appear that the Sandpoort Formation was deposited on the subaqueous delta-front platform. A substantial proportion of these sediments could have been deposited in various sheltered shelf environments (tidal flat, bay, etc.) since streaky rhythmitites are common in these environments. Some of the dark mudrocks could represent bay or marsh muds.

E 3. Provenances

Theron (1972), while postulating a northern "Winterberg Mountainland" (Fig. 66) as a source of the Bokkeveld sediments in the writer's study area, does not speculate directly on the lithological character of this source area. Csåky and others (1969) also postulate a source area (or source areas) to the north of the basin. The latter authors (p.13, 17) state that the source area(s) were probably of granitic composition, in view of the abundance of quartz, feldspar and mica and the paucity of lime and limestone. The present writer knows of no sound reasons for disagreeing with this interpretation.

CHAPTER XIII

WITTEBERG GROUP

A. STRATIGRAPHY

A 1 General stratigraphic interrelationships

A 1.1 Lithostratigraphic interrelationships

See Folder 1, as well as Section A 1.1 under the Bokkeveld Group.

The Skitterykloof Member of the Witpoort Sandstone (not depicted on Folder 1) is sporadically present at the top of the Perdepoort Member.

A 1.2 Chronostratigraphic relationships

According to Theron (1972, p.120) flora from the Traka Subgroup and basal Witteberg beds indicate a Middle Devonian age. Palaeoniscoid fish from the Upper Witteberg (Waaipoort Formation) point to a Lower Carboniferous (Visean) age (Gardiner, 1969). A Late Devonian to Early Carboniferous age for the Witteberg Group thus seems the most likely possibility in the light of our present knowledge.

A 2 Basic concepts and distinguishing features

Witteberg Group.- Siliceous ultra-quartzose sandstone plus generally micaceous streaky rhythmitite and mudrock.

Weltevrede Formation.- Grey (reddish-weathering), micaceous, streaky rhythmitite lithosomes plus subordinate pale grey, fine-grained, siliceous, ultra-quartzose sandstone lithosomes, generally occurring in the form of coarsening-upward cycles. Two distinct facies variants can be recognised:

a. Northern facies: Characterised by abundance of prominent thick sandstone lithosomes, abundance of cross-bedding in the sandstone, and relatively large total thickness (800 m +).

b. Southern facies: Distinguished from the above facies by the considerably reduced relative abundance of sandstone, thinness of sandstone lithosomes, virtual absence of cross-bedding in the sandstone, and much reduced total thickness (about half that of the northern facies).

Driekuilen Sandstone Member.- Grey, fine-grained, siliceous, slightly feldspathic quartzose sandstone.

writer (1966, p.20). Both the writer and Theron (1972) accorded formation status to the Driekuilen and placed it within the Bokkeveld Group. Recent work has however established the equivalence of the Driekuilen and the basal Witteberg sandstone units of the western Cape Province (see A 1.1 under Bokkeveld Group). The name was obtained from the farm Driekuilen east of Steytlerville (W13), on which the type section is located.

Blinkberg Sandstone Member.- A prominent group of sandstones roughly 120 m thick, the top of which lies about 400 m below the top of the Weltevrede Formation, has been tentatively correlated with the Blinkberg Sandstone of the western Cape Province. The name Blinkberg was proposed by J.N. Theron (personal communication) and was derived from a geographic feature in the western Cape Province.

Witpoort Sandstone.- This formation has been described in some detail in the eastern Cape Province by a number of workers, e.g. Mountain (1946, 1962), Meyer (1965), Johnson (1966), Wright (1969). In the past there has been no consistency in the naming of this unit. Mountain (1946) refers to this formation as the "Witteberg Series", since he included the underlying shaly strata with the Bokkeveld Group and the overlying strata with the Lower Dwyka shales. Du Toit (1954, p.261) refers to it as the "main quartzites of the Witteberg". Theron (1962, p.374) talks of the "Main Sandstone" (which in turn forms the uppermost three-quarters of the "Main Witteberg"). The present writer referred to these sandstones in 1966 (p.23 ff.) as "The Witteberg Quartzites". Loock (1967, p.17) proposed the name "Wittepoort Formation", but since only the atypical uppermost member appears to be present at Wittepoort itself (north of Alicedale), the name was hardly ideal. Loock (personal communication) has now proposed that "Witpoort Sandstone" be used, the name being derived from the Witpoort on the Dwyka River west of Prince Albert.

The names Rooirand Sandstone Member and Skitterykloof Member were both supplied by Loock (personal communications to Cape working group) and obtained from geographic features west of the study area. The name "Perdepoort Sandstone Member" (from the Perdepoort north of Willowmore) is here proposed as a substitute for the so-called "White Streak" (Afrikaans: "Witstreep") of Rossouw and others (1964, p.27).

Lake Mentz Subgroup.- The term "Lake Mentz Shales" (derived from the Lake Mentz dam on the Sundays River - W14) was used by the present writer (1966) to encompass all the strata lying between the top of the main Witteberg quartzites and the Miller Diamictite (i.e. the "Upper Witteberg shales" of Rossouw (1953, p.16) and other workers). This usage was followed by Loock (1967). However, a formal stratigraphic distinction has now been drawn between the basal shale unit (Kweekvlei Shale), an overlying cyclic succession characterised by red colours and quartzitic sandstones (Floriskraal Formation) and an upper non-cyclic, non-red assemblage of largely argillaceous strata (Waaipoort Formation). This has necessitated raising the rank of the Lake Mentz Shale, which now becomes the Lake Mentz Subgroup.

Prior to 1953 it had been customary to recognise both an Upper Witteberg Shale unit and a Lower Dwyka Shale unit (cf. Rogers, 1902; Rogers and Du Toit, 1909; Du Toit, 1926, 1939, 1954). The boundary between these two units was located at the top of the uppermost Witteberg quartzite lithosome. In 1953 Rossouw (p.16) proposed that the old "Lower Dwyka shales" be included with the Upper Witteberg, while Du Toit (1926, p.198, 207) had previously expressed a similar opinion. However, Rossouw still regarded the so-called "basal tillite" (Miller Diamictite) as part of the Dwyka Series which thus also embraced the overlying Soutkloof Shale and Dirkskraal Siltstone. Many years previously Haughton (1928, Cape Sheet 9) had taken Loock's (1967) Swartwaterspoort Sandstone - which occurs at the same stratigraphic level as the "basal tillite" - as the uppermost quartzite of the Witteberg Series (at least in those areas where it is present). As a result the Witteberg-Dwyka boundary which Rossouw proposed in 1953 merely brought the situation into line with what Haughton had already depicted on his map of 1928 - although it is fairly certain that nobody was aware of the fact at the time.

Kweekvlei Shale.- The first description of this unit as a laterally extensive subdivision of the "Upper Witteberg" in the study area is given by Rossouw (1953, p.16). The Cape working group of the South African Committee for Stratigraphy has proposed the name "Kweekvlei Shale", obtained from the name of a farm on the outskirts of Prince Albert.

Floriskraal Formation.- Loock (1967, p.35; Table 1) introduced the term "Floriskraal Sandstone Member" as a collective name for the four quartzitic sandstone units present in the Lake Mentz Subgroup at the Floriskraal Dam south-east of Laingsburg, with the interbedded shale units plus the present Kweekvlei Shale being termed the Leeukloofpoort Shale (p.34). The Cape working group of SACS has now decided to assign the name "Floriskraal Formation" to the group of quartzitic sandstones and interbedded "shale" units overlying the Kweekvlei Shale. In the western part of the study area the most prominent component of this formation is the so-called "cross-bedded quartzite" of Rossouw (1953, p.16, 19).

Waaipoort Formation.- The name of this formation was derived from Waaipoort (W 12) on the Steytlerville-Baroe road; the type section is located near the northern entrance to this poort. This unit corresponds to the third subdivision of the "Upper Witteberg" recognised by Rossouw (1953, p. 19).

Kommadagga Subgroup.- Loock (1967) proposed the name "Kommadagga Formation" to embrace his "Dirkskraal Sandstone Member" and "Dirkskraal Shale Member". However, since two quite distinct lithological entities are involved, the above-mentioned "members" clearly constitute separate formations. On the other hand, in view of the relative thinness of each of these formations, it would be convenient for map representation if some form of grouping could be effected. In addition, Loock (p. 25) points out that "the Kommadagga Formation, with its 'Karroo' appearance can be distinguished from the Lake Mentz Formation by its rocks having a better sorting and less mica and by its tendency to remain darker when weathered". As a compromise, it is proposed that the basic sense of Loock's Kommadagga Formation be retained, but that the rank be raised to subgroup. Since Loock interprets the mud-, silt- and sandstones of the Kommadagga Formation as proglacial sediments produced during the initial stages of glaciation, it is clear that the Miller Diamictite, together with the overlying (or interbedded) Swartwaterspoort Sandstone will also have to be included in the Kommadagga Subgroup. Had Loock been aware that the so-called "basal tillite" of the Willowmore area (Rossouw, 1953) is present at the base of his Kommadagga Formation in the area south of Kommadagga, it would have considerably strengthened his arguments for placing the Cape-Karoo contact where he did. In addition, it would then also have been clear that the strata concerned do not extend much farther west than Willowmore and that the correlation of strata at Droëkloof and Floriskraal with the Kommadagga Formation (Loock, 1967, Table 1) would be untenable.

The name Kommadagga is derived from Kommadagga station north-west of Alicedale.

Venter (1969, p. 13) used the term Kruidfontein Formation to designate the same group of strata that are included in the Kommadagga Subgroup. However, the name Kruidfontein is already in use for a carbonatite body in the Transvaal (Verwoerd, 1965, p. 153).

Miller Diamictite.- The first description of this unit appeared in Rossouw (1953, p. 20) who refers to it as the "basal tillite". Since it attains its maximum thickness in the vicinity of the farm Kruidfontein (north of Willowmore), where good representative exposures also occur, "Kruidfontein" was originally felt to be the most suitable designation. However, as pointed out above, a Kruidfontein Carbonatite already exists, and an alternative name had to be found; representative (though incomplete) exposures occur near Miller station (W9) and this name has accordingly been assigned to this unit.

Swartwaterspoort Sandstone.- Haughton (Cape sheet 9) appears to have regarded the Swartwaterspoort Sandstone as the uppermost quartzite of the Upper Witteberg, and in the area north of Swartwaterspoort at any rate he mapped it as the Upper Witteberg - Lower Dwyka boundary. This sandstone was actually first regarded as a distinct mappable (or at least laterally traceable) entity by Loock (1967) who assigned the name "Swartwaterspoort" to it because of the presence of typical exposures north of the Swartwaterspoort gorge 15 km west of Riebeeck-East (W18). Although Rossouw (1953, p.20) notes the sporadic presence of quartzitic sandstone lenses closely associated with the "basal tillite", he does not appear to have regarded them as forming a stratigraphic unit. Loock, on the other hand, miscorrelated this unit in his western sections through failure to take account the descriptions given by Rossouw for Lake Mentz - Kommadagga strata in the Willowmore-Steytlerville area as well as the partly unconformable nature of the Dwyka Tillite basal contact.

Soutkloof Shale.- This unit was first recognised and described by Rossouw (1953, p.20, 21) who informally refers to it as "the fissile shale". Loock (1967, p.23) named it the "Dirkskraal Shale". However, since it is not admissable to use the same geographic name for more than one lithostratigraphic unit, and since it was decided to retain Loock's "Dirkskraal Siltstone" (Dirkskraal Sandstone), another name had to be found. The name Soutkloof (suggested by Loock - personal communication) was derived from the Soutkloof stream south of Kommadagga (W17), in and near which exposures displaying the typical appearance of the strata occur.

Dirkskraal Sandstone.- This sandstone was first described as a distinct entity by Rossouw (1953, p.21) but it was not named. Loock (1967, p.23) assigned the name "Dirkskraal Siltstone" to the unit under discussion and included it in his "Kommadagga Formation". However, grain-size analyses of typical samples from this formation give mean sizes that fall in the very fine to medium sand classes; "Dirkskraal Sandstone" is hence more correct, and has been adopted in this text. The name was derived from the farm Dirks Kraal south of Kommadagga (W17) on which typical exposures occur.

A 5. Boundaries

Traka Subgroup - Weltevrede Formation

Nature of boundary.- Conformable: gradational on local scale. Transition zone: 1 - 2 m.

Definition of boundary.- The actual selection of this boundary (which constitutes the base of the Witteberg Group) has occasioned some difficulty in the past. According to Haughton (1969, p.341), "the boundary between the two [i.e. Bokkeveld and Witteberg] has for almost a century been drawn at the base of the first prominent white-weathering sandstone". In the area east of Steytlerville, this would probably have meant placing the boundary at the base of the Driekuilen Sandstone. However, Theron (1972, p.53) stated that the contact is best defined by the "first arenaceous unit characterised by specific petrographic attributes". Although he mentions a "distinctive increase in the brookite percentage upwards from the base of the Bokkeveld Group to the lower Witteberg", Theron does not in fact present an unequivocal definition of the boundary in terms of brookite percentages (or in terms of any other "specific petrographic attributes"). Nevertheless, on the basis of his heavy mineral data Theron assigned the Driekuilen Sandstone to the Bokkeveld Group, taking a higher sandstone unit as the base of the Witteberg Group. Certain other considerations (e.g. the grey rather than white appearance of the sandstone) also influenced his decision (Theron, personal communication). However, the physical correlation of the Driekuilen Sandstone with the basal Witteberg sandstones of the Western Cape Province (see section A 1.1 in the previous chapter) has finally resolved this problem and confirmed that the Driekuilen Sandstone does in fact represent the first Witteberg sandstone unit.

Weltevrede Formation - Witpoort Sandstone

Nature of boundary.- Conformable: sharp/intercalated. Transition zone: 0 - 50 m. In general, the boundary is fairly sharp and abrupt in the eastern area (Grahamstown) but much less well-defined towards the west.

Definition of boundary.- Horizon above which sandstone is conspicuously more abundant than argillaceous sediments (i.e. mudrock and streaky rhythmitite).

Witpoort Sandstone - Kweekvlei Shale

Nature of boundary.- Conformable: sharp/intertongued. Transition zone (where boundary is intertongued) is a few metres thick.

Definition of boundary.- Base of thick mudrock unit overlying quartzitic sandstone succession.

Kweekvlei Shale - Floriskraal Formation

Nature of boundary.- Conformable: gradational/intertongued. Transition zone 2 - 20 m.

Definition of boundary.- Base of first Floriskraal quartzitic sandstone unit or horizon above which well-developed, reddish-weathering "streaky" rhythmitite predominates.

Floriskraal Formation - Waaipoort Shale

Nature of boundary.- Conformable, sharp (?) or transitional (intertongued/gradational; transition zone up to 50 m).

Definition of boundary.- Top of uppermost whitish quartzitic sandstone. Difficulty can arise where the last cyclic sandstone unit is overlain by further clearly cyclic sediments (including red-weathering rhythmitite) which do not include the sandstone member of the cycle. If these sediments reach a significant thickness they should be included with the Floriskraal Formation.

Waaipoort Shale - Miller Diamictite

Nature of boundary.- Conformable (?), sharp.

Definition of boundary.- Shale-diamictite contact.

Miller Diamictite - Swartwaterspoort Sandstone

Nature of boundary.- The relationship between these two formations is a complex one due to the lenticular, discontinuous nature of the sandstone as well as the generally chaotic and disturbed nature of the bedding. In general, the boundary between sandstone and diamictite is a sharp one.

Swartwaterspoort Sandstone - Soutkloof Shale

Nature of boundary.- Conformable: sharp/gradational (transition zone less than 2 metres). The actual contact was only seen at one locality, where the Swartwaterspoort grades upwards into Soutkloof Shale via a few metres of gritty, diamictite-like material. Where (and if) this material is absent, the contact is presumably a sharp one, although this situation was never seen in actual practice.

Definition of boundary.- Top of whitish sandstone unit.

Miller Diamictite - Soutkloof Shale

Nature of boundary.- Conformable (sharp/gradational; transition zone less than one metre thick).

Definition of boundary.- Horizon separating diamictite and shale.

Soutkloof Shale - Dirkskraal Sandstone

Nature of boundary.- Generally conformable (gradational/intertongued; transition zone 5 - 10 m). Less commonly sharp (even, flat surface), possibly unconformable.

Definition of boundary.- Horizon above which sandstone is predominant.

A 6. Overall Lithology

Weltevrede Formation

Northern facies (Waaipoort, W12):

Sandstone: 30 - 40%
Streaky rhythmitite/mudrock: 60 - 70%

Southern facies (Losberg, W13)

Sandstone: ± 20%
Streaky rhythmitite/mudrock: ± 80%

Witpoort Sandstone, Rooirand Member (Waaipoort, W 12)

Sandstone: 94%
Mudrock/streaky rhythmitite: 6%

Witpoort Sandstone, Perdepoort Member

Sandstone: 100%

Witpoort Sandstone, Skitterykloof Member

Sandstone: 60 - 90%
Mudrock/rhythmitite: 10 - 40%

Witpoort Sandstone, eastern area (Grahamstown)

Sandstone: 95 - 98%
Streaky rhythmitite/ mudrock: 2 - 5%

Kweekvlei Shale

Mudrock: ± 70%
Streaky rhythmitite: ± 30%

Floriskraal Formation

Sandstone: 20 - 50%

Mudrock/streaky rhythmitite:	50 - 80%

Waaipoort Formation

Sandstone:	10 - 15%
Streaky rhythmitite/mudrock:	85 - 90%

Miller Diamictite

Diamictite:	100%

Swartwaterspoort Sandstone

Sandstone:	100%

Soutkloof Shale

Sandstone:	0 - 10%
"Varved" rhythmitite:	30 - 60%
Streaky rhythmitite:	20 - 50%
Mudrock:	10 - 20%

Dirkskraal Sandstone

Sandstone:	90 -100%
Mudrock/rhythmitite:	0 - 10%

A 7. Dimensions and shape

Thickness data

Weltevrede Formation.- Minimum thicknesses of 685 m (± 50 m) and 600 m (± 50 m) were obtained for the northern facies at Vledermuis Poort (W7) and Waaipoort (W12) respectively. In neither case could the sections be extended as far as the Driekuilen Sandstone Member (which constitutes the base of the formation). However, a few km south of the first locality what appears to be the Driekuilen Sandstone crops out about 120 m below a persistent sandstone unit at which the northern section commenced. Further to the west (W6) the Driekuilen Sandstone itself possesses a minimum thickness of 50 m. A total thickness of about 850 m (± 50 m) is thus indicated for the Weltevrede Formation. An additional check on this thickness is afforded by the fact that the Blinkberg Sandstone Member can apparently be identified in both sections; since the thickness of the interval between the Driekuilen Sandstone and the top of the Blinkberg Sandstone west of Willowmore and west of Prince Albert is about 400 m (calculated for near-vertical outcrops from aerial photographs), and since the thickness of the material above the Blinkberg Sandstone at W7 and W12 is also about 400 m, a total thickness of about 800 m is again obtained.

At Losberg (W 13) the southern facies was estimated to be about 450 m (± 50 m) thick. The Driekuilen Sandstone Member is here about 60 - 70 m thick. For the area south-west of Grahamstown D.K. Toerien (unpub. report) also gives a thickness of 450 m.

The Blinkberg Sandstone Member is about 120 m thick at both W7 and W12.

Witpoort Sandstone.- Between 23° and 25°E four measurements (various sources) gave thickness values varying from 275 to 335 m (average 300 m). Mountain (1946, p.14) quotes a figure of 730 m measured east of Grahamstown while D.K. Toerien (unpublished report) gives thicknesses of 850 m and 885 m obtained west of Grahamstown. A marked eastward increase in thickness thus appears to have taken place. Meyer (1965, p.46) mentions a thickness of over 1200 m measured west of Alicedale. While this value seems unlikely to be correct, Meyer's suggestion that drag-folding could be responsible for this abnormal thickness also does not seem very plausible.

The Perdepoort Member varies from 30 to 60 m in thickness.

Lake Mentz Subgroup.- According to Rossouw (1953) a mean thickness of 325 m was obtained in the area west of Miller station (W 9), and an average of 360 m between Miller station and Waaipoort (W 12). The writer measured 400 m (± 25 m) at Waaipoort, the Kweekvlei Shale being about 25 m thick, the Floriskraal about 40 m and the Waaipoort Formation about 340 m. Rossouw (1953) noted a progressive increase in the thickness of the basal shale unit underlying a prominent "cross-bedded quartzite" marker (part of the Floriskraal Formation) from 50 m at Waaipoort (W 12) to 140 m west of Miller station (W 9). The cross-bedded quartzite itself averages about 10 m. Since the basal shale unit is more or less equivalent to the Kweekvlei Shale, this unit must increase markedly in thickness towards the western edge of the study area at the expense of the Waaipoort Formation (since the total thickness of the Lake Mentz Subgroup remains more or less constant).

For the eastern area (south of Kommadagga, W 17) Loock (1967, Table 1) reports a total thickness of 2115 feet (645 m) for the Lake Mentz Subgroup; his basal shale unit (the Kweekvlei Shale) is 740 feet (225 m) and the overlying white sandstones and micaceous shales 255 feet (80 m). However, outcrop width and dip angles shown on the map (Fig. 2) accompanying the text correspond to much smaller thicknesses. Recalculation of the Lake Mentz thickness using aerial photographs gave a value of 510 m.

East of Grahamstown, Mountain (1946, p.16) obtained a total Lake Mentz-Kommadagga thickness of 550 m.

At the Beervlei Dam north of Willowmore (W5) a thickness of only 190 m was obtained, but it is probable that pre-Dwyka erosion was responsible for removing a substantial thickness of Waaipoort strata originally present.

Kommadagga Subgroup.- According to Rossouw (1953, p.20) this unit reaches a maximum total thickness of 435 m (Dirkskraal Sandstone: 175 m; Soutkloof Shale: 165 m; Miller Diamictite: 95 m) at Kruidfontein north of Willowmore (W2). However, in the same area the writer obtained a thickness of only 110 m for the Dirkskraal Sandstone.

A general eastward decrease in the thicknesses of the Kommadagga Subgroup takes place. At Kamferspoort (W 10) it is 205 m (Rossouw, 1953: 245 m). Individual thicknesses are as follows: Dirkskraal Sandstone: 57 m (Rossouw: 100 m); Soutkloof Shale: 145 m; Miller Diamictite: 3m. At Waaipoort (W12) 97 m was obtained (Dirkskraal Sandstone: 42 m; Soutkloof Shale: 46 m; Miller Diamictite: 9 m). In the Kommadagga area (W17), Loock obtained a total thickness of 260 m, made up as follows: Dirkskraal Sandstone, 107 m; Soutkloof Shale, 146 m; Swartwaterspoort Sandstone, 6 m. D.J. Roby (personal communication) obtained slightly lower thicknesses for the Soutkloof Shale and Dirkskraal Sandstone in the same general area, while the Miller Diamictite was found to be about 6 m thick (maximum).

Witteberg Group.- Total Witteberg Group thicknesses of 1650 m (± 100 m) and 1730 m (± 150 m) were obtained for the Waaipoort (W12) and Grahamstown areas respectively.

Lateral extent and shape of units

With the exception of the Kommadagga Subgroup all the formations and members of the Witteberg Group extend from west of Touws River in the western Cape Province to at least the Waaipoort (W 12) - Losberg (W 13) area east of Steytlerville, a distance of about 450 km. The Witpoort Formation extends the entire length of the Witteberg Group outcrop area, a distance of over 700 km, while the Weltevrede Formation probably also continues all the way to the easternmost Witteberg Group outcrops (total outcrop length over 650 km). While the Lake Mentz Subgroup also extends as far as the easternmost outcrops it is not certain whether the Kweekvlei, Floriskraal and Waaipoort Formations can be distinguished east of 26°30'E (which corresponds to a minimum lateral extent of over 600 km).

The Kommadagga Subgroup is known to be present between 23°10'E and 26°30'E (a distance of 300 km) and probably extends farther eastwards. While the Soutkloof Shale is present throughout this distance, the remaining units are not present everywhere (although all 4 units are present at both extremities of the outcrop area).

From the above data it can be seen that all the Witteberg units possess a markedly tabular shape in an east-west direction. This is especially evident in the case of the thinner units (Driekuilen Sandstone Member, Blinkberg Sandstone Member, Perdepoort Sandstone Member, Kweekvlei Shale, Floriskraal Formation) where thicknesses in the order of 100 m or less and horizontal distances of 450 - 650 km are involved, giving width/thickness ratios of 5000 or more and negligible thickness change rates. Apart from the Kommadagga Subgroup (where pre-Dwyka erosion is involved), significant thickness change rates could be calculated for the Weltevrede Formation between Waaipoort (W 12) and Losberg (W 13) (20 m/km) and for the Witpoort Formation between Waaipoort (W 12) and Grahamstown (W 20) (2,5 m/km).

A 8. Stratotypes

Weltevrede Formation

Unit-stratotype.- The unit-stratotype is located beyond the western edge of the study area on the farm Weltevrede near the Gamka Dam west of Prince Albert (J.C. Loock, personal communication).

Reference stratotype 1.- Vledermuis Poort (W 7)

Nature of stratotype: Reasonably continuous natural exposures across steeply dipping strata up the flank of a hill. Lower contact probably not present.

Accessibility: Good.

Location: See Fig. XIII-1a.

Reference stratotype 2.- Losberg (W 13)

Nature of stratotype: A series of natural exposures (not complete) across steeply-dipping strata on the southern flank of Losberg hill.

Accessibility: Fair.

Location: See Fig. XIII-1b.

Reference stratotype 3.- Waaipoort (W 12)

Nature of stratotype: A series of fairly continuous natural exposures up the flank of a hill as well as in the bed of the Soutkloof stream. Lower contact uncertain. Strata are steeply dipping.

Accessibility: Fair/Good.

Location: See Fig. XIII-1c.

Driekuilen Sandstone Member

Unit-stratotype.- Driekuilen, south of Losberg (W 13)

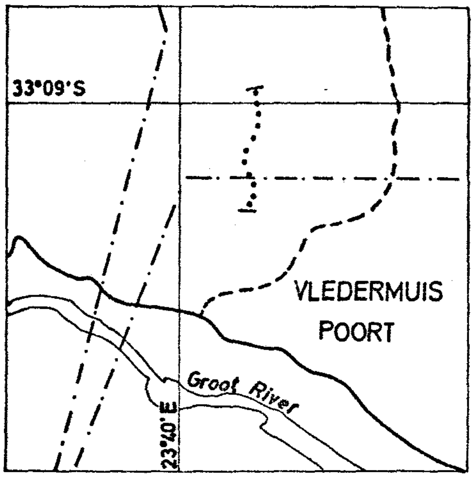
Nature of stratotype: Fairly fresh outcrops in the bed and bank of the Erekroons stream.

Accessibility: Fair.

FIG XIII-1
STRATOTYPES : WITTEBERG GROUP

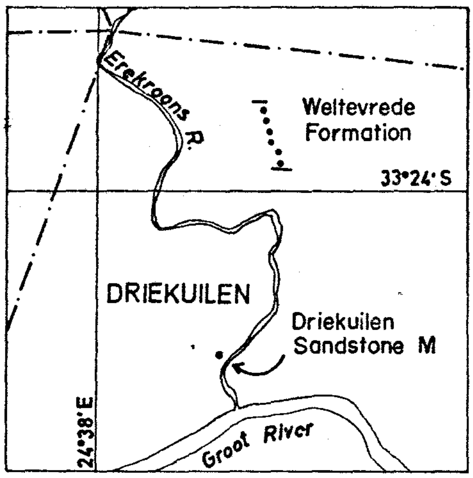
SCALE OF MAPS : 1: 50000

••••••• Stratotype
——— – – Road
≈≈≈ River
–·–·–· Farm boundary



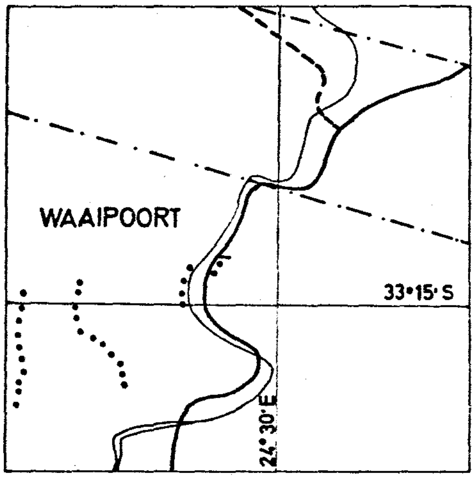
a. Weltevrede Formation
Reference stratotype I.

Map ref.: 3323 BA

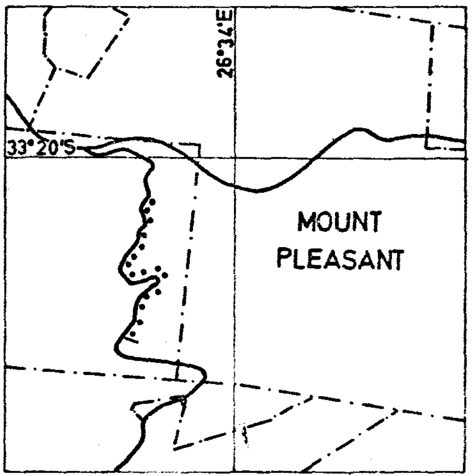


b. Weltevrede Formation. | Driekuilen M.
Reference stratotype 2. | Unit-stratotype

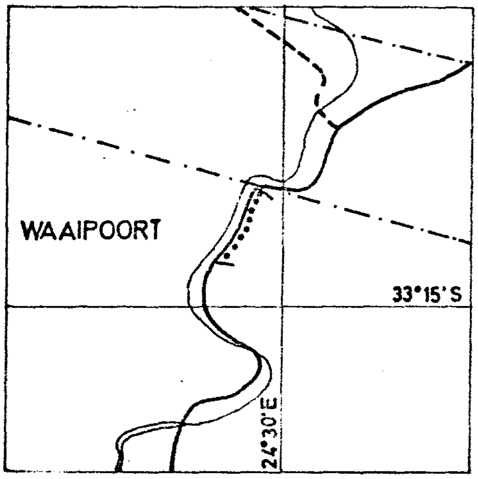
Map ref. 3324 BC



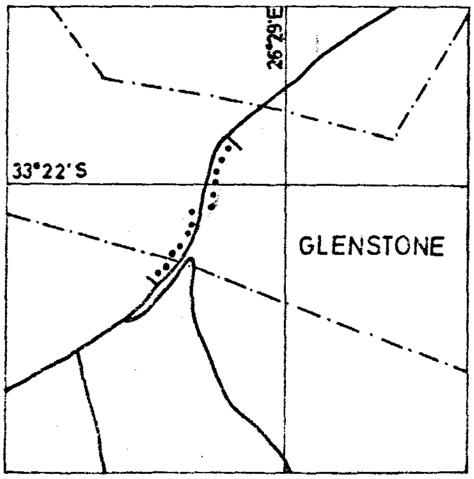
c. Weltevrede Formation.
Reference stratotype 3.
Map. ref.: 3324 AB, AD, BA, BC



d. Witpoort Sandstone
Reference stratotype I.
Map ref.: 3326 BC



e. Witpoort Sandstone
Reference stratotype 2
Map ref.: 3324 AB, AD, BA, BC



f. Witpoort Sandstone
Reference stratotype 3
Map ref.: 3326 AD

Location: See Fig. XIII-1b.

Blinkberg Sandstone Member

Unit-stratotype.- Blinkberg mountain in the western Cape Province (J.C. Loock, personal communication).

Witpoort Sandstone

Unit-stratotype.- The Witpoort on the Dwyka River west of Prince Albert (J.C. Loock, personal communication).

Reference stratotype 1.- Wuest Hill Pass (W 21)

Nature of stratotype: Fresh, continuous exposures across lower half of formation in road cuttings; dips are moderately steep. A few typical but isolated exposures of the upper half of the formation occur in road cuttings alongside the main road to Port Alfred a few km east of the section in Wuest Hill; these exposures can be considered to form a part of the stratotype.

Accessibility: Excellent.

Location: See Fig. XIII-1d.

Reference stratotype 2.- Waaipoort (W 12)

Nature of stratotype: Fresh, continuous exposures in road cuttings through the whole formation (including the upper and lower contacts). Strata approximately vertical.

Accessibility: Excellent.

Location: See Fig. XIII-1e.

Reference stratotype 3.- Howieson's Poort (W 20)

Nature of stratotype: Road cuttings through lowermost portion of formation; nature of bottom contact well displayed. Strata occur in an open syncline, and dip angles vary from sub-horizontal to moderately steep.

Accessibility: Excellent.

Location: See Fig. XIII-1f.

Rooirand Sandstone Member

Unit-stratotype.- The Rooirand range of hills in the vicinity of the Gamka Dam west of Prince Albert (J.C. Loock, personal communication).

Perdepoort Sandstone Member

Unit-stratotype.- Perdepoort north of Willowmore (W 3)

Nature of stratotype: Fresh exposures through whole succession in roadside quarry.

Accessibility: Excellent.

Location: Quarry east of road in Perdepoort 14,5 km north of Willowmore along Willowmore-Aberdeen road.

Skitterykloof Member

Unit-stratotype.- The Skitterykloof northeast of Ceres in the western Cape Province (J.C. Loock, personal communication).

Kweekvlei Shale

Unit-stratotype.- The farm Kweekvlei south of Prince Albert (west of the study area).

Floriskraal Formation

Unit-stratotype.- Below the Floriskraal Dam south-east of Laingsburg, west of the study area (J.C. Loock, personal communication).

Reference stratotype.- North of Waaipoort (W 12)

Nature of stratotype: Natural exposures in a shallow gully. Strata are steeply dipping.

Accessibility: Good.

Location: See Fig. XIII-2a.

Waaipoort Formation

Unit-stratotype.- North of Waaipoort (W 12)

Nature of stratotype: Series of almost complete, relatively fresh exposures adjacent to and in the bed of the Soutkloof stream and nearby gullies. Upper and lower contacts are both exposed. Strata are steeply dipping.

Accessibility: Excellent.

Location: See Fig. XIII-2b.

Miller Diamictite

Unit-stratotype.- North of Saltaire station (W 17)

Nature of stratotype: Fresh, continuous exposure of nearly the whole unit (basal part covered) in cliff face adjacent to stream. Dip angle moderately low.

Accessibility: Fair.

Location: See Fig. XIII-2c.

Reference stratotype.- North of Waaipoort (W 12). For details see Kommadagga Subgroup below.

Swartwaterspoort Sandstone

Unit-stratotype.- North of Swartwaterspoort (W 18)

Nature of stratotype: Natural exposure of major portion of unit (top and base covered). Dip angle moderately steep.

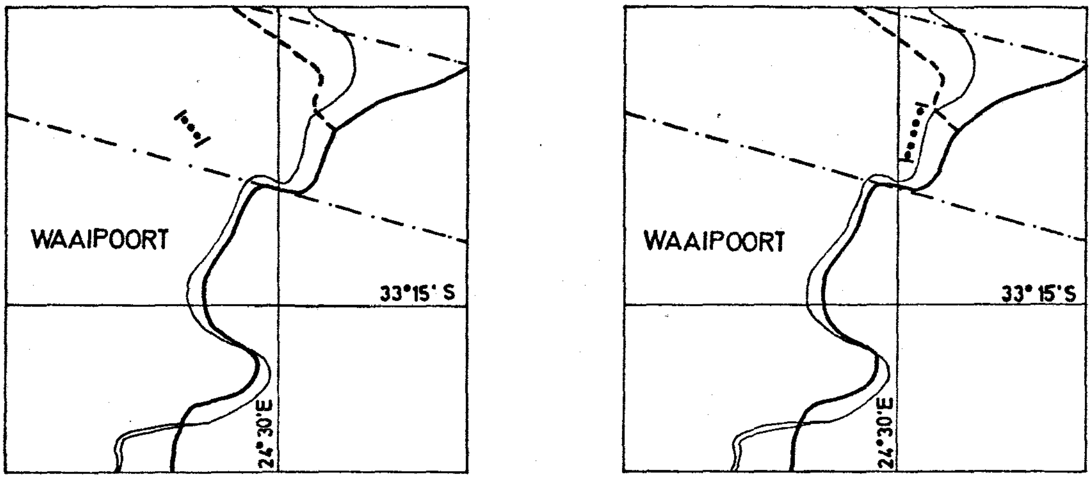
Accessibility: Good.

Location: See Fig. XIII-2d.

FIG XIII-2
STRATOTYPES: WITTEBERG GROUP

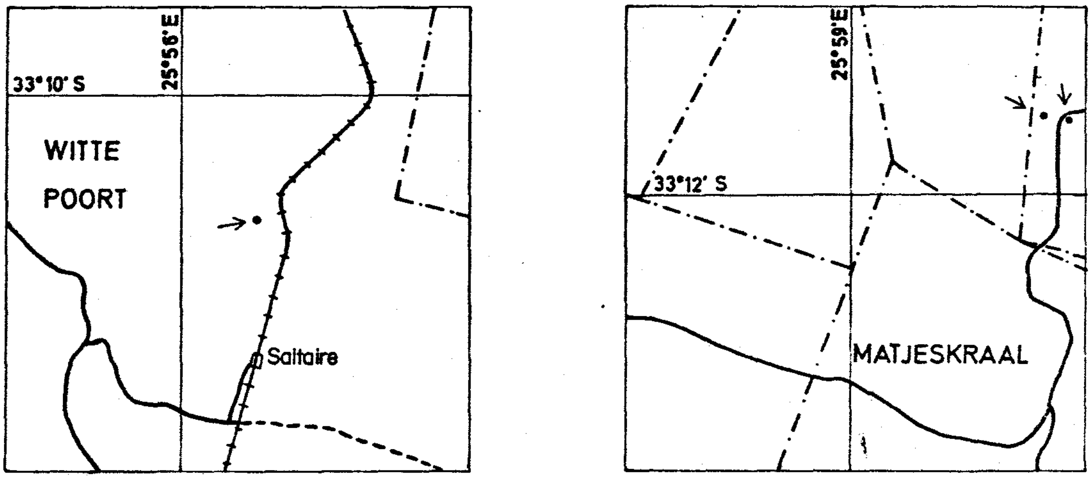
SCALE OF MAPS: 1:50000

• • • • • • Stratotype
— — — Road
River
— · — · — Farm boundary



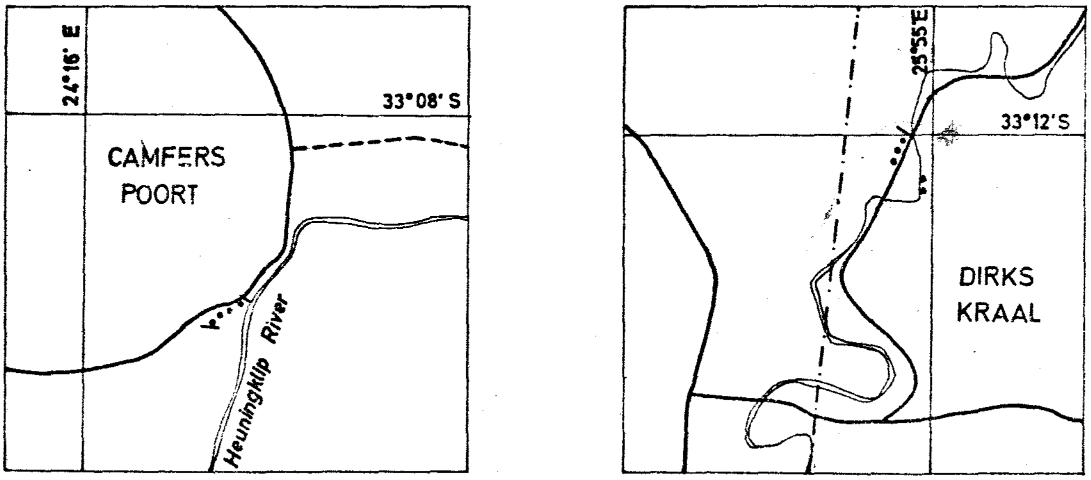
a. Floriskraal Formation
Reference stratotype
Map ref.: 3324 AB, AD, BA, BC

b. Waaipoort Formation
Unit-stratotype
Map ref.: 3324 AB, AD, BA, BC



c. Miller Diamictite.
Unit-stratotype
Map ref.: 3325 BB

d. Swartwaterspoort Sandstone
Unit-stratotype
Map ref.: 3325 BB



e. Soutkloof Shale
Reference stratotype
Map ref.: 3324 AB

f. Soutkloof Shale
Unit-stratotype
Map ref.: 3325 BB

Reference stratotype 1.- Dirks Kraal (W 17)

Nature of stratotype: Natural exposure of complete thickness of unit (including top and base). Typical features (chaotic bedding and inclusions) well displayed. This stratotype is in fact superior to the unit-stratotype. Dip angle moderately steep.

