STRATIGRAPHY AND SEDIMENTOLOGY OF THE MOLTENO FORMATION IN THE ELLIOT AND INDWE AREA, CAPE PROVINCE.

by

ANGUS DAVID MACKAY CHRISTIE

Submitted in partial fulfillment of
the requirements for the degree of
Master of Science, in the Department
of Geology, University of Natal,
Durban, 1981.

PREFACE

This thesis represents original work by the candidate and has not been submitted in part, or in whole, to any other University.

The research was carried out in the Department of Geology, University of Natal, Durban, under the supervision of Professor R. Tavener-Smith.

A.D.M. Christie

ABSTRACT

An investigation of the stratigraphy and sedimentology of the Molteno Formation was undertaken in the Elliot, Indwe and Cala areas of the north-eastern Cape Province.

Measured sections indicated the Molteno in the present field area to be about 600 m thick and to comprise six members (in stratigraphic order):

Loskop Member
Tsomo Member
Qiba Member
Mayaputi Member
Indwe Sandstone Member
Bamboesberg Member

The lower two members are the same as those recognized by Turner (1975a) whereas the remainder are first described in this thesis.

The Bamboesberg Member consists of dominantly fine- to medium-grained sandstones and is unconformably overlain by the Indwe Sandstone Member. The Indwe Sandstone is a coarse-grained to very coarse-grained sandstone unit which is abruptly overlain by the argillaceous Mayaputi Member. The Qiba Member is a medium-grained sandstone unit in the east of the field area, but becomes progressively more argillaceous toward the west. The argillaceous Tsomo Member rests on the Qiba Member and the Loskop Member comprises an alternating sequence of coarse-grained sandstone and argillaceous units.

Two coals, the Indwe and Guba Seams, occur at the top of the Bamboesberg Member in the vicinity of Indwe. The Cala Pass Seam is developed at the top of the Mayaputi Member in the Indwe and Cala Pass areas. The Ulin Seam is present about three quarters of the way above the base of the Qiba Member in the Ulin area.

The Loskop Member contains two relatively insignificant coals, the Umnachean and Offa Seams, both developed to the west of Elliot. All the Molteno coals are of semi-anthracite to anthracite rank, have a high ash and low volatile content and are of little economic importance today.

The major sandstone sequences of the Molteno Formation (including the sandstones of the Loskop Member) are interpreted as being deposited by coallescing braided streams. The argillaceous units were formed under low-energy, flood-plain conditions. The climate prevailing during the deposition of the Molteno was initially cool and wet, but conditions became progressively hotter and more arid during Loskop times.

The sandstones consist mainly of quartz, though the Qiba Member has an anomalously high plagioclase feldspar content. Polycrystalline quartz grains and secondary quartz-overgrowths are most abundant in the Indwe Sandstone Member and sandstone units of the Loskop Member. Petrographic evidence suggests a provenance of mainly acid-plutonic and associated metamorphic rocks. Metasediments from the Cape Supergroup (Witteberg) and sediments from the Karoo Supergroup (Ecca or Beaufort Groups) also made minor contributions.

Cross bedding data indicates a predominantly north-westerly flow direction, with subordinate flow towards the north-east, south-east and south-west.

The major control of first-order (large scale) cyclicity in the Molteno is believed to be source-area tectonism related to the Cape Diastrophism. The cause of the diastrophism is attributed to the convergence of the African and South American continental plates. Climate is considered to have been the major control of second-order (small scale) cyclicity.