Accessibility: Good.

Location: Exposure adjoins lower (northern) contact of Soutkloof Shale on Fig. XIII-2f.

Reference stratotype 2.- North of Saltaire (W 17)

Nature of stratotype: Complete exposure (including top and bottom contacts) in cliff face. Chaotic bedding very well displayed. Dip angle moderately low.

Accessibility: Fair.

Location: Exposures overlie Miller Diamictite at the locality depicted on Fig. XIII-2c.

Soutkloof Shale

Unit-stratotype.- Dirks Kraal (W 17)

Nature of stratotype: Representative exposures of a major part of the succession (including basal contact with the Swartwaterspoort Sandstone) in a shallow road cutting and stream bank. Dip angle moderate. Tectonic disturbance is evident and a number of faults are present. The varve-like nature of the shale is well displayed.

Accessibility: Good.

Location: See Fig. XIII-2f.

Reference stratotype 1.- Kamferspoort (W 10)

Nature of stratotype: A series of isolated but representative exposures in a gravel pit and a series of shallow gullies. Base exposed; gradational upper contact partially exposed. Dip angle moderately steep.

Accessibility: Good.

Location: See Fig. XIII-2e.

Reference stratotype 2.- North of Waaipoort (W 12)

For details see Kommadagga Subgroup below. It should be borne in mind that at this locality the uppermost portion of the formation may have been removed by erosion prior to deposition of the Dirkskraal Sandstone.

Dirkskraal Sandstone

Unit-stratotype.- Dirks Kraal (W 17)

Nature of stratotype: Natural exposures of most of this unit adjacent to shallow stream bed. Dip angle moderate.

Accessibility: Good.

Location: See Fig. XIII-3a.

Reference stratotype 1.- North of Waaipoort (W 12)

For details see under Kommadagga Subgroup below. This reference section is significant in that the sandstone unit here possesses a sharp base and displays a fining-upward tendency.

Reference stratotype 2.- Modderfontein (W 16)

Nature of stratotype: Continuous series of exposures in a shallow roadcutting. Only upper contact is well exposed. Sandstone here is unusual due to its clean quartzitic nature near the top contact and the conspicuously speckled appearance of the remainder of the sandstone. Dip angle is moderately steep.

Accessibility: Good.

Location: See Fig. XIII-3b.

Kommadagga Subgroup (Miller, Soutkloof and Dirkskraal Formations)

Reference stratotype.- North of Waaipoort (W 12)

Nature of stratotype: Almost complete exposure of all three formations (including contacts) in and near a shallow stream bed. Dip angles are moderately high.

Accessibility: Excellent.

Location: See Fig. XIII-3c.

B. PALAEONTOLOGY

Fish remains have been recovered from a number of localities in the Waaipoort Formation (e.g. Marais, 1963). Some small, poorly preserved marine invertebrate fossils, including brachiopods and at least one trilobite species, have been found in the Weltevrede Formation near Grahamstown (W 20) by D.K. Toerien (personal communication). The streaky rhythmitites and thin sandstones in the Weltevrede Formation also contain numerous trace fossils (burrows, tubes, tracks and trails of various kinds). These include the distinctive "Spirophyton" (Zoophycus) illustrated by Theron (1962, Plate IIE-G) and Plumstead (1967, Plate XXII; 1969, Plate VI-8).

Plant stems, particularly proto-lycopods, occur in both the Weltevrede and Witpoort Formations.

C. MACRO-SEDIMENTOGRAPHY

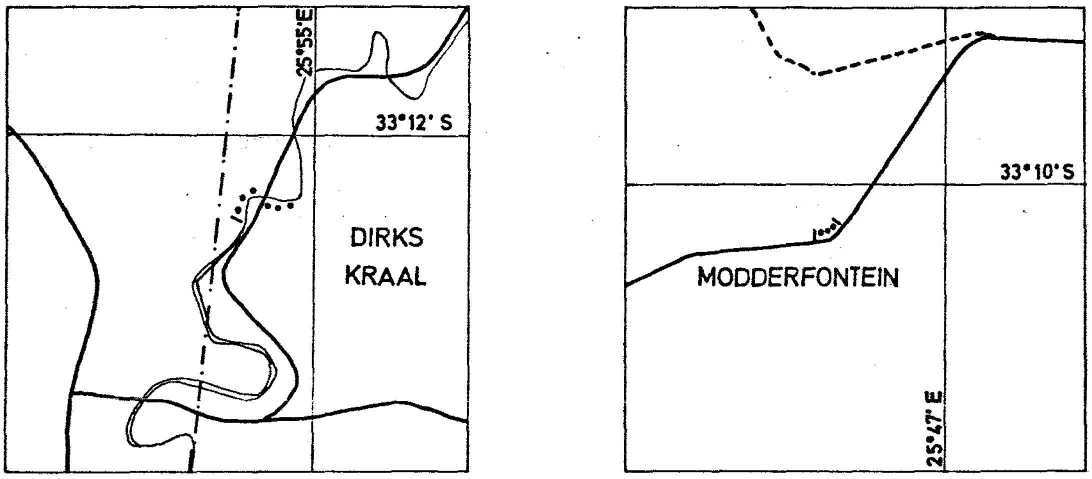
C 1. Cyclicity

Weltevrede Formation

Northern facies.- Distinct coarsening-upward cycles do not appear

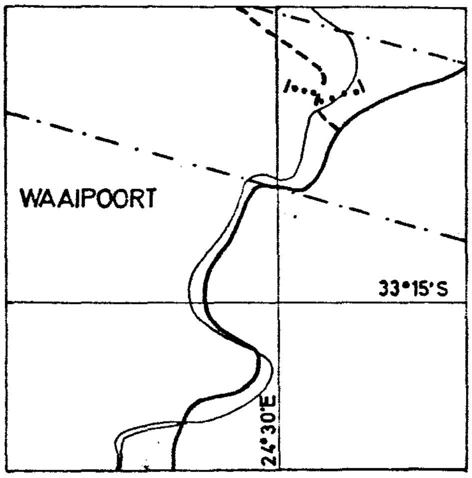
FIG XIII-3
STRATOTYPES: WITTEBERG GROUP

SCALE OF MAPS: 1:50000



a. Dirkskraal Sandstone
Unit-stratotype
Map ref.: 3325 BB

b. Dirkskraal Sandstone
Reference stratotype
Map ref.: 3325 BB



c. Kommadagga Subgroup
Combined reference stratotype
Map ref.: 3324 AB, AD, BA, BC

to be well developed. Instead, strata occur in the form of simple sandstone-mudrock/rhythmitite alternations, generally on two scales. The first involves the alternation of "major" sandstone units and "major" heterogeneous (predominantly argillaceous) units each a few metres to a few tens of metres thick; the second embraces the alternation of relatively minor sandstone and mudrock/rhythmitite zones (each a few decimetres to a few metres thick) within the "heterogeneous" units. The distinction between major and minor units is not always a clear-cut one, however.

Southern facies.- The succession here consists of both coarsening-upward cycles and simple sandstone - mudrock/rhythmitite alternations. The coarsening-upward cycles when complete are composed of micaceous silty mudrock (dark grey or black when fresh) at the base, grading upwards through micaceous streaky rhythmitites (usually reddish-weathering) into very fine-grained or fine-grained sandstones. These cycles generally vary from 3 m to 15 m in thickness (typically 6 - 8 m). Where distinct coarsening-upward cycles are absent strata occur as alternating argillaceous and relatively arenaceous zones, each zone generally being 2 - 6 m thick. Lateral extent and cross-sectional shape of cycles (or couplets) are not known, but they are probably reasonably tabular.

Lake Mentz Subgroup

At least one well-developed coarsening-upward cycle occurs at the base of the succession (embracing the Kweekvlei Shale and the lowermost sandstone of the overlying Floriskraal Formation) and the remaining Floriskraal strata may also in fact belong to less well-developed (incomplete) cycles. At Waaipoort (W 12) the main cycle is nearly 30 m thick, and from descriptions of the shale unit given in Rossouw (1953, p.16) and Loock (1967) it would appear to be considerably thicker elsewhere. The remaining "cycles" are thinner. The main cycle appears to continue right across the whole study area (± 300 km) which implies a moderately to highly tabular shape, at least in an east - west direction.

C 2. Lithosome dimensions and shape

Weltevrede Formation

Northern facies.- In general three main sandstone types can be recognised:

1. Major cross-bedded sandstones with an average thickness of about 15 m (maximum 34 m). These appear to be largely confined to the lower half

of the formation (i.e. the Blinkberg and Driekuilen Members). It seems possible to correlate the individual sandstone lithosomes between localities W7 and W12, a distance of about 80 km. This corresponds to a minimum average width/thickness ratio of 5 000 (i.e. a moderately tabular shape).

2. Major non-cross-bedded sandstones with an average thickness of about 8 m (maximum 36 m), characterising the upper half of the formation. These also appear to extend for considerable distances and would generally constitute good "marker" horizons; shape is probably moderately to highly tabular in most cases.

3. Minor sandstones. These are interbedded and intimately associated with the streaky rhythmitites and mudrocks, and vary from a few cm to one or two metres in thickness. Lateral extent could not be ascertained, but these lithosomes are normally parallel-sided and hence are presumed to be generally tabular in shape.

In general, major sandstones are thicker than one metre, and minor sandstones thinner than one metre.

Southern facies .- Only the second and third of the above three sandstone categories occur here. Thicknesses are considerably less, but shape factors are probably similar, although the presence of "lenticular" sandstones was noted.

Floriskraal Formation

In the Waaipoort - Losberg area (W 12, W 13) an average thickness of about 6m (maximum 10 m) was obtained for the three sandstone lithosomes present in this formation. According to Rossouw (1953, p.16), the most prominent sandstone unit (the so-called "cross-bedded quartzite") varies in thickness from 3 m to 23 m (average about 12 m) and extends from Waaipoort (W 12) to well beyond the western edge of the present study area, a total distance of about 200 km. This puts it in the highly tabular category. Not much is known about the lateral extent and shape of the remaining sandstone units, but they are probably also moderately tabular in an east-west direction.

Waaipoort Formation

"Sandstone" units are generally similar to the "minor sandstones" in the Weltevrede Formation (see above), although definite lenticular beds also occur. A group of thicker sandstones (total 22m) occurs about 70 m below the top of the formation at Waaipoort (W 12).

C 3. Lithosome boundaries

Weltevrede Formation

Major sandstones .- In the Losberg (W 13) area upper contacts of sandstones units are reasonably sharp (even, flat) while lower contacts are generally intertongued over a distance of a few cm to a few metres and thus transitional to the underlying rhythmitites. In the northern area boundary relationships are not as clear; in general sandstone lower boundaries are probably more transitional than upper boundaries except in the case of the major cross-bedded sandstone class where the reverse situation possibly applies. No information on lateral boundaries is available.

Minor sandstones.- Both upper and lower boundaries are generally intertongued on a small scale.

Floriskraal Formation

A well-developed intertongued transitional basal contact (extending over a few metres) and a fairly sharp upper contact characterises the main (lowermost) sandstone lithosome of this formation and although not as well-defined a similar situation probably obtains in the case of the remaining sandstone units as well. An incipient lateral pinch-out by interfingering was also observed in the case of the main sandstone unit at Waaipoort (W 12).

Waaipoort Formation

Upper and lower boundaries are normally intertongued on a small scale. Lenticular units may possess sharp, concave upwards lower boundaries.

C 4. Colours

Weltevrede Formation

Sandstone.- Waaipoort (W 12) : Varies from light olive grey (5Y6/1 or 5Y5/1) to medium light grey (N6); occasionally light grey (N7). Losberg (W 13): medium grey (N5) to light grey (N7) Occasionally light brownish grey (5YR6/1) or light olive grey (5Y6/1).

Streaky rhythmitite.- Generally medium grey (N5) to light olive grey (5Y6/1), brownish grey (5YR4/1) to light brownish grey (5YR6/1) or pale red (5R6/2) to greyish red (5R4/2). When completely fresh and unweathered brownish black (5YR2/1) or greyish black (N2) appear to be the true colours.

Mudrock.- Brownish black (5YR2/1) or greyish black (N2) weathering to various lighter hues eg. light olive grey (5Y6/1).

Witpoort Sandstone: Rooirand Member

Sandstone.- Waaipoort (W 12): Light olive grey (5Y6/1 or 5Y5/1) to medium light grey (N6). Grahamstown (W 20, 21): Medium light grey (N6) to light grey (N7). Weathered specimens light brownish-grey (5YR6/1) to pinkish grey (5YR8/1).

Streaky rhythmitite/mudrock.- Colours similar to those for Weltevrede Formation (see above).

Witpoort Sandstone: Perdepoort Member

Sandstone.- Light grey (N7), in places light brownish grey (5YR6/1). Near the upper boundary medium light grey (N6) to medium grey (N5) colours are present.

Witpoort Sandstone: Skitterykloof Member

Sandstone.- Light olive grey (5Y6/1) to medium light grey (N6).

Streaky rhythmitite/mudrock.- Colours similar to those of Weltevrede Formation (see above).

Kweekvlei Shale

Greyish black (N2) to blackish red (5R2/2) when fresh.

Floriskraal Formation

Sandstone.- Generally light olive grey (5Y6/1 or 5Y5/1) or, less commonly, medium light grey (N6) to light grey (N7).

Mudrock/streaky rhythmitite.- Colours similar to those occurring in the Weltevrede Formation (see above).

Waaipoort Formation

Sandstone.- Medium grey (N5).

Mudrock/streaky rhythmitite.- Mudrock and fine-grained rhythmitite components are generally dark grey (N3) but vary from moderately dark grey (N4) to greyish black (N2). Silty/sandy rhythmitite layers are generally medium grey (N5) but vary from medium dark grey (N4) to medium light grey (N6).

Miller Diamictite

Medium dark grey (N4) to dark grey (N5). Olive grey (5Y4/1) when weathered.

Swartwaterspoort Sandstone

Light grey/very light grey (N7/N8).

Soutkloof Shale

Medium dark grey (N4) to dark grey (N3).

Dirkskraal Sandstone

Medium light grey (N6) to medium grey (N5) to medium olive grey (5Y5/1).

C 5. Sedimentary structures

Weltevrede Formation (northern facies)

Major sandstones.- In the upper half of the formation (i.e. above the Blinkberg Member), these sandstones are generally medium-bedded (ranging from thin- to thick-bedded) with beds parallel-sided and tabular or (less commonly) somewhat lenticular. Flat-bedding (horizontal lamination), wavy lamination, micro-cross-lamination, massive bedding and, more rarely, bioturbation and cross-bedding (including low-angle varieties) are the main syndepositional current structures. Lebensspuren are occasionally present on bedding planes.

In the lower half of the formation, sandstones are medium- to thick-bedded; beds vary from lenticular (in the case of cross-bedded units) to parallel-sided and non-lenticular (in the case of most non-cross-bedded units). Micro-cross-lamination, cross-bedding, flat-bedding and (more rarely) wavy bedding and bioturbation are the predominant structures. "Massive" beds are also common. Cross-bedding generally appears to be of the trough variety; sets are up to 75 cm thick (average about 30 - 40 cm).

North-east of Willowmore (W 6) the Driekuilen Sandstone is characterised by irregular, lenticular bedding. Large-scale cut-and-fill structures, with channels up to 3 m deep, are also present. Micro-cross-lamination and wavy bedding are more common than flat-bedding and trough cross-bedding. Cross-bed sets average 30 cm in thickness (maximum 1 m).

Minor sandstones.- These are generally thin- to medium-bedded, with beds tabular and parallel-sided. Main syndepositional current structures are flat-bedding, wavy bedding and micro-cross-lamination. Poorly-developed oscillation ripple marks and trace fossils occur sporadically. Bioturbation is common.

Mudrock/streaky rhythmitite.- Rhythmitites vary from mudrock with thin silty laminae a few mm thick to sandstone with equally thin argillaceous intercalations. Thickness of "couplets" varies from a few mm to 10 cm or more. Internally, the rhythmitites are generally characterised by wavy bedding which may grade into horizontal lamination on the one hand and micro-cross-lamination on the other. Trace fossils are common.

Weltevrede Formation (southern facies)

Sandstone.- Individual beds vary from tabular (parallel-sided) to lenticular; generally thin- to medium-bedded. Sub-horizontal flat-bedding, horizontal flat-bedding, micro-cross-lamination, wavy-bedding and bioturbation are the main internal structures. Trace fossils are common on bedding-planes, while oscillation ripple marks (5 - 8 cm wave-length) are occasionally present. Cross-bedding appears to be absent or very rare.

Mudrock/streaky rhythmitite.- See under northern facies.

Witpoort Formation (western area)

Rooirand Member

Sandstones are medium- to thick-bedded; individual beds are commonly lenticular. Flat-bedding, cross-bedding and micro-cross-lamination are the most common internal structures observed. Many beds are, however, superficially structureless and it is thus difficult to arrive at the true proportions of the various internal primary structures present. Most cross-bedding is probably of the trough variety, although it was generally not possible to ascertain the true nature of the cross-bedding. Average thicknesses of sets is about 30 cm.

Mudrock/rhythmitite interbeds resemble those occurring in the Weltevrede Formation.

Perdepoort Member

Beds are parallel-sided and tabular, generally medium or thick, with the former predominating. The regularity of the general bedding contrasts markedly with the nature of the bedding in the Rooirand Member. Internal syndepositional structures include horizontal or sub-horizontal flat-bedding, inclined bedding, and, less commonly, low-angle cross-bedding.

Skitterykloof Member

The sandstones are characterised by massive bedding , flat-bedding and small-scale cross-bedding. Current ripple marks occur. Mudrock/rhythmitite structures resemble those present in the Weltevrede Formation.

Witpoort Formation (eastern area)

While most sedimentation units are superficially massive, cross-bedding is the most common identifiable internal syndepositional current structure. Both tabular and trough varieties occur, with the former tending to be more common in the upper half of the formation than the lower half. Trough cross-bedding predominates near the base of the formation, and occurs in sets of up to 180 cm thick (average 40 - 50 cm). Average thickness of tabular cross-bedding sets tends to be about 30 cm. Micro-cross-lamination and flat-bedding were observed, but both appear to be uncommon. Overturned cross-bedding occurs at various levels.

Kweekvlei Shale

The mudrock is generally massive (structureless), while the streaky rhythmitites resemble those present in the Weltevrede Formation.

Floriskraal Formation

Sandstone units display flat-bedding (sub-horizontal) and small- to medium-scale low-angle cross-bedding (sets 10 - 30 cm thick; maximum 45 cm). Well-developed oscillation ripple marks (wave length 10 - 15 cm; maximum 20 cm) are common and trace fossils occur. Mud-flake conglomerate horizons were also noted.

Streaky rhythmitites are similar to those in the Weltevrede Formation.

Waaipoort Formation

Wavy bedding, micro-cross-lamination, flat-bedding and streaked-out, low-amplitude wavy bedding are the main structures present. Massive bedding is also not uncommon. Beds are generally parallel-sided and tabular, but lenticular beds also occur.

Miller Diamictite

No primary structures were observed in the diamictite.

Swartwaterspoort Sandstone

Wherever internal structures can be seen, extensively-developed contorted bedding in the form of spectacular intra-formational recumbent folds characterise the whole of the formation. Massive bedding is common, and flat-bedding is also present.

Soutkloof Shale

"Varved" rhythmitite couplets are generally a few mm thick (range: 2 - 10 mm). Streaky rhythmitites are characterised by horizontal lamination, wavy bedding (low-angle) and occasional micro-cross-lamination. Low-amplitude symmetrical ripple marks are occasionally present in the sandier strata.

Dirkskraal Sandstone

Cut-and-fill structures are well developed at some localities. At Camferspoort (W 9) a channel 20 - 30 m deep was encountered.

Flat-bedding (plus parting lineation), inclined bedding, micro-cross-lamination and wavy bedding are the most abundant syndepositional current structures. Cross-bedding (generally trough cross-bedding, with sets 15 - 30 cm thick) is relatively uncommon. Flat-bedding cosets are up to 4 m thick, while micro-cross-lamination cosets are up to 2 m thick. Climbing ripples occur locally. Many beds are superficially massive. Considerable local variation in the nature and relative proportions of the various internal structures was noted.

Orientation data

Orientation data for cross-bedding in the Witteberg Group are contained in Tables XIII-1 and XIII-2.

Table XIII-1. Statistical measures calculated from orientation data for cross-bedding in the Witteberg Group.

Unit/locality	n	$\bar{x}_v$	$\bar{a}$	s
Perdepoort (W3)	14	113°	0,85	34°
Perdepoort (W8)	11	177°	0,80	39°
Perdepoort (W12)	15	209°	0,97	15°
Rooirand (W3)	58	271°	0,64	55°
Rooirand (W8)	39	283°	0,82	37°
Rooirand (W11)	35	297°	0,74	45°
Rooirand (W12)	55	294°	0,51	66°
Rooirand (W14)	40	285°	0,71	48°
Rooirand (W15)	38	217°	0,77	42°
Rooirand (W18)	52	221°	0,76	43°
[1]Rooirand (W20)	50	189°	0,89	28°
[1]Rooirand (W21)	55	188°	0,70	49°
[2]Rooirand (W22)	51	233°	0,65	54°
[2]Rooirand (W23)	31	239°	0,89	28°
Rooirand (W24)	45	212°	0,82	37°
[3]Weltevrede (W3)	84	156°	0,44	72°
[3]Weltevrede (W8)	54	189°	0,64	55°
[3]Weltevrede (W11)	16	213°	0,70	49°
[3]Weltevrede (W12)	48	216°	0,39	76°
[4]Driekuilen (W1)	50	107°	0,31	82°
Driekuilen (W6)	57	174°	0,58	60°

(Footnotes on following page)

[1] Lower half of formation.

[2] Upper half of formation.

[3] Excluding Driekuilen Sandstone Member.

[4] Theron (1972).

n = number of readings, $\bar{x}_v$ = vector mean, $\bar{a}$ = vector strength, s = standard deviation.

Table XIII-2. Orientation of cross-bedding dip directions in the Witteberg Group: number of readings per 30° class interval.

	Class mid-points(°)											
Unit/locality	15	45	75	105	135	165	195	225	255	285	315	345
Perdepoort (W3)				9½	3½				1			
Perdepoort (W8)					3	3	3	1	1			
Perdepoort (W12)						1½	5½	8				
Rooirand (W3)		1			3	2	3	7½	13½	13½	10½	3½
Rooirand (W8)	1						1	3	9½	11½	11½	1½
Rooirand (W11)	3						1	2	8½	6½	8	6
Rooirand (W12)	3½	½		1	1	1	5½	8	4	7½	11	12
Rooirand (W14)							4½	4½	5	8½	10½	7
Rooirand (W15)				1½	½	4	10	11	7	3½	½	
Rooirand (W18)						7½	17½	11	6	9	½	½
[1] Rooirand (W20)					3	19½	16½	9	2			
[1] Rooirand (W21)	1		1	1½	4½	11½	24	3½	2½	½	4	1
[2] Rooirand (W22)		1½	2	1½	1	3	5	16½	13½	5	2	
[2] Rooirand (W23)							5½	11	8	6½		
Rooirand (W24)						6½	16	10½	7½	3½		
[3] Weltevrede (W3)		4	11	10½	15	12	9	6	9	5½	2	
[3] Weltevrede (W8)			2	3	9	11	9	10	7½	2½		
[3] Weltevrede (W11)				2	1		5½	3½	2½	1½		
[3] Weltevrede (W12)			1	9	2	3	7½	8	5	6½	5	1
[3] Weltevrede (W12) (micro-cross-lam.)		1	1½	1½			1½	3½		3	1	
Driekuilen (W6)			4	11½	6½	5	13	9½	6½	1		
Weltevrede Total (cross-bedding)		4	18	36	33½	31	44	37	30½	17	7	1

[1] Lower half of formation

[2] Upper half of formation

[3] Excluding Driekuilen Sandstone Member

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Grain-size data for Witteberg Group sandstones, based on the long axes of quartz and feldspar grains plus secondary overgrowths where these cannot be distinguished from the original grains, are contained in Table XIII-3. Presence of secondary overgrowths on quartz grains prevented the determination of roundness and shape.

Table XIII-3. Grain-size data for Witteberg Group sandstones.

Unit/locality	n	x̄(ø)	S(ø)	MD(ø)	d(ø)	x̄ - d	M(%)
Dirkskraal (W2, 12)	3	3,50 (2,8 - 4,0)	0,64	0,52	2,00	1,50	31,5
Dirkskraal (W16,19)	2	2,26	0,87 0,59	0,63 0,43			6,5
Dirkskraal (W16,17)	4	3,53 (3,3 - 3,7)	0,46	0,36	2,20	1,33	25
Swartwaterspoort (W5, 9, 18)	4	1,70 (1,4 - 2,5)	0,73	0,54	-0,75	2,45	7
[1]Miller (W17)	2	1,66	1,02	0,81	-0,60	2,26	
Miller (W2, 9, 12)	3	2,75 (2,4 - 3,2)	1,05	0,86	-0,25	3,00	43,5
Miller (W17)	3	2,99 (2,9 - 3,1)	1,10	0,89	0,13	2,86	48
Waaipoort (W12)	2	3,57	0,67	0,52			
Floriskraal (W12)	6	2,20 (0,7 - 3,4)	0,51	0,39	0,26	1,94	11,5
Floriskraal (W18)	3	1,95 (0,2 - 2,8)	[2]0,66	[3]0,52	-0,06	2,01	10
Skitterykloof (W12)	3	1,45 (1,1 - 2,1)	[4]0,86	[5]0,70	-0,21	1,66	6,5
Perdepooort (W12)	5	1,67 (0,7 - 2,3)	[6]0,73	[7]0,58	0,28	1,39	3
Rooirand (W12)	10	2,63 (2,2 - 3,52)	0,51	0,39	1,69	0,94	9,5
Rooirand (W20, 21)	10	1,83 (0,8 - 2,6)	0,61	0,46	0,60	1,23	4,5
[8]Weltevrede (W12)	17	2,59 (1,9 - 3,4)	0,49	0,37	1,63	0,96	6
[8]Weltevrede (W13)	4	3,26 (3,1 - 3,4)	0,48	0,37	2,40	0,86	
Driekuilen (W4)	2	2,08	0,49	0,39	0,81	1,27	6
Driekuilen (W12)	5	3,14 (2,8 - 3,6)	0,51	0,41	2,08	1,06	16
Driekuilen (W12) (Theron, 1972)	2	3,15	0,49				

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[1] Samples from interbedded sandstone horizon

[2] Range: 0,43 - 0,92

[3] Range: 0,36 - 0,73

[4] Range: 0,57 - 1,19

[5] Range: 0,46 - 1,00

[6] Range: 0,47 - 1,06

[7] Range: 0,40 - 0,89

[8] Excl. Driekuilen Member

n = number of samples (50 grains per sample)
x̄ = mean size (range in brackets)
S = standard deviation
MD= mean deviation
d = maximum thin-section diameter
M = matrix content

D 2. Composition

Mineral composition of Witteberg Group sandstones is presented in Table XIII-4.

Table XIII-4. Mineral composition of Witteberg Group sandstones.

Unit/locality	n	Q	F	R	Acc.	Cem.	M	Q : F : R
Dirkskraal (W2,12)	3	38,5	16	10,5	1	2,5	31,5	59,5 : 24,5 : 16
Dirkskraal?(W12?)	1	75	-	15,5	1,5	5	3	83 : 0 : 17
Dirkskraal (W16,19)	2	63	20	9,5	1	tr.	6,5	68 : 21,5 : 10,5
Dirkskraal (W17)	3	33	28	12,5	0,5	1	25	45 : 38 : 17
Swartwaterspoort (W5, 9, 18)	4	92	tr.	1	-	-	7	99 : 0 : 1
Miller (W2,9,12)	3	46,5	6	1,5	0,5	2	43,5	86 : 11 : 3
Miller (W17)	3	40	7,5	2,5	-	2	48	80 : 15 : 5
Waaipoort (W12)	2	46,5	20	3,5	1	1	28	66,5 : 28,5 : 5
Floriskraal (W12)	6	84,5	1,5	-	2,5	-	11,5	98,5 : 1,5 : 0
Floriskraal (W18)	3	86	0,5	tr.	0,5	3	10	99 : 1 : 0
Skitterykloof (W12)	2	92	0,5	-	1	-	6,5	99,5 : 0,5 : 0
Perdepoort (W12)	5	96,5	tr.?	-	0,5	-	3	100 : 0 : 0
Rooirand (u)(W12)	7	90,5	tr.	-	2	-	7,5	100 : 0 : 0
Rooirand (l)(W12)	4	79	3	-	3,5	-	14,5	96,5 : 3,5 : 0
Rooirand (b)(W12)	3	64	4	-	4	-	28	94 : 6 : 0
Rooirand (W20,21)	10	95,5	tr.	tr.	tr.	-	4,5	100 : 0 : 0
[1]Weltevrede (W12)	17	91,5	0,5	-	2	-	6	99,5 : 0,5 : 0
[1]Weltevrede (W13)	4	90	tr.	tr.	2	-	8	100 : 0 : 0
Driekuilen (W4)	2	84	9	tr.	1	-	6	90 : 10 : 0
Driekuilen (W13)	5	75	4	tr.?	3	2	16	95 : 5 : 0

[1] Excluding Driekuilen Sandstone Member

n = number of samples (200 - 300 points per sample)

Q = quartz (including secondary quartz)

F = feldspar

R = rock fragments

Acc. = accessory minerals (including large mica flakes)

Cem. = cement plus secondary minerals (excluding secondary quartz)

M = Matrix

u = upper

l = lower

b = basal

E. SEDIMENTOGENESIS

E 1. Dispersal patterns

Weltevrede Formation (northern facies)

Cross-bedding orientation data gave both unimodal and bimodal (90°) palaeocurrent patterns and intermediate to low vector strengths (see Folder 4b). With the exception of an eastward mean direction obtained by Theron (1972) at Vondeling (W1), calculated vector means indicate a general southward current trend. The bimodal patterns (W4, W11, 12) display a main mode directed approximately SSW and a secondary mode directed ESE.

Witpoort Sandstone

Rooirand Member.- Two distinct trends are present in this unit. West of 25°30'E the general transport direction is slightly north of west. The patterns appear to be unimodal, and vector strengths are high. East of 25°30'E, on the other hand, palaeocurrents are directed towards the south or south-west. In the Grahamstown area currents directed slightly west of south were encountered towards the base of the formation, while in the upper half the direction proved to be slightly west of south-west. In all cases unimodal patterns and high (occasionally very high) vector strengths were displayed.

Perdepoort Member.- Both easterly and southerly directions were obtained, coupled with very high vector strengths.

E 2. Sedimentary processes and palaeoenvironments

Weltevrede Formation

Any environmental hypothesis proposed for the Weltevrede Formation must account for the following features:

1. The presence of coarsening-upward cycles (in at least the southern facies).

2. The volumetric importance of streaky rhythmitites similar to those reported from a variety of modern near-shore sub-environments in the shelf, sheltered shelf and delta environments (cf. Van Straaten, 1959; Coleman and Gagliano, 1965; Visher, 1965; Reineck and Singh, 1973). The most important possibilities are tidal flats and lagoons, the transitional zone, and the outer delta-front platform or upper pro-delta slope.

3. The presence of thick tabular cross-bedded sandstones displaying unimodal palaeocurrent directions orientated mainly downslope and at right angles to the shoreline as deduced from the regional facies and thickness changes, as well as the rapid southward disappearance of the cross-bedded character of the sandstones.

4. The southward decrease in total formation thickness as well as abundance and thickness of sandstones.

5. Presence of extensive, relatively thick sandstones without cross-bedding.

6. Abundance of trace fossils and bioturbation.

The above combination of features can be most satisfactorily explained in terms of a general deltaic environment with strong marine influence. Thus on this interpretation the thick cross-bedded sandstones represent coalescent distributary channel and distributary mouth bar deposits, while the thicker tabular non-cross-bedded sandstones are interpreted as coalescent delta-front sheet sands (Reineck and Singh, 1973, p.270). The fine-grained strata (mudrock and streaky rhythmitite) represent upper prodelta slope, outer delta-front platform and interdistributary bay and tidal flat sediments. Visher (1965, p.53) notes that interdistributary sediments often contain abundant carbonaceous material, while bioturbation is common. Since the deltaic process is a hybrid between regressive marine and fluvial processes (Visher, 1965, p.50), coarsening-upward cycles, which normally characterise the regressive marine model, can be expected as the deltas prograde into areas where previously only mud was being deposited. The general lithological heterogeneity, substantial thickness and overall trends in thickness and facies changes all support the deltaic interpretation. The great lateral extent and apparently tabular shape of the cross-bedded sandstone lithosomes are, however, difficult to explain in a deltaic environment; they can perhaps best be accounted for by postulating the simultaneous progradation of a series of sandy deltas along the whole length of the shoreline during regressive episodes.

Witpoort Sandstone

Rooirand Member.- This unit, consisting almost entirely of quartzitic sandstone with thin mudrock/rhythmitite intercalations, is characterised west of 25°30'E by unimodal palaeocurrents trending parallel to the east-west basin axis and assumed palaeostrike as deduced from the regional shape and facies relationships of the Cape Supergroup as a whole. If the assumption that the palaeostrike and shoreline paralleled the axis of the basin of deposition is correct, then the Rooirand must be interpreted as a shoreface deposit produced largely by longshore drift. Any other interpretation will involve a north-south oriented shoreline, which will be difficult to fit into a regional palaeogeographic reconstruction for the Cape Supergroup.

The interpretation given above involves a change from a lobate (deltaic) shoreline to a linear clastic shoreline (using Selley's terminology - 1970, p.74) as one proceeds from the Losberg Formation to the Witpoort Sandstone.

This change must reflect a decrease in the rate of injection into the shoreline system of land-derived sediments, enabling marine processes to gain the upper hand. The intercalated argillaceous zones could reflect either local deposition in sheltered shelf environments or periods of transgression which allowed transitional zone deposits to encroach on the shoreface sands.

East of 25°30'E the exact relationship between the basin axis, palaeoslope and shoreline on the one hand, and the southerly to southwesterly palaeocurrent trends on the other, is not known. The strata can be interpreted either as a deltaic/fluviatile deposit with the palaeocurrents directed at right angles to an ESE-WNW palaeostrike and shoreline, or as a shoreface (longshore drift) deposit produced by currents flowing parallel to a NE-SW shoreline. The palaeocurrent directions in the eastern outcrop area are in fact very similar to those characterising the Pondoland sandstones described by Hobday and Mathew (1974; see discussion under Table Mountain Group). If the latter are in fact of Witteberg age, a consistent picture of longshore transport operative throughout the whole area is obtained.

Perdepoort Member.- This unit possesses a number of features which suggest a beach deposit. It is an exceptionally clean, relatively coarse-grained unit possessing a highly tabular shape and great lateral extent (both in an east-west direction) and characterised by the presence of both high-angle and low-angle cross-bedding.

Kweekvlei and Floriskraal Formations

The extensive fine-grained Kweekvlei Shale with which the Lake Mentz Subgroup commences represents an accumulation of mud in the offshore zone of the shelf. Such an abrupt increase in water depth must reflect a major transgressive episode.

The coarsening-upward cycle of which the Kweekvlei Shale forms the lower part fits very well into a regressive sequence in which rhythmitites of the transition zone overlie offshore zone muds and are in turn overlain by sands deposited in the lower and middle shoreface (cf. Visher, 1965, p.44 ff.). The deposition of the remainder of the Floriskraal Formation appears to have been confined to the transition zone and shoreface. The presence of horizontal lamination, small-scale cross-bedding and wave-formed ripple marks, and absence of medium- to large-scale cross-bedding in the sandstones indicate a lower rather than upper shoreface environment.

Waaipoort Formation

This unit, over 500 km in extent and consisting of streaky rhythmitite, mudrock, plus some dirty, very fine-grained sandstone, must have been deposited seaward of the high-energy nearshore zone. It is rather similar to the Adolphspoort Siltstone of the Bokkeveld Group in appearance and size and again a delta environment, specifically the upper prodelta slope and outer delta-front platform, seems to be indicated. Overall thickness and absence of distinct shelf muds or shoreface sands render a non-deltaic shelf environment of a linear shoreline a less likely alternative.

Miller Diamictite/Swartwaterspoort Sandstone

The Miller Diamictite is characterised by a reasonable degree of lateral persistence (about 300 km in an east-west direction) complete lack of sedimentary structures, very poor sorting (comparable to that obtained for the Dwyka Tillite) and the presence of scattered granules and very small pebbles composed of quartz or chert. This unit was interpreted by Rossouw (1953, p.20) as a tillite, although the "erratics" differ markedly from the lithologically heterogeneous assemblage of pebbles, cobbles and boulders found in the Dwyka Tillite. Crowell (1957) has discussed the various possible origins of pebbly mudstones. Only two of the possibilities which Crowell mentions need be considered here, namely slumping in association with turbidity current deposits and glacier action.

The diamictite itself does not display any evidence of slumping, nor is there any evidence of turbidity-current activity. The diamictite does, however, in places occur together with the Swartwaterspoort Sandstone which is invariably highly contorted throughout its thickness; in places it is composed entirely of recumbent overfolds. Although the contorted nature of the Swartwaterspoort Sandstone may be due to large-scale slumping, it could just as conceivably be caused by drag from an overriding glacier. The fact that the Miller Diamictite and Swartwaterspoort Sandstone form two quite distinct units without any mixing cannot be readily accounted for if they are both slump deposits. The close proximity in time and space to the later Dwyka Tillite also favours a glacial hypothesis.

As far as can be ascertained the Swartwaterspoort Sandstone was characterised by parallel or sub-parallel laminations prior to being deformed; cross-bedding appears to have been rare or absent. This indicates that it accumulated as a beach deposit (characterised by gently inclined foreshore bedding) rather than a fluvioglacial or glacial outwash deposit. Since the sandstone contains the same suite of quartz and chert granules and pebbles which occur in the diamictite, it possibly originated through reworking by waves of glacial outwash material, or even through reworking of some of the diamictite itself (since it is only moderately sorted).

Soutkloof Shale/Dirkskraal Sandstone

The thin and rhythmic lamination and fine grain of the Soutkloof indicate deposition in quiet, relatively deep water (offshore zone). This clearly reflects retreat of the ice and an extensive marine transgression. It is possible that the rhythmic layers characterising the lower half of the formation may represent annual varves.

At most localities the Soutkloof Shale becomes progressively coarser upwards, and grades into the overlying Dirkskraal Sandstone. This could be interpreted as a regressive cycle, with transition zone clayey silt and silty sand followed by sandstone deposited in the shoreface zone, or possibly even the beach since horizontal or sub-horizontal lamination is common in the sandstone and cross-bedding is comparatively rare. However at one locality at least the sandstone rests directly on the fine-grained shale with a sharp contact, indicating erosion prior to deposition. This feature could be due to the presence of distributary channels, indicating a lobate (deltaic) rather than a linear (non-deltaic) shoreline.

E 3. Provenances

As in the case of the Table Mountain Group, the ultra-quartzose sandstones constituting the bulk of the Witteberg Group give little indication of the nature of the source area(s). Again it seems most likely that a relatively quartz-rich granite-metamorphic-sedimentary terrain of low relief lying to the north of the depositional basin provided the bulk of the Witteberg sediments. The sudden increase in the feldspar content of the sandstones towards the top of the succession may be associated with a reduction in the rate of chemical weathering due to the onset of cooler, drier conditions prior to the Carboniferous glaciations.

CHAPTER XIV

DWYKA TILLITE

A. STRATIGRAPHY

A.1. General stratigraphic interrelationships

A 1.1. Lithostratigraphic relationships

See Folder 1.

A 1.2. Chronostratigraphic relationships

According to Du Toit (1954, p.280) an Upper Carboniferous age can be assigned to this formation.

A 2. Geographic distribution

The outcrop distribution of the Dwyka Tillite is, for all practical purposes, identical to that of the "Dwyka Series" depicted on the 1:1 000 000 scale geological map of the Republic of South Africa (Geological Survey, 1970). On this map the thin Prince Albert and Whitehill Shales were included in the "Dwyka Series".

A 3. General concept and distinguishing features

Diamictite plus a few very subordinate "shale" and sandstone lithosomes. The diamictite is normally massive.

A 4. History and nomenclature

According to Corstorphine (1904, p.156) the name "Dwyka Conglomerate" was introduced by Dunn in 1875 on his "Geological Sketch Map of South Africa" (2nd edition), the name being derived from the Dwyka River near Prince Albert (Dunn, 1879). Later, after the recognition of the glacial origin of this unit, the rock name "tillite" was suggested in 1905 by A. Penck (Rogers, 1938) and the name "Dwyka Tillite" subsequently became firmly established in the literature. Although some writers are of the opinion that "till" and "tillite" should be restricted to sediments deposited as ground-moraine (see Gary et al., 1972), Harland and others (1966, p.232) support the use of tillite to cover ice-rafted marine deposits. In addition, a recommendation in the South African Stratigraphic Code (SACS, 1971, p.118) that "genetic terms such as tillite, turbidite, ignimbrite, etc., should be avoided wherever possible" can be circumvented on the grounds that the glacial origin of the Dwyka has been established beyond all reasonable doubt, while the ISSC (1970 a, p.16) give "Niari Tillite" as an example of an acceptable formation name.

Returning to the historical aspect, Dunn's original usage of "Dwyka" was subsequently expanded, some of the underlying and overlying shale being included with the tillite to form a "Dwyka Series" (Rogers and Schwarz 1897; Rogers, 1902). This classification was subsequently followed in nearly all the textbooks on South African geology, up to and including the 3rd (1954) edition of Du Toit's "Geology of South Africa". An alternative possibility involved incorporating the tillite in the "Ecca Beds" (Dunn, 1879). Although Hatch and Corstorphine (1909) attempted to revive this usage, it was not generally accepted.

The "Lower Dwyka Shales" were "officially" transferred to the Witteberg Series by Rossouw (1953, p.16) while the suggestion that the "Upper Dwyka Shale" be included with the Ecca strata (Venter, 1969, p.32, 33; Winter and Venter, 1970, p.396) has been formally adopted by the Karoo working group of the South African Committee for Stratigraphy.

A 5. Boundaries

A 5.1. Lower boundary

Nature of boundary.- Conformable (?) to disconformable: sharp or gradational (transition zone less than one metre).

In the area under consideration this contact has generally been regarded as conformable (see Mountain, 1946, p.17; Du Toit, 1954, p.269; Loock, 1967, p.127) although Haughton (1969, p.352) states that the relationship is a disconformable one in the western and central parts of the southern Cape outcrop belt. In the course of studying the stratigraphy of the strata lying below the Dwyka Tillite, certain facts emerged which seem to confirm the presence of a disconformable relationship between the main tillite and the underlying strata over a substantial part of the study area:

1. In the Willowmore area it was found that from south to north the Dwyka Tillite rests on strata occupying progressively lower levels in the upper Witteberg Group succession. On Kruidfontein, where the Kommadagga Subgroup attains its maximum thickness, the Dwyka Tillite overlies 177 m of Dirkskraal Sandstone. A few km. to the north it rests directly on the Soutkloof Shale and at the northernmost exposures of the contact near the Beervlei Dam it rests directly on strata belonging to the Lake Mentz Subgroup (which is here only 200 m. thick). The systematic elimination of the higher stratigraphic units points to an erosional relationship rather than simple stratigraphic pinch-outs. This view is supported by the generally erratic development of the Dirkskraal Sandstone, especially those cases where it is completely absent a few km from localities where it displays its normal thickness.

It is significant that at Tierberg (east of Prince Albert) the Dwyka Tillite lies on the first quartzitic sandstone unit of the Floriskraal Formation, or even the Kweekvlei Shale (Rossouw and others, 1964, p.29) which means that, in addition to the Kommadagga Subgroup, the Waaipoort Formation and most of the Floriskraal Formation had also been removed prior to deposition of the tillite. A close examination of the actual contact revealed a comparatively undisturbed relationship, implying that tectonic activity (faulting, etc.) could not be held responsible for the observed features (i.e. the absence of the Kommadagga Subgroup and the bulk of the Lake Mentz Subgroup).

2. Rossouw (1953, p.20; 1970, p.205) had assumed that the Miller Diamictite (the so-called "basal tillite") represented a tongue of the main Dwyka Tillite, and that the Soutkloof Shale and Dirkskraal Sandstone simply represented an unusually thick development of normal sediments within the Dwyka Tillite. Stratten (1968, p.24) accepted this interpretation. However, the nature of the pebbly inclusions within the Miller Diamictite differs markedly from the inclusions present in the main tillite, in that the clasts appear to consist entirely of quartz, quartzite and dark chert, in contrast to the wide variety of lithologies present in the main Dwyka Tillite. Especially significant is the absence of granitic fragments from the Miller Diamictite compared with their ubiquitous presence in the "main" tillite. In addition, clasts larger than 1 cm in diameter are extemely rare in the Miller Diamictite, but are abundant in the main tillite, even right at its base. The supposition that the Dwyka Tillite and Miller Diamictite constitute two separate and unconnected stratigraphic units was confirmed west of Willowmore, where the Dwyka Tillite was observed to cut right through the Miller Diamictite over a distance of about 1 km; west of this point the main Dwyka Tillite rests directly on strata belonging to the Lake Mentz Subgroup, and the Kommadagga Subgroup no longer appears to be present.

To conclude, the complete absence of the Kommadagga Subgroup (and, locally, a large part of the Lake Mentz Subgroup as well) points to the existence of a general unconformity (disconformity) at the base of the Dwyka Tillite west of Willowmore. East of Willowmore the situation appears to be somewhat different since the same relatively thin formation (i.e. the Dirkskraal Sandstone) underlies the Dwyka Tillite throughout most of the area. It would seem that the relationship is, in general, probably more or less conformable, but locally there appears to have been a certain amount of pre-Dwyka erosion removing the Dirkskraal Sandstone and giving rise to a disconformable relationship.

Definition of boundary.- Base of main tillite mass.

A 5.2. Upper boundary

See A 5.1 under Prince Albert Shale.

A 6. Overall lithology and facies changes

Diamictite : 90 - 100%
Mudrock (shale): 0 - 10%
Sandstone : 0 - 5%

A 7. Dimensions and shape

Available thickness data for the Dwyka Tillite in the study area were summarised by the present writer (1966, p. 28ff.). Thickness values obtained by various workers in the southern outcrop area (Cape Fold Belt) have been remarkably consistent, varying from 565 m to 755 m, an average of 680 m being obtained from 8 measurements. Stratten (1968, p. 44) mentions a maximum thickness of over 900 m, but does not state where exactly this was measured. Du Toit (1920, p. 21) gives a thickness of 455 m for northern Pondoland in the Transkei.

A 8. Stratotypes

Unit-stratotype.- Dwyka River area.

A unit stratoype for this formation has not yet been located and precisely defined. Historical considerations favour the location of such a type section at or near the point where the Dwyka River crosses the formation (i.e. beyond the western edge of the study area) provided exposures are suitable.

Reference stratotype.- Ecca Pass (north of Grahamstown)

Nature of stratotype : A continuous series of fresh exposures occurring in road cuttings through the upper two-thirds of the formation. Actual contacts not exposed. Angle of dip is $30^\circ - 40^\circ$.

Accessibility : Excellent

Location : The section is located along the Grahamstown - Fort Beaufort road and extends from the start of the Ecca Pass (near the A.G. Bain monument) to the point at which the Prince Albert Shale is first encountered.

B. PALAEONTOLOGY

Fossils are not known to occur in this formation in the study area.

C. MACRO-SEDIMENTOGRAPHY

C 1 - 3. Lithosome data

Although sandstone and "shale" units (the latter up to 100 m thick) occur sporadically at various levels within the Dwyka Tillite, they are generally poorly exposed and not much data is available on them. It is possible that a fairly thick (± 60 m) "shale" unit which occurs about 400 m above the base of the tillite north-west of Grahamstown (Wright, 1969, p. 71) may represent a potentially mappable member.

C 4. Colours

The fresh tillite is generally dark bluish grey (5B3/1) in colour, weathered material being more or less olive grey (5Y4/1).

C 5. Sedimentary structures

The tillite is normally completely massive and structureless although close inspection may reveal a crude stratification (R.S. Hill, personal communication). Small-scale cross-bedding and micro-cross-lamination are present in the intercalated sandstone layers (e.g. near E6 on Folder 3).

Orientation data.- Till fabric analyses undertaken by Stratten (1968) indicate a strongly preferred east-west orientation which tends to change to a more or less NW - SE orientation east of Grahamstown. Stratten also obtained eastward-directed cross-bedding dip directions measured in interbedded sandstones at four localities west of Klipplaat (Table 6, p. 111, 112).

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Grain-size analyses carried out in thin section on the sand-sized fraction of three tillite samples obtained north of Grahamstown gave an average mean grain size ($\bar{x}$) of 3,1ϕ and an average standard deviation (s) of 1,28 ϕ.

The erratics possess a maximum size of about 2 m, and mean size (geometric mean, volume frequency) of about 2 - 5 cm (estimated).

D 2. Composition

Modal analyses of three tillite samples collected north of Grahamstown gave the following average composition:

Quartz : 19%
Feldspar : 12,5%
Rock fragments : 4%
Accessory minerals : 1%
Matrix : 63%
Secondary material : 0,5%
Q : F : R 54 : 35 : 11

According to Stratten (1968, Plate XXII) 40 - 90% (average about 70%) of the tillite pebbles are composed of quartzite and 10 - 60% (average about 30%) of granitic rocks. The percentage of granitic rocks increases progressively from west to east across the study area (Stratten, p. 101, cf. Plate XIV, graphs 3, 4).

E. SEDIMENTOGENESIS

E 1. Dispersal patterns

Stratten (1968, p. 130) states that the general direction of ice flow along the southern Cape Fold Belt was towards the east. From Grahamstown to where the outcrop of the Dwyka Tillite passes into the Indian Ocean this easterly direction of flow bent towards the south-east. These directions were based on till fabric analysis, with the actual sense of the direction (east or west) being obtained from supplementary data such as structures in interbedded sandstones (on the assumption that the sandstones were transported in the same direction as the tillite). Thus cross-bedding measurements made on small sandstones lenses and beds within the tillite at four localities in the Schoorsteenberg - Klipplaat area indicate consistent easterly current directions (Table 6, p.111, 112). However, the remarkable parallelism between the tillite fabric orientations obtained by Stratten and the fold axes in the Cape Fold Belt cause one to wonder to what extent the observed fabric is original or secondary, or, alternatively, to what extent it is simply a result of measuring directions in steeply-dipping beds.

Theron and Blignaut (1973) have recently presented evidence which indicates that the direction of ice movement in the south-western Cape Province was in fact from east to west rather than from west to east. Since the tillite erratics must have been derived from beyond the area initially covered by Cape Supergroup strata, it is clear that the direction of transport must in fact have been from east to west throughout the whole southern Cape Province (since this entire area is covered by Cape Supergroup rocks).

E 2. Sedimentary processes and palaeoenvironments

According to Stratten (p. 35), there is no longer the least doubt concerning the glacial origin of the Dwyka Tillite in South Africa. The evidence is reviewed by Stratten, as well as by Du Toit (1921, 1954). While Du Toit felt that the thick southern tillite largely represents ice-rafted material, with the ice-front discharging into fairly deep water, Stratten feels that it represents material which accumulated as a terrestrial ground moraine. Stratten's interpretation is based mainly on his observation that even though there are signs of drop pebbles in the varve shales along the southern Cape Province, the massive tillite itself mostly possesses a fabric of orientated elongated pebbles that can only have been induced by flowing ice (p.32). While the whole process of producing such enormous thicknesses of till is difficult to determine in detail, according to Stratten (p. 47) a series of massive advances and retreats of the ice sheet appears to be the most plausible explanation.

More recently Theron and Blignaut (1973) have shown that the Dwyka Tillite in the western Cape Province is composed of four distinct cycles, each of which represents an advance and retreat of an ice sheet. Cycles commence with a thick massive tillite unit (interpreted as a melt-out till from a grounded ice shelf), overlain by stratified sediments (associated with a floating ice shelf). The stratified deposits include stratified diamictite, sheet and shoestring arenites, boulder beds and massive till-flow units.

E 3. Source area(s)

According to Stratten (1968, p. 131 - 133; plates XXVII, XXVIII, XXXI, XXXII) four source areas contributed to the tillite in the study area:

a. The central and eastern Transvaal source area, which produced the Transvaal Ice Sheet, moving south towards the outcrop area in the Fold Belt (Plate XXXI).

b. A source area off the present Natal coast, which produced the Natal Ice Sheet flowing towards the west and south-west and depositing material in the eastern part of the area.

c. A source area off the present western Cape coast which produced the Atlantic Ice Sheet. This ice sheet flowed towards the east and deposited material in the present-day outcrop area and to the north of it.

d. A source area off the present southern Cape coast which produced the Southern Cape Ice Sheet. This ice flowed towards the north-west (Plate XVIII) and deposited a little material in the southern Cape (mainly south of the present outcrop belt).

The views on transport directions presented by Theron and Blignaut (see above) imply that a westward-moving Southern Cape Ice Sheet originating on a source area off the southern (and southeastern) Cape coast was mainly (if not entirely) responsible for the deposition of tillite in the southern Cape outcrop area.

CHAPTER XV

ECCA GROUP

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1. Lithostratigraphic relationships

See Folder 1.

The Prince Albert and Whitehill Shales have until recently been almost universally regarded as part of a "Dwyka Series" whose main constituent was the Dwyka Tillite (cf. Du Toit, 1954; Haughton, 1969). This usage was apparently introduced by Rogers (1902, p.8, 9). However, since there are no sound lithological reasons for grouping these shales with the underlying tillite in a "Dwyka Group", it has been decided to include them in the overlying Ecca Group (Johnson and others, 1975).

The Koonap Formation (as defined in this text) was included in the Ecca Group by Mountain (1946, p.20) who referred to it as the "upper division" of the Ecca Series, and by Johnson (1966) but has now been placed in the Beaufort Group for reasons outlined below (section A2).

The present Waterford Formation, embracing the writer's Waterford Member, Middlewater Shale Member and overlying "shale and sandstone" of 1966, was originally regarded by him as part of the Koonap Formation, which in turn originally included all traditional "Upper Ecca" strata, i.e. all strata lying between the Fort Brown Shale or "Middle Ecca" and the first "red" mudstone (which was taken as the start of the Beaufort Group). In the present scheme the redefined Waterford Formation is separated from the Koonap Formation and included in the Ecca Group (see A 2 below).

A 1.2. Chronostratigraphic relationships

There would appear to be general agreement that the Prince Albert and Whitehill Shales, together constituting the old "Upper Dwyka Shale" , are of Early Permian age (Du Toit, 1954, p.280, 356; Dickins, 1961, p.138; Romer, 1970 p.111; Anderson, 1973, Chart 35). However, Plumstead (1969, p.38) places these units in the Late Carboniferous. Du Toit (p.356) regards the rest of the Ecca Group (i.e. the old "Ecca Series") as Early Permian, while Romer also implies an Early Permian age, since he assigns a Middle Permian age to the lowermost Beaufort strata. Plumstead (1969), on the other hand, postulates a Late Carboniferous to Early (and possibly Middle) Permian age, while Anderson (1973, Chart 35) indicates an Early to Middle Permian (Gaudalupian) age. If one accepts a two-fold subdivision of the Permian rather than a three-fold one, then the Ecca Group is probably Lower Permian and the "Lower Beaufort" (Adelaide Subgroup) Upper Permian.

A 2. General concepts and distinguishing features

Ecca Group

The Ecca Group in the study area consists of "varved" rhythmitite, mudrock, and dark, massive, fine- to very fine-grained lithofeldspathic sandstone.

In order to establish sound operational criteria for the assignment of formations to either the Ecca or the Beaufort Groups throughout South Africa the Karoo working group of the South African Committee for Stratigraphy has listed what it considers to be the most important unifying lithologic features which serve to distinguish them from each other (Johnson and others, 1975). They are as follows:

1. The Ecca Group consists essentially of shale; sandstone is prominently developed only at the basin margins.
2. Argillaceous rocks are generally laminated and platy- or flaky-weathering in the Ecca, and massive (blocky-weathering) in the Beaufort.
3. "Red" mudrocks are common in the Beaufort, absent in the Ecca. In general, Ecca shales are characteristically dark grey and carbonaceous, while Beaufort mudstones are greenish-grey, bluish-grey or "red".
4. Cross-bedded sandstones are common in the Beaufort, rare in the Ecca (except in the north-eastern area).
5. Fining-upwards cycles (fluviatile) are ubiquitous in the Beaufort, absent in the Ecca (except in the north-eastern region).
6. Reptilian remains are common in the Beaufort, absent in the Ecca (with the sole exception of one species in the so-called "White Band"). In the earlier descriptions this criterion was considered to be of paramount importance (see below).

The differences listed above are considered to reflect a major change in environment, namely from deposition in a large body of water (possibly marine) in the case of the Ecca, to generally "continental" (mainly fluviatile) conditions in the case of the Beaufort. It is recognised that this change is unlikely to have taken place at the same time everywhere, and that the Ecca - Beaufort boundary will hence be a diachronous one.

Since the subject of the Ecca - Beaufort boundary has given rise to considerable discussion and controversy, and since varying opinions concerning the basic concepts and distinguishing features of both the Ecca and Beaufort Groups lay behind much of this discussion, a brief historical review may be appropriate at this point.

Du Toit (1926, p.225) has pointed out that the Beaufort Beds were never clearly separated from the Ecca strata by any of the earlier geologists. It would appear that the presence of vertebrate remains has usually been regarded as the main definitive feature of the Beaufort "Series". Jones (1867, Table, p.172) introduced the name Beaufort Beds as the equivalent of Wyley's (1859) "Proper Reptilian or Dicynodon Beds". In 1896 Schwarz wrote (p.29) that the top of the Ecca (i.e. the base of the Beaufort, or "true Karoo beds", to use his terminology) would be reached "when the first bed containing reptilian remains was found". Rogers (1905, p.8) writes that the Beaufort series is "distinguished by containing the remains of several forms of reptiles". Hatch and Corstorphine (1909, p.244) state that "the Beaufort series included all the beds from the lowest Pareiasaurus zone to the plant-bearing shales of the Molteno beds at the base of the Stormberg series". Du Toit (1926, p.215, 216) refers to the "strata with reptilian remains styled the Beaufort Beds". Mountain (1946, p.19) maintained that "the true distinction between Beaufort and Ecca series must of course be ultimately based on palaeontological characters", while Haughton (1969, p.357) confirms that "the finding of fossil reptilian remains has been considered to be indicative of the presence of the Beaufort Series".

In view of the difficulty involved in mapping a fossil horizon as such, the boundary has in practice been taken at some convenient lithological boundary thought to approximately coincide with the first appearance of vertebrate fossil remains. Thus Rogers writes in 1902 (p.112) that in the Gough (western Cape Province), where the bones of Pareiasaurus and other reptiles are rather abundant, the Ecca boundary is drawn just below the lowest beds containing them. In adjacent areas, where bones were not found, the boundary was taken at the base of some red-weathering sandstones, a horizon corresponding approximately to the first appearance of bones in the Gough area (p.112). Referring to the southern Karoo area, Rogers (1917, p.5) states that "The upper limit of the (Ecca) series is taken at the base of a thick band of sandstones above which the bones of certain reptiles are found in the shales and sandstones belonging to the Beaufort series". According to Rogers, the Beaufort beds appear 5 miles north of the end of the Ecca Pass on the Grahamstown-Fort Beaufort road; this point corresponds to the base of the Koonap Formation - i.e. the first prominent sandstones above the Ecca shales.

Commencing in 1939, detailed mapping of the Ecca and lowermost Beaufort between 21°E and 25°E was undertaken by the Geological Survey, in the process of which it was decided to draw the boundary between Ecca and Beaufort at the "basal purple shale of the succession that is typically Beaufort" (Rossouw, 1953, p. 24). It was felt that this was in practice the most satisfactory means of distinguishing between "rocks of Ecca nature and those of Beaufort nature". Rossouw states further that no fossil bones have been found below the first purple shale, and goes on to affirm that "the placing of the contact between the Ecca and the Beaufort therefore rests on a change in depositional conditions, the purple shales and the presence of cross-bedded sandstones, channelling ,fossil bones of vertebrates with a terrestrial mode of life, and fresh-water lamellibranchs signifying terrestrial conditions". In addition, it was noted elsewhere (Blignaut et al., 1948, p.9), with reference to the same area, that the shales assigned to the Ecca weather in pencil-like fragments, while those assigned to the Beaufort weather into blocky fragments.

The incoming of reddish and purplish mudstones as a criterion for delimiting the base of the Beaufort had been proposed independently by Mountain (1946, p. 19), on the grounds that if, as was generally believed, the reddish and purplish character of sediments is due chiefly to the peculiar climatic conditions under which the deposits were formed, such characters would be more suited to widespread correlation than any horizon characterised by particular lithological characters which depend rather upon depth of deposition or supply of sediment. Unfortunately, Mountain's hopes for "widespread correlation" were not realised, since there is a difference of about 1200 m between the stratigraphic position of the first "purple" shale in the area which he mapped and the area which Rossouw describes - a distance of only 150 km (Johnson, 1966, p. 44).

In an attempt to overcome the inconsistencies involved in the use of the first "purple" mudstone as the Ecca - Beaufort boundary, the suggestion has been made that the boundary should be everywhere taken as the first prominent massive sandstone overlying the Ecca shales (Venter, 1969, p. 31). This would have the effect of bringing the southern Cape into line with procedures that are followed throughout the rest of the depositional basin (cf. Du Toit, 1939, p. 261). However, in the southern Cape itself this procedure suffers from the same sort of drawbacks as the "purple" mudstone method : the actual horizon changes its position - relative to the Middlewater Shale Member marker - by up to 700 m. Moreover, whereas the "purple" mudstone method results in the inclusion of up to 1300 m of Beaufort-type strata (the Koonap Formation) with the Ecca Group, the use of the first sandstone results in the inclusion of up to 770 m of Ecca-type strata (the Waterford Formation) with the Beaufort Group.

The only successful solution to the problem would seem to be to recognise as valid the reasoning behind the decision to employ the first "purple" shale in the southern Karoo area, as outlined in the quotations above, and attempt to apply the broader lithological features in the delimitation of the two groups. In other words, we should recognise that our groupings should reflect the fact that we can distinguish between "rocks of Ecca nature and those of Beaufort nature", and that this distinction should be based on those changes in lithology which reflect a change in depositional conditions, namely from deposition in a large body of water to deposition under essentially terrestrial conditions. A boundary based on environmental criteria should in theory coincide with definitions based on fossil (reptile) remains, since these will presumably not be encountered below the postulated boundary and may be found anywhere above such a boundary. The criteria adopted by the Karoo working group of SACS for distinguishing Ecca and Beaufort strata (listed at the beginning of this section) are consistent with these principles.

Prince Albert Shale

Approximately 100 m of dark grey mudrock.

Whitehill Shale

Black (white-weathering) thin-bedded carbonaceous shale plus subordinate thin layers or lenses of chert. Intense small-scale internal contortion is commonly seen in weathered outcrops.

Collingham Formation

A rhythmically-bedded alternation of thin beds of hard grey siliceous shale and very thin beds of softer, yellowish tuffaceous (?) material; total thickness about 30 m.

Ripon Formation

Up to 1000 m of dark grey fine- to very fine-grained lithofeldspathic sandstones plus interbedded "varved" rhythmitite and mudrock. Except for graded bedding and sole markings near the base of the formation, sedimentary structures are virtually absent.

Fort Brown Shale

About 1000 m of "varved" rhythmitite, subordinate mudrock and minor sandstones.

Waterford Formation

Alternating grey (commonly speckled), massive, very fine-grained lithofeldspathic sandstone, "varved" rhythmitite, shale, and mudstone lithosomes. Oscillation ripple marks are common in the argillacous rocks. Maximum thickness is about 770 m.

The Middlewater Shale Member is distinguished from the overlying and underlying strata by the absence of sandstone. It consists of fine-grained fissile shale grading upwards into "varved" rhythmitite.

The "transitional member" is characterised by the increasing abundance of mudstone and the common occurrence of disturbed bedding, especially ball- and- pillow structures.

A 3. Geographic distribution

The distribution of the whole group is shown on the geological map of the Republic of South Africa (Geological Survey, 1970; see also Folder 3). The Prince Albert, Whitehill and Collingham Formations are present at the base of the group throughout the study area, while the Ripon and Fort Brown Formations, constituting the bulk of the group, are also present everywhere. The Waterford Formation, on the other hand, is only present west of 26°E while the Middlewater Shale Member probably does not extend much beyond the western edge of the study area.

A 4. History and nomenclature

Ecca Group

Rubidge (1859) is credited by Rogers (1938, p. 126), Mountain (1946, p. 22), Du Toit (1954, p. 280) and Haughton (1969, p. 355) with having first used the name "Ecca" in a stratigraphic sense, but his reference to "the plant-beds of Ecca" (Rubidge, p. 198), on which this opinion is apparently based, is too vague to really qualify him for this honour. Jones (1867) appears to have been the first to use "Ecca Beds" as a formal name. However, his "Ecca Beds" embraced the Dwyka Conglomerate and uppermost Witteberg strata as well as the present Ecca Group strata. Schenk (1888) used the term Ecca Beds with more of less the present definition. Rogers (1902) introduced the term Ecca "Series", while the "group" designation was first employed by the present writer (1966).

The name "Ecca" was derived from the Ecca Pass north of Grahamstown, which descends to the Brack River, the original name of which was the Ecca River (Mountain, 1946, p. 22).

Prince Albert Shale

This formation has, together with the overlying Whitehill Shale ("White Band"), been mapped and/or described in the eastern Cape Province by a number of workers (e.g. Haughton, 1928, 1935; Mountain, 1946; Blignaut and others, 1948; Rossouw, 1953; Johnson, 1966; Stratten, 1968).

The name "Prince Albert Formation" was suggested by B.J.V. Botha (personal communication to Karoo working group of SACS, 1971). The name is derived from the the town of Prince Albert (beyond the western edge of the study area), in the vicinity of which typical exposures occur.

The Prince Albert Shale plus the overlying Whitehill Shale have in the past been referred to as the "Upper Dwyka Shales" (e.g. Haughton, 1928, 1935; Mountain 1946; Du Toit, 1954), "Upper Dwyka Stage" (e.g. Blignaut and others, 1948; Rossouw, 1953; Haughton, 1969) or "Dwyka Shales" (e.g. Johnson, 1966).

Whitehill Shale

This unit was previously known simply as the "White Band" (cf. Du Toit, 1954, p. 278). The name "Whitehill Formation" was proposed by T. Stratten (personal communication to Karoo working group); the name is derived from Whitehill railway siding west of Laingsburg in the Western Cape Province.

See the section above on the Prince Albert Shale for further references to earlier work.

Collingham Formation

This unit is here proposed as a separate formation for the first time. The name was derived from Collingham Outspan at the Ecca Pass north of Grahamstown.

Ripon Formation

This formation was first described in the western part of the area by Rossouw (1953) as the "Lower Ecca Stage" and in the eastern part by Mountain (1946) as the "Lower Ecca". Du Toit (1954) refers to these strata as the "Lower Shales and Sandstones" of the Ecca Series. Ryan (1967, p.16) proposed referring to this unit as the "Upper Arenaceous Formation" of the "Lower Ecca Group". The present writer (1966, p.35) proposed the name "Ecca Pass Formation" in view of the unsurpassed exposures in the Ecca Pass north of Grahamstown. However, the Karoo working group decided that "Ecca Pass" is unsuitable in view of the use of "Ecca" as a group designation. "Ripon Formation", proposed by the writer as an alternative name and derived from Ripon station south of Cookhouse, near which representative exposures occur in the banks of the Little Fish River, has now been accepted.

Fort Brown Shale

This formation has been mapped and/or described in the eastern Cape Province by Mountain (1946), Rossouw (1953) and Johnson (1966). Previously known as the Middle Ecca Shale (or Stage) (cf. Rossouw, 1953) the present writer proposed the name "Fort Brown Shales" (1966, p.37). The name was derived from the type locality north and south of Fort Brown on the Grahamstown - Fort Beaufort road. Ryan (1967, p.19) referred to this unit as the "Middle Ecca Group".

The Waterford Formation

The "Upper Ecca" described by Rossouw (1953) and Rossouw and others (1964) corresponds fairly closely to this formation. The three individual members were first recognised, described and correlated by the present writer (Johnson, 1966). In the original description all three members were placed within the Koonap Formation, while the name "Waterford" was restricted to the present "main member" (underlying the Middlewater Shale Member). However, comparison of the lithologic features of the original Koonap Formation with those now regarded as defining the essential differences between the Ecca and Beaufort Groups (see A 2 above) led to the redefinition of the Koonap Formation and the establishment of a Waterford Formation (embracing the original Waterford Member, Middlewater Shale Member and the overlying "transitional" strata) with the former characterised by Beaufort-type features and the latter by Ecca-type features. Since no suitable name could be found for the three members which had been separated from the original Koonap Formation, it was decided to extend the original "Waterford" concept to include the two overlying members. Although it is recognised that such redefinition is undesirable, there seemed to be no other satisfactory solution; in any case, the basic "Waterford" concept is not really altered in the process. The new Waterford Formation thus includes one formally named member (the Middlewater Shale Member) while the remainder of the formation is undifferentiated. It is suggested that the strata above and below the Middlewater Shale be informally referred to as the "transitional" and "main" members respectively.

The name "Waterford" was derived from the village of Waterford, north of which typical exposures of this formation are to be found, while the name "Middlewater" was obtained from the Middlewater police station east of Waterford.

A 5. Boundaries

Prince Albert Shale: lower boundary

See A 5 under Dwyka Tillite.

Prince Albert Shale - Whitehill Shale boundary

Nature of boundary.- Conformable: gradational/intercalated. Transition zone: < 1 m.

Definition of boundary.- First appearance of distinctly white-weathering carbonaceous shale.

Whitehill Shale - Collingham Formation boundary

Nature of boundary.- Conformable: sharp (Rossouw, 1953) or intercalated. Transition zone: < 1 m.

Definition of boundary.- Last appearance of white-weathering carbonaceous shale.

In the western part of the area the top of the "Upper Dwyka Shales" has in the past been taken at a prominent and laterally persistent 0,3 m thick chert bed located ± 10 m above the top of the actual white-weathering shales of the White Band (see Rossouw, 1953, p.23). However, apart from the fact that this bed does not extend into the easternmost part of the study area, use of this marker to delimit the top of the Whitehill Formation results in the inclusion of strata which differ markedly from the Whitehill shales and which are at the same time lithologically indistinguishable from the overlying strata.

Collingham Formation - Ripon Formation boundary

Nature of boundary.- Conformable: sharp.

Definition of boundary.- Base of first sandstone/coarse siltstone lithosome encountered in the succession.

Ripon Formation - Fort Brown Shale boundary

Nature of boundary.- Conformable: locally sharp or intertongued (transition zone up to 100 m) but always intertongued when viewed regionally (transition zone up to 100 m).

Definition of boundary.- Top of uppermost prominent sandstone lithosome encountered. Due to wedge-out of sandstone bodies, this boundary is not always at the same stratigraphic level.

Fort Brown Shale: upper boundary

The Fort Brown Shale is overlain west of 26°E by the Waterford Formation, and east of this line by the Koonap Formation.

Nature of boundary.- Conformable: intertongued on regional scale; transition zone: 50 - 100 m or more.

Definition of boundary.- Horizon at which a marked increase in relative sandstone abundance takes place.

Waterford Formation "main member": lateral boundary (eastern termination)

Both sandstone content and thickness decrease eastwards and this unit eventually becomes unrecognisable a few km west of Ripon station (i.e. at about $23^{o}45'$E).

Adjacent lithology.- "Varved" rhythmitite plus very subordinate sandstone and mudstone (Fort Brown Shale).

Nature of boundary.- Intertongued/gradational.

Definition of boundary.- Point beyond which the unit can no longer be differentiated from the Fort Brown Shale as a mappable unit. The actual boundary thus amounts to an arbitrary vertical cut-off.

Middlewater Shale Member: lower boundary.

Nature of boundary.- Conformable: sharp

Definition of boundary.- Top of uppermost "main member" sandstone.

Middlewater Shale Member: upper boundary

Nature of boundary.- Conformable: intertongued/gradational. Transition zone: 10 - 20 m.

Definition of boundary.- Horizon above which sandstone and siltstone layers are relatively common (constituting more than 10% of the total thickness).

Middlewater Shale Member: eastern boundary

The Middlewater Shale retains its distinctive appearance and character at least as far as the Port Elizabeth - Cookhouse railway line north of Ripon station (E7). East of this point - the main member of the Waterford having lost its distinctive characters a few km to the west - it becomes increasingly difficult to distinguish the Middlewater Shale from the underlying Fort Brown Shale. It is proposed that an arbitrary cut-off point be chosen north of Ripon station.

Waterford Formation, "transitional member": upper boundary

Nature of boundary.- Conformable: intertongued. Transition zone: ± 50 m.

Definition of boundary.- Horizon above which mudstone is more abundant than shale or rhythmitite.

Waterford Formation, "transitional member": eastern boundary

It will in practice prove difficult, if not impossible, to extend this formation eastwards beyond the cut-off point of the Middlewater Shale Member, since it is a transitional unit between the Middlewater and the sandstones and mudstones of the overlying Koonap Formation. An arbitrary vertical cut-off point will therefore have to be selected corresponding to the cut-off of the Middlewater Shale; eastwards the equivalent strata will form part of the Koonap Formation.

A 6. Overall lithology

Prince Albert Shale

Mudrock:	100%

Whitehill Shale

Mudrock:	90 - 95% (estimated)
"Chert":	5 - 10% (estimated)

Collingham Formation

Mudrock:	70%
"Tuff" (metabentonite):	30%

Ripon Formation

See Table XV-1.

Table XV-1. Overall lithology, Ripon Formation.

Locality	"Member"	Sandstone %	Mudrock/ rhythmitite %
[1]Aberdeen Road (E2)		27	73
Baroe (E3)		80	20
Ecca Pass (E9)	"Upper member" (± 400 m)	44	56
	"Middle argillaceous member" (± 250 m)	10	90
	"Lower arenaceous member" (± 350 m)	85	15
	Overall	49	51
[2]East London (Bf47)		58	42

[1] Based on simplified lithological column prepared from detailed SOEKOR borehole logs by Van Vuuren and Beer (unpublished report, 1974).

[2] Leith, 1970b.

Fort Brown Shale

Sandstone:	2 - 5% (estimated)
Rhythmitite:	95 - 98% (estimated)
Crystal tuff:	trace

Leith (1970 a,b) reports 2% and 7% sandstone in the Fort Brown Shale in the Pearston (Bf7) and East London (Bf47) boreholes respectively.

Waterford Formation, main member

See Table XV-2.

Table XV-2. Overall lithology, main member of Waterford Formation.

Locality	Sandstone %	Mudrock/rhythmitite %
Du Plessis River (E1)	50	50
North of Baroe (E4)	59	41
Waterford (E5)	53	47

Waterford Formation, Middlewater Shale Member

Sandstone:	0 - 5%
Mudrock/rhythmitite:	95 - 100%

Waterford Formation, transitional member

Sandstone:	30% (estimated)
Mudrock/rhythmitite:	70% (estimated)

A 7. Dimensions and shape

Ecca Group

The following total thicknesses have been obtained using the available data for the thicknesses of the various constituent formations:

Miller - Baroe (E1-E4)(approx. average)	2 900 m (± 200 m)
Aberdeen Road (subsurface)(E2)	1 800 m (see comment below)
Middlewater (E6)	2 400 m (± 150 m)
North of Grahamstown (E9)	1 970 m (± 150 m)
East London (subsurface)(Bf47)	1 646 m
Pearston (subsurface)(Bf7)	1 644 m
South of Aliwal North (subsurface)(Bf57)	907 m

The Aberdeen Road thickness is based on an assumed total thickness of 135 m for the Prince Albert and Whitehill Shales, since the actual thickness obtained in the borehole (567 m) is generally believed to be incorrect as a result of structural complications.