ACKNOWLEDGEMENTS

I would like to extend my grateful thanks to the persons and organisations who assisted in the preparation of this thesis:

1) The Atomic Energy Board for financing this project.
2) General Mining and Finance Corporation for allowing me access to borehole logs from the Indwe area.
3) Union Carbide for allowing me to log borehole core from the Ficksburg area.
4) Professor R. Tavener-Smith, my supervisor, for his assistance and constructive criticism both in the field and during the preparation of the manuscript.
5) Mr. J.P. le Roux of the Atomic Energy Board for the interest he showed throughout the duration of the thesis.
6) Dr. T.R. Mason for his practical advice regarding Markov chain analysis.
7) Professor P.E. Matthews for his advice with statistical analyses.
8) Post-graduate members of the Geology Department: Dr. E.G. Charlesworth, D.L. Roberts and A.M. Smith for helpful discussions and advice.
9) The technical staff of the Geology Department: Mr. A. Norris-Rogers, Mr. G. Chetty, Mr. N. Moodley and Mr. S. Perumal.
10) Mr. and Mrs. D. Dobrowsky of Elliot for their hospitality and friendship during the fieldwork.
11) My parents and parents-in-law for their support and encouragement.
12) My wife Janet, for her encouragement, support and help throughout the period of this thesis, and for typing the manuscript.

CONTENTS

CHAPTER 1

INTRODUCTION

A) AIMS AND APPROACH

The primary aim of the study was to investigate the nature of the Molteno Formation in the Elliot, Indwe and Cala area of the north-eastern Cape Province. This included an examination of depositional environments, uranium mineralization and coal seam development. The relationship between cyclicity and source-area tectonism was also considered.

Fieldwork was carried out between April and December, 1979. Extensive dolerite intrusions in parts of the area, and poor exposure in many others precluded the use of conventional mapping techniques, and therefore the method of measuring vertical sections was adopted. Attention was centered on localities where outcrops permitted detailed study of the strata, and in the Indwe district borehole data supplemented information obtained from outcrops.

Vertical sections were measured using an alidade and tape and later expressed graphically as successions of sedimentary facies. Markov chain analysis provided a means of testing for the presence of cyclic patterns of facies arrangement and to explore mutual relationships between facies in the Bamboesberg and Indwe Sandstone Members. A Chemtron G-12 gamma-ray scintillometer was used to measure the U_3O_8 content of the sediments for the Atomic Energy Board, who were interested in the area. Thin sections were analysed with the help of a Swift point counter to measure the textural parameters of the rock, and to explore the compositional variation between the stratigraphic components of the Molteno Formation. Palaeocurrent data were used to establish current dispersal patterns and provide an indication of a possible source area.

B) PHYSICAL GEOGRAPHY

The project was carried out over an area 500 km^2 in extent along the foothills of the southern Drakensberg, in the north-eastern Cape Province. The area included the towns of Elliot, Indwe and Cala. (Fig. 1). The Molteno Formation is expressed topographically as an escarpment along the foothills of the Drakensberg range at an elevation of between 1200 and 1500 m above sea-level. This escarpment is dissected by a youthful drainage system, and underlain by alternating layers of resistant cliff-forming sandstones and soft argillaceous sediments. These elements combine to form a terraced topographic profile. The highest point in the area is Loskop, just west of Elliot, situated at a height of 1745 m above sea-level. The drainage system is dominated by the Tsomo, Indwe and Guba Rivers which drain towards the south where they join the Kei River.

A continental type climate prevails, with mean daily temperatures of 23 $^{\circ}C$ during summer and 7.5 $^{\circ}C$ during winter. Extremes of over 30 $^{\circ}C$ and -7 $^{\circ}C$ occur, and snow may fall during the coldest months of winter. The area receives an average