The above figures indicate that the thickness of the Ecca Group decreases both northwards and eastwards from a maximum in the Miller - Baroe area. From Baroe (E4) to Ecca Pass (E9) thickness decreases at a rate of 5 m/km, while from Ecca Pass to Bf57 south of Aliwal North the rate works out at 4 m/km.

Prince Albert Shale, Whitehill Shale

Since these two formations were always described collectively as the Upper Dwyka Shale in the past, only combined thickness values are normally given in the literature. In addition, since the "White Band chert" marker occurring within the Collingham Formation 10 - 15 m above the top of the Whitehill Shale in the western half of the area was regarded as the top of the Upper Dwyka Shale, the thicknesses quoted had to be adjusted accordingly in order to obtain true combined Prince Albert - Whitehill thicknesses.

Data supplied by Rossouw (1953, table, p.23) enable one to derive a mean combined thickness of 135 m (443 feet), based on 12 measurements, for the area between 23°E and 24°E, after subtracting 9 m (30 feet) for the interval between the Whitehill Shale and the chert marker (Rossouw, p.23;Blignaut et al., 1948, p. 9). Between 24°E and 25°E, an average combined thickness of 122 m (400 feet), based on 12 measurements, is obtained after adjusting for the 15 m (50 feet) of material between the Whitehill and the chert marker (Rossouw, p.23;H.D.Russell,unpub.report, p.4). According to Russell (p.5) combined thicknesses vary from about 76 m (250 feet) to 183 m (600 feet), the values quoted being corrected as before. For the area between 23°30'E and 24°30'E Rossouw (in an unpublished report) gives thicknesses for the Whitehill Shale ranging from 21 m (70 feet) to 95 m (310 feet), the average of five values being 56 m (184 feet).

West of Ripon (E7) the present writer obtained thicknesses of 52 m (170 feet) and 29 m (95 feet) for the Prince Albert and Whitehill Shales respectively, giving a total of 81 m (265 feet). South of Ripon a combined thickness 82 m (270 feet) was obtained, while 123 m (405 feet) was measured north of Grahamstown.

Mountain (1946, p.15) quotes a combined thickness of 150 m (490 feet) for a locality 30 km east of Grahamstown (E10). According to Mountain the thickness of the Whitehill Shale in the area which he mapped (east of 26°30'E) is about 40 to 50 feet (12 - 15 m).

Subsurface thicknesses obtained in various SOEKOR boreholes are listed in Table XV-3. The figures obtained at Aberdeen Road for the combined thickness of the Prince Albert and Whitehill (567 m) is assumed to be grossly exaggerated due to tectonism (H. de la R. Winter, pers. comm.).

Although there is some local variation in thickness, both the Prince Albert and Whitehill Shales maintain an essentially constant thickness throughout the area, with a thickness change rate of nearly zero and minimum width/thickness ratios in an east - west direction of about 5 000. Both units are known to extend across the full width of the Karoo basin, from Port St. Johns in the east to Loeriesfontein in the west, a distance of nearly 1 000 km.

Table XV-3. Subsurface thicknesses (m) of Prince Albert and Whitehill Shales.

Locality/reference	Prince Albert Shale	Whitehill Shale	Total
Aberdeen Road (E2)			567
Pearston (Bf7)(Leith, 1970 a)	66	44	110
East London (Bf47)(Leith, 1970 b)	32	37	69
Aliwal North (Bf57)(Leith and Trümpelmann, 1967)	92	30	122

Collingham Formation

Summarising data for the whole southern Karoo area west of 25°E, Rossouw (1953, p.25) states that the "White Band chert" is overlain by an average of 46 m (150 feet) of shales resembling those directly underlying it. Since the shales between the chert and the Whitehill Shale are about 9m (30 feet) thick (p.23), a total thickness of about 55 m is obtained for the Collingham Formation.

Blignaut and others (1948, p.8, 10) give thicknesses of 9 m (30 feet) and 24 m (80 feet) for the similar shales underlying and overlying the "White Band chert" respectively, giving a total thickness of 33 m for the Collingham Formation in the Schoorsteenberg area (between 23°30'E and 24°30'E).

The present writer obtained thicknesses of 32 m and 29 m 30 km west of Ripon (E6) and north of Grahamstown (E9) respectively.

Like the Prince Albert and Whitehill Shales, the Collingham Formation is essentially tabular. It is present throughout the study area, with a minimum lateral extent of 400 km.

Ripon Formation

Rossouw (1953, p.26) quotes thicknesses ranging from 600 m (2 000 feet) to 700 m (2 300 feet) for the area west of 25°E. If we deduct the strata now assigned to the Collingham Formation (about 24 m, cf. Blignaut and others, p.8) from a partially weighted mean thickness of 664 m (2 180 feet), we obtain a corrected mean thickness of about 640 m (2 100 feet). In the same general area the present writer obtained a thickness of 550 m (± 30 m) north of Baroe (E3); the discrepancy is probably a result of the transitional nature of the upper boundary and the consequent arbitrariness involved in locating it in the field.

East of the above area the following thicknesses were obtained by the writer:

Middlewater (E6) : 715 m (± 50 m)
Ripon (E7) : 915 m (± 50 m)
South of Pigotts's Bridge (E8) : 1 100 m (± 100 m)(?)
North of Grahamstown (E9) : 1 000 m (± 20 m)

South of Committees Drift (E10) Mountain (1946, p.22) measured 1 065 m, the general thickness of the Collingham Formation (about 30 m) having been deducted from the actual figure given (3 590 feet).

North of the outcrop area the following thicknesses have been obtained in boreholes drilled by SOEKOR:

Aberdeen Road (E2) : 510 m (Winter and Venter, 1970, Table 1; the approx. thickness of the Collingham Formation (60 ft - 18 m) has been subtracted from the 1 731 ft (528 m) given in the table)

East London (Bf47) : 650 m (Leith, 1970 b, p.16)

The formation is absent at Pearston (B7) (Leith, 1970 a, p.15, 16)

The Ripon Formation thins both eastwards and westwards from a maximum thickness of 1 000 m at Ecca Pass (E9) to about 600 m at Baroe (E3) and 650 m at East London (Bf47), corresponding to thickness change rates of 2 m/km and 3 m/km respectively. As a consequence of rapid facies changes, the formation extends only a short distance north of the outcrop area. Thus it is absent in the SOEKOR borehole near Pearston (B7), 70 km north of where it is about 600 km thick.

The Ripon Formation has a minimum lateral extent of 600 km (from Coffee Bay (E11) to beyond the western edge of the study area).

Fort Brown Shale

Rossouw (1953, p.27) gives thicknesses of 1 380 m (4 530 feet) north of Miller, 1 430 m (4 700 feet) south of Jansenville and 1 280 m (4 200 feet) east of the latter locality. However, in the area south of Jansenville (E4), the writer obtained a thickness for the Waterford Formation considerably less than that given by H.D. Russell (unpublished report) and Rossouw (p.28). Examination of the aerial photographs used by Russell showed that the writer had placed the Fort Brown - Waterford boundary at a stratigraphic level about 200 m higher than that chosen by Russell. If this interval is added to the Fort Brown Shale, thicknesses of 1 630 m and 1 480 m are obtained for the last two localities mentioned by Rossouw.

The writer obtained the following thicknesses east of the area described by Rossouw:

East of Middlewater (E6) : 1 225 m (± 100 m)
Ripon (E7) : 1 470 m (± 100 m)

The last figure includes the lateral equivalent of the Middlewater Shale Member (170 m) and part of the "transitional member" (100 m). The remaining values given below must also embrace the lateral equivalent of at least the Middlewater Shale, even though this unit is no longer recognisable as such.

South of Pigott's Bridge (E8) : 975 m (± 100 m)
North of Grahamstown (E9) : 850 m (± 100 m)

In the Committees Drift area (E10) Mountain (1946, p.22) obtained 730 m (2 400 feet).

The following subsurface thicknesses have been obtained:

Aberdeen Road (E2) : 1 155 m (3 790 ft: Winter and Venter, 1970, Table 1)
East London (Bf47) : 927 m (3 040 ft: Leith, 1970 b, p.16)

At Pearston (Bf7) the Ripon Formation can no longer be recognised, with the result that there is a single "shale" unit extending from the top of the Whitehill Shale to the base of the Beaufort Group. This unit, which is equivalent to the Tierberg Shale (i.e. the "Central Ecca Phase" of Du Toit, 1954; renamed by L.Nel,pers.comm.),has a total thickness of 1 534 m (Leith, 1970 a, p.20). South of Aliwal North (Bf57) this shale interval is 785 m thick (Leith and Trümpelmann, 1967, p.11).

The Fort Brown Shale thins eastwards from Ripon (E7) to Ecca Pass (E9) at a rate of 8 m/km.

Waterford Formation

Thicknesses obtained by the writer are presented in Table XV-4.

Table XV-4. Waterford Formation thickness data (in m).

Member	E1	E4	E5	E6
"Transitional member"	165	120 (est.)	105	97
Middlewater Shale Member	45	95	90	143
"Main member"	560	320	195	140
Total	770 (± 50)	535 (± 50)	390 (± 30)	380 (± 30)

The thicknesses given above are considerably less than those given by Rossouw (1953, p.28) for the "Upper Ecca" in comparable areas. It must be borne in mind, however, that Rossouw's "Upper Ecca" included at least 200 m of strata now classified as belonging to the Koonap Formation; in addition, as mentioned above, the lower contact of the Waterford Formation has at at least one locality been placed nearly 200 m higher in the succession. Also, with the rapid wedge-out of sandstones northwards thickness values obtained for the "main member" near Waterford can be expected to be much less than those obtained for the same interval when it reappears about 13 km to the south on the southern flank of the syncline running south of Waterford. Rossouw's values range from 1 120 m (3 680 feet) north of Miller to 790 m (2 600 feet) south of Jansenville.

The Waterford Formation extends from Ripon (E7) to beyond Prince Albert (22°E), a minimum distance of 400 km. From north of Miller (E1) to Ripon (E7) the formation thins at an average rate of 4,5 m/km, although this thickness change reflects lateral facies changes rather than a physical diminution in thickness.

A 8. Stratotypes

Prince Albert Shale

Type Locality.- Prince Albert area (west of study area).

A unit stratotype has still to be located somewhere in the type area.

Reference stratotype.- Ecca Pass (E9).

Nature of stratotype: Typical exposures occurring in both shallow road cuttings and a small gully west of the road. The strata dip at about 40°.

Accessibility: Excellent.

Location: See Fig. XV-1a.

Whitehill Shale

Type locality.- Whitehill siding area (west of study area).

A unit stratotype has still to be located somewhere in the type area.

Reference stratotype.- Ecca Pass (E9).

Nature of stratotype: The complete thickness, including both contacts, is exposed in a road cutting, while further exposures occur in a nearby gravel pit. The strata dip at about 40°.

Accessibility: Excellent.

Location: See Fig. XV-1a

Collingham Formation

Unit-stratotype.- Ecca Pass (E9).

Nature of stratotype: Complete exposure of the whole formation in a road cutting; general dip is about 40°.

Accessibility: Excellent.

Location: See Fig. XV-1a.

Ripon Formation

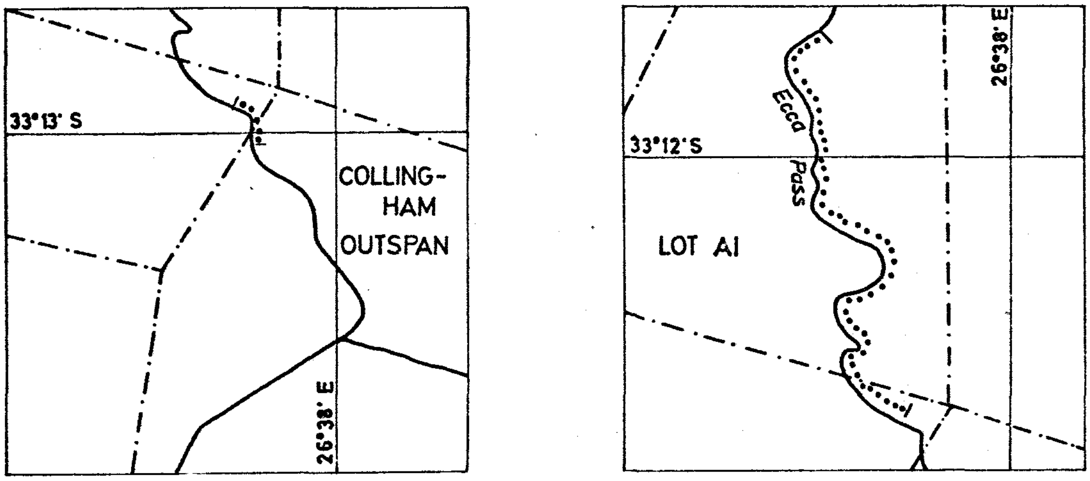
Unit-stratotype.- Ecca Pass (E9).

Nature of stratotype: A series of road cuttings exposing virtually the whole succession in comparatively unweathered form. The general dip is

FIG XV-1
STRATOTYPES: ECCA GROUP

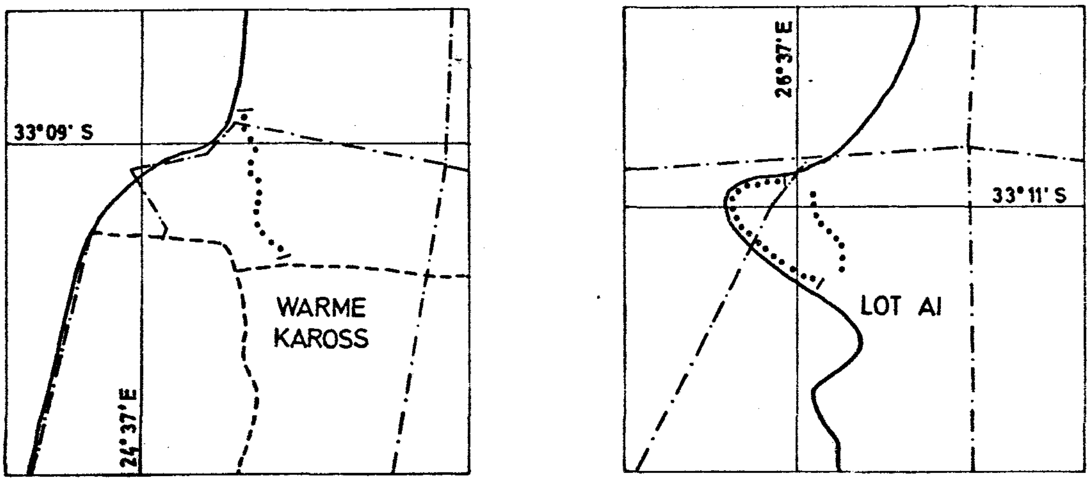
SCALE OF MAPS: 1:50000

••••••• Stratotype
— — — Road
River
—·—·— Farm boundary



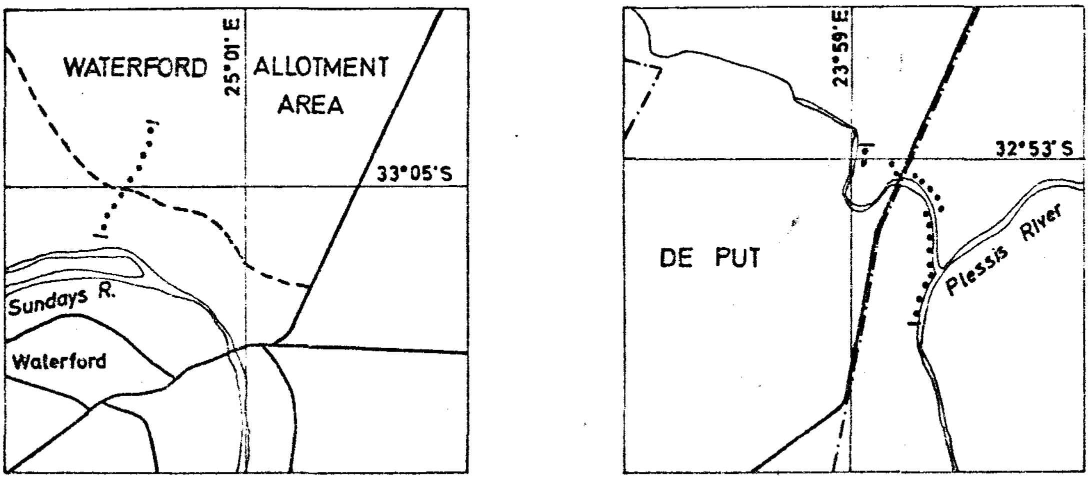
a. Prince Albert, Whitehill, Collingham Fms.
Reference stratotype
Map ref.: 3326 BA

b. Ripon Formation.
Unit-stratotype
Map ref.: 3326 BA



c. Ripon Formation
Reference stratotype
Map ref.: 3324 BA

d. Fort Brown Formation.
Unit-stratotype
Map ref.: 3326 BA



e. Waterford Formation.
Unit-stratotype
Map ref.: 3325 AA

f. Waterford Formation.
Reference stratotype
Map ref.: 3223 DD

about 30° - 40°, and the strata are relatively unaffected by the tectonism.

Accessibility: Excellent.

Location: See Fig. XV-1b.

Reference stratotype.- North of Baroe (E3).

Nature of stratotype: Fairly continuous exposures along dry stream course. Strata dip steeply.

Accessibility: Good.

Location: See Fig. XV-1c.

Fort Brown Shale

Unit-stratotype.- Fort Brown (E9).

Nature of stratotype: A series of isolated road cuttings and natural exposures which display the characteristic features of this unit. Strata gently folded.

Accessibility: Excellent.

Location: From the top of the Ripon Formation at the bottom of Ecca Pass (see Fig. XV-1b) to the base of the Koonap Formation north of Fort Brown (see A 8 under Koonap Formation) along the Grahamstown - Fort Beaufort road. The main exposures are indicated on Fig. XV-1d.

Waterford Formation

Unit-stratotype.- Waterford (E5).

Nature of stratotype: Series of reasonably complete exposures along a dry stream course. The general dip is about 30° - 40°.

Accessibility: Good.

Location: See Fig. XV-1e.

The above stratotype is applicable to all three members of the Waterford Formation.

Reference stratotype.- Plessis River (E1).

Nature of stratotype: Fairly complete exposures in stream banks. Strata dip moderately steeply.

Accessibility: Good.

Location: See Fig. XV-1f.

B. PALAEONTOLOGY

The Ecca Group in the study area is remarkably unfossiliferous, evidences of animal life being limited to trace fossils while plant life is represented by unidentifiable plant remains which are largely confined to the turbidite sandstones at the base of the Ripon Formation (where they may be quite abundant).

"Worm" trails and burrows occur sporadically in both the Ripon and

Waterford Formations, a particular fucoidal type displaying burrows filled with pale material which contrasts strongly with the surrounding dark shale being especially common at the base of the Collingham Formation. Invertebrate tracks occur in the Ripon Formation, but are not common. A very distinctive trail consisting of two (occasionally four) parallel sinuous grooves is fairly abundant along certain horizons towards the middle of the Fort Brown Shale (see Johnson, 1966, Figs. 8-10). Haughton (1928, p.15) suggested that the markings were produced by the ventral spines of a fish.

C. MACRO-SEDIMENTOGRAPHY

C 1. Cyclicity

Large-scale fining-upward cycles commencing with sandstone with a sharp base and grading upward through siltstone into rhythmitite and mudrock are present in the upper half of the Ripon Formation in the eastern part of the study area. These range up to about 80 m in thickness, with an average thickness in the region of 30 m. The lateral extent and cross-sectional shape of these cyclic units are not known, but the regional geological setting in which they occur points to a sub-tabular shape.

With the possible exception of a single coarsening-upward cycle commencing at the base of the Middlewater Shale Member and extending into the overlying "transitional member" no clearly defined cycles were observed in the Waterford Formation.

C 2. Lithosome dimensions and shape

Collingham Formation

The yellow-weathering "tuff" layers possess an average thickness of 1,5 - 2 cm, with a maximum thickness of 5 cm. The interbedded mudrock layers have an average thickness of about 4 cm (maximum 20 cm). Bed-by-bed thickness measurements through parts of the Collingham Formation at Ecca Pass (E9) and west of Alicedale (near W17) enabled the writer to correlate most of the individual layers in a 1 m thick section. Since these localities are about 65 km apart, this means that most "tuff" layers possess a width/thickness ratio of at least 3.10^6, and that both "tuff" and mudrock layers are ultra-tabular in shape.

Ripon Formation

Sandstone thickness.- South of Jansenville (E3): average, 15 m; maximum, 30 m. North of Grahamstown (E9): average, 12 m; maximum, 44 m. The figures quoted are based on data for the succession above the lowermost 50 m (in which sandstones average about 30 cm in thickness).

Sandstone shape and lateral extent.- Lithosomes are parallel-sided and tabular in individual outcrops, but due to lack of continuous outcrops no quantitative information is available regarding lateral extent and shape on a regional scale. By analogy with similar facies described elsewhere in the world, the sandstones in the lowermost 50 m are assumed to be highly tabular, and those in the bulk of the formation are probably sub-tabular to moderately tabular.

Waterford Formation

Sandstone thickness.- North of Miller (E1): average, 6,5 m; maximum, 17 m. South of Jansenville (E4): average, 7 m; maximum, 18 m. North of Waterford (E5): average, 6 m; maximum, 15 m. The thin arenaceous rhythmitite layers which are often present at a number of levels within lithosomes composed essentially of sandstone were disregarded in the above calculations. Their presence does, however, indicate that most sandstone lithosomes are probably "welded" (composite) units.

Sandstone shape and lateral extent.- Sandstone lithosomes in this formation generally appear to be parallel-sided and tabular in single outcrops, but again lack of continuous exposures meant that no actual data is available regarding lateral extent and shape. However, comparison of thicknesses obtained for individual sandstone bodies in two sections south of Jansenville (E4) located 450 m apart indicated that these units probably vary from sub-lenticular to moderately tabular.

C 3. Lithosome boundaries

Ripon Formation

Lower boundaries of sandstone lithosomes are sharp and generally flat and even, but local irregularities in the form of groove casts, load casts and flame structures occur, especially near the base of the formation.

Upper sandstone boundaries are normally gradational, with a transition zone varying from a few mm to a few metres (generally a few cm).

Waterford Formation

Sandstone lithosome lower boundaries tend to be sharp and flat, but intertongued relationships also occur, especially at the base of thinner bodies. Upper boundaries may be gradational or intertongued, with the transition zone ranging from a few cm to a few metres in thickness.

C 4. Colours

Sandstones

Medium grey (N5) to medium light grey (N6). A characteristic feature is the presence in many sandstones of numerous closely-spaced pale spots set in a dark matrix, giving the rock a distinctly "mottled" appearance. These spots are generally 2 - 5 cm in diameter and are often concentrated in layers about 5 cm thick (in which the spots have engulfed virtually the whole rock) which alternate with dark layers in which spots have not developed, giving the rock a banded appearance. The bands are not sharply demarcated but grade into each other.

Mottling characterises roughly half the sandstone in the Ecca Group (Ripon and Waterford Formations). However, large local variation was noticed. For example, in the Waterford Formation south of Jansenville (E4) mottled sandstone (generally banded) is approximately twice as abundant as non-mottled sandstone, while north of Miller (E1) mottled sandstone is virtually absent.

Mineralogically the pale spots are characterised by a concentration of calc-silicates such as laumontite, prehnite, pumpellyite, etc. (Martini, 1974, p.114). Martini also gives references to other rock sequences in which a similar mottled effect was observed. The actual colour difference is due to the presence of dark semi-opaque disseminated material which is common in the sandstone matrix in the areas between the pale spots, but rare in the spots themselves. According to Reynolds (1971, p.16) the dark brown staining represents iron oxide, possibly with the addition of a certain amount of carbonaceous matter (although the present writer feels that carbonaceous staining predominates). Reynolds suggested that the whitish spots were formed as a result of the migration of the dark material away from the spots, to become concentrated in the intervening areas. Reynolds failed to discover any other mineralogical differences between the pale and dark areas, while Martini (personal communication) concedes that the differences which he noted are not always obvious.

Mudrock/rhythmitite

Generally medium dark grey (N4) but dark grey (N3) in the Prince Albert Shale and greyish black (N2) in the Whitehill Shale (fresh material). Weathered shale belonging to the Whitehill Formation displays various shades of red and yellow, as well as the characteristic white.

"Tuff" (Collingham Formation)

Yellowish grey to greyish yellow (5Y7/2 to 5Y8/4) (Lock and Wilson, 1975).

C 5. Sedimentary structures

General bedding characteristics

Sandstone.- Beds are generally subequal or unequal in thickness (ranging from thin to very thick), laterally uniform and continuous (less frequently laterally variable and discontinuous).

Rhythmitite.- Individual couplets are equal or subequal in thickness (varying from one to five cm) laterally uniform and continuous. All couplets appear to extend indefinitely when traced laterally across the length of an exposure, pointing to a highly tabular to ultra-tabular shape. Within couplets the coarse component is generally thinner than the fine component.

Pre-depositional structures

Ripon Formation.- Groove casts are fairly common towards the base of this formation (i.e. in the lowermost 50 m). Bounce, skip, and prod marks are occasionally associated with the groove casts. Groove marks and related structures are rare in the rest of the formation, while throughout flute casts are rare.

Syn-depositional current structures

Ripon Formation.- Graded bedding is common in sandstone and coarse siltstone near the base of the formation (lowermost 50 m) and occurs sporadically at higher levels. Average thickness of beds is about 30 cm (maximum thickness 90 cm). Small-scale graded beds (1 - 2 cm thick) are common in the rhythmitites occurring in the basal zone of the formation.

Small-scale "cross-bedding" (wavy bedding, inclined bedding, ripple drift cross-lamination), with sets 2 - 10 cm thick, are present, especially in the basal zone. Conventional cross-bedding is absent.

"Massive bedding" (no visible structures, individual beds varying from a few cm to 6 m in thickness) characterises the vast majority of sandstones in the Ripon Formation. Many of these beds may in fact be slightly graded, but such grading, if present, is not obvious.

Poorly-developed, low-amplitude asymmetrical ripple marks are occasionally present. According to Ryan (1967, p.99) symmetrical ripple marks also occur; an average ripple index of just over 10 was calculated by the writer from data supplied by Ryan (Appendix 5) on 30 ripple marks from the writer's study area.

Fort Brown Shale.- Oscillation ripple marks often occur on the upper surfaces of thicker-than-average sandy/silty layers within the uppermost 100 - 200 m of this formation. Initially (at the base of this upper zone) the ripple marks are poorly developed, with very low amplitudes; on going upwards in the succession they become more abundant and more pronounced, with dimensions similar to those in the Waterford Formation (see below).

Waterford Formation.- In order of abundance, sandstones display massive bedding, flat-bedding, inclined bedding, cross-bedding and micro-cross-lamination, with the last-named two structures being relatively rare. Close inspection of some of the superficially structureless sandstones often reveals the presence of horizontal lamination or (less frequently) inclined bedding; it is suspected that, as in the case of the Gamka Sandstone of the Bokkeveld Group, suitable etching or weathering (along the coast, for example) would reveal the ubiquitous presence of horizontal or sub-horizontal bedding, inclined bedding, and related structures. Beds range from a few cm to over a metre in thickness.

Well-developed oscillation ripple marks (wave length 5 - 8 cm, amplitude 7 - 10 mm and average ripple index about 7) are common in the more arenaceous rhythmitites and the thin-bedded sandstones. Thicker sandstone beds also occasionally display ripple-marked upper surfaces. Ryan (Appendix 5) supplied ripple index data on 111 ripple marks from the writer's study area; an average value of 5,7 was calculated from this data.

Deformational structures

Ripon Formation.- Load casts, flame structures and convolute bedding are common towards the base of the Ripon Formation. Sandstone dykes and slump structures were noted at various levels within the formation, but are comparatively rare. Thin layers and lenses of mud-flake conglomerate are occasionally present; isolated shale fragments are often present in the sandstones.

Fort Brown Shale.- Slump structures, in the form of well-developed recumbent folds, are prominently displayed in the lower part of the formation north of Ripon (E7) and probably occur elsewhere as well.

Ball-and-pillow structures are commonly developed towards the top of the formation. The structures range from a boudinage effect in sandstone layers to the development of isolated sandstone balls up to a metre or more in length completely surrounded by mudrock.

Waterford Formation.- Ball-and-pillow and related deformation structures are relatively common throughout the Waterford Formation, but are especially abundant in the "transitional member" at the top of the unit. These structures are well displayed in the section at Waterford itself (E5). A particularly common variety is one in which isolated, contorted sandstone blocks, balls, lenses and stringers occur within a massive very fine sandstone or siltstone unit; slumping as well as foundering appears to have been involved. Individual "balls" vary from about 10 cm to over a metre in diameter.

Occasional thin mud-flake conglomerate layers were observed.

Chemical structures

Phosphatic concretions varying in shape and size from lenticular layers up to 15 cm thick and a few metres long (in the lower part of the succession) to short, thick lenses up to 30 cm or more in diameter (in the upper part of the formation) characterise the Prince Albert Shale, especially in the western half of the area (Rossouw, 1953, p.22).

Calcareous concretions occur in both the arenaceous and argillaceous rocks of the Ecca Group. Roughly spherical concretions 10 - 15 cm in diameter (often containing a shale fragment nucleus) are fairly common in the sandstones of the Ripon Formation. Larger, brown-weathering generally oval calcareous bodies 30 - 150 cm in diameter occur in both the Ripon and Waterford sandstones. Flattened, bun-shaped concretions 30 - 100 cm in diameter and 10 - 30 cm thick are present in the argillaceous rocks of the Ripon, Fort Brown and Waterford Formations.

Biogenic structures

Trace fossils (trails, tubes, burrows) are fairly common near the base of the Collingham Formation, towards the top of the Fort Brown Shale and throughout the Waterford Formation. They also occur sporadically in the Ripon Formation. A distinctive and unusual trail, consisting of two (occasionally four) parallel sinuous grooves spaced 1,5 - 3 cm apart is common along some horizons in the Fort Brown Shale and occasionally present in the upper part of the Ripon Formation (see Marais and Johnson, 1965, Plates I, II). Tracks of small invertebrates are occasionally present in the Ripon Formation.

Directional data

The summary presented below is based on the raw data presented by Ryan (1967).

Ripon Formation.- A total of 41 groove casts from 6 localities were measured by Ryan within the study area, and a further 41 at 7 localities west of the study area. In both areas the mean orientations obtained at the various localities indicated a direction either slightly west of north or slightly north of west (see Ryan's Folder 3).

Ryan recorded average orientation values for "symmetrical" ripple marks at 7 localities, representing a total of 30 readings. No preferred orientation is, however, apparent, a vector strength of only 0,10 being obtained on attempting to calculate a mean value from the 7 average directions given.

Waterford Formation (including uppermost Fort Brown Shale).- Ryan's data (contained in his appendix 5) enabled the writer to calculate a vector mean of $105^{\circ}/285^{\circ}$ for the orientation of 80 symmetrical ripple mark crests between $24^{\circ}30'$E and $25^{\circ}30'$E (vector strength: 0,70; standard deviation: 20°).

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Grain-size data for Ecca Group sandstones are summarised in Table XV-5. Original outlines of quartz grains are rarely preserved, with the result that roundness values could not be obtained.

Table XV-5. Grain-size data for Ecca Group sandstones.

Unit/locality	n	$\bar{x}$(Ø)	s(Ø)	MD(Ø)	d(Ø)	$\bar{x} - d$	M(%)
Waterford (E1)	6	3,31 (2,7 - 3,6)	0,52	0,41	2,17	1,14	20
Waterford (E5)	3	3,35 (3,1 - 3,6)	0,50	0,39	2,31	1,04	19
[1]Fort Brown (E6)	1	-0,09	0,59	0,46	-	-	-
Ripon (E3)	5	3,13 (2,9 - 3,4)	0,84	0,69	1,35	1,78	20,5
Ripon (E9)	11	3,25 (2,7 - 3,8)	0,78	0,63	1,56	1,69	34,5

[1] "Crystal tuff" sample

n = number of samples (50 grains per sample)

$\bar{x}$ = mean size (range in brackets)

s = standard deviation

MD = mean deviation

d = maximum thin-section diameter

M = matrix content ($< 20 - 30\mu$)

D 2. Composition

Results of modal analyses carried out on Ecca Group sandstones are presented in Table XV-6. Table XV-7 gives an indication of the relative abundance of the various rock fragment types encountered.

The chief authigenic minerals present appear to be calcite, prehnite, laumontite and pumpellyite (cf. Martini, 1974, p.114). Martini has discussed the volcanic fragments occurring in the Ecca Group, and includes a number of photomicrographs illustrating the main varieties.

Table XV-6. Mineral composition of Ecca Group sandstones.

Unit/locality	n	Q	F	R	Acc.	Cem.	M	Q : F : R
Waterford (upper mb.) (E1, 5)	3	24	24,5	28,5	2	1	20	31 : 32 : 37
Waterford (main mb.) (E1)	4	22,5	21,5	32,5	2	1,5	20	29,5 : 28 : 42,5
Waterford (main mb.) (E5)	4	13	23	40,5	1,5	3	19	17 : 30 : 53
[1]Fort Brown (E6)	1							7 : 90 : 3
Ripon (E3)	7	12,5	20,5	39	1,5	6	20,5	17,5 : 28,5 : 54
Ripon (E9)	10	10,5	21	30,5	1,5	2	34,5	17 : 34 : 49

[1]"Crystal tuff" sample

n = number of samples (200 - 300 points per sample)

Q = quartz (including secondary quartz)

F = feldspar

R = rock fragments

Acc. = accessory minerals

Cem. = cement plus secondary minerals (excluding silica cement)

M = matrix

mb. = member

Table XV-7. Relative abundance of rock fragment types in Ecca Group sandstones, expressed as a percentage of total rock composition.

Unit/locality	n	m	s	c	f	p	g	?
Waterford (upper mb.) (E1, 5)	3	10,5	2,5	tr.	11	0,5	1,5	2,5
Waterford (main mb.) (E1)	4	14,5	3,5	0,5	7	0,5	2	4,5
Waterford (main mb.) (E5)	4	14	4	0,5	17	0,5	1	3,5
Ripon (E3)	7	9,5	4	1	14	3,5	2	5
Ripon (E9)	10	6,5	4	1	12	2	2	4

n = number of samples

m = micaceous fragments (mica/clay minerals/chlorite)

s = schistose fragments (mica/clay minerals/chlorite + quartz/feldspar)

c = chert, microcrystalline quartz

f = felsite (fine-grained quartz-feldspar mosaic)

p = pilotaxitic/porphyritic igneous rocks (distinct feldspar laths present)

g = granite/gneiss fragments(?)

(?)= unidentified fragments

mb.= member

E. SEDIMENTOGENESIS

E1. Dispersal patterns

Groove casts measured by Ryan (1967, Folder 3) in the Ripon Formation indicate two main transport directions, namely NNW (or SSE) and ENE (or WSW).

E2. Sedimentary processes and palaeoenvironments

Prince Albert Shale

A laterally extensive, uniformly fine-grained homogeneous deposit of this nature, lacking sandstone intercalations and current structures, could only have accumulated in the relatively deep, undisturbed areas of a large body of water (deep-sea basin/trench, abyssal plain, continental slope, or outer offshore zone of an epicontinental sea). The subsequent depositional history of the Ecca Group would seem to favour a deep-sea basin as the most likely environment. Ryan (1967) reviews some of the palaeontologic evidence favouring marine conditions.

Whitehill Shale

The laterally extensive, ultra-tabular nature of this deposit again points to deposition in the deeper portions of a large body of water. Most of the characteristics listed by Pettijohn (1957 a, p. 622) for the black shale (euxinic) facies are true of the Whitehill Shale. These include black colour, thin laminations, abnormally high content of carbon, richness in iron sulfide (pyrite), restricted fauna, presence of interbedded thin layers of chert, limited thickness and great extent.

According to Pettijohn (p.625) true euxinic sediments are exclusively marine. "Euxinic sediments seem commonly to occur above the carbonate-orthoquartzite association and below the graywacke-shale assemblage. Their occurrence is perhaps a record of the transition between the open-sea deposition of carbonates and craton-derived sands and the influx of sediments from a rising island arc. The initial rise of the future arc results in shoals or barriers which lead to partial isolation of the locus of deposition and restricted or inhibited circulation - conditions conducive to stagnation of bottom waters and deposition of reduzates and related sediments" (p. 626).

Collingham Formation

As in the case of the previous two formations, absence of all current indications, great lateral extent, fine-grained character and extreme continuity (ultra-tabular shape) of individual beds point to deposition in relatively deep water (deep-sea basin). The observation that the yellow-weathering layers, which are generally 1 - 5 cm thick, can be followed laterally for at least 65 km, lends strong support to the suggestion that they represent tuff layers (metabentonite - Lock and Wilson, 1975).

Ripon Formation

The lowermost 50 m displays features generally considered to be diagnostic of turbidity current deposits. These include abundance, relative thinness (average 30 cm) and tabular shape of individual sandstone lithosomes, presence of graded bedding in most sandstone units, presence of groove casts and related sole markings on some sandstone soles, and the absence of all structures denoting traction currents (e.g. cross-bedding, flat-bedding, micro-cross-lamination).

The bulk of the Ripon Formation, on the other hand, is characterised by an absence both of structures denoting traction currents and of features which normally characterise turbidity current deposits. Thus true graded bedding is rare, and sole markings virtually absent, although most sandstone units have sharp bases and tops that grade into the overlying argillaceous strata over a distance of a few cm.

Using available published descriptions, Walker (1967, Table 3) has tabulated the characteristics of what had become known as "fluxoturbidites". According to Walker (p. 38) the term "fluxoturbidite" was introduced by Dzulynski and others (1959) to describe a "type of flysch ...... transitional between true turbidites and pure slides, because it shows a mixture of features characteristic of the two mechanisms of transport". From Walker's tabulation (drawn from 9 published descriptions) it would appear that all "fluxoturbidites" are characterised by unusually coarse grain-size, thicker-than-usual beds (typically 3 - 8 m, max. 20 m) poor grading or absence of grading, and scarcity of sole marks, while most display multiple beds or repeated grading, interbedded turbidites, and irregularity as well as non-parallel-sidedness of individual beds. Walker gives reasons for abandoning the term "fluxoturbidite" altogether, and suggests that the deposits displaying the above features be descriptively named by reference to the continuous series : conglomerates → pebbly mudstones → proximal turbidites.

A comparison of the features displayed by the sandstones in the Ripon Formation with the characteristics of proximal and distal turbidites presented by Walker (1967, Table 2) suggests that the sandstones in the basal 50 m represent distal turbidites and those in the remainder of the formation proximal turbidites (fluxoturbidites). However, in neither case is the "fit" a perfect one (e.g. the fine-grained nature of the "proximal" sandstones is anomalous) and more attention will have to be given to this problem in detailed studies such as that at present being undertaken by C.S. Kingsley.

Turning from the question of depositional processes to the actual environments involved, the descriptions given by Reineck and Singh (1973, p. 390 - 394) suggest that the bulk of the Ripon Formation must represent deposition in submarine canyons, with only the basal strata being deposited on the continental rise or deep-sea fan region. However, it is difficult to envisage a situation in which submarine canyon deposits as such can build up a 1000 m thick deposit extending over 500 km and we may in fact be dealing with a situation in which the present is not a key to the past. If we envisage a deep-sea basin or trench unaccompanied by a well-developed continental shelf, we could postulate a series of rivers building small sandy deltas which periodically became over-steepened and gave rise to slumps which in turn developed into turbidity currents, which deposited thick wedge-like fans of proximal turbidites on the basin slope and floor. The large variation in the character (thickness, sandstone percentage) of the Ripon Formation between Baroe (E 3) and Ecca Pass (E 9) supports the contention that we may be dealing with a series of overlapping and interdigitating deep-sea fans. The absence of material coarser than fine sand may simply be due to the fact that the rivers were bringing only fine-grained material to the basin edge and that coarser material was therefore simply not available.

Finally, the significance of the palaeocurrent data obtained by Ryan needs to be assessed in the light of the above interpretations. Since the groove casts are largely confined to the distal turbidites constituting the lowermost 50 m of the formation, they can only bear on the depositional history of these particular beds. The predominant ENE - WSW direction must represent transport along the axis of the basin (a situation encountered in many other flysch basin, cf. Kuenen, 1958). Since these lower sands die out westwards, transport must have been from east to west, and not west to east as postulated by Ryan (1967, p, 135).

The "symmetrical" ripple marks measured by Ryan in the Ripon Formation are anomalous, but similar structures have been photographed on the sea floor at great depth (cf. Heezen and Hollister, 1971, Figs. 9.12, 9.15, 9.32). They are in any case rare; the present writer has not observed any in the course of measuring a number of detailed sections.

Fort Brown Shale

The general lithological homogeneity, the extreme regularity of the bedding and the exceptional lateral persistence of individual silty and clayey layers (which were never observed to pinch out) point to deposition under quiet conditions in an extensive body of water. Deposition must have taken place below wave base, since it is only towards the top of the formation that wave-formed ripple marks, associated with a more heterogeneous lithology, make their appearance.

The origin of the rhythmic small-scale coarse-fine alternation characterising the bulk of this formation is not readily explained. The writer has not encountered any definitive descriptions or detailed analyses of similar sediments (modern or ancient) although relatively thin sequences of similar-looking rhythmitites interbedded with other facies types have been illustrated. Examples are the "black mudstone facies" of De Raaf and others (1965, p. 13) , the "striped siltstones" of Collinson (1969, p. 198) and the alternating thin graded silty mud (light coloured) turbidites and silty clay (darker coloured) laminae found by Stanley (1969, Fig. DJS - 20) in a core collected near the base of slope of the Nova Scotian shelf.

De Raaf and others (p. 50) assign their rhythmically-bedded "black mudstone facies" to a pro-delta environment, but do not attempt to explain the cause of the thin layering. Collinson (p. 199) ascribes his "striped siltstones" to "fluctuating sediment supply, which may be related to climatic factors", and includes these sediments in an "interdistributary complex association" (p. 209). Even though the individual layers in his core sample average about 1 cm in thickness, Stanley (p. DJS 8 - 12) feels that they represent turbidites. Finally, Reineck and Singh (1972; 1973, p. 308, 323) have described what they term "storm sand layers" in shelf mud.These are sandy layers ranging from more than 2 cm to under 1 cm in thickness spaced at intervals of 5 - 10 cm within the muddy sediments. Their interpretation of these layers is based on the observation that turbulent water flowing away from the coast after a hurricane or storm can transport sand in suspension to the open shelf in large quantities, forming sand or silt layers which begin with a sharp base and mostly grade upwards into overlying mud layers. The sand layers are either evenly laminated, or are developed as "laminated rhythmites" in which the individual laminae constituting a layer are thicker and coarse grained at the base and grade upwards into thinner and fine-grained laminae (1972, p. 123). Storm sand layers in areas near the coast often show wave-formed ripples on the surface in recent as well as ancient examples (1972, p. 127). Hayes (1967) suggested that currents set in motion by hurricanes can deposit a thin layer (0,5 to 1,5 inches) of sand over what was previously a sandy mud bottom out to a depth of 60 feet (18 m) and also a graded layer of fine sand, silt or clay (i.e. a turbidite) farther out on the shelf. Reineck and Singh (1972, p. 124) are however critical of the turbidity current explanation for the outer sand layer.

Turning now to the Fort Brown Shales themselves, the storm-sand layer theory seems to account most satisfactorily for the observed rhythmic coarse-fine layering. Although Lock (1973 b) has proposed a turbidity current origin for the sand/silt layers, it is significant that the "turbidite" illustrated in his Plate II is virtually identical in appearance to a recent "storm-sand layer" shown by Reineck and Singh (1972, Fig. 2). The main argument against a turbidity-current origin is, however, the fact that towards the top of the succession the thicker sandy/silty layers show the development of wave-formed ripple marks on their upper surfaces, while in the overlying Waterford Formation wave ripple marks are commonly associated with Fort Brown-type rhythmitites which are here interbedded with thick sandstones. Clearly,then, the main bulk of Fort Brown rhythmitites, apparently deposited on an undisturbed bottom <u>below</u> wave base,grade upwards without any perceptible break into rhythmitites deposited <u>above</u> wave base,i.e. in relatively shallow water. In addition, a turbidite hypothesis would involve the anomaly of <u>extremely distal</u> turbidites directly overlying the very thick proximal turbidites of the Ripon Formation in a basin which was becoming progressively shallower, with the shoreline moving steadily northwards.

Having discussed the depositional processes involved, we need to suggest the most probable environment. There would seem to be only two possibilities: the offshore region of the shelf or a pro-delta slope and outer delta-front platform. A continental shelf environment is ruled out, on the grounds that the surface of deposition sloped towards the continent and not away from it (since the underlying proximal turbidites grade into shales northwards, while the overlying sandstones were deposited from northward-flowing rivers). A pro-delta slope environment is thus the most likely (see discussion below). The presence of slump structures, ball-and-pillow structures and related features indicate that the depositional surface was relatively steep.

Waterford Formation

The abundance throughout the Waterford Formation of well-developed wave-formed ripple marks usually showing long straight crests and covering extensive surfaces, indicate that this unit accumulated in relatively shallow water. A delta-front platform would appear to be the most likely environment. The presence of horizontal lamination (apparently unaccompanied by current lineation) and inclined bedding (often filling shallow erosional hollows with gently sloping sides) as the main internal structures rather than cross-bedding points to redistribution of material brought in by distributaries by relatively sluggish "marine" currents.

Synthesis

Selley (1970, Fig. 5.4), using data supplied by Reading (1964), Walker (1966) and Collinson (1969), presented a generalised composite section of a succession of formations from the Carboniferous of Northern England and their corresponding environments which almost exactly duplicates the situation encountered in the Ecca Group. Thus the sequence commences with the Edale Shales (dark grey mudstones, often carbonaceous and with disseminated pyrite, displaying a well-developed and laterally continuous lamination) interpreted as a basinal marine deposit. This is followed upwards by the Mam Tor Series (distal turbidites), the Shale Grit (proximal submarine channel fill turbidites) and the Grindslow Shales, an upward-coarsening sequence of laminated mudstones, siltstones and fine flat-bedded and rippled silty sandstones, interpreted as a delta slope deposit, overlain by a heterogeneous assemblage of siltstones and fine sandstones which are often laminated, rippled, and intensively burrowed, pierced by channels of coarser cross-bedded sands and interpreted as a subaqueous delta top (i.e. delta-front platform) deposit. Finally, the sequence is capped by the Kinderscout Grit, an alluvial coastal plain succession.

Walker (1966, Fig. 18) presented a hypothetical environmental reconstruction of the deposition of the above sequence, arranging the formations laterally rather than vertically so that the observed vertical sequence could be visualised in terms of a southward advance of adjacent facies belts.

E 3. Provenance(s)

The close similarities in the composition of Ecca and Beaufort Group sandstones indicate that they must have been derived from the same general source area. Any reconstruction of the nature and location of this source area should therefore preferably be based on data drawn from both groups so that much of what is said here will not be repeated again in the equivalent section of the Beaufort Group description.

Ryan (1967, p.151) stated that "There is no evidence to suggest that a highland source existed along the south-eastern margins of the Karoo basin during Permian times". However, palaeocurrent data from the Adelaide Subgroup (overlying the Ecca Group) clearly indicates the existence of a regional palaeoslope inclined towards the north-west, and, by implication, a general source area off the south-east coast (i.e. that portion of the coast extending roughly from Port Elizabeth to Port St. Johns). The enormous volume of detritus which was carried into the basin to form the Ecca and Beaufort Groups (as well as the overlying Molteno and Elliot Formations) points moreover to a source area of considerable areal extent. The limited palaeocurrent data available for the Ripon Formation are consistent with a southern or south-eastern source. The fine- to very fine-grained character of the sandstones, as well as the well-rounded nature of the quartzite pebbles which occur in the Katberg Sandstone of the Beaufort Group indicate that the source area was not particularly close to the present coast (possibly 200 - 300 km seaward of it). Ryan (p.148) suggested that the source of the sediments constituting his "Southern Ecca Facies" lay some 200 miles to the south of the present outcrop belt.

Turning now to the nature of the source area rocks, the abundance of volcanic (generally felsitic) rock fragments in the sandstones of both the Ecca and Beaufort Groups in especially the eastern part of the area (15 - 25% of the total sandstone composition) and the abundance of both quartz-feldspar porphyry and non-porphyritic "lava" pebbles in the Katberg Sandstone points to the existence of intermediate to acid volcanics as a prominent constituent of the source area. Contemporaneous volcanic activity is indicated by the presence of numerous thin tuffaceous layers in the Collingham Formation as well as a thin crystal tuff layer in the Fort Brown Shale (Lock and Johnson, 1974). Much of the quartz and feldspar is probably also of volcanic origin. The nonvolcanic rock fragments must have been largely derived from a metamorphic terrain containing slates, schists and similar rocks, while the granite, gneiss and quartzite, which contributed significantly to the Katberg pebble assemblage, indicate that these rocks were also present in appreciable amounts in the source area - probably also forming part of a general metamorphic area. Granite and porphyry pebbles from the Katberg Sandstone have K/Ar minimum ages ranging from 295 to 220 m.y., while lack of metamorphism of the pebbles suggests that the intrusive rocks were emplaced during the Gondwanide orogenic cycle and are not part of the Precambrian basement exposed along the southern margin of Africa (Elliot and Johnson, 1972, p.498).

Ryan (1967, p.148) postulated a linear source area composed mainly of granitic rocks, while Theron (1973, p.69, 70) envisaged a large metamorphic terrain with garnetiferous gneiss as the principal rock type. According to the latter author, in any reconstruction of Gondwanaland a large area consisting predominantly of Precambrian rocks should be placed to the south-east of Southern Africa. The data presented here suggest that these views need to be modified somewhat. Theron deduced a granitic source area from the supposedly feldspathic nature of both the Katberg Sandstone and the Molteno Formation (although the latter in actual fact contains very little feldspar) as well as the high garnet content of the Ecca and Beaufort sandstones (which he feels can be connected with the common presence of garnet in all the rocks of the present-day southern Natal granitic basement). This data is, however, not inconsistent with the fuller picture given by the light fraction of the sandstones and the Katberg pebble assemblage.

CHAPTER XVI

BEAUFORT GROUP

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1. Lithostratigraphic interrelationships

See Folder 1.

Lithological variation within the Balfour Formation has led to the recognition of four fairly distinct zones, which may eventually constitute formal members. These zones are listed below (from top to bottom); tentative member names are assigned to two of the zones :

Zone 4 (Palingkloof member). Red mudstone common. A comparatively thin unit (50 - 100 m). Type area: Hills surrounding Palingkloof (Bf20) on Tarkastad - Cradock road.

Zone 3. Tabular, relatively thick sandstones characteristic. Type area: Road cuttings east of Balfour (Bf32).

Zone 2 (Daggaboersnek member). Stratification even and regular; sandstone lithosomes relatively thin; wave-ripple-marked shales common. Type area: Daggaboersnek (Bf16) on Cookhouse - Cradock road.

Zone 1. Lenticular sandstones characteristic. Type area: South of Fort Beaufort (Bf30).

A 1.2. Chronostratigraphic relationships

Romer (1970) regards what is here termed the Adelaide Subgroup as Middle to Late Permian in age, and the Tarkastad Subgroup as Early Triassic. He does, however, note that there is some evidence that the Katberg Sandstone (Middle Beaufort) may be partly, if not entirely, Late Permian (cf. Anderson and Anderson, 1970, Chart 21). Du Toit (1954, p.357) differs from Romer in giving a Middle Triassic age for the Upper Beaufort (Burgersdorp Formation).

A 1.3. Biostratigraphic relationships

Vertebrate remains have in the past been the primary basis on which the subdivision of the Beaufort Group has been effected. Until recently the following scheme (essentially that proposed by Broom, 1906) has been generally accepted:

Cynognathus zone)	Upper Beaufort
Procolophon zone)	
Lystrosaurus zone	Middle Beaufort

Cistecephalus zone)
Endothiodon zone) Lower Beaufort
Tapinocephalus zone)

In 1918 Du Toit (p.xxvi) remarked that "the only zone of such geographical persistence as to be of practical service in mapping is that marked by the genus Lystrosaurus". Subsequent developments have not materially altered the picture. In the above scheme the Lower Beaufort corresponds approximately to the Adelaide Subgroup, while the Middle and Upper Beaufort together are embraced by the Tarkastad Subgroup.

Kitching (1970, p.310) has recently proposed a modification of the above biostratigraphic scheme which he feels is more in accord with the paleontologic data. His scheme is as follows (from top to bottom):

Cynognathus zone Upper Beaufort
Lystrosaurus zone Middle Beaufort
Daptocephalus zone)
Cistecephalus zone) Lower Beaufort
Tapinocephalus zone)

It would appear that the Cynognathus zone-Lystrosaurus zone boundary occurs somewhere in the lower half of the Burgersdorp Formation, while the Daptocephalus zone-Lystrosaurus zone boundary is generally 50 - 100 m below the base of the Katberg Formation (i.e. probably near the base of "Palingkloof member" of the Balfour Formation). When traced eastwards, the arenaceous zone occurring within the Cistecephalus zone in the Graaff Reinet district ("Oudeberg" unit, as A.W. Keyser has termed it - personal communication), seems to coincide more or less with the Middleton-Balfour boundary. The Tapinocephalus zone fossils are confined to the lowermost Beaufort strata in the area west of the study area. Stratigraphically, they occur in strata that must be more or less equivalent to the Koonap Formation and the lower Middleton Formation in the east. Due to the general lack of suitable outcrops, not much fossil material has been recovered from the Beaufort strata of the eastern Cape Province (with the partial exception of the Burgersdorp Formation). As a result the precise relationships between the lithostratigraphic units established in the eastern Cape Province and biostratigraphic units (which are based mainly on collecting done in the western and central Karoo) are not as clear as they could otherwise be.

The writer is indebted to Dr. A.W. Keyser for clarifying various aspects of the tentative relationships that have been outlined above.

A 2. General concepts and distinguishing features

Beaufort Group

The Beaufort Group consists of alternating fine-grained lithofeldspathic sandstone and mudstone lithosomes, normally forming fining-upward cycles and displaying features generally considered to be characteristic of continental (fluviatile) deposition. See also A 2 under Ecca Group for fuller details concerning features which serve to distinguish the Ecca and Beaufort Groups.

Adelaide and Tarkastad Subgroups: distinguishing features

The Tarkastad Subgroup is characterised by a greater abundance of both sandstone and "red" mudstone than the Adelaide Subgroup. The boundary between them represents the only readily identifiable and laterally persistent dividing line in the Beaufort Group and can possibly be traced throughout the greater part of the main Karoo basin.

Koonap, Middleton and Balfour Formations: distinguishing features

"Red" mudstone is relatively common in the Middleton Formation, and very rare or absent in the Koonap and Balfour Formations.

Katberg and Burgersdorp Formations: distinguishing features

South of 32°S sandstone is more abundant than mudstone in the Katberg Formation and vice versa in the Burgersdorp Formation. In the type area (the Winterberg range south of Queenstown) and in the small coastal exposures north-east and south-west of East London, sandstone constitutes over 90 percent of the Katberg Sandstone. North of 32°S, however, sandstone is not necessarily always predominant in the Katberg Formation and it will have to be distinguished purely on the grounds of its more arenaceous character relative to the Burgersdorp Formation. Northof 31°S the distinction between these two formations is no longer obvious and they will probably have to be regarded as a single formation.

A 3. Geographic distribution of units

The approximate geographic distribution of the various formations is depicted on Folders 1 and 3. As a result of lateral facies changes it becomes difficult, and eventually impossible, to distinguish between the Middleton and Balfour Formations west of Pearston , while west of 25°40'E the Koonap Formation is confined to a narrow, linear strip following the Ecca-Beaufort boundary.

A 4. History and nomenclature

Beaufort Group

The "Middle Coal Measures" of Wyley (1859), which embraced what he termed "proper reptilian or dicynodon beds", were roughly equivalent in scope to the present Beaufort Group, although the lowermost strata (roughly the

Koonap Formation) were assigned to the "Lower Coal Measures", while the topographically higher strata in the Roggeveld, Nuweveld and Sneeuberg ranges were, together with the Stormberg beds, termed the "Upper Coal Measures". Rupert Jones (1867) presented a sequence for the Karoo strata in which the term "Beaufort Beds" was apparently used for the first time for the reptilian-bearing strata both at Beaufort West and Fort Beaufort instead of Wyley's "Reptilian Beds". Although Bain (1856) had introduced the name "Fort Beaufort Grit", the map, cross-sections and diagram accompanying the original paper all show that the name was applied by Bain to a thin lens or tongue within his "third division" of the "Karoo Series" (i.e. the division indicated on the map legend as "sandstones, etc. with reptilian remains"). Thus Hatch and Corstorphine (1909, p.2, 219) are not justified in crediting Bain with introducing the name Beaufort for what later became known as the Beaufort Series (or Group).

Rogers (1902) introduced the term "Beaufort Series" and the present writer (1966) suggested the use of the "group" designation.

Adelaide Subgroup

The name Adelaide Subgroup is used here for the first time; the name is derived from the town of Adelaide.

Koonap Formation

Jones (1867) introduced the term "Koonap Beds" for Wyley's "Lower Coal Measures" (1859) which in turn correspond to Bain's second division within his "Karoo Series" (1856). The last-mentioned unit as shown on Bain's map occupied approximately the same stratigraphic position as the present writer's Koonap Formation (at least in the area north of Grahamstown). The name was presumably derived from the Koonap River.

This formation was subsequently precisely defined, described and mapped by Mountain (1946) who referred to it as the "upper division" of the "Ecca Series". The present writer (1966, p.39) assigned the name "Koonap Formation" to the old "Upper Ecca" of Mountain (1946), Blignaut and others (1948) and Rossouw (1953), that is, all the strata between the top of the Fort Brown Shales and the first maroon/purple mudstone (which had previously been regarded as marking the base of the Beaufort "Series"). However, it was remarked at the time that "eventually the Koonap Formation will probably have to be defined in terms of the general absence of shale on the one hand and the absence of red mudstone on the other" (Johnson, 1966, p.45). For reasons outlined earlier (see A 4 under Ecca Group) this has now been done; the Waterford Member, Middlewater Shale Member and the overlying "transitional" shales and sandstones have been separated from the original Koonap Formation and assigned to the Ecca Group (collectively forming the "Waterford Formation").

Middleton Formation

This formation was first considered to be a distinct mappable unit and described by the present writer (1966, p.49 ff.). The name was derived from Middleton station, north and south of which both road and railway cuttings display the typical and characteristic features of this formation.

Balfour Formation

This formation was first proposed and described as a separate unit by the writer (1966, p.49, 52 ff.). The name was derived from the village of Balfour, near which a series of road cuttings display the characteristic features of this formation.

Tarkastad Subgroup

The Tarkastad Subgroup is proposed here for the first time, the name being derived from the town Tarkastad.

Katberg Sandstone/Formation

This formation was first recognised and mapped as a separate unit by J.A.H. Marais, E.F.R. Drewes and P. Mellet in the Katberg-Hogsback area (Annals geol. Surv. S.Afr.,Vol.1.,1962, p.23). In 1966 the present writer suggested the name Katberg Sandstone, the name being derived from the Katberg Pass in the Winterberg mountains north of Balfour. For the northern areas the name Katberg Sandstone is no longer valid, and the designation Katberg Formation will have to be employed.

Du Toit (1917, 1929) working in the Transkei mapped and described as "Middle Beaufort" a group of strata which are probably partly equivalent to the Katberg Sandstone, as at present defined, while Mountain (1939) noted the presence of this unit in the East London area.

Burgersdorp Formation

Du Toit (1904, p.77) assigned the name "Burghersdorp Beds" to strata containing abundant red and purple mudstones and minor sandstones which he encountered below the Molteno Beds in the Aliwal North district. He found these beds to be typically developed around the town of Burgersdorp and to extend through Steynsburg, Queenstown, and Glen Grey to Xalanga in the Transkei. Subsequently, after the Beaufort had been subdivided into Upper, Middle and Lower divisions on the basis of vertebrate remains, the Burghersdorp Beds were identified with the Upper Beaufort (cf. Rogers and Du Toit, 1909, p.204). Since the location of the lower boundary was never fully discussed or defined by Du Toit in his original description, and in view of the uncertain relationships between this formation and the underlying Katberg Sandstone in the Burgersdorp area, the present writer (1966) introduced the name "Queenstown Formation" for the predominantly argillaceous strata overlying the Katberg Sandstone. However, the Karoo working group of the South African Committee for Stratigraphy has decided to retain the historical name "Burghersdorp" in spite of the vagueness of the original concept and the palaeontological overtones which subsequently became paramount, since the unit does correspond approximately to Du Toit's "Burghersdorp Beds" as regards both lithology and stratigraphic position. In addition, the modern spelling "Burgersdorp" has been adopted.

A 5. Boundaries

Koonap Formation, lower boundary

See A 5 under Waterford and Fort Brown Formations (Ecca Group).

Koonap-Middleton boundary

Nature of boundary.- Conformable: intertongued. Transition zone: ± 100 m, but may be up to 1000 m (west of Ripon).

Definition of boundary.- Horizon below which "red" mudstones are absent.

Middleton-Balfour boundary

Nature of boundary.- Conformable: intertongued. Transition zone: ± 100 m.

Definition of boundary.- Horizon above which "red" mudstones are absent (or very rare).

Balfour-Katberg boundary

Nature of boundary.- Conformable: intertongued. Transition zone varies from a few metres to a few tens of metres.

Definition of boundary.- South of 32°S: Horizon above which sandstone is predominant. North of 32°S: Horizon above which a sudden and marked increase in sandstone abundance takes place. The above boundary is normally underlain by ± 50 m of strata in which "red" mudstones are prominent. In the southern area, an additional boundary criterion is the change in sandstone colour from bluish grey (in the Balfour) to a paler reddish grey.

Katberg-Burgersdorp boundary

Nature of boundary.- Conformable: intertongued. Transition zone: ± 100 m.

Definition of boundary.- South of 32°S: Horizon above which mudstone is more abundant than sandstone. North of 32°S: Horizon above which mudstone is markedly more abundant than sandstone. Further work needs to be done in the northern area to establish just how effective the above criterion is in distinguishing Katberg and Burgersdorp strata where the Katberg Formation is predominantly mudstone. It may eventually prove impossible to effectively separate the Burgersdorp Formation from the underlying more arenaceous strata, in which case they will have to be mapped as a combined unit - i.e. a "Tarkastad Formation" which will be the equivalent of the Tarkastad Subgroup in the south.

A 6. Overall lithology

Adelaide Subgroup (General remarks)

Except for the middle member of the Balfour Formation (where "varved" rhythmitite is fairly common), this subgroup is composed almost entirely of mudstone and sandstone, with the former predominating. However, the sporadic and fragmentary nature of the exposures generally made it impossible to obtain reliable estimates of the relative percentages of mud- and sandstone. Isolated artificial exposures in road-cuttings, etc. tend to be confined to the most resistant (arenaceous) parts of each formation and percentages based on detailed measured sections made at such localities will not be a true reflection of the actual percentages present in the formations concerned. The approximate lithologic compositions indicated below are based largely on visual estimates.

Koonap Formation

Sandstone generally constitutes about 20 - 30% of the Koonap Formation, and mudrock about 70 - 80%. Locally in the succession the proportion of sandstone may be much higher than that indicated above, e.g. towards the top of the formation north of Grahamstown (Bf29) and in the basal 150 m of the formation north of Ripon (Bf14), while north of Waterford (Bf9), where this unit is relatively thin due to the incoming of red mudstones at a much lower stratigraphic level than is the case further east, sandstone constitutes only 10 - 15% of the total (Johnson, 1966, p.41).

Middleton Formation

In a detailed section through part of this unit north of Waterford (Bf8) sandstone was found to constitute just over 20% of the total thickness (Johnson, 1966, p.51); this is probably a reasonably representative value for the formation as a whole. Further east the sandstone proportion is undoubtedly higher (due to closer proximity to the source area) but is unlikely to exceed 25 - 30%.

Balfour Formation

Along the coast north-east of East London (Bf50) three sections involving altogether 600 m of strata were measured in the upper half of the Balfour Formation and gave sandstone percentages varying from 20% to 60% (average 32%). Westwards and northwards the sandstone proportion decreases markedly; in the Cradock-Graaff-Reinet area the sandstone percentage, at least in the upper half of the unit, probably does not exceed 10%. In the Stutterheim-King William's Town-Chalumna area (Bf40, 41, 45) the overall sandstone percentage has been estimated at 20 - 25% (Johnson, 1966, p.53).

In the above summary the "Daggaboersnek member" has not been discussed separately; this central portion of the Balfour Formation is characterised by a significantly lower sandstone percentage than the underlying and overlying strata. In addition, most of the "mudrock" consists of poorly-developed to moderately well-developed "varved" rhythmitite which therefore constitutes 5 - 10% of the total Balfour thickness.

SOEKOR borehole data, Adelaide Subgroup

Aberdeen Road (E2; borehole SC3/67).- The borehole log (as contained in an unpublished report compiled by C.J. van Vuuren and H.M. Beer) indicates that sandstone constitutes just under 20 percent of a 2 300 m thick succession that embraces the lateral equivalent of the Koonap Formation and a major part of the Middleton Formation. At this particular locality the first red mudstone is encountered very high up in the succession (2 000 m above the top of the Ecca Group, assuming this boundary to be more or less correct).

Pearston (Bf7; borehole CR1/68).- According to Leith (1970 a, Table XI) sandstone constitutes 39 percent of the "Middleton Formation" and 48 percent of the "Koonap Formation". The substantial increase in sandstone content compared with the outcrop area to the south is unexpected, and probably reflects the use of a different operational definition of the sandstone - siltstone (mudrock) boundary in the interpretation of the geophysical logs on which the borehole lithology is based (M.J. Leith, personal communication).

East London (Bf 47; borehole SP1/69).- Leith (1970 b, Table IX) gives sandstone percentages of over 50 for both Koonap and Middleton Formations. Again the values are unexpectedly high.

South of Aliwal North (Bf57; borehole WE1/66). Leith and Trümpelmann (1967, p.10) obtained 27 percent sandstone for the Adelaide Subgroup.

Katberg Formation

Sandstone proportion decreases from nearly 100% in the coastal areas (Bf 44, 53) and 90 - 95% in the Winterberg-Stutterheim area (Bf33-Bf40) to about 60% (visually estimated) south-west of Tarkastad and 30 - 35% (visually estimated) in the Cradock-Hofmeyr area. In the Lootsberg Pass east of New Bethesda (Bf5) a detailed measured section of 210 m through the lower half of the formation gave 54% sandstone; in general sandstone appeared to be more abundant than mudstone in the area north of New Bethesda, representing an anomalous reversal of the trend for sandstone percentages to decrease in a northwesterly direction (if the estimates north of Cradock are reasonably correct). Sandstone percentages also decrease markedly north-eastwards from the Winterberg-Stutterheim area (Bf33 - Bf40); at Bacela (Bf37) sandstone constitutes about 70% of the total and the proportion diminishes steadily towards Umtata and the Transkei area.

An unexpectedly high figure of 52% sandstone was encountered in the SOEKOR borehole (WE1/66) south of Aliwal North (Bf57), calculated from the simplified borehole log accompanying the well completion report by Leith and Trümpelmann (1967), with the upper boundary position slightly modified.

Burgersdorp Formation

In the Queenstown area sandstone normally constitutes 20 - 30 percent of this formation, e.g. 26% in a 100 m measured section at Nonesi's Nek (Bf35). However, the sandstone proportion increases markedly towards the lower and upper boundaries with the Katberg and Molteno Formations respectively. Along the coast north-east of East London (Bf54) sandstone is much more abundant, forming between one-third and half of the total. However, northwards from Queenstown the lithology facies change pattern is not clear in view of uncertainty regarding the Katberg-Burgersdorp boundary and the possibility of an erosional contact at the base of the Molteno Formation. Unexpectedly high sandstone values have been obtained in a SOEKOR borehole south of Aliwal North (Bf57) (31%, being the writer's own calculation, which involved slight readjustment of boundaries compared with those adopted by Leith and Trümpelmann, 1967) and by Theron (1965) in the Smithfield area (southern Orange Free State).

A 7. Dimensions and shape

Beaufort Group

Available evidence points to a total original (pre-erosion) thickness of between 6 000 m and 7 000 m in the East London - Fort Beaufort area. Drilling undertaken by SOEKOR has established total thicknesses of 1 725 m and 1 500 m south of Aliwal North (Bf57) and in the Matatiele - Swartberg area (Bf58, 59) respectively. The former figure is based on data supplied by Leith and Trümpelmann (1967), while the latter is based on the present writer's own correlation of the Matatiele (Bf58) and Swartberg (Bf59) borehole logs, which differs from that adopted by SOEKOR geologists (see Winter and Venter, 1970,

Fig.12) who arrived at a thickness of less than 1 000 m.

The above figures indicate a rapid northward wedging of the whole group, a 75 percent thickness reduction having taken place between Fort Beaufort and the Aliwal North borehole over a distance of just on 200 km. This corresponds to a thickness change rate of 24 m/km.

Adelaide Subgroup

The writer has obtained the following thicknesses for the Adelaide Subgroup:

Pearston area : 5 000 m ± 500 m. This figure was derived by adding an appropriate minimum thickness of the Balfour Formation in the mountains north of Pearston (1 100 m) to that obtained for the Koonap - Middleton succession south of Pearston.

Cookhouse area : 5 400 m ± 500 m

Fort Beaufort area : 5 100 m ± 500 m

East London area : 4 200 m ± 500 m. This value involves the assumption that the SOEKOR borehole west of East London (Bf47) commenced 500 m below the top of the Middleton Formation, and was obtained by combining borehole data (Leith, 1970 b) for the Koonap and Middleton Formations with a thickness obtained by the writer for the Balfour Formation north-east of East London (Bf50).

The following figures were obtained from SOEKOR boreholes:

South of Aliwal North (Bf57) : 830 m (Leith and Trümpelmann, 1967, p.11).

Swartberg (Bf59) : 745 m. This figure is based on a correlation between the Matatiele (Bf58) and Swartberg (Bf59) boreholes which differs from that originally adopted by SOEKOR geologists (see Winter and Venter, 1970, Fig. 12). The earlier correlation resulted in a lower thickness value (just over 600 m).

The above figures reveal a rapid northward thinning of the Adelaide Subgroup (proportionally more rapid than the general average for the whole Beaufort Group). Thus the thickness in the Aliwal North borehole (830 m) is only one-sixth that measured in the Pearston - Fort Beaufort - East London area (5 000 m average). The distance involved is about 200 km, which corresponds to a thickness change rate of over 20 m/km.

Koonap Formation

Thickness data:

Schoorsteenberg (Bf1) : 200 m (± 50 m)

Waterford (Bf9) ; south of anticline : 220 m (± 30 m)

Waterford (Bf9) , north of anticline : 430 m (± 50 m)

Middlewater (Bf12) : 375 m (± 30 m)

South of Cookhouse (Bf14) : 1 450 m (-300 m, + 100 m)
South of Kroomie (Bf26) : 1 250 m (± 150 m)
South of Fort Beaufort (Bf29) : 1 320 m (± 150 m)
Committees (Bf28) : 1 265 m (Mountain, 1946)
SOEKOR borehole, Pearston (Bf7) : 827 m (Leith, 1970 a, p.20)
SOEKOR borehole, East London (Bf47) : 893 m (Leith, 1970 b, p.16)

The apparent rapid increase in thickness between Bf12 and Bf14 is simply due to an upward shift in the stratigraphic position of the first red mudstone, which marks the base of the Middleton Formation, and does not necessarily reflect an actual physical increase in the thickness of the strata.

The thickness quoted for the Pearston borehole involves the assumption that the Waterford Formation is not present. In view of the rapid disappearance of the Waterford Formation east of Waterford, this assumption is not unreasonable.

Middleton Formation

Thickness data:
Waterford - Pearston (Bf8) : 3 480 m (± 500 m)
Middleton - Cookhouse (Bf15) : 2 700 m (- 500 m, + 200 m)
South of Kroomie (Bf25) : 1 550 m (± 300 m)
South of Fort Beaufort (Bf29) : 1 650 m (± 300 m)
Chalumna area (Bf43) : 1 600 m (± 300 m)

SOEKOR borehole, Pearston (Bf7) : 1 500 m (± 100 m) (Leith, 1970 a, p.15, 20). This thickness includes the 200 m of Middleton strata estimated to be present above the top of the borehole (Leith, p.15).

SOEKOR borehole, East London (Bf47) : 990 m + (Leith, 1970 b, p.16)

The first and second figures quoted above are anomalously large as a result of shifts in the stratigraphic positions of both the first and last red mudstones encountered in the succession, which define the lower and upper contacts of the Middleton Formation; the total thickness of the Adelaide Subgroup appears to remain fairly constant in the Fort Beaufort, Cookhouse and Pearston areas (see earlier figures). The thicknesses obtained for the Koonap and Middleton Formations in the Pearston borehole (Bf7) appear to reflect both an upward shift in the position of the first red mudstone (with the result that the Koonap Formation is thicker and the Middleton Formation much thinner than the corresponding outcrops to the south indicate) and an overall decrease in thickness of the strata. Thus the Koonap + Middleton total in the borehole is about 2 300 m, compared with 3 900 m obtained for the same interval in the Waterford - Pearston area. The bulk of this thickness was measured in a steeply-dipping interval about 45 km south of the borehole; if this is regarded as the actual point of measurement, we can calculate a thickness change rate of

35 m/km. This is much higher than the general average calculated for the Adelaide Subgroup (20 m/km), but not impossible since thickness changes could be expected to take place more rapidly closer to the axis of the basin.

Balfour Formation

Thickness data:

Platberg (Bf2) : approx. 450 m (A.W. Keyser, personal communication)

North of Cookhouse (Bf16) : 1 220 m (± 150 m)

Fort Beaufort - Balfour (Bf31) : 2 150 m (± 300 m)

King William's Town - Stutterheim (Bf41) : 2 350 m (± 500 m)

Kwelera area (Bf50) : 1 800 m (± 150 m)

Chalumna area (Bf45) : 4 000 m (± 200 m)

The last figure given above is about double the expected thickness; in view of the extensive faulting present in this area, it is considered most likely that duplication of strata, rather than an actual increase in thickness, is largely responsible for this anomalous value (cf. Johnson, 1966, p.54).

Tarkastad Subgroup

Thickness data:

Queenstown area (Bf33, 34) : 1 750 m (± 150 m)

Kwelera area (Bf53, 54) : 1 900 m (± 100 m)

SOEKOR borehole, south of Aliwal North (Bf57) : 895 m (Leith and Trümpelmann, 1967)

SOEKOR borehole, Matatiele (Bf58) : 755 m (writer's interpretation of borehole logs; Winter and Venter, 1970, Fig.12, indicate a thickness of about 360 m).

The above data indicate a relatively gradual northward reduction in thickness throughout the East London - Queenstown area. North of Queenstown, however, a thickness reduction of 850 m takes place over a distance of 130 km, corresponding to a thickness change rate of 6,5 m/km.

Katberg Formation

Thickness data:

Kompasberg (Bf3) : 400 m + (Keyser, 1973, p.16)

Speelmanskop (Bf11) : 400 m +

Palingkloof area (Bf20) : 500 m (± 100 m)

Groot Winterberg (Bf23) : 760 m (± 50 m)

Bacela (Bf37) : 600 m (± 100 m)

Chalumna (Bf44) : 1 070 m (± 100 m). Faulting may here be responsible for a certain amount of duplication, and this figure is best regarded as a maximum.

Kwelera (Bf51, 53) : 925 m (± 50 m). This figure represents an average of two determinations (900 m and 950 m).

SOEKOR borehole, south of Aliwal North (Bf57) : 455 m

SOEKOR borehole, Matatiele (Bf58) : 510 m

The last two values are based on the writer's own interpretation of the original borehole logs. In the case of the Aliwal North borehole, Leith and Trümpelmann (1967) gave a thickness of 570 m. The Matatiele borehole is discussed in greater detail under the Burgersdorp Formation (see below).

Burgersdorp Formation

North-east of East London (Bf54) a minimum thickness of 1 000 m (± 100 m) was measured; the uppermost contact is, however, uncertain. In the Queenstown area (Bf34) 1 070 m was obtained but the long distance between the Katberg - Burgersdorp contact and the closest Molteno outcrop (± 35 km) makes this figure rather unreliable and, in view of the figure of 1 000 m obtained at the coast, probably somewhat on the high side and should be regarded as a maximum value. A figure of 950 m (± 150 m) is probably more acceptable. Elevation differences alone account for about 600 m of the total thickness, and the slight northward dip (less than one degree on the average) for the remainder. No major dolerites cross the line of section.

In the borehole drilled by SOEKOR south of Aliwal North (Bf57), 110 km north of Queenstown, a thickness of 1 450 feet (440 m) was obtained after slight readjustment of the upper and lower boundaries originally selected by Leith and Trümpelmann (1967, p.11) who give a thickness of 1 275 feet (390 m). Examination of the log of a borehole drilled by SOEKOR near Matatiele (Bf58) 250 km north-east of Queenstown, led the writer to correlate the thick "red mudstone unit" underlying the Molteno strata with the Burgersdorp Formation; this unit has a thickness of 800 feet (244 m). In neither borehole, however, is there a clear-cut division between Katberg and Burgersdorp or even a very significant difference in lithology; thus in the Matatiele borehole the Tarkastad Subgroup consists of a thick basal sandstone-rich zone (800 ft, 244 m), followed by a comparatively argillaceous zone (400 ft, 122 m), a second relatively arenaceous zone (400 ft, 122 m) and finally a second thick relatively argillaceous zone (800 ft, 244 m). Du Toit (1917, p.10 ; 1929, p.11) gives thicknesses for the Burgersdorp Beds ranging from 2 000 feet (620 m) west of Umtata to 1 500 feet (460 m) in the Matatiele area. However, it is clear that Du Toit placed the lower boundary of the Burghersdorp Beds at the top of the lower arenaceous unit, since the thickness of the strata between this horizon and the base of the Molteno amounts to 1 680 feet (510 m) in the borehole referred to above. This is confirmed by the fact that Du Toit

(1917, p.9, 10) regarded the "Middle Beaufort" (Lystrosaurus Zone) as a relatively thin group of sediments - "some 700 to 800 feet in thickness" - sandwiched between the Upper and Lower Beaufort Beds, and consisting of a "group of red, purple, and green softer rocks with calcareous nodules like those of the Upper division, capped by a thick medium-grained sandstone which generally makes a conspicuous feature."

A 8. Stratotypes

Koonap Formation

Unit-stratotype.- North of Fort Brown (Bf27).

Nature of stratotype: A series of representative but discontinuous exposures occurring in the form of both road cuttings and natural exposures in the banks of the Fish River. The strata are gently folded with dips up to 20°.

Accessibility: Excellent.

Location: Along the Grahamstown - Fort Beaufort road, from a point 3,5 km north of the Fish River bridge (i.e. the first left-hand bend in the road north of the bridge) to a point about 4 km north of the Koonap River bridge (i.e. approximately the top of the "pass").

Middleton Formation

Unit-stratotype.- South of Fort Beaufort (Bf28).

Nature of stratotype: A series of isolated road cuttings and natural exposures displaying the characteristic features of the formation. The strata dip northwards at low angles.

Accessibility: Excellent.

Location: From the top of the Koonap Formation (see above) to "The Tower" hill (about 8 km south of Fort Beaufort) on the Grahamstown - Fort Beaufort road.

Reference stratotype.- Keiskamma River bridge area (Bf41).

Nature of stratotype: Excellent continuous exposures through central portion of formation in a series of road cuttings. The strata dip gently northwards.

Accessibility: Excellent.

Location: The sections are located in road cuttings on either side of the Keiskamma River bridge on the Grahamstown - King Williams Town road.

Balfour Formation

Unit-stratotype.- Fort Beaufort - Balfour (Bf29 - 31).

Nature of stratotype: A series of isolated road cuttings and natural exposures displaying the characteristic features of the formation. Strata are sub-horizontal. Occasional small dolerite intrusions occur.

Accessibility: Excellent.

Location: The stratotype is located along the Grahamstown - Queenstown road between the top of the Middleton Formation (see above) and the base of the Katberg Sandstone in the Katberg Pass north of Balfour (described below).

Katberg Formation

Unit-stratotype.- Katberg - Poplar Grove (Bf32).

Nature of stratotype: A series of road cuttings and cliff-face exposures in mountainous territory. Strata are flat-lying and undisturbed, except for occasional intrusions of dolerite.

Accessibility: Excellent.

Location: Between the intersection of the 3 700 ft contour with the Katberg Pass road (about one km beyond the Katberg forest station) and Poplar Grove (west of Whittlesea).

Reference stratotype 1.-Kwelera (Bf50).

Nature of stratotype: Virtually continuous fresh exposures through the whole formation in road cuttings. Actual base not exposed. Strata display a uniform dip of about 15°.

Accessibility: Excellent.

Location: Along the East London - Butterworth national road, commencing 2,5 km south of the Kwelera River bridge (near the Cintsa Mouth turn-off) and ending 1,5 km north of the bridge (both distances being measured along the road).

Reference stratotype 2.-Lootsberg Pass (Bf5).

Nature of stratotype: Continuous fresh exposures in road cuttings through the lower half of the formation. Strata are flat-lying and undisturbed.

Accessibility: Excellent.

Location: From the base to the top of the Lootsberg Pass between Graaff-Reinet and Middelburg.

Burgersdorp Formation

Unit-stratotype.- Nonesi's Nek (Bf34).

Nature of stratotype: Continuous representative exposures through middle portion of formation in road cuttings in pass as well as natural exposures in surrounding hills. Strata are horizontal.

Accessibility: Excellent.

Location: The entire Nonesi's Nek Pass, ± 15 km from Queenstown on the Queenstown - Lady Frere road.

B. PALAEONTOLOGY

Palaeontologically the Beaufort Group is noted chiefly for the numerous vertebrate remains that have been discovered in it. Du Toit (1954, p.340, 341) lists a total of 122 reptile genera, 14 amphibian genera and 14 fish genera for the whole of the Beaufort Group in South Africa. It is not known how many of these have actually been found within the study area itself. Three-quarters of the reptilian genera occur in the "Lower Beaufort" (Adelaide Subgroup) and most of the finds are probably confined to the area west of the present study area. Most of the amphibian and fish genera come from the "Middle" and "Upper" Beaufort (i.e. the Tarkastad Subgroup).

Plant remains occur sporadically throughout the Beaufort Group. Parts of silicified tree trunks and stems are fairly common, especially in the Adelaide Subgroup. Flattened, striated stems 1 - 2 cm in diameter have been noted in the Middleton Formation as well as towards the top of the Katberg Sandstone. Well-preserved leaves (Glossopteris sp.) occur near the base of the Koonap Formation at various localities and also in the "Daggaboersnek member" of the Balfour Formation.

Non-marine molluscs have been reported from the Adelaide Subgroup at a number of localities (Rossouw, 1970).

C. MACRO-SEDIMENTOGRAPHY

C 1. Cyclicity

Except for the Katberg Sandstone south of 32°S and the Zone 2 member of the Balfour formation, the Beaufort Group in the study area is characterised by the ubiquitous presence of fining-upward cycles composed of sandstone and mudstone. These cycles generally vary from a few metres to a few tens of metres in thickness; the average thickness is generally about 10 - 20 m.

C 2. Lithosome dimensions and shape

C 2.1 Thickness data

Adelaide Subgroup

In the area north of Waterford (Bf8) average and maximum thicknesses of sandstone lithosomes in the Koonap - Middleton succession are about 1,5 m and 15 m respectively. These values increase eastwards to about 5 m and 60 m (both visual estimates) for average and maximum thicknesses in the East London area. In the latter area average and maximum thicknesses of 7 m and 58 m were obtained in a series of measured sections across a total of 600 m of Balfour Formation strata. Westwards these values decrease so that in the central and western parts of the study area average and maximum thicknesses of about 2 - 3 m and about 20 m (visual estimates) are the rule, with these values being considerably less (perhaps one-third) in the case of the "Daggaboersnek" member of the Balfour Formation.

Tarkastad Subgroup

Katberg Formation.- At Lootsberg Pass (Bf5) average and maximum thicknesses of 5,5 m and 21 m were obtained.

Burgersdorp Formation.- At Nonesi's Nek (Bf35) average and maximum thicknesses of 1,8 m and 5,5 m were obtained (disregarding thin siltstone/ sandstone layers interbedded with thick mudstones and regarded as flood plain deposits). These figures are probably representative of the middle portion of the formation; towards the upper and lower contacts sandstone thicknesses increase markedly.

C 2.2 Lateral extent

Beaufort Group sandstones normally display a very limited lateral persistence although not many quantitative data are available. Thus the thinnest sandstones generally have a lateral extent measured in tens of metres, the "average" sandstones extending a few hundred metres to a few kilometres and the thickest sandstones a few kilometres to a few tens of kilometres at the most. The most persistent sandstone lithosomes occur in the middle and upper parts of the Balfour Formation. In the area south of Cradock a 20-m-thick sandstone unit situated in the upper part of the Balfour Formation could be traced for at least 30 km.

C 2.3 Cross-sectional shape

With the exception of the middle and upper members of the Balfour Formation, sandstone lithosomes are generally subtabular to moderately lenticular in shape (occasionally highly lenticular). The "Daggaboersnek member" of the Balfour formation is characterised by regular, generally non-lenticular, overall stratification (lithosomes subtabular to moderately tabular). Balfour "Zone 3" sandstones, while less tabular than those in the middle member, tend to be more persistent than those in the rest of the group (i.e. generally sublenticular to subtabular or moderately tabular).

C 3. Lithosome boundaries

Sandstone lithosomes

Lower boundaries.- A sharp, uneven surface, locally showing development of channels cutting a few metres into the underlying material.

Upper boundaries.- Usually gradational (transition zone a few cm to more than a metre thick). Occasionally intertongued or sharp.

C 4. Colour

Koonap Formation

Sandstone.- Generally between medium grey/medium light grey (N5/N6) and greenish grey (5GY6/1), medium greenish grey (5G5/1) or medium bluish grey (5B5/1). Whitish speckling is common.

Mudstone.- Varies from medium greenish grey (5GY5/1) to medium to dark bluish grey (5B5/1 to 5B4/1) to slightly greenish medium grey (between N5 and 5GY5/1).

Middleton Formation

Sandstone.- Generally light grey (N7) to medium light grey (N6) or occasionally medium grey (N5) when fresh. Light olive grey (5Y6/1) to greenish grey (5GY6/1) when slightly weathered.

Mudstone.- As above (Koonap Formation) but with addition of thin (up to one metre) subordinate beds of greyish red (5R4/2) or greyish red purple (5RP4/2) mudstone.

Balfour Formation

Sandstone.- Light grey (N7) to medium light grey (N6) - occasionally medium grey (N5) - when fresh. Medium olive grey (5Y5/1) to light olive grey (5Y6/1) when slightly weathered. White speckling is sometimes present.

Mudstone.- Varies from slightly greenish (or slightly bluish) medium grey (between N5 and 5GY5/1 or 5B5/1) to medium or dark bluish grey (5B5/1 or 5B4/1). In the "Daggaboersnek member" the colour ranges to medium dark grey (N4), while in the "Palingkloof member" greyish red (5R4/2) and medium greenish grey (5G5/1) beds are fairly common.

Katberg Formation

Sandstone.- Light brownish grey (5YR6/1), occasionally greenish-grey (5GY6/1), in the type area and at the coast. In the northern part of the area, the sandstone is generally paler and less reddish in colour; slightly greenish light to very light grey (N7/N8) shades predominate.

Mudstone.- Greyish red (5R4/2) or medium greenish grey (5GY5/1).

Queenstown Formation

Sandstone.- Light brownish grey (5YR6/1), light olive grey (5Y6/1), greenish grey (5GY6/1) and light grey (N7).

Mudstone.- Greyish red (5R4/2) to dusky red (5R3/4); less commonly medium greenish grey (5G5/1) or medium bluish grey (5B5/1).

C 5. Sedimentary structures

General bedding characteristics

Beds are subequal or unequal in thickness, laterally variable and discontinuous.

Pre-depositional (erosional) current structures

A variety of scour forms occur on the base of most sandstone lithosomes, varying from a few cm to a few metres in depth.

Syn-depositional current structures

Internal syn-depositional structures.- Trough cross-bedding, flat-bedding (accompanied by parting lineation) and micro-cross-lamination are the most abundant primary structures in the sandstones. Micro-cross-lamination is especially common in the finer material occurring towards the top of sandstone units, while massive bedding may occur near the base of such units. The Katberg Sandstone and "Daggaboersnek member" of the Balfour Formation differ from the general pattern in that micro-cross-lamination is rare or absent in the former while cross-bedding and flat-bedding are rare in the latter. Although massive bedding often seems very common, if not predominant, the available evidence indicates that under favourable conditions most such apparently structureless beds would be seen to be characterized by various internal structures.

Cross-bed sets generally range from 20 cm to 60 cm in thickness (maximum 120 cm), while the dip angle of the foresets averages about 18°.

The mudstones are generally massive-bedded, although a form of multiple graded bedding is not uncommon in the Adelaide Subgroup.

External syn-depositional structures.- Ripple marks and related structures are relatively uncommon in the Beaufort Group. In the Koonap, Middleton, and lower Balfour Formations small oscillation ripple marks are occasionally present. The crests are generally roughly symmetrical, but distinctly asymmetrical examples also occur, although in all cases they remain readily distinguishable from true current ripples. Thirty-six measurements, ranging from 1 cm to 5 cm, gave an average wave-length of 2,4 cm and a ripple index of 9. In the "Daggaboersnek member" of the Balfour Formation distinctly larger ripple marks are fairly common in the Cradock - Adelaide area. Average wave-length is about 7 cm and ripple index about 9.

Post-depositional structures

Rain prints were observed at one locality towards the top of the Middleton Formation near East London.

Large mud cracks (30 cm deep) were seen at the top of the Balfour Formation (probably just below the base of the Katberg Sandstone) north-east of Cradock. Small "mud cracks", up to 1 cm across and a few mm deep were seen near New Bethesda in strata tentatively correlated with the "Daggaboersnek member" of the Balfour Formation.

Clastic dykes up to 10 cm wide and a few metres high are occasionally present in the Katberg and Burgersdorp Formations.

Deformed ("slumped") cross-bedding has been observed in the Katberg Formation but is not common.

Dislocation structures, with irregular sandstone "erratics" up to 1 m in diameter enclosed in sandstone of a different colour or texture, are present at or near the base of the Koonap Formation at a number of localities.

Chemical structures

Calcareous nodules and concretions, varying considerably in size and shape (from sub-rounded lumps a few cm in diameter to flattened, irregular, discontinuous bodies a few metres long) occur in the mudstones throughout the Beaufort Group. Large (20 - 100 cm diameter) calcareous concretions are occasionally present in the sandstones of the Adelaide Subgroup.

Oval to spherical calcareous concretions are common in the Katberg Formation. These generally vary from 3 cm to 10 cm in length (average about 7,5 cm), with the maximum length generally encountered being about 15 cm. Internally, a distinct concentric zoning is often present, with the nucleus being displaced towards one end of the structure. Calcite constitutes about 50% of those concretions that have been examined in thin section. These structures are more fully described in an Appendix.

Biogenic structures

Organic structures are comparatively rare in the Beaufort Group. "Worm" burrows are occasionally present, and one set of tetrapod footprints was discovered near the top of the Katberg Sandstone west of Tarkastad.

Orientation data

Orientation data for various primary structures are summarised in Tables XVI-1 and XVI-2. Mean directions have also been plotted on the general palaeocurrent map (Folder 3), while rose diagrams based on the data in Table XVI-2 are presented on Folder 4a.

In addition to the data presented in the tables, use was also made on Folder 3 of three directional arrows derived from a moving average palaeocurrent map presented by Theron (1973, Fig.6.1). Care was taken to select arrows representing data derived from areas underlain entirely by the formation (or subgroup) concerned. Thus the arrow at Bf7 and the one between Bf30 and Bf31 are based on cross-bedding (trough axes) derived from the Adelaide Subgroup, while the open arrow at Bf35 represents Burgersdorp Formation data.

Table XVI-1. Statistical measures calculated from orientation data for sedimentary structures in the Beaufort Group.

Unit, locality, structure	n	$\bar{x}_v$	$\bar{a}$	s
[1]Burgersdorp (Bf21) x-bd	43	335°	0,86	
[1]Burgersdorp (Bf35) x-bd	16	325°	0,97	
Katberg (Bf5) x-bd	33	355°	0,83	36°
Katberg (Bf5) p.c.l.	16	170°/350°	0,56	31°
Katberg (Bf19) x-bd	29	346°	0,93	22°
Katberg (Bf19) p.c.l.	27	157°/337°	0,66	26½°
Katberg (Bf22) x-bd	42	346°	0,80	39°
Katberg (Bf22) p.c.l.	28	154°/334°	0,59	29½°
Katberg (Bf22) concr.	14	339°		9°
Katberg (Bf36) concr.	24	146°/326°		6½°
Katberg (Bf38) concr.	55	159°/339°		7°
Katberg (Bf44) p.c.l.	103	141°/321°	0,75	22°
Katberg (Bf44) concr.	203	140°/320°		7½°
Katberg (Bf53) x-bd	141	351°	0,88	30°
Katberg (Bf51, 53) p.c.l.	106	170°/350°	0,67	26°
Katberg (Bf53) concr.	152	169°/349°		6½°
Katberg (Bf55) concr.	49	3°/183°		7°
Balfour (Bf4) x-bd	12	325°	0,91	26°
Balfour (Bf4) m.c.l.	16	342°	0,69	50°
Balfour (Bf17) w.r.m.	76	60°/240°	0,30	41½°
Balfour (Bf18) x-bd	52	306°	0,50	67°
Balfour (Bf18) m.c.l.	20	305°	0,62	57°
Balfour (Bf18) p.c.l.	64	121°/301°	0,39	38°
Balfour (Bf40) x-bd	7	346°	0,84	35°
Balfour (Bf39) x-bd	27	310°	0,40	75°
Balfour (Bf39) m.c.l.	8	308°	0,91	26°
Balfour (Bf39) p.c.l.	8	11°/191°	0,48	34½°
Balfour (Bf46) x-bd	77	315°	0,46	70°

Table XVI-1 (contd.)

Unit, locality, structure	n	$\bar{x}_v$	$\bar{a}$	s
Balfour (Bf46) m.c.l.	5	319°	0,92	24°
Balfour (Bf46) p.c.l.	39	115°/295°	0,41	37°
Balfour (Bf50) x-bd	101	318°	0,58	60°
Balfour (Bf50) m.c.l.	8	328°	0,92	24°
Balfour (Bf50) p.c.l.	13	127°/307°	0,47	24½°
Balf.+ M'ton (Bf10) x-bd	16	312°	0,87	31°
Balf.+ M'ton (Bf10) m.c.l.	7	331°	0,95	18°
Balf.+ M'ton (Bf10) p.c.l.	5	131°/311°	0,36	39°
Middleton (Bf48) x-bd	112	325°	0,77	42°
Middleton (Bf48) m.c.l.	9	330°	0,94	20°
Middleton (Bf48) p.c.l.	11	122°/302°	0,87	15½°
Middleton (Bf48) w.r.m.	34	154°/334°	0,32	40½°
Middleton (Bf48) ms. concr.	24	133°/313°	0,55	31½°
M'ton/Koonap (Bf13) x-bd	14	352°	0,81	38°
M'ton/Koonap (Bf13) w.r.m.	26	132°/312°	0,33	40½°
[2]Adelaide (Bf56) x-bd	20	358°		
[2]Koonap (Bf14) x-bd	16	352°		
[2]Koonap (Bf24) x-bd	8	3°		
Koonap (Bf27) x-bd	20	340°	0,77	42°

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[1] Data supplied by A.F.Meyboom (personal communication)

[2] Data from Ryan (1967)

n = number of measurements

$\bar{x}_v$ = vector mean

$\bar{a}$ = vector strength

s = standard deviation

Balf. = Balfour

M'ton = Middleton

x-bd = cross-bedding

p.c.l. = primary current lineation

concr. = concretion long axes

m.c.l. = micro-cross-lamination

w.r.m. = wave ripple marks

ms. = mudstone

Table XVI-2. Orientation of sedimentary structures in the Beaufort Group: number of readings per 30° class interval.

Unit, locality, structure	Class mid-points (°) 15	45	75	105	135	165	195	225	255	285	315	345
[1]B'dorp (Bf21) x	3	3							2	2	13	20
[1]B'dorp (Bf35) x											12	4
Katberg (Bf5) x	9	5	1							1½	6	10½
Katberg (Bf5) p	2½	3		½	4	6						
Katberg (Bf19) x	7									1½	4½	16
Katberg (Bf19) p	3	1		3	7	13						
Katberg (Bf22) x	10½	4						1	1½	2½	6½	16
Katberg (Bf22) p	4½	2	1	1½	11½	7½						
Katberg (Bf22) c					2	12						
Katberg (Bf36) c					18½	5½						
Katberg (Bf38) c					6	49						
Katberg (Bf44) p	7½	2		12½	61	20						
Katberg (Bf44) c				2	185	16						
Katberg (Bf53) x	43	10	1							4½	23	59½
Katberg (Bf 51,53)p	27½	6½	1½	1½	18	51						
Katberg (Bf53) c	7					145						
Katberg (Bf55) c	33					16						
Balfour (Bf4) x	1									2½	5	3½
Balfour (Bf4) m	2	½	1½	1						2	5½	3½
Balfour (Bf17) w	10½	18	23½	6	11	7						
Balfour (Bf18) x	7½	1			1	2½	5½	2½	5½	7	8½	11
Balfour (Bf18) m				1		1	1		2	5	4½	5½
Balfour (Bf18) p	3½	3½	12½	17	19½	8						
Balfour (Bf40) x	2								1			4
Balfour (Bf39) x	2½	1½		½	1½	1½	2	2½	1	2½	6½	5
Balfour (Bf39) m										5	1	2
Balfour (Bf39) p	3½		1½	½		2½						
Balfour (Bf46) x	7½	6½	5	½	2	½	2	4½	15	11½	9	13
Balfour (Bf46) m										1½	1½	2
Balfour (Bf46) p	1	3	9½	7½	14½	3½						
Balfour (Bf50) x	13½	6½	3	1	2		2	4	14	18	16½	19½
Balfour (Bf50) m	1									1½	2	3½
Balfour (Bf50) p							½	2		3½	6½	½
Balf.+ M'ton (Bf10)x									2	3½	5	5½

Table XVI-2 (contd.)

Unit, locality, structure	Class mid-points (°) 15	45	75	105	135	165	195	225	255	285	315	345
Balf. + M'ton (Bf10) m	½									½	3½	2½
Balf. + M'ton (Bf10) p	½		½	1½	1	1½						
M'ton (Bf48) x	17	7½	1	1					8½	23	31½	22½
M'ton (Bf48) m										½	3½	5
M'ton (Bf48) p	1		1	6	2	1						
M'ton (Bf48) w	7½	1½	3	5½	7½	9						
M'ton (Bf48) ms. concr.	1	1	1½	7	9	4½						
M'ton/Koonap (Bf13)x	5	2								3	1	3
M'ton/Koonap (Bf13)w	2½	1½	4	4½	8	5½						
Koonap (Bf27) x	5½	1½						½	1	2½	3	6

[1] Data supplied by A.F. Meyboom (personal communication)

B'dorp = Burgersdorp

Balf. = Balfour

M'ton = Middleton

x = cross-bedding

p = primary current lineation

m = micro-cross-lamination

c = concretion long axes (sandstone)

w = wave ripple marks

ms. concr. = concretion long axes (mudstone)

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Grain-size data for Beaufort Group sandstones are presented in Table XVI-3. Non-preservation of original grain outlines precluded determination of roundness.

D 2. Composition

Relative abundance of pebble types occurring in the Katberg Sandstone is given in Table XVI-4. Mineral composition data for Beaufort sandstones is contained in Table XVI-5. Rock fragment types and relative abundance are indicated in Table XVI-6.

Table XVI-3. Grain-size data for Beaufort Group sandstones.

Unit/locality	n	$\bar{x}$(φ)	s(φ)	MD(φ)	d(φ)	$\bar{x}$ - d	M(%)
Burgersdorp (Bf35)	5	2,56 (2,26/2,80)	0,61	0,47	1,32	1,24	14
Burgersdorp (Bf54)	5	2,37 (2,15/2,66)	0,63	0,50	0,98	1,39	14
Katberg (Bf5)	4	3,05 (2,29/3,63)	0,58	0,47	1,68	1,37	12,5
Katberg (Bf37)	5	2,36 (2,15/2,54)	0,48	0,37	1,13	1,23	
Katberg (Bf51)	12	2,18 (1,42/3,27)	0,63	0,48	0,69	1,49	8,5
Balfour (Bf6)	3	3,18	0,48	0,38	2,02	1,16	11
Balfour (Bf18)	3	2,87	0,54	0,43	1,66	1,21	11
Balfour (Bf30,31,32)	9	2,74 (2,29/3,19)	0,60	0,47	1,58	1,16	10,5
Balfour (Bf40,41,52)	7	2,07 (1,77/2,47)	0,48	0,36	1,05	1,02	6
Middleton (Bf13,15)	4	2,67 (1,96/3,48)	0,52	0,41	1,48	1,19	10
Middleton (Bf29)	6	3,23 (2,36/4,27)	0,58	0,46	1,97	1,26	14,5
Middleton (Bf49)	3	2,28	0,46	0,38	1,28	1,00	6,5
Koonap (Bf1,9,12)	3	3,37	0,52	0,43	2,19	1,18	19
Koonap (Bf27)	5	2,78 (2,60/2,90)	0,54	0,43	1,55	1,23	13

n = number of samples (50 grains per sample)
$\bar{x}$ = mean size (range in brackets)
s = standard deviation
MD = mean deviation
d = maximum thin-section diameter
M = matrix content

Table XVI-4. Composition of Katberg Sandstone pebbles.

Rock Type	Percentage
Quartzite/quartzitic sandstone	43
Arkose (?)	5
Chert/silicified wood	9
Granite/gneiss	10
Quartz - feldspar porphyry	15
"Devitrified lava" (?)	18

Table XVI-5. Mineral composition of Beaufort Group sandstones.

Unit/locality	n	Q	F	R	Acc.	Cem.	M	Q : F : R
Burgersdorp (Bf35)	5	42,5	9	32	0,5	2	14	51 : 11 : 38
Burgersdorp (Bf54)	5	41	8,5	35,5	0,5	0,5	14	48 : 10 : 42
Katberg(b) (Bf5)	4	30	21	34,5	1	1	12,5	35 : 24,5 : 40,5
Katberg(t) (Bf51)	3	44,5	8	37	2,5	tr.	8	50 : 9 : 41
Katberg(m) (Bf51)	8	35,5	14	37,5	1	2	10	40,5 : 16 : 43,5
Katberg(b) (Bf51)	3	31	23	38	0,5	2,5	5	34 : 24,5 : 41,5
Katberg (Bf51)	14	36,5	14,5	37,5	1,5	1,5	8,5	41 : 16,5 : 42,5
Balfour (Bf6)	4	16,5	27	41	2,5	2	11	19,5 : 32 : 48,5
Balfour (Bf18)	3	18,5	30	36,5	1	3	11	22 : 35,5 : 42,5
Balfour (Bf30,31,32)	9	17	28,5	41,5	0,5	2	10,5	19,5 : 33 : 47,5
Balfour (Bf40,41,52)	7	22,5	28,5	39	0,5	3,5	6	25 : 31,5 : 43,5
Middleton (Bf13,15)	4	17,5	26,5	39	1,5	5,5	10	21 : 32 : 47
Middleton (Bf29)	6	19	25,5	30	1	10	14,5	25,5 : 34 : 40,5
Middleton (Bf49)	3	20	33,5	35,5	2	2,5	6,5	22,5 : 37,5 : 40
M'ton/Koonap (Bf8)	8	20,5	29,5	28,5	1	4	16,5	26 : 37,5 : 36,5
Koonap (Bf1,9,12)	3	17	20	36,5	1	6,5	19	23,5 : 27,5 : 49
Koonap (Bf27)	5	18	29	32,5	1	6,5	13	22,5 : 36,5 : 41

n = number of samples (200 - 300 points per sample)
Q = Quartz (including secondary quartz)
F = Feldspar
R = Rock fragments
Acc. = Accessory minerals
Cem. = Cement plus secondary minerals (excluding silica cement)
M = Matrix
t = top
m = middle
b = base
M'ton = Middleton
tr. = trace

Table XVI-6. Relative abundance of rock fragment types in Beaufort Group sandstones, expressed as percentages of total rock composition.

Unit/locality	n	m	s	c	f	p	g	?
Burgersdorp (Bf35)	5	11,5	4	1,5	11,5	tr.	1	2,5
Burgersdorp (Bf54)	5	12	5,5	1	14,5	tr.	0,5	2
Katberg (Bf5)	4	12	4,5	1	15	tr.	0,5	1,5
Katberg (Bf51)	14	6	3,5	1,5	18,5	2	1,5	5
Balfour (Bf6)	4	13,5	3,5	1	15	1	0,5	6,5
Balfour (Bf18)	3	4	2	1	20,5	2	1	6
Balfour (Bf30,31,32)	9	6,5	3	1	22,5	1,5	1,5	5,5
Balfour (Bf40,41,52)	7	2	2	1	23,5	5	2,5	3
Middleton (Bf13,15)	4	5	3	0,5	21,5	1,5	1,5	6
Middleton (Bf29)	6	4,5	2,5	0,5	17	1,5	1	3
Middleton (Bf49)	3	5	4	2	13,5	5	3	3
M'ton/Koonap (Bf8)	8	4,5	4	0,5	14,5	1	1	3
Koonap (Bf1,9,12)	3	11,5	2,5	0,5	17	tr.	tr.	5
Koonap (Bf27)	5	7,5	3	1	17,5	1	1	1,5

n = number of samples
m = micaceous fragments (mica/clay minerals/chlorite)
s = schistose fragments (mica/clay minerals/chlorite + quartz/feldspar)
c = chert, microcrystalline quartz
f = felsite (fine-grained quartz-feldspar mosaic)
p = pilotaxitic/porphyritic igneous rocks (distinct feldspar laths present)
g = granite/gneiss fragments
? = unidentified fragments

E. SEDIMENTOGENESIS

E 1. Dispersal patterns

Adelaide Subgroup

Throughout the area under discussion unimodal northwesterly palaeocurrent directions with intermediate to high vector strengths (0,40-0,77 for localities with n>20) were obtained.

Tarkastad Subgroup

The relationship between the orientation of the long axes of calcareous concretions encountered in the Katberg Sandstone and the palaeoslope is discussed in an Appendix.

Nearly all palaeocurrent data in this subgroup were obtained from the Katberg Sandstone. Unimodal patterns and very high vector strengths (0,80 - 0,93) were obtained for cross-bedding data at all localities. In the central area (main outcrop area) fairly consistent north-northwesterly transport directions were measured. A difference of 30° was obtained in the palaeocurrent directions measured at the Chalumna (Bf44) and Kwelera (Bf53) outcrops south-west and north-east of East London respectively; a further 10° difference was found between Kwelera (Bf53) and Qolora (Bf55). These three localities would appear to form part of what was originally a single radiating distribution pattern embracing a 45° arc.

E 2. Sedimentary processes and palaeoenvironments

Basically, sedimentation in the bulk of the Beaufort Group represents variations on a single theme, namely deposition in a terrestial river environment. The main key to the understanding of the genesis of the Beaufort Group sediments is the fining-upward cycle concept, as developed by Allen (1965a, 1965b, etc.) and other workers.

Allen (1965a) noted the striking similarity in both the gross lithological sequence and the smaller-scale sedimentary features (primary structures) characterising the cycles composing various sedimentary formations generally considered to have formed in an alluvial environment. These cycles were found to vary in thickness from a few metres to a few tens of metres, and consisted of a lower, relatively coarse-grained (sandstone) member (with a sharp irregular erosive base) succeeded by an upper relatively fine-grained (mudstone) member. The sandstone member usually commenced with a thin basal conglomerate containing intraformational clasts. The bulk of the sandstone unit was invariably characterised by cross-bedding (generally trough cross-bedding) and flat-bedding (with primary current lineation). Towards the top of the sandstone unit the grain size normally decreased and micro-cross-lamination became common. Almost invariably the contact with the overlying fine-grained member was not abrupt, but was either a gradual transition or an intertonguing of contrasting lithologies. The upper member was generally silty and often characterised by blocky weathering and general lack of bedding.

Allen (p.238, ff.) found furthermore that virtually all the features displayed by the fining-upward cycles in the various formations which he studied could be matched in the alluvial deposits of modern floodplains. Both in the fining-upward cycles in ancient sediments and in recent floodplain alluvium a fine-grained member gradationally succeeds a coarse-grained member which rests on an erosional and, in places, channelled surface. In recent alluvium the coarse member is deposited in stream channels, mainly through lateral accretion as the channels wandered, whereas the fine member represents deposition of suspended fine sediment on the floodplain after overbank flooding. Channel wandering also results in both the erosional base of coarse members and the production of intraformational clasts as it incises previously deposited fine-grained cohesive sediment. The three main primary structures encountered in the sandstones (cross-bedding, flat-bedding and micro-lamination) are also common on the point bars of meandering rivers or the channel bars of braided ones and are readily explained in terms of deposition under varying flow regime conditions. Finally, in both modern alluvial deposits and the ancient examples reviewed by Allen, thin sandstone interbeds occur within the fine member; these presumably form part of levee and crevasse splay deposits, the sandstones of which are usually characterised by sharp bases and upward grading from coarse to fine (Allen, 1970, p.142; cf. Reineck and Singh, 1973, p.244 - 248).

The depositional model outlined above (which strictly speaking applies only to meandering river conditions), accounts very well for most of the sedimentary features observed in the Koonap, Middleton, upper and lower Balfour, northern Katberg and Burgersdorp Formations. The southern Katberg Sandstone and the central Balfour Formation, however, differ in many respects from the basic fluviatile model, and require additional discussion.

Although Reineck and Singh (1973, p.261) warn that "great care and detailed study" is needed to differentiate between low-sinuosity (braided) and high-sinuosity (meandering) stream deposits, nevertheless application of the criteria for distinguishing braided and meandering stream deposits supplied by Selley (1970, p.22 - 25, 218 - 219), Allen (1970, p.140 - 143) and Reineck and Singh (1973, p.261) point quite definitely to deposition of the Katberg Sandstone in a braided stream environment. The main diagnostic features are the relatively coarse grain, virtual absence of interbedded mudstone layers (and hence lack of distinct fining-upward cycles composed of alternating channel and floodbasin deposits), absence of micro-cross-lamination and ripple marks, low scatter of palaeocurrent data and presence of a fan-shaped palaeocurrent pattern. Allen (1970, p.140) points out that it is not uncommon in braided stream deposits to find gravel-sized mud clasts as the only witness to the deposition of beds of silt or clay. That the Katberg sandstones are definitely fluviatile is established by the fact that the formation grades downstream into a "red bed" facies displaying typical fining-upward cycles, and not a marine facies.

Turning now to the "Daggaboersnek member" (zone 2) of the Balfour Formation, we have to account for the following distinctive features: regular bedding, abundance of thin, tabular sandstones, presence of wave-ripple-marked surfaces displaying a mean ENE - WSW orientation, and presence of dark shales with occasional leaf impressions. These features cannot be accounted for in a purely fluviatile environment, since the formation of numerous wave-formed ripple marks of moderate size orientated approximately at right angles to the general palaeoslope as deduced from current directions in the overlying and underlying strata would be impossible. The bulk of the "Daggaboersnek" sediments must have been formed within a fairly extensive inland "sea" or lake sufficiently large to permit the development of wave systems capable of forming well-developed ripple marks trending roughly parallel to an ancient shoreline as well as currents capable of producing sheet sands. Dark, carbonaceous shales and plant remains point to the presence of coastal marshes and swamps.

Finally, we need to consider briefly the significance of the variation in mudstone colour between the different formations. It is now generally agreed that the red colour in "red beds" is due to the presence of finely-divided haematite, and that the colour reflects deposition under oxidising conditions; grey and dark-coloured sediments (especially muds) on the other hand point to deposition in a reducing environment (Jones, 1965; Reineck and Singh, 1973, p.132). Jones, in his study of "red beds" in Northeastern Nigeria, concluded that they were derived from red soils produced in the source area under warm, humid conditions with alternating wet and dry seasons. The colour differences which he observed (both red and non-red siltstones being present in the formation he was studying) seemed to depend on whether the siltstones accumulated in reducing conditions, or remained exposed to the air allowing oxidation and preservation of the pigment. "Reducing conditions may occur where the sediment includes organic material or is laid down under standing-water conditions that impede circulation of oxygen. Where the pigment and mud were deposited on alluvial flats, the subsequent dry season would have preserved those open to the air, while reduction would have occurred in the muds associated with organic debris or laid down in stagnant pools or backwaters of the main stream" (Jones, p.245). On this interpretation, the Koonap and Balfour Formations represent deposition under humid conditions, with the floodplain being waterlogged and swampy for most of the year. The Middleton Formation must have formed under drier conditions, with semi-permanent backswamps on part of the floodplain and permanent subaerial exposure on others. In the Tarkastad Subgroup the abundant red mudstones indicate that dry conditions characterised the floodplain for most of the time.

E 3. Provenance(s)

Palaeocurrent and mineralogical evidence indicate that the same general provenance acted as a source for both the Ecca and Beaufort sediments, and the discussion in Section E 3 under the Ecca Group is in most respects equally applicable to the Beaufort Group. The main change in sandstone mineralogy which must reflect a change in source area lithology (if it is not due to climatic factors) is the decrease in feldspar content (and increase in quartz) which took place during the deposition of the Katberg Sandstone. The most likely explanation for this phenomenon is the commencement of uplift, folding and erosion of Witteberg and/or Table Mountain Group sandstones in the south at this stage.

CHAPTER XVII

MOLTENO FORMATION

A. STRATIGRAPHY

A 1. General stratigraphic relationships

A 1.1 Lithostratigraphic interrelationships

See Folder 1.

The Molteno Formation, together with the overlying Elliot Formation ("Red Beds"), Clarens Formation ("Cave Sandstone") and Drakensberg Group were previously all regarded as belonging to the Stormberg "Series" (see Rogers, 1902; Du Toit, 1954). However, in view of the absence of unifying lithologic features in these various formations which would distinguish them collectively from the underlying Beaufort Group, the Karoo working group of the South African Committee for Stratigraphy has decided that the continued use of "Stormberg" as a group designation in a formal lithostratigraphic scheme cannot be justified (Johnson and others, unpublished report, 1975).

A number of mappable subdivisions (members and beds) can be recognised within the Molteno Formation. Some of these have in the past been accorded geographic names, the best-known examples probably being the Indwe and Gubenxa Sandstones (Du Toit, 1903, p.175 ff.). Robinson and others (1969, p.16 ff.) proposed a three-fold subdivision of the Molteno Formation into a basal "Boesmanshoek Pass Member", a middle "Indwe Member" (embracing the Indwe Sandstone and the overlying argillaceous unit) and an upper "Kramberg Member". Turner (Ph.D. thesis, in preparation) has introduced the designation "Bamboesberg Member" for the strata below the Indwe Sandstone unit (i.e. the "Boesmanshoek Pass Member" of Robinson et al.).

A 1.2 Chronostratigraphic relationships

Du Toit (1954, p.356) assigned a Late Triassic age to the Molteno Formation. However, Plumstead (1969, p.51) believed a Middle Triassic age to be more acceptable. Anderson (1974, p.1) has stated recently that the Molteno is approximately of lowest Upper Triassic age (?Carnian).

A 2. General concept and distinguishing features

The Molteno Formation consists of alternating pale, "glittering", fine- to coarse-grained sandstone and pale olive mudstone lithosomes generally forming fining-upward cycles. The mudstone often grades into shale (which locally contains abundant plant remains), while occasional conglomerate and coal layers are also present.

A 3. Geographic distribution

The Molteno Formation is present above the Burgersdorp Formation (Beaufort Group) throughout the area depicted on Folder 3. The actual distribution is given by B.R. Turner (Ph.D. thesis, in preparation).

A 4. History and nomenclature

Dunn (1878) was apparently the first to regard the formation under discussion as a distinct entity within the "Stormberg Beds" of Wyley (1859) and Jones (1867). He referred to this unit as the "Coal Measures". The name "Molteno Beds" was introduced by Green (1883, p.6), and was derived from the village of Molteno, in the vicinity of which typical exposures occur.

A 5. Boundaries

Lower boundary

Nature of boundary.- Conformable: intertongued. Transition zone: 50 - 100 m. Towards the northern edge of the area the contact appears to become an unconformable, sharp one.

According to Robinson and others (1969, p.9), the contact in the southern outcrop area (i.e. where their "Boesmanshoek Pass Member" is present) in part represents a facies boundary, with sandstone beds occupying progressively higher stratigraphic positions passing from the Molteno Formation into the Burgersdorp Formation on going from south to north. Further north, where the Indwe Sandstone constitutes the base of the Molteno Formation, a significant amount of erosion may have preceded deposition of the Molteno Formation (p.10). Palaeontological data, such as the wedging out of the Upper Beaufort Cynognathus Zone, also strongly suggest a chronological gap, and hence an unconformable relationship (p.10).

Definition of boundary.- The base of an abrupt upward increase in sandstone/shale ratio (Robinson et al., 1969, p.8).

Robinson and others (p.8) point out that above the boundary the sandstone/shale ratio usually exceeds 0,5, while ratios exceeding 0,25 are unusual in the uppermost portion of the Burgersdorp Formation. In addition, other lithological dissimilarities accompany this change in sandstone/shale ratio, and to avoid erroneously fixing the contact at other sandstone/shale ratio changes occurring within the Molteno or Burgersdorp Formations, these must also be taken into account. They include the following (p.8):

1. A typical absence of red mudstone within the Molteno Formation.
2. A practical restriction of coal and carbonaceous shale to the Molteno Formation.
3. A relative coarseness of Molteno sandstones compared with those of the Burgersdorp Formation.
4. Occurrence of scattered pebbles and boulders within Molteno sandstones.
5. A greater relative frequency of scour-and-fill structures and trough cross-bedding within Molteno sandstones, and, conversely, a greater development of flat-bedding in Burgersdorp sandstones.
6. Concretions in the Molteno are ferruginous and are practically restricted to sandstones, while calcareous concretions are typical of the Burgersdorp and occur in both sandstones and mudstones.

Upper boundary

See A 5 under Elliot Formation.

A 6. Overall lithology

Examination of the sandstone/shale map presented by Robinson and others (1969, map 5.3) for the "Boesmanshoek Pass Member" (i.e. the strata below the Indwe Sandstone), indicates that in those areas where its thickness exceeds 100 m (the southern area extending more or less from Engcobo to beyond Molteno) the sandstone content ranges from 30 to 50 percent, although in the text (p.22) it is stated that mudstone constitutes less than 60 percent of the succession. Anomalously high sandstone proportions were obtained at Cala (93 percent) and west of Molteno (up to 75 percent).

For the strata above the base of the Indwe Sandstone (combining maps 6.3 and 7.3) general average values of about 30 percent and 70 percent were obtained for sandstone and mudrock respectively. Conglomerate possibly constitutes about one percent of the total, and coal less than one percent.

A 7. Dimensions and shape

According to Du Toit (1954, p.296) the Molteno Formation reaches a maximum thickness of 610 m south-west of Elliot. Botha and Theron (1968, Fig. 2) supply thicknesses of 550 to 610 m for the area around Elliot. The writer (1966, p.61) measured 670 m near Indwe, but Robinson and others quote a figure of 495 m for the same locality; this discrepancy appears to be due to a difference of opinion about the location of the upper boundary, since the thickness obtained by them for the Elliot Formation here is 165 m greater than that obtained by the writer.

Although Du Toit (1905, p.106) states that the Molteno Formation is 365 - 425 m thick south of the Stormberg (i.e. the southernmost outcrops in the Molteno - Sterkstroom - Dordrecht area), Rust (1962, p.181) gives a figure of 550 m for the Molteno Formation near Molteno, while Robinson and others (1969, Map 4) quote 455 m; an incomplete section south of Molteno gave a minimum thickness of 515 m. The figures quoted by Botha and Theron (1968, Fig. 2) on their isopach map (230 - 305 m) for this area would thus seem to be too low.

The Molteno Formation shows a fairly rapid northward diminution in thickness, from the values quoted above for the southernmost outcrops to 245 - 275 m in the Aliwal North - Burgersdorp area, and 385 m in the north-east near Matatiele (Robinson et al., 1969, Map 4). For the former area Du Toit (1904, p.85) gives thicknesses of 305 - 365 m, while Turner (1969, p.11) considers the Molteno to be 90 - 150 m thick in this area. Turner points out that the differences between himself and Du Toit can probably be ascribed to the use of different criteria for determining the formation boundaries (p.9) and more detailed work (such as that at present being carried out by Turner) is needed to clarify the issue.

Finally, an examination of the data contained in the literature indicates that the "narrow but very deep" trough postulated by Botha and Theron (1968, p.161), and aligned approximately along a line joining Elliot and Aliwal North, probably does not exist. Instead, the available evidence points to a fairly rapid wedging of the Molteno Formation in a northerly direction. Maximum rate of thickness change in the western area is about 200 m per 30 km i.e. 7 m/km. The change in thickness of the interval below the Indwe Sandstone is mainly responsible for this rapid rate. Average rate of thickness change in the whole area is probably about 3 m/km.

A 8. Stratotypes

In view of the extensive investigations that have recently been undertaken by B.R. Turner (Ph.D. thesis, in preparation), no stratotypes will be proposed here since the selection of both unit-stratotypes and reference stratotypes should wherever possible be based on extensive field work involving the examination of a large number of potential stratotypes in order to ensure that the best localities available are chosen.

B. PALAEONTOLOGY

According to Du Toit (1954, p.298) silicified tree trunks are common in the sandstones, while well-preserved plant remains (leaves and stems) are abundant in the shales, especially in the lower half of the formation. Du Toit (p.350, 351) lists over 20 genera, embracing nearly 50 species.

Vertebrate remains are extremely rare.

C. MACRO-SEDIMENTOGRAPHY

C 1. Cyclicity

According to Robinson and others (1969, p.14), fifteen to twenty typical fining-upward cycles can usually be distinguished in the south-east around Molteno, Indwe and Mount Fletcher, this number diminishing northwards with thinning of the formation. Average cycle thickness must be about 30 m, and maximum thickness is about 60 m.

The base of each cycle represents a scoured surface. The cycle usually commences with a thin relatively coarse-grained layer containing numerous mudstone clasts eroded from underlying material, as well as scattered quartzite pebbles and boulders in places. This coarse basal layer is overlain by fine- to coarse-grained sandstone which becomes progressively finer upwards and is in turn overlain by mudstone,the contact between the two being a gradational one. Finally, shale occurs in the uppermost few tens of feet of some cycles and coal is occasionally developed near the top (Robinson et al., p.15).

C 2. Lithosome dimensions and shape

"Major" sandstones are generally between 5 m and 20 m thick,while according to Du Toit (1954, p.297) the maximum thickness is about 60 m.

Most sandstones are fairly persistent laterally, tending to form distinct ledges that can in many cases be followed for a few tens of kilometres. The Indwe Sandstone can be traced throughout the study area (see Robinson and others, 1969 Map 6.2) and must thus have a minimum width of over 300 km.

Lithosomes vary from subtabular to moderately tabular, with width: thickness ratios ranging from about 500 to about 5 000.

C 3. Lithosome boundaries

Sandstone lower boundaries

Sharp, channelled, uneven. Depth of erosion scours ranges from a few cm for minor irregularities to a few metres in some channels.

Sandstone upper boundaries

Gradational. Transition zone varies from a few cm to a few metres. Some intertonguing may also be present. Mudstone overlies the sandstone.

C 4. Colours

The colour descriptions given below are based largely on data supplied by Robinson and others (1969).

Sandstone.- Light grey (N7) to yellowish grey (5Y8/1).

Mudstone.- Pale olive (10Y6/2). Reddish or medium dark grey (N4) varieties also occur, but are rare.

Shale.- Medium dark grey (N4) to dark grey (N3).

C 5. Sedimentary structures

The description which follows is largely drawn from Robinson and others (1969).

General bedding characteristics

Individual beds are unequal to subequal in thickness, laterally variable and discontinuous.

Syn-depositional current structures

Since the sandstones form part of fining-upward cycles, the internal structures also tend to display a cyclic arrangement. Thus the basal part of each sandstone is usually massive to poorly cross-bedded, followed by the main zone displaying cross-bedding (generally trough type) and flat-bedding, with the former normally predominating except in the finer-grained sandstones. Towards the top flat-bedding (and associated parting lineation) becomes more common as the sandstone becomes finer-grained and micro-cross-lamination is typically developed just below the contact with the overlying mudstone unit. Cross-bed sets range from 30 to 120 cm in thickness.

Asymmetric and interference ripple marks are sometimes present near or at the top of sandstone units.

Mudrock is invariably "massive-bedded", but laminated or very thinly-bedded shale forms about 5 - 10% of the mudrock total.

Deformational structures

Turner (1968-69) has reported the presence of overturned and deformed cross-bedding in Molteno Formation sandstones.

Chemical structures

Ferruginous (limonitic) concretions are common in the sandstones. These are generally about 5 - 7,5 cm in diameter (Robinson et al., p.19).

Orientation data

A number of workers have presented orientation data for primary structures in the Molteno Formation. These data were derived almost entirely from cross-bedding (although it is not always clear to what extent they represent trough axis orientations). The available information has been summarised in Tables XVII-1 and XVII-2, and the sources used are discussed below.

Rust and Ryan confined their studies to small areas in the vicinity of Molteno and Indwe respectively. Turner's work was restricted to the area between Aliwal North and Molteno. The remaining workers present directional data obtained from localities scattered throughout the study area. For comparative purposes the area was arbitrarily divided along 27°30'E into a western and eastern sector and an overall mean calculated for each sector, using the data given by these writers. The points M3-9 represent the approximate "centres of gravity" of the various authors' data.

The techniques used for deriving the means and vector strengths given in the table from the raw data presented by the authors need some comment.

Rust presented his data in the form of points on a series of stereographic projections (Plate IV). These diagrams were divided into 30° segments by the writer and the individual readings tallied to obtain the data needed for Table XVII-2.

Turner's data was presented in two rose diagrams (Folder 3).

Botha and Theron presented only a map showing directional arrows at various localities; the directions of these arrows had to be obtained directly from the map and an unweighted vector mean calculated for the eastern and western areas from these azimuths (since no indication was given of the number of readings on which the individual arrows were based).

Le Roux tabulated the data which he obtained at various localities (Addendum II), each mean and vector strength value he listed being based on an average of about 70 readings. The vector means given in Table XVII-1 are weighted vector means calculated from the individual vector means, but the vector strengths are simply unweighted arithmetic means of those quoted by Le Roux. In addition to cross-bedding (trough axis) orientations, Le Roux's data also incorporated measurements derived from current lineations and current ripple marks (p.121).

Table XVII-1. Statistical measures calculated from orientation data for cross-bedding in the Molteno Formation.

Locality/author	n	$\bar{x}_v$	$\bar{a}$	s
M1 (Rust, 1962)	557	344	0,40	75
M2 (Turner, 1969)	296	340	0,83	36
M3 (Botha & Theron, 1968)	?	347		
M4 (Le Roux, 1974)	771	326	0,75	44
M5 (Robinson, et al., 1969)	308	3	0,48	69
M6 (Ryan, 1963)	337	343	0,52	65
M7 (Robinson, et al., 1969)	97	349	0,46	70
M8 (Botha & Theron, 1968)	?	358		
M9 (Le Roux, 1974)	332	3	0,72	47

n = number of measurements

$\bar{x}_v$ = vector mean

$\bar{a}$ = vector strength

s = standard deviation

Table XVII-2. Cross-bedding dip directions in the Molteno Formation: number of readings per 30° class interval.

Locality/Author	15	45	75	105	135	165	195	225	255	285	315	345
M1 (Rust, 1962)	82	56	36	24	21	14	13	31	50	44	82	104
M2 (Turner, 1969)	51	25½							3½	40	62	114
M5 (Rob., et al)	49½	48	34	12	5	8½	4½	12½	17½	19½	39	58
M6 (Ryan, 1963)	62	44	17	6	3	10	8	6	24	48	51	58
M7 (Rob., et al.)	14	11	8	4½	3½	2½	1½	1	5	16½	14	15½
E13 (Botha, 1968)	14	10	4	1						1	6	18

Rob., et al. = Robinson et al., 1969.

Robinson and others used an unusual (and not very satisfactory) method of depicting their palaeocurrent data. At each locality an arc was drawn passing through the mean and indicating the range obtained (the mean itself not being shown). On the actual measured sections accompanying the report, the cross-bed dip directions were plotted adjacent to the individual sandstones in which they were measured, the same method being used. Where only one or two readings were obtained from a particular sandstone, the actual values could be readily obtained by measuring the direction of the plotted arrows. In the case of three or more readings the arrows bounding the arc represent two of the actual values; it was then assumed that the remaining readings were evenly distributed between the two extreme readings. The values derived in this way from the sections were used to calculate the means and vector strengths in Table XVII-1.

The data quoted for Ryan were obtained from a "histogram" summarising all his data in the form of number of readings per 10° class interval (Fig. 72).

The number of readings per 30° class interval given for Botha (1968) in Table XVII-2 were obtained from a rose diagram in which 15° intervals were used (Fig. 1). The measurements apparently represent trough axis orientations (p.105).

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Grain size

According to Rust (1962, p.198) the mean grain diameter of the sandstone horizons in the Molteno area, as measured by sieving techniques, generally varies between 0,125 mm (3ϕ) and 0,150 mm (2,73ϕ), the overall mean being 0,142 mm (2,82ϕ). Certain sandstones (especially the Indwe Sandstone) are, however, much coarser than average. For the Burgersdorp - Aliwal North area Turner (1969, Table 1) gives mean diameters for 30 samples ranging from 0,87ϕ to 2,05ϕ, with the exception of one sample which possessed a mean size of 3,08ϕ. Both sieving and thin-section techniques were used, and an overall mean of 1,60ϕ was calculated. It is hard to account for the more than two-fold size difference obtained in the two areas, especially since Turner's area is situated farther from the provenance. The writer obtained an average mean grain size of 1,30ϕ (thin-section examination) for ten samples supplied by B.R. Turner and A.F. Meyboom and collected from various localities throughout the study area. Generally speaking, it would appear that the Molteno Formation sandstones can be described as medium- to fine-grained, with coarse varieties occasionally present.

Detailed analyses carried out on three of the above-mentioned ten samples gave an average standard deviation of 0,57ϕ.

Roundness

According to Rust (p.198), Ryan (1963, p.72) and Turner (p.90) the smaller quartz grains are subangular to subrounded, while the larger grains are often well-rounded (using the terminology of Pettijohn, 1957).

D 2. Composition

Mineral composition data for Molteno Formation sandstones have been presented by Rust (1962), Ryan (1963), and Turner (1969). Average percentages obtained by these authors, as well as values obtained by the writer from eight samples collected at various localities within the study area (kindly supplied by B.R. Turner and A.F. Meyboom) are presented in Table XVII-3. In the case of Rust and Ryan, the figures quoted are approximate averages deduced from their ternary Quartz-Feldspar-Matrix diagrams (Figs. 9 and 43 respectively).

Table XVII-3. Molteno sandstone composition.

Author	Q	F	R	M	n
Rust (1962, Fig.9)	[1]60	2	-	38	20
Ryan (1963 Fig.43)	[1]65	7	-	28	16
Turner (1969, Table 2)	62	3	[2]6	[3]29	25
This study	72	2,5	[4]12,5	13	8

[1] Includes "quartzite" and chert

[2] "Metaquartzite" rock fragments

[3] Includes 2-3% mica

[4] Quartzite, chert, "felsite", micaceous rock fragments, etc.

Q = Quartz, F = feldspar R = rock fragments

M = matrix n = number of samples

The present writer feels that much of the material classified as "matrix" by previous workers would on closer inspection prove to consist of discrete rock fragments. For the sandstones examined in this study a Q:F:R ratio of 83:3:14 was obtained.

E. SEDIMENTOGENESIS

E 1. Dispersal patterns

Cross-bedding orientation data derived from a number of sources are summarised in Table XVII-1. From this data unweighted arithmetic mean directions of 344° and 357° were calculated for the western and eastern areas respectively. Unimodal patterns were normally obtained, with moderate to high vector strengths (ranging from 0,40 to 0,83).

E 2. Sedimentary processes and palaeoenvironments

As in the case of the Beaufort Group (see previous discussion) the fining-upward cycle concept is regarded as the key to the correct interpretation of the genesis of the Molteno Formation (cf. Robinson and others, 1969; Turner, 1970). According to Turner (1970) the Molteno is characterised by a cyclic pattern of deposition which can be divided into four major facies according to lithology, grain size, and sedimentary structures. The basal facies (A), consisting of conglomerate overlying a laterally continuous erosion surface of low relief, appears to be the result of erosion and deposition within a braided river channel wandering across a floodplain. The overlying sandstone facies (B) can be divided into three sub-facies and shows all the characteristics of a modern point bar complex. The lowermost part of the facies (subfacies (B_1) is composed of a coarse-grained gritty sandstone with local pebble washes. Cross-bedding (mainly trough cross-bedding) is the dominant type of sedimentary structure. Subfacies B_2 consists of more medium-grained flat-bedded sandstone in which primary current lineation is often conspicuous. Subfacies B_3 consists of fine sandstone and siltstone with ripple marks (mainly linguoid type). The fine sandstone, siltstone, and silty shale facies (C) represents a transitional facies deposited mainly from suspension in the quiet parts of the channel or in abandoned channels during low water. If the clastic facies in the sequence represents channel deposits, then the shale and coal facies (D) probably records overbank deposits from flood waters in the quiet backswamp areas of the flood plain. The environment was permanently inundated by water of such depth as to allow for the growth of plants and the formation of peat swamps.

Turner (p.315) believes that since the sandstone facies making up the greater part of the Molteno cycle is mostly coarse-grained, it was probably deposited by braided rivers which usually carry coarse detritus. Robinson and others (1969, p.38) postulate stream sinuosities varying from low to high. Thus they suggest that the internal structures and fine-grained character of the Bamboesberg Member sandstones favour sinuous (meandering) streams, in spite of the relatively high sandstone/shale ratio (which would normally indicate relatively low sinuosities). The thick, coarse-grained "Indwe Sandstone" is regarded as a product of coalescing deposits of low sinuosity (braided) streams, while the thick overbank component is on the other hand considered to have been associated with high sinuosity streams. The coarse-grained sandstones in the remainder of the succession are also taken to indicate low stream sinuosities, while the finer-grained sandstones and thick mudstone units would presumably again have to be regarded as high sinuosity (meandering) stream deposits.

A comparison of vector strengths for cross-bedding data given by Le Roux (1974) and Robinson and others (1969) for the Molteno and Elliot Formations in the western half of the area (see Tables XVII-1, XVIII-1) indicates that these workers actually encountered greater average dispersion values (i.e. lower vector strengths) in the Molteno Formation than in the Elliot Formation. In addition, relatively low vector strengths of 0,40 and 0,52 were calculated for the orientation data supplied by Rust (1962) and Ryan (1963) respectively (Table XVII-1). Since the Elliot Formation is a fairly definite meandering stream deposit (see below), and since braided stream deposits invariably show a distinctly lower scatter of orientation data compared with meandering stream deposits (Selley, p.218, 219), the palaeocurrent evidence favours a meandering stream interpretation for the Molteno Formation.

As pointed out previously (in the discussion of Beaufort Group sedimentation) Reineck and Singh (1973, p.261) are of the opinion that the differences between low-sinuosity and high-sinuosity stream deposits are rather vague and that great care and detailed study is needed to make such differentiation. They also state that there seem to be no well-defined differences between point bar sequences (in meandering streams) and channel bar sequences (in braided streams). It would seem that in the case of the Molteno Formation there is no conclusive evidence for either a braided or meandering stream environment. The present writer feels,however, that the balance of evidence favours a relatively high sinuosity (meandering) stream environment for the bulk of the Molteno Formation.

E 3. Provenances

As in the case of the underlying formations, palaeocurrent data point to the existence of a source area situated south of the depositional basin.

Although the Molteno Formation sandstones display a higher quartz and lower feldspar content compared with the underlying Burgersdorp Formation sandstones, the fact that the feldspar and rock fragment content increases again in the overlying Elliot Formation indicates that the low feldspar and rock fragment content of the Molteno may be partly due to more intense chemical weathering associated with more humid climatic conditions (as evidenced by the abundant remains of plant life and absence of red beds). The quartzitic sandstone pebbles were presumably derived from either the Table Mountain or Witteberg Groups, as no doubt was much of the quartz in the sandstones themselves.

CHAPTER XVIII

ELLIOT FORMATION

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1 Lithostratigraphic interrelationships

See Folder 1, as well as A 1.1 under Molteno Formation for comment on the "Stormberg Series".

After measuring at least 32 partial and complete sections through the Elliot Formation at localities scattered throughout the whole outcrop area, Le Roux (1974, p.107) is of the opinion that no subdivision of the formation on lithological grounds is possible.

A 1.2 Chronostratigraphic relationships

Both Du Toit (1954, p.356) and Romer (1970, p.117) assign a Late Triassic age to the Elliot Formation.

A 2. General concept and distinguishing features

Alternating fine-grained sandstone and mudstone lithosomes, generally occurring as fining-upward cycles. Mudstone is the predominant lithology and is greyish red (occasionally greenish grey) in colour.

A 3. Geographic distribution

The Elliot Formation is present throughout the combined Molteno - Elliot - Clarens outcrop area depicted on the map (Folder 3), occupying roughly the inner half of the outcrop belt. The actual distribution is given by Le Roux (1974, Folder 1).

A 4. History and nomenclature

This unit was apparently first regarded and described as a distinct entity by Dunn (1878). The name "Elliot Beds" was proposed by Botha (1968, p.110; 1969, p.764) and was derived from the town of Elliot, north of which the full succession is very well exposed in the Barkly Pass (which also constitutes the unit-stratotype). Johnson (1966, p.59) had used the name

"Barkly Pass Formation", but this was felt to be less suitable in view of the different spelling of "pass" in Afrikaans ("pas").

A 5. Boundaries

Lower boundary

Nature of boundary.- Conformable: intertongued (transition zone: 30 - 150 m).

Definition of boundary.- Robinson and others (1969, p.11) define the boundary as a level above which there is a sharp decrease in sandstone/shale ratio. In actual fact, sandstone/shale ratio maps presented by these writers fail to indicate a significant difference in the sandstone content of the two formations.

As the above authors point out, the Elliot Formation closely resembles the Burgersdorp Formation so that criteria applied in demarcating the top of the Molteno Formation are similar to those used in fixing its base. The six ancillary criteria used to fix the Burgersdorp - Molteno boundary (see A 5 under Molteno Formation) are, according to Robinson and others (p.11 - 12), equally applicable to the Molteno - Elliot boundary.

Upper boundary

See A 5 under Clarens Sandstone.

A 6. Overall lithology

The sandstone/shale ratio map presented by Robinson and others (1969, map 9.3) indicates that in the area under review the Elliot Formation is generally composed of about 30 percent sandstone and 70 percent mudrock. Le Roux (1969, Folder VI) presents a sandstone percentage map for the Elliot Formation; averaging the values obtained at 9 localities south of 31°30'S gives 34 percent sandstone and 66 percent mudrock. With one exception (23 percent sandstone), all sandstone percentage values lie between 29 and 40. Both maps fail to show any well-defined regional lithologic variation. Botha (1968, p.112) quotes a sandstone content of 43 percent for the Barkly Pass (E13) section.

A 7. Dimensions and shape

Thickness values plotted on isopach maps presented by Robinson and others (1969, map 9.2) and Le Roux (Folder 3) indicate that the Elliot Formation thins northwards and westwards from a maximum thickness of 484 m north of Elliot (Barkly Pass) to about 250 m in the Aliwal North - Lady Grey -

Sterkspruit area, to under 300 m north of Matatiele, and to under 250 m north of Molteno. Although Robinson and others quote a thickness of 585 m (1 920 feet) for the Elliot Formation north of Elliot and 582 m (1 910 feet) near Ugie (north-east of Elliot) thicknesses of 488 m (1 600 feet) and 484 m (1 587 feet) obtained in the Elliot area by Du Toit (1904, p.296) and Botha (1968, p.109) respectively support the lower value of Le Roux.

Anomalously low thickness of 250 m and 184 m were obtained by Le Roux in the Dordrecht - Jamestown area, 448 m (1 470 feet) having been measured in the same area by Robinson and others. A review by the present writer of the earlier work done by Du Toit and others indicated that the thickness of the Elliot Formation in the Dordrecht - Jamestown - Molteno region is usually about 600 feet (about 185 m), the maximum in this area bing 900 feet (about 275 m) (Johnson, 1966, p.61). Since thicknesses of 290 m (950 feet) and about 455 m (1 500 feet) were obtained by the writer (p.61) and Du Toit (1903, p.175) respectively at the same locality near Indwe, the latter value also being obtained by Robinson and others, it seems clear that ambiguity regarding the Molteno - Elliot contact may be largely responsible for the anomalous and widely divergent thickness values encountered in the literature.

A 8. Stratotypes

Unit-stratotype: Barkly Pass (E13)

Nature of stratotype.- Road cuttings in mountain pass with virtually complete exposure of the whole succession. The section commences either at or just above the basal contact, while the upper contact is also present.

Accessibility.- Excellent.

Location.- From the base of the Barkly Pass (± 10 km north of Elliot on the Elliot - Barkly-East road) to the start of the thick massive sandstones of the Clarens Sandstone near the top of the pass.

B. PALAEONTOLOGY

Silicified wood is fairly common, sometimes occurring as trunks 30 - 60 cm in diameter. Leaves are rarely preserved (Du Toit, 1954, p.298). A variety of vertebrate fossils (principally dinosaur remains) occur; Du Toit (p.342) lists 14 reptile genera, and one fish genus. It is not known how many of these have actually been found in the study area itself.

C. MACRO-SEDIMENTOGRAPHY

C 1. Cyclicity

As in the case of the Burgersdorp and Molteno Formations, the Elliot Formation is composed of alternating sandstone and mudstone lithosomes arranged in fining-upward cycles. According to Robinson and others (1969, p.27), Elliot Formation cycles are similar to those previously described for the Molteno Formation, the main differences being the predominantly reddish colour of the argillaceous portion, and the absence of carbonaceous shale and coal.

From the sections presented by Le Roux (1974, Folder II) an average cycle thickness of 25 m was calculated, the maximum thickness generally being about 50 m. Since cycle widths are determined by the widths of the sandstone component, the lenticular nature of the latter means that the cycles are also lenticular in shape, lateral extent generally not exceeding a few km.

C 2. Lithosome dimensions and shape

According to Robinson and others (1969, p.27), most sandstones are between 6 m (20 feet) and 15 m (50 feet) thick, while calculations based on Le Roux's sections (1974, Folder II) gave an average sandstone thickness of 8 m (maximum about 30 m).

Both Le Roux (p.107, 108) and Robinson and others (p.31) refer to the limited lateral extent of the sandstone units, Le Roux stating that even thick sandstones can seldom be followed for more than a few km. Most sandstones are probably sublenticular, with moderately lenticular varieties also relatively common.

C 3. Lithosome boundaries

Sandstone lower boundaries.- Sharp, uneven. Depth of scours range from a few cm to one metre or more.

Sandstone upper boundaries.- Gradational. Transition zone varies from a few cm to a few metres.

C 4. Colours

The following summary is based on the descriptions given by Botha (1968), Robinson and others (1969) and Le Roux (1974).

Sandstone.- Typical fine- and very fine-grained sandstones are yellowish grey (5Y7/2) to dusky yellow (5Y6/4), with dirty very fine-grained sandstone commonly being pale red (5R6/2 to 10R6/2).

Mudrock.- Greyish red (10R4/2) or pale red (5R6/2) varieties predominate, but yellowish grey to light olive grey (5Y5/2 to 7/2) or pale olive (10Y6/2) colours are also common and predominate at some localities. Le Roux (p.72 - 74) has described a section near Dordrecht in which red sediments are absent altogether (although red colours are common in another section only a few km distant). According to Le Roux (p.115) the average percentage of red sediment in the Elliot Formation is 53. This means that about two-thirds of the mudrock is normally red.

C 5. Sedimentary structures

General bedding characteristics

Individual beds are unequal to subequal in thickness, laterally variable and discontinuous.

Pre-depositional current structures

The bases of most sandstone lithosomes are characterised by scours up to one metre deep. Occasionally much larger channels are also encountered.

Syn-depositional current structures

Internal structures.- The basal portion of each sandstone (up to one metre thick) is usually "massive-bedded". The bulk of the sandstone is characterised by flat-bedding (with parting lineation) and trough cross-bedding. Tabular cross-bedding is rare. Sedimentation units are generally 30 - 100 cm thick, and lenticular. Micro-cross-lamination is common near the top of the sandstone.

Mudrocks are normally massive-bedded.

External structures.- Oscillation and current ripple marks are occasionally present (Robinson, et al., 1969, p.27).

Deformational structures

Robinson and others (1969, p.27) report the presence of dessication cracks, while Le Roux (1974, p.228) found some examples of ball-and-pillow structures.

Chemical structures

Calcareous concretions are common within the sandstones, particularly towards the top of the formation; concretions also occur in the mudstones. (Robinson et al., 1969, p.12, 29).

Orientation data

Available orientation data for primary structures (mainly axes of trough cross-bedding) are summarised in Tables XVIII-1 and XVIII-2. Comments on the nature of the original data from which the tabulated figures were derived have already been given for Le Roux (1974) and Robinson and others (1969) under the Molteno Formation. Botha (1968) appears to have measured trough axis orientations (p.105) and the data in Tables XVIII-1 and XVIII-2 were derived from a series of rose diagrams (Figs 2-13).

Table XVIII-1. Statistical measures calculated from orientation data for cross-bedding in the Elliot Formation.

Locality/Author	n	$\bar{x}_v$	$\bar{a}$	s
El 1 (Le Roux, 1974)	1285	331	0,81	38
El 2 (Robinson et al., 1969)	90	350	0,62	57
El 3 (Robinson et al., 1969)	50	37	0,70	49
El 3 (Botha, 1968)	271	49	0,43	73
El 3 (Le Roux, 1974)	133	27		
El 4 (Le Roux, 1974)	438	345	0,53	64

n = number of measurements

$\bar{x}_v$ = vector mean

$\bar{a}$ = vector strength

s = standard deviation

Table XVIII-2. Cross-bedding dip directions in the Elliot Formation: number of readings per 30° class interval.

Locality/author	15°	45°	75°	105°	135°	165°	195°	225°	255°	285°	315°	345°
El 2 (Rob. et al.)	11	14	8	1		1	1	1	4	9	17½	22½
El 3 (Rob. et al.)	9½	10	10	6½	½	½	½				3½	9
El 3 (Botha, 1968)	44	36	48	20	24	15	15	6	3	4	13	43

Rob. et al. = Robinson et al., 1969

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Grain size

The following average values were obtained from three sandstone samples collected at Barkly Pass (El3) :

Mean size:	2,48 ø
Standard deviation:	0,57 ø
Maximum size:	1,11 ø
Matrix content:	10%

D 2. Composition

The following average percentages were derived from the three sandstone samples from Barkly Pass (El3) : quartz (including secondary quartz): 59,5%; feldspar: 9%; rock fragments: 17,5%; accessory minerals: 1%; cement and secondary minerals (mainly calcite): 3%; matrix: 10% A Q:F:R ratio of 69: 10,5:20,5 was obtained.

E. SEDIMENTOGENESIS

E 1. Dispersal patterns

The cross-bedding orientation data summarised in Tables XVIII-1 indicate a general NNW transport direction in both the western and eastern halves of the area, with an anomalous NNE to NE direction in the Barkly Pass (El 3) area. Unimodal patterns and moderate to high vector strengths were obtained.

E 2. Sedimentary processes and palaeoenvironments

The sediments constituting the Elliot Formation form typical fining-upward cycles and, as in the case of the Beaufort Group and the Molteno Formation, these cycles can be readily accounted for only in a fluviatile environment (cf. Robinson and others, 1969, p.36-38). Furthermore, the distinct predominance of mudstone over sandstone points to meandering rivers rather than braided ones (Selley, 1970, p.218, 219; Allen, 1970, p.140 ff.), with the sandstone accumulating on point bars in the laterally migrating river channels and the mudstones constituting overbank deposits accumulating on the floodplain. The predominance of red colour in the mudstone is indicative of oxidising conditions associated with subaerial exposure and hence much drier conditions than those prevailing during the deposition of the Molteno Formation.

E 3. Provenances

As regards both nature and location, the source area probably remained basically similar to that operative during deposition of the uppermost Beaufort Group and Molteno, although the somewhat higher quartz content compared with the Tarkastad Subgroup could reflect a greater contribution from Cape Supergroup rocks.

CHAPTER XIX

CLARENS SANDSTONE

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1 Lithostratigraphic interrelationships

See A 1.1 under Molteno Formation for comments on the earlier grouping of this unit as part of the "Stormberg Series".

Beukes (1969, p.26 ff.) suggested that three distinct subdivisions could generally be identified within this formation. These comprise a basal massive silty sandstone member ("zone 1"), a middle generally cross-bedded fine-grained to very fine-grained sandstone member ("zone II") and an upper member composed of massive siltstone and silty sandstone ("zone III"). The last-mentioned member is, in the area under consideration, generally substantially thicker than the underlying members. B.J.V. Botha (personal communication to SACS Karoo Working group) has proposed the names "Golden Gate member", "Cathedral Peak member" and "Rhodes member" for Beuke's zones I, II and III respectively.

A close examination of the sixteen profiles which Beukes has measured in the southern outcrop area shows that material which could be labelled zone II on the basis of the definitions supplied above only occurs in nine out of the sixteen cases. Even in those cases where this material is present, we have no proof that direct correlation between sections is always valid; each example may represent an independent local development. It would thus seem premature at this stage to introduce a formal lithostratigraphic terminology for these members and it is here suggested that they can just as satisfactorily be referred to informally as the basal (or transitional) member, the cross-bedded member (Beukes, p.31, refers to the "cross-bedded zone") and the main massive member.

A 1.2 Chronostratigraphic relationships

Du Toit (1954, p.356) and Romer (1970, p.117) both give a Late Triassic age for the Clarens Sandstone.

A 2. General concept and distinguishing features

Very pale orange or cream fine- to very fine-grained sandstone or coarse siltstone plus minor mudstone intercalations. The sandstone/siltstone is normally massive-bedded (structureless), but large-scale trough (festoon) cross-bedding is locally a conspicuous feature. Topographically, this unit characteristically forms impressive cliffs which are often undercut at the base and hollowed out to form shallow caves.

A 3. Geographic distribution

Beukes (1969, Plate X) presents a map showing the distribution of the Clarens Sandstone. It occurs in a narrow outcrop zone surrounding the overlying Drakensberg Group throughout the area depicted on the accompanying map (Folder 3) although a few very local hiatuses do occur, for example those mapped by Du Toit north-east of Indwe (on Cape Sheet 26), west of Mount Fletcher and north of Matatiele (on Cape Sheet 35).

A 4. History and nomenclature

This unit was first described as a separate lithologic entity by Dunn (1878, p.9), who introduced the name "Cave Sandstone". However, apart from the fact that the use of a non-geographic name does not conform to current stratigraphic practice, to the uninitiated the Afrikaans equivalent ("Holkranssandsteen") bears no resemblance to the English name. The present name was proposed by N.J. Beukes (personal communication to the SACS Karoo working group) and derived from the village of Clarens in the north-eastern Orange Free State. The present writer had earlier suggested the name "Rhodes Sandstone" (1966, p.59), but the Karoo working group felt that this designation was not as suitable, since the full succession is not displayed in the vicinity of Rhodes village (north-eastern Cape Province).

A 5. Boundaries

Lower boundary

Nature of boundary.- Normally conformable. May be sharp, gradational or intertongued (cf. Robinson, et al., 1969, p.13; Beukes, 1969, p.18). Transition zone thickness: 0 - 100 m. Erosion channels are occasionally present (Beukes, p.124).

Definition of boundary.- The precise definition of this boundary has occasioned considerable difficulty in the past (cf. Beukes, 1969, p.18 ff.; Robinson et al., 1969, p.13 ff.; Le Roux, 1974, p.13 ff.). According to Robinson and others (p.13) "a satisfactory boundary is determined by the level below which mudstone is more extensive (i.e. Cave Sandstone-like bodies are discontinuous) and above which mudstone bodies are discontinuous". Beukes (p.22) placed the boundary at the base of the fine- to very fine-grained sandstone/siltstone succession which appears massive from a distance. Le Roux (p.13) drew the contact at the base of the first thick sandstone. In practice all three definitions seek to demarcate a formation which is largely or almost entirely composed of aeolian material.

A 6. Overall lithology

Sandstone/coarse siltstone	:	95 - 100%
Mudrock	:	0 - 5%

A 7. Dimensions and shape

Thickness

Data presented by Beukes (1969, Plates XIE, XII) indicate that the maximum development of this unit is in the Elliot - Barkly East - Rhodes area, where thicknesses are in the region of 200 - 300 m, a maximum of 305 m being obtained north-east of Barkly-East. Outside of this area thicknesses generally vary between 20 m and 80 m. Both Du Toit (see references under A 3 above) and Robinson and others (1969, p.33) mention that this formation is locally absent altogether - a fact which the isopach map presented by Beukes (1969, Plate XII) fails to reflect. This and other discrepancies between the isopach contours and the thicknesses obtained at the various measured profiles on which the map is supposedly based are, according to Beukes (personal communication) due to the fact that the contours were drawn using "moving average" thicknesses rather than the actual measured thicknesses.

Shape and lateral extent

Since the Clarens Sandstone has a minimum lateral extent of over 400 km (from Molteno in the south-west to Harrismith in the north-east) and a general thickness of about 50 m, it is seen to possess an essentially tabular shape when viewed regionally. Locally, however, considerable thickness fluctuations take place over relatively short distances, and for these areas high thickness change rates (up to 10 m/km) can be calculated.

A 8. Stratotypes

Type locality: Clarens area (in the northeastern Orange Free State)

A suitable unit-stratotype must still be defined somewhere within the general type area.

Reference stratotype: Barkly Pass (E13)

Nature of stratotype.- Road cuttings and natural exposures showing typical appearance of formation. Lower contact is exposed, but uppermost part of formation is absent.

Accessibility.- Excellent.

Location.- Uppermost part of the Barkly Pass north of Elliot on the Elliot - Barkly-East road.

B. PALAEONTOLOGY

Fossils are generally scarce, but according to Du Toit (1954, p.300) silicified wood, vertebrate fossils and crustaceans are occasionally found. The vertebrate remains include one or more fish genera and eight reptile genera (Du Toit, p.342).

C. MACRO-SEDIMENTOGRAPHY

C 1-3. Lithosome data

No distinct lithosomes occur in the Clarens Sandstone.

C 4. Colours

Colours range from yellowish grey (5Y7/2) through very pale orange (10YR8/2) to greyish orange pink (5YR7/2).

C 5. Sedimentary structures

General bedding characteristics

Bedding is usually poorly developed and, except for some thin beds near the base and thick to very thick lenticular cross-bedded units which are present in the lower part of the formation at some localities, this unit has a typical unbedded homogeneous appearance. However, Beukes (1969, p.11, 12, 16) feels that the formation is in fact quite well-bedded but that for various reasons this bedding is not readily apparent in most outcrops.

Syn-depositional current structures

One of the most striking features of the Clarens Formation is the extraordinarily massive, structureless appearance of the bulk of the sediments consituting it. On the other hand, Beukes (1969, p.16) doubts whether all or even most of the "massive" beds are really without any internal structures. However, in view of the unusual grain-size of the massive zones (coarse silt/ very fine sand) and their general similarity to loess, which is normally regarded as a massive deposit since it is formed through the accumulation of material carried in suspension, the present writer feels that most of the Clarens Formation is probably genuinely structureless.

In addition to the massive-bedded material, medium- to very large-scale trough (festoon) or tabular cross-bedding, with sets ranging up to 10 m in thickness, is locally well developed in the lower part of the sequence. Micro-cross-lamination is occasionally present (Beukes, p.16, 17).

Symmetrical ripple marks occur near the base of the formation (Robinson et al., p.33), associated with thin- to medium-bedded sandstone/ siltstone.

Deformational structures

Dessication cracks have been observed in the interbedded mudstone by Beukes (1969, p.16) and Robinson and others (1969, p.32). The latter authors also mention the occurrence of ball-and-pillow structures at the base of the formation.

Chemical structures

Beukes (1969, p.17, 18) describes three kinds of concretions occurring in the Clarens Formation: oval to spheroidal calcareous concretions, 2 - 15 cm in diameter; irregular, sometimes coalescent calcareous concretionary bodies up to 30 cm in diameter, and oval or spheroidal siliceous concretions, formed through silicification around a nucleus after deposition of the sandstone.

Directional data

Beukes (1969, Fig.18) presented a map on which he plotted mean cross-bedding dip directions for a number of localities in the study area. The data in Table XIX-1 are derived directly from this map.

Table XIX-1. Directional data, Clarens Sandstone (based on data supplied by Beukes, 1969).

Locality	n	$\bar{x}_v$	$\bar{a}$	s
Jamestown (C1)	52	84°	0,89	28°
Herschel (C2)	9	86°	0,89	28°
[1]"Barkly-East" (C3)	29	77°	0,74	45°
Matatiele (C5)	9	71°	0,89	28°
All readings	99	81°	[2]0,85	34°

(Footnotes on following page)

[1] Data represent a weighted mean based on five separate sites scattered around locality C3.

[2] Average vector strength

n = number of readings $\bar{x}_v$ = vector mean $\bar{a}$ = vector strength

s = standard deviation.

D. MICRO-SEDIMENTOGRAPHY

D 1. Texture

Size data were obtained from 3 samples collected from the top of Barkly Pass (C 4). The following results were obtained:

Mean size ($\bar{x}$) : 3,90Ø
Standard deviation (s) : 0,63Ø
Matrix percent : 34,5%

According to Beukes (1969, p.34 and Fig. 6, p.36) the bulk of the Clarens Formation in the writer's study area consists of "silt-sandstone" and "siltstone" belonging to his uppermost zone (Zone III). Beukes obtained grain-size data on these rock-types using thin sections cut from ten samples collected throughout the total Clarens Formation outcrop area. Long axes of "quartz" grains (including untwinned and relatively unaltered feldspar grains) were measured, measurements being confined to grains coarser than 5,5Ø (Fig. 29, p.86). From the results tabulated on p.87 (Table X), overall mean grain size and "sorting" values of 3,7Ø and 0,62Ø were calculated, the latter representing the "graphic standard deviation" of Inman (1952). If two anomalously coarse samples (2 and 4) are omitted, the remaining 8 samples give average values of 3,8Ø and 0,60Ø for mean grain size and "sorting" respectively. These results agree closely with those obtained by the present writer at Barkly Pass (C 4).

Slightly coarser massive sandstone appears to be present in "Zone III" along the western edge of the study area (and locally in the south and east) as well as in the generally cross-bedded "Zone II". Two samples from the writer's study area gave an overall mean grain size value of about 3,3Ø, using sieve analysis (Beukes, Table V, p.69). The cross-bedded sandstones themselves (which occur very sporadically in the study area) are slightly coarser with 8 samples from the study area giving an overall sieving mean of 3,2Ø (Beukes, Table IV, p.168).

Le Roux (1974, p.150) obtained an overall mean grain size of 3,8Ø for the Clarens Formation, based on sieve analysis of 26 samples collected throughout the whole outcrop area.

D 2. Composition

Mineral composition data for the Clarens Formation are presented in Table XIX-2. All figures have been rounded off to the nearest 0,5 percent.

In the case of the data obtained from Beukes (rows 2 - 4) "Q" embraces "quartz fragments", silica cement, untwinned feldspar and unaltered or slightly altered feldspar. Zone III (a) represents the "silt-sandstone" and "siltstone" of Zone III (Table XVIII, p.107) while Zone III (b) represents the "sandstone" (Table XVI, p.103). Figures for Zone II (Table XV, p.100) are for cross-bedded sandstone. In all cases samples were obtained from widely scattered localities throughout the whole Clarens Sandstone outcrop area.

Table XIX-2. Mineral composition of Clarens Formation sandstones.

Locality, etc.	n	Q	F	R	Acc	Cem	M	Q	F	R
C4	3	36	20	8	-	1,5	34,5	56 :	31 :	13
Beukes (1969): Zone III (a)	10	49,5	2,5	3,5	1		43,5	89 :	4,5 :	6,5
Beukes (1969): Zone III (b)	5	70,5	5	4	0,5		20	88,5 :	6,5 :	5
Beukes (1969): Zone II	5	78	3,5	2	0,5		16	93,5 :	4 :	2,5

Q = Quartz (including silica cement)
F = Feldspar
R = Rock fragments
Acc = Accessory minerals
Cem = Secondary minerals
M = Matrix

E. SEDIMENTOGENESIS

E 1. Palaeocurrents and dispersal patterns

The data collected by Beukes (1969, Figs. 18, 19) some of which have been summarised above (under C 5), have established that the cross-bedded sandstones in the Clarens Formation were transported by very consistent currents directed almost due east over a large area. Both locally and regionally dispersion values are very low.

E 2. Depositional processes and palaeoenvironments

"The vast area that the 'Cave Sandstone' and its equivalents must have covered, the marvellous uniformity both in grain and in bulk of the material, the cream or pinkish and frequently red colouration, the general lack of conspicuous stratification, the presence of broad false-bedding, the irregular calcareous concretions near the base, the relatively rapid variation in thickness and the lack of practically all signs of plant life force one to regard this uppermost zone of the Karoo System as being in the main an aeolian deposit comparable in certain respects with the Pleistocene loess of the Northern Hemisphere. It appears to have been formed at the conclusion of a period of semi-aridity evidenced by the Red Beds, but a certain though probably limited amount of water must have been present, as shown by the scanty remains of fishes and crustacea, terrestrial life being represented by dinosaurs" (Du Toit, 1918, p.xxxv).

No serious attempt has been made to disprove the aeolian origin of the Clarens Sandstone, although Truswell (1970, p.128) feels that only some of the sandstones are definitely aeolian in origin, and that it is an invalid extrapolation to assume that it is entirely a deposit of this nature. However, as Selley (1970, p.63) points out, it often helps to ask the question: "If this facies is not aeolian, what else could it be?" Truswell does not attempt to answer the question.

Most recent reviews of the characteristics and distinguishing features of dune sands have, however, emphasised the difficulties involved in identifying ancient wind-blown sediments (cf. Selley, 1970, p.61; Allen, 1970, p.114; Pettijohn and others, 1972, p.514; Bigarella, 1972, p.14, 38). "Could it be that most of the sands regarded as ancient aeolianites are in fact water-laid?" ask Pettijohn and his co-writers (p.514), and they go on to say that, "We regard identification of the aeolian environment of a sand as an exceedingly difficult problem, one that requires a very careful, thorough analysis of all aspects of the deposit and its associated lithologies". According to Allen (1970, p.114), the problem of reliable identification becomes particularly severe in the case of wind-blown silts.

In spite of the general pessimism regarding the correct interpretation of ancient dune sands, in the case of the Clarens Formation the case for the aeolian origin of the cross-bedded sandstones seems unassailable. This opinion is based on the presence of large-scale tabular cross-beds (sets up to 10 m thick, and commonly over 2 m thick) composed of fine-grained to very fine-grained well-sorted sand, coupled with the remarkably consistent palaeocurrent directions obtained from these cross-bedded units not only in the Clarens Formation in the area studied by Beukes (1969) but in its correlates in the Transvaal and in South West Africa (Bigarella, 1970, Table IV). Moreover, the actual directions obtained by Beukes are oriented at right angles to those prevailing in the underlying thick fluviatile formations (Molteno and Elliot Formations).

In view of their tabular nature, Beukes (p.52) suggests that the cross-beds originated as transverse dunes, a hypothesis consistent with the low scatters (high vector strengths) encountered in the measurement of cross-bed dip directions (Figs.18, 19; cf. Reineck and Singh, 1973, p.202). Although Reineck and Singh (p.197) point out that barchan and seif dunes are normally the most abundant and important dune varieties, they note that transverse dunes are common forms in several deserts.

With regard to the massive very fine-grained sandstone/coarse siltstone constituting the bulk of the Clarens Formation in the study area, Beukes (p.92) queries the suggestion that these deposits could represent an ancient loess, on the grounds that they are too coarse-grained. While he does point out (p.128) that there are a number of similarities between the finer-grained massive rocks and loess (e.g. irregular concretions, homogeneity, poor stratification, massive appearance and calcitic matrix) he is of the opinion that the absence of cross-bedding structures is in fact due to obliteration by rainwater, which gives rise to sand-flows in saturated dunes and results in horizontal bedding (p.125, 130; cf. Bigarella, 1970, p.89). Although Beukes maintains that the grain size is too coarse for loess, a review of the literature indicates on the contrary that this deposit is probably too fine-grained to have been deposited as dunes. In order to establish this conclusion the pertinent data relating to both loess and dune sand will first be summarised, followed by a discussion of the implications of this data.

(a) <u>Loess</u>

Loess can be defined as a laterally extensive, generally unstratified, well-sorted (homogeneous), fine-grained (predominantly coarse silt) aeolian deposit (cf. Butler, 1956, p.146; Flint, 1957, p.181; Smalley and Vita-Finzi, 1968; Gary and others, 1972). Glennie (1970, p.118) states that loess is an accumulation of wind-blown dust ranging in size from fine sand to clay-sized particles. Most of the particles fall within the range 20 μ (5,65 φ) to 100 μ (3,32 φ) with the bulk varying between 30 μ (5,06 φ) and 80 μ (3,65 φ). According to Smalley and Vita-Finzi (p.767), the modal diameter can vary from 20 μ (5,65 φ) to 50 μ (4,32 φ), while Kukal (1971, Fig.41a) shows that the median grain size can range from 4 φ to about 5,65 φ (or 0,06 mm to 0,02 mm - see p.131). Allen (1970, p.104) states that loess deposits have a mean grain size seldom less than 0,015 mm (6,06 φ) and rarely greater than

0,045 mm (4,47 Ø).

Smalley and Vita-Finzi (1968) have briefly reviewed the origins of all the definite loess deposits known at present and have concluded that only one minor deposit (the Negev loess) seems to have a well-established desert origin (i.e. with the constituent material being formed under desert conditions). The remainder all appear to consist of material which was originally formed by glacial processes and subsequently transported and deposited by wind (Smalley, 1966).

(b) Dune sands

According to Bagnold (1941, p.6) the predominant diameter of the finest wind-blown sands is never less than 0,08 mm (3,65 Ø); usually the mean size lies between 0,3 and 0,15 mm (1,74 Ø and 2,74 Ø). Later Bagnold (p.98) states that for the normal winds prevailing on the earth's surfaces, the critical diameter below which sand grains can be carried in suspension is about 0,2 mm (2,32 Ø), thus accounting for the fact that grains of this size are found to predominate in the finest dune sand, namely, that which collects at the tops of dunes. "Deposits of sand of peak diameter less than 0,15 mm are rare" (p.165).

Allen (1970, p.103) states that wind-blown dune sands are chiefly unimodal in size distribution, with a mean size seldom less than 0,20 mm (2,32 Ø) and rarely greater than 0,45 mm (1,15 Ø). Kukal (1971, p.123) states that the median of about 90% of aeolian sands varies between 0,15 mm (2,74 Ø) and 0,25 mm (2 Ø), although inspection of his Fig. 41a indicates that these figures should actually have read 1,5 Ø (0,35 mm) and 2,5 Ø (0,18 mm).

Discussion

While Kukal (p.121, 130) is of the opinion that 0,05 mm (4,32 Ø) (which he regards as a natural boundary between silts and sands) is a "perfect genetic boundary" between loess and dune sand, this is not borne out by the upper size limit which he quotes for the former (0,06 mm) and the lower size limit of the latter (0,15 or 0,18 mm). The literature reviewed above indicates that there is general agreement that 0,15 mm (2,75 Ø) normally represents the lower limit for dune sands, with an absolute limit of 0,05 mm (3,65 Ø) (Bagnold, p.6). It thus seems clear that although somewhat coarser than modern loess, the fine-grained massive sandstones and siltstones of the Clarens Formation (3,8 Ø to 3,9 Ø) must, like loess, also represent deposition from suspension. This would give rise to a homogeneous, structureless deposit, rather than dunes which are produced by sand which is being moved by a combination of saltation and surface creep.

E 3. Provenance(s)

Palaeowind data deduced from cross-bedding dip directions indicate that the source area of the Clarens Formation sediments must have been situated to the west of the present outcrop area. The very fine-grained nature of the strata points to considerable distance from the source area, while the high feldspar content indicates that feldspathic sandstone and/or granite-gneiss was common. Beukes (1969, p.121) suggests that the underlying, semi-consolidated sediments of the Karoo Sequence (and particularly the Beaufort Group) acted as the main source of the Clarens Formation sandstones and siltstones. However, the present distribution of wind-blown sandstone correlatable with the Clarens Sandstone indicates that the original loess blanket was extremely extensive and that a source area to the west of the Cape - Karoo basin (i.e. in what is now South America) is perhaps more likely.

CHAPTER XX

DRAKENSBERG GROUP

A. STRATIGRAPHY

A 1. General stratigraphic interrelationships

A 1.1 Lithostratigraphic relationships

This unit overlies the Clarens Sandstone and was previously regarded as the uppermost component of the Stormberg "Series" (cf. Rogers 1902; Du Toit, 1954). However as explained previously (see A 1.1 under Molteno Formation) no justification exists for such a grouping in a formal lithostratigraphic scheme. Lock and others (1974) have identified and named a number of mappable subdivisions (formations and members) in the lower part of the Drakensberg Group in the southern outcrop area, but in view of the preliminary nature of the investigation and the possibly restricted areal distribution of these units, they have not yet been formally recognised by the Karoo working group of SACS.

A 1.2 Chronostratigraphic relationships

Fitch and Miller (1971) obtained an average radiometric age of 187 ± 7 m.y. from basalt samples in Lesotho, using the K - Ar method. This corresponds to an Early Jurassic age.

A 2. Basic concept and distinguishing features

The Drakensberg Group consists essentially of basalt, with geographically restricted, relatively thin, pyroclastic intercalations near the base.

A 3. Geographic distribution

The geographic distribution of the Drakensberg Group is shown on Folder 3.

A 4. History and nomenclature

One of the earliest references to the unit under discussion is that of Dunn (1878), who referred to it as the "Volcanic Beds". This term remained in general use until Rogers and Du Toit (1909) introduced the term "Drakensberg Beds", the name being derived from the Drakensberg range. The present writer (1966, p.63) used the name "Drakensberg Volcanics", while Lock and others (1974, p.118) envisaged a "Volcanic Group" consisting of an upper silica-rich "Lebombo Subgroup" and a lower basaltic "Drakensberg Subgroup" (cf. Stratten, 1970). The Karoo working group of SACS has decided to recognise a "Lebombo Group" embracing all the volcanic rocks (including the basalts) of the Lebombo - Zululand area, and a "Drakensberg Group" confined to Lesotho and the adjacent areas (Johnson and others, unpublished report, 1975).

A 5. Boundaries

Lower boundary

Underlying lithology.- Sandstone/siltstone.

Nature of boundary.- Generally conformable (?); sharp and even (flat) or intertongued (transition zone up to 30 cm thick). In places unconformable (with an uneven, sometimes deeply channeled, surface). The above summary is based on descriptions provided by Du Toit (1954, p.301, 302), Beukes (1969, p.24-26) and Lock and others (1974, p.121).

Definition of boundary.- Base of first prominent lava flow or pyroclastic unit.

Upper boundary

Not preserved.

A 6. Overall lithology

Basalt:	90 - 100%
Pyroclastics:	0 - 10%
Sandstone/mudrock:	0 - 5%

The maximum percentages given for pyroclastics (10%) and sediments (5%) are approximate values based on the descriptions given by Du Toit (1903, 1904, 1954), Beukes (1969), and Lock (1974). Pyroclastics and sedimentary rocks, where present, are confined to the lowermost 300 m of the succession.

A 7. Dimensions and shape

Du Toit (1954, p.301) quotes a thickness of about 1200 m (4000 feet) obtained in the Matatiele District; this represents more or less the maximum thickness present in the study area. However, since the top of the succession is nowhere preserved, the original maximum thickness is not known.

The Drakensberg Group, as presently defined, has a maximum known lateral extent of over 400 km. However, the original lava field, of which the Drakensberg Group is but a part, was considerably more extensive and probably covered most of Southern Africa, with a lateral extent in South Africa alone of over 1200 km.

A 8. Stratotypes

No actual stratotypes have yet been proposed. The Drakensberg and escarpment along the eastern boundary of Lesotho can be regarded as a general type area.

B. PETROGRAPHY/PETROGENESIS

A detailed discussion of the petrographic and genetic features of the lavas and associated pyroclastics is beyond the scope of this study. These aspects have in any case been fairly fully described by Du Toit (1954, p.300 ff.) while Lock and others (1974) provide important additional information on the various subdivisions present in the lower part of the sequence in the Barkly East area. The latter authors (p.118) provide the following concise summary of the "depositional history" of the Drakensberg Group.

"The deposition of Drakensberg Subgroup commenced with activity at discrete centres. Shield-shaped masses of basalt accumulated and caldera collapse took place in some cases. This phase of the volcanic history was characterised by a greater degree of explosiveness than that which followed and pyroclastic rocks are relatively abundant, at least in the north-eastern Cape Province. The remaining, and greater, part of the basalt sequence was erupted under different circumstances - fissure-vents are believed to have supplied most, if not all, of the material in the form of quiet effusions of highly mobile lava".

CHAPTER XXI

GENERAL SUMMARY

A. INTRODUCTION

The sedimentary history of the Cape and Karoo Sequences embraces a total period of roughly 300 million years, from the commencement of the Ordovician Period to the close of the Triassic. During this interval, characterised almost entirely by negative crustal movement in the part of the basin under consideration, an enormous thickness of sediments was deposited. Using the maximum known thicknesses of all the formations, a stratigraphic column representing 20 km of strata can be constructed (cf. Folder 1). This does not imply that the total thickness at any one particular point ever reached this value, but it does give some idea of the volume of sediment that was transported and deposited.

It has in the past been standard practice to relate thick sedimentary sequences such as the Cape-Karoo succession to one of the standard geosynclinal classifications. However, it is now being seriously questioned whether the geosynclinal concept, and in particular its special role in orogenesis, may not have outlived its usefulness (Hsü, 1973, p.67). According to Hsü three factors have mainly contributed to this assessment:

1. What exactly constitutes a geosyncline has received no consensus. "Because there have been many different kinds of troughs, filled, or not filled, with different sequences of sediments, we have a kaleidoscope of geosynclines. Some are yours, some are mine; some are true, others not quite; most are gluttonous, a few are starved" (p.66).
2. With the popularisation of sea-floor spreading concepts and plate-tectonics, the geosynclinal theory began to seem superfluous. Even an alpine authority such as Laubscher was moved to state that the geosyncline concept is incompatible with the recent information (Hsü, p.82).
3. There is a clear tendency for ancient sediments to be more and more interpreted on an actualistic basis (i.e. by reference to known modern analogues) (p.86).

Hsü (p.87) envisaged that "future development will emphasise the descriptive and more factual aspects of geosynclinal rock suites" and that there would be less temptation for us to indulge in "speculative or dogmatic pronouncements that are unrelated to actualistic settings".

In reviewing the history of the Cape-Karoo basin in the study area the most significant developments probably concern changes which took place in overall lithology, sandstone petrography, location and nature of source areas, sites of major positive and negative movements, palaeoslope and palaeocurrent directions, palaeoenvironments, and water depths.

B. ORDOVICIAN PERIOD

Sedimentation in the Cape-Karoo basin commenced during the Ordovician Period with the deposition of a thick (2000 m) unit of medium-grained ultra-quartzose sandstone (Peninsula Sandstone) followed by a comparatively thin mudrock unit (Cedarberg Shale). No palaeocurrent data could be obtained but the overlying units indicate a southward paleoslope. Accumulation of the sediments appears to have taken place under shallow marine (shelf) conditions in a basin which was elongated in an east-west direction. Locus of maximum subsidence (i.e. the basin axis) was probably situated along an east-west line slightly north of the 34^{o}S line of latitude. The upwarped zone forming the source area for the sediments was probably situated north of 32^{o}S. Assuming the duration of the Ordovician Period to be 65 m.y., an average sedimentation rate of 3,5 cm/1000 yrs. can be calculated.

C. SILURIAN PERIOD

The greater part of the Silurian Period was characterised by the deposition of fine- to medium-grained ultra-quartzose or slightly feldspathic quartzose sandstones with a total thickness of about 600 m (Tchando and Kouga Sandstones). However, a marked change in lithology took place in the uppermost Silurian (Baviaanskloof Formation) which is represented by mudrocks and both dirty and clean subfeldspathic to feldspathic sandstones. The Tchando and Kouga Sandstones can be interpreted as braided stream deposits which accumulated on a broad coastal plain, while the Baviaanskloof sediments probably represent both offshore shelf and beach conditions. Palaeocurrents indicate a southward palaeoslope and a source area to the north similar to that which was operative during the Ordovician. Basin subsidence also probably followed a similar pattern. A 40 m.y. duration for the Silurian Period indicates a very slow overall sedimentation rate (2 cm/1000 yrs).

D. DEVONIAN PERIOD

A considerable thickness (1700 - 3700 m) of mudrock, rhythmitite and subordinate relatively fine-grained clean to dirty feldspathic to sub-feldpathic sandstones (the Bokkeveld Group) accumulated during the Early and Middle Devonian. The Ceres Subgroup (lower Bokkeveld) mudrock units are interpreted as shallow marine (offshore shelf) deposits, with the intercalated sandstone units representing nearshore shelf sands. The rhythmitites characterising the bulk of the Traka Subgroup (upper Bokkeveld) appear to represent prodelta slope and delta-front platform muds and silts. The somewhat limited palaeocurrent data point to a southward palaeoslope (and hence a northern provenance) while thickness data indicate that maximum downward movement must have taken place along an east-west basin axis situated roughly along 33°30'S latitude.

The Upper Devonian (?) consists of a 400 - 800 m thickness of rhythmitites and clean, fine-grained, ultra-quartzose sandstones (the Weltevrede Formation) overlain by 300 - 800 m of clean, fine- to medium-grained ultra-quartzose sandstone (Witpoort Formation). These strata are all considered to be shallow-water near-shore marine and deltaic deposits. Palaeocurrent information shows the continued presence of a northern source area and southward palaeoslope, while thickness data indicate an east-west basin axis situated more or less along the 33°15'S latitude.

The overall Devonian sedimentation rate (applicable to that part of the Bokkeveld Group for which thicknesses were measured) varies from 6 cm/1000 yrs. in the west to 10 cm/1000 yrs. in the east, based on a 50 m.y. total age for the Devonian. This represents a considerable increase over the Silurian rate.

E. CARBONIFEROUS PERIOD

The Carboniferous Period marks a major transition from the deposition of shallow marine sediments on a "stable shelf" throughout the Devonian to the deposition of flysch-type sediments in a deep trough at the commencement of the Permian. At the same time source areas situated south and south-east of the basin began to contribute to the basin fill, while the palaeoslope underwent a complete reversal, sloping northwards at the commencement of the Permian. The basin itself expanded considerably, extending far to the north of the northern edge of the Cape (Ordovician - Devonian) basin so that areas which previously displayed positive movement now became sites of deposition. The actual transition is, however, completely masked by the development of a major glacial episode which brought all normal sedimentation to a standstill, and, instead gave rise to a 600-700 m thick diamictite deposit (the Dwyka Tillite).

During the earlier part of the Carboniferous the Lake Mentz and Kommadagga Subgroups, a 600 - 800 m thick heterogeneous assemblage of mudrocks, rhythmitites and sandstones (ranging from ultra-quartzose to feldspathic) accumulated in a generally shallow-water marine shelf environment. Very little palaeocurrent or other data bearing on source area location and palaeoslope are available, and it is thus uncertain to what extent source areas other than the northern ones (which were apparently the only ones active hitherto) contributed to the Lake Mentz and Kommadagga sediments.

Locally, a certain amount of erosion preceded the deposition of the diamictite, especially near the western edge of the study area. This could be due to either a certain amount of uplift in the areas concerned, or a general lowering of sea level associated with the glaciation (or possibly both).

There is still much uncertainty concerning both the direction of movement of the ice sheets and the mode of deposition of the diamictite in the study area. It is generally agreed, however, that one of the major ice sheets which contributed material to the basin was situated off the southern to south-eastern Cape coast. Other ice sheets have been postulated which moved towards the basin from the north-east, north and west.

Sedimentation during the Carboniferous was very slow, an average rate of 2 cm/1000 yrs. being obtained if the Carboniferous Period is taken as lasting 65 m.y.

F. PERMIAN PERIOD

The Permian Period commenced with the deposition of relatively thin but very extensive fine-grained mudrock units (Prince Albert, Whitehill, and Collingham Formations) in comparatively deep water throughout the whole study area. The uppermost unit is characterised by the presence of numerous thin layers of what appears to be altered volcanic ash. These units possess a total thickness of about 200 m.

The subsequent history of the basin during the Permian can be regarded as representing a progressive infilling process, commencing with the deposition of a thin (50 m) sequence of distal turbidites and deep-water shales, followed by a thick sequence (500-1000 m) of proximal turbidites and interbedded shales (together constituting the Ripon Formation) and an even thicker sequence (600 - 1600 m) of "varved" rhythmitite (the Fort Brown Shale) deposited in a large body of water of steadily diminishing depth. In the western half of the area the Waterford Formation (up to 770 m thick, and consisting of alternating sandstone and "varved" rhythmitite units) appears to represent a largely deltaic deposit which accumulated contemporaneously with the upper part of the Fort Brown Shale in the east. Finally, with the infilling process completed, the whole pattern of sedimentation changed and the 5000 m thick Adelaide Subgroup, consisting of alternating mudstone and thinner sandstone units, was deposited almost entirely under fluviatile conditions.

During the Permian the position of the shoreline moved right across the entire basin. At the commencement of the Permian, with the whole study area probably submerged, the shoreline was situated well to the south at the margin of the depositional basin. As the basin was progressively filled in from the south, the shoreline shifted northwards, being situated more or less along the present Ecca outcrop belt (and orientated parallel to it) during the deposition of the Ecca-Beaufort transition strata at that locality. The fluviatile character of the bulk of the Adelaide Subgroup throughout the study area implies that the shoreline was located somewhere to the north of the area although it is probable that the originally extensive arm of the sea had in the meantime become more and more isolated from the open ocean so that it may be rather meaningless to talk of a "shoreline" at all. However, the "Daggaboersnek member" of the Balfour Formation provides evidence for the existence of a fairly extensive inland body of water, with a NE - SW trending shoreline in the study area which on occasions during the deposition of this member was situated, well to the south.

Throughout the Permian sandstone grain size and composition remained remarkably constant. Virtually all the sandstones are fine- to very fine-grained and fall into the ultra-lithofeldspathic field (see Folders 6, 7). The Ripon Formation sandstones are relatively poorly sorted, but the rest of the sandstones show "normal" sorting (S = 0,5 - 0,6 ø).

Palaeocurrent data from the Adelaide Subgroup clearly establishes the existence of a regional palaeoslope inclined towards the north-west, and a general source area off the south-east coast. The petrographic similarity of the sandstones indicates that the same source area was operative throughout the Permian. The existence of significant volcanic activity in the source area is demonstrated by the abundance of volcanic rock fragments in the sandstones as well as the presence of the thin tuff layers mentioned earlier. A source area consisting of volcanic and metamorphic rocks (including granite-gneiss) situated 200 - 300 km seaward of the present coast is envisaged.

The locus of maximum subsidence appears to have changed from a relatively narrow linear east-west orientated downwarp situated more or less along the 33°S latitude line during the deposition of the Ecca Group to a broader, more ill-defined area north of 33°S during the deposition of the Adelaide Subgroup. Overall rate of sedimentation (13,5 cm/1000 yrs, assuming 55 m.y. for the Permian) is the fastest in the whole succession.

G. TRIASSIC PERIOD

The Triassic Period represents a continuation of the terrestrial conditions established during the later part of the Permian. The period commences with the deposition of a 1000 m thick arenaceous formation (the Katberg Sandstone), followed by mainly argillaceous units (Burgersdorp, Molteno and Elliot Formations) with a maximum total thickness of about 2000 m. The Clarens Sandstone, a very fine-grained, wind-blown, loess-type deposit up to 300 m thick (usually considerably less) brings the Triassic to a close.

With the exception of the Clarens Sandstone, the various Triassic formations represent fluviatile deposits. The plant remains (including coal layers) and absence of red mudstones indicate that relatively moist conditions prevailed during the accumulation of the Molteno Formation; the rest of the Triassic fluviatile units are typical "red bed" facies deposits.

Palaeocurrent patterns indicate a regional palaeoslope inclined towards the NNW. At the commencement of the Triassic the character and location of the source areas, as indicated by the composition of the lowermost Katberg Formation sandstones, was similar to that of the late Permian. However, a progressive upward increase in quartz content of the sandstones (chiefly at the expense of feldspar and reaching a maximum in the Molteno Formation), indicates that a significant change in the composition of the source area had taken place. The overall increase in quartz probably reflects uplift and erosion of Table Mountain and Witteberg Group strata. The Cape orogeny would thus appear to have started in the Early Triassic (cf. De Villiers, 1944, p.200). Palaeowind directions reflect a westerly source area for the Clarens Sandstone.

Thickness data indicate that maximum subsidence probably took place in an area east of 26°E and south of 32°S. If the duration of the Triassic is taken as 30 m.y. the maximum overall rate of sedimentation is 10 cm/1000 yrs.

H. JURASSIC PERIOD

Sedimentation in the Karoo basin was brought to a halt at the beginning of the Jurassic by the effusion of over 1000 m of basaltic lavas and the intrusion into the Karoo strata of numerous dykes, sills and inclined sheets of dolerite.

I. CONCLUSION

Despite the negative note sounded by Hsü (1973) and others concerning the geosyncline concept, the temptation to compare the Cape - Karoo succession with the "normal geosynclinal cycle" outlined by Pettijohn (1957a, p.637) cannot be resisted in view of the close correspondence which exists between the two. According to Pettijohn (Table 116, Fig.165) a geosynclinal (or tectonic) cycle when fully developed consists of the following four types of sedimentary fill (in order of decreasing age):

1. Pre-orogenic (shield-derived orthoquartzites and carbonates deposited on the flooded craton or along the cratonic border of the geosyncline).
2. Euxinic (black shales, cherts, etc. deposited in a silled basin).
3. Flysch (rhythmically-bedded dark shales and graywackes, usually with evidence of turbidity currents, e.g. graded bedding, in the graywackes; submarine extrusives and tuffs).
4. Molasse (nonmarine sediments, both deltaic and fluvial, giving rise to coal measures and red beds).

Finally deformation and uplift complete the cycle.

Although carbonates are absent, the Table Mountain - Bokkeveld - Witteberg succession clearly represents the pre-orogenic phase of Pettijohn's cycle. Because of its unique origin, the succeeding Dwyka Tillite cannot be fitted into the cycle. The remaining elements of the cycle are all fairly well developed, the Prince Albert, Whilehill and Collingham Formations representing the euxinic stage, the Ripon and Fort Brown the flysch stage and the overlying strata the molasse stage. Although the molasse stage should theoretically commence with a coal measure (deltaic) succession followed by a red bed (fluvial) succession, this is not true for the case under discussion, although the Waterford Formation can be considered to partly represent a deltaic stage. True coal measures (in the Molteno Formation) are, however, only present much higher in the sequence, interbedded with typical red bed strata.

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APPENDIX

ORIENTED CONCRETIONS IN THE KATBERG SANDSTONE

A distinctive feature of the Katberg Sandstone (Beaufort Group) in the two coastal outcrop areas north-east and south-west of East London, as well as the southern part of the main outcrop, is the presence of numerous oval, rounded, and irregular calcareous concretions 3 - 15 cm in diameter. Interest centres mainly on the distinctly oval varieties, since they display a remarkably sub-parallel orientation, which coincides with the direction of the regional palaeoslope.

Rose diagrams illustrating the very low scatter of the orientation of the long axes of concretions are contained in the fourth row of diagrams on Folder 4a. Standard deviation values are generally about 7°, considerably smaller than the values which normally apply in the case of other sedimentary structures.

The parallelism between concretion orientations and the palaeoslope is demonstrated by the fact that north-east of East London (Bf 51,53) vector means of 351°, 350° and 349° were obtained for cross-bedding dip directions (141 readings), current lineation orientations (106 readings), and concretion orientations (152 readings) respectively. Similar results were obtained in the Chalumna area (Bf 44) where current lineation and concretion orientations gave vector means of 321° (based on 103 readings) and 320° (based on 203 readings) respectively.

Plates 1a and 1b illustrate the external form and internal structure of the concretions. It would appear that the concretions were formed through the intermittent deposition of calcite in roughly concentric layers around a nucleus. However, in the oval, oriented, concretions the nucleus is invariably situated nearer the upcurrent end of the concretion (see Plate 1b), indicating that deposition took place more rapidly on the lee side of the developing concretions. Modal analyses show that although calcite constitutes about 50% of the total volume of concretions, the remaining constituents (quartz, feldspar, rock fragments and matrix) are present in about the same relative proportions as in the surrounding rock.

The considerably lower scatter in the orientation angles of the concretions compared with cross-bedding and current lineation demonstrates that they were not formed by the currents which produced the latter structures. On the other hand, the coincidence of the main orientation angle indicates that they formed before regional tilting or crustal movement had produced any significant change in the regional slope prevailing in the depositional area. It is suggested that the concretions were formed soon after deposition by precipitation of calcite from groundwater moving in the direction of the regional subsurface drainage.

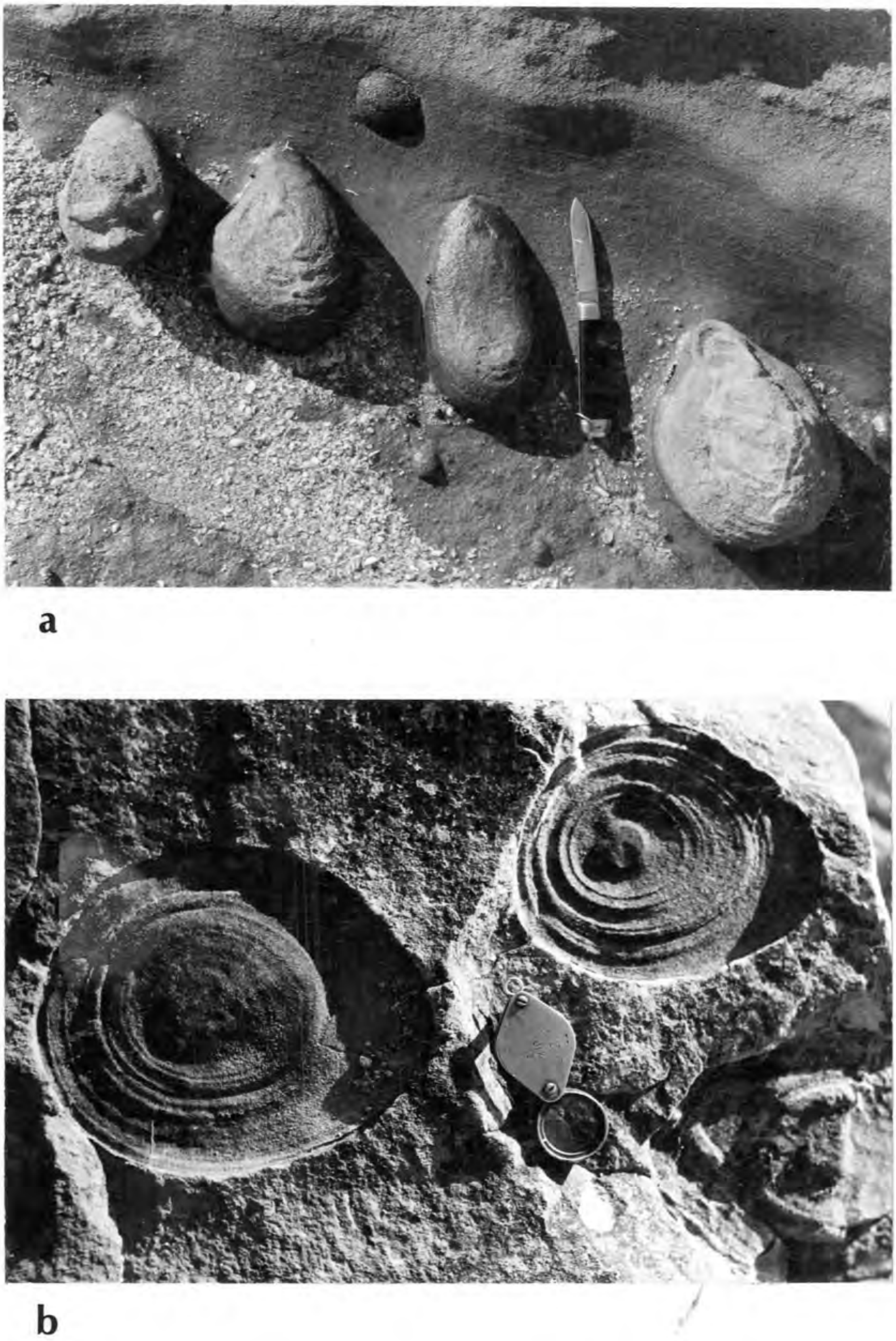

Plate 1. Katberg Sandstone concretions

a : External appearance
b : Internal structure