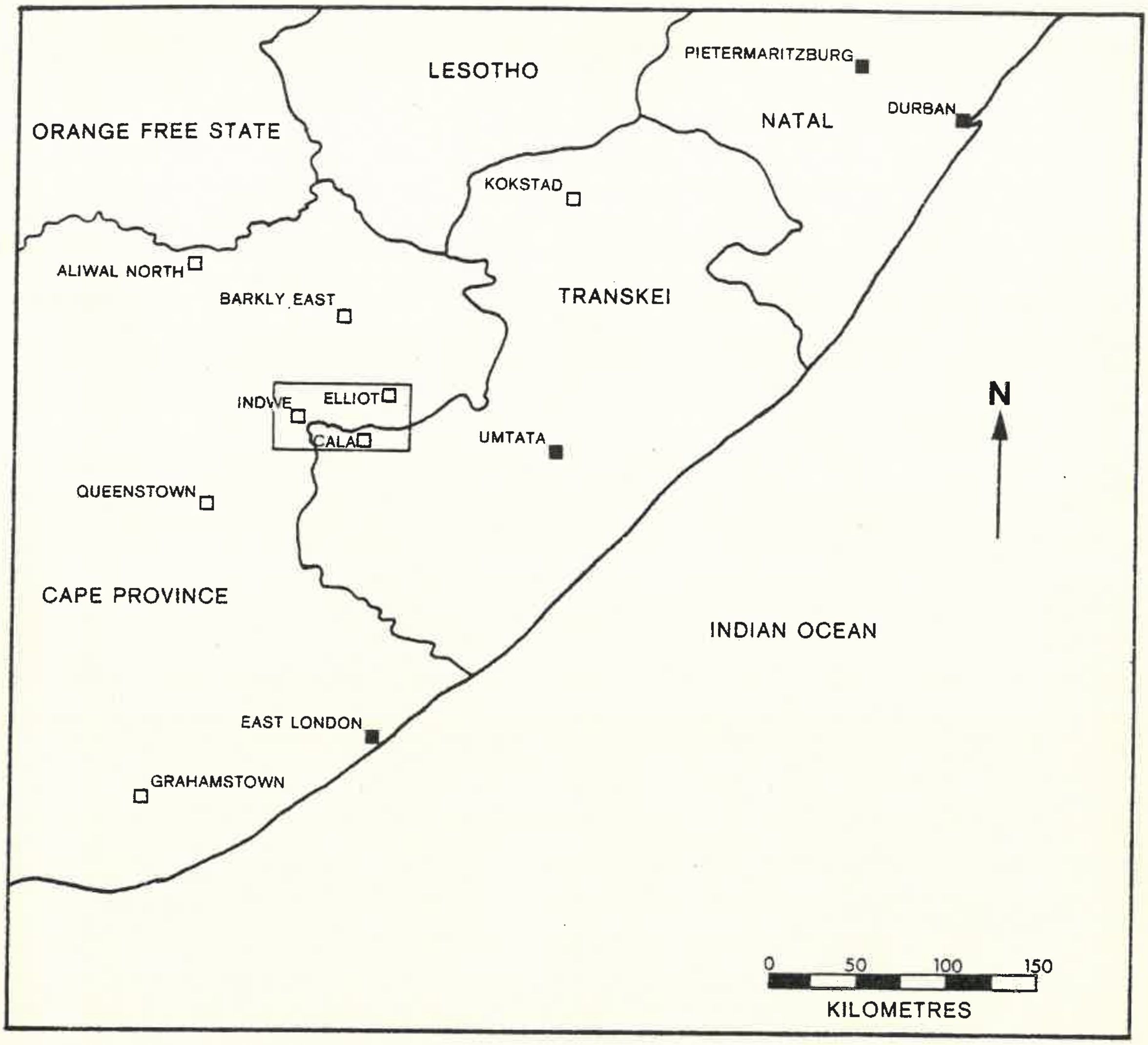


Figure 1. Regional setting of the field area.

annual rainfall of 600 mm, occurring mainly during the summer months. During the period of field work the north-eastern Cape experienced a drought, so that dry conditions prevailed.

The vegetation is of temperate grassland type, with sparse indigenous bush growing on the mountain slopes and in river valleys. Aloes are common in the Cala district while pines, gums, poplars and wattle trees are commonly found around farm homesteads.

Communications within the area are provided by sand roads linking the three main towns, while minor roads and farm tracks allow additional access. A tar road is under construction between Elliot and Indwe and these towns are also linked by a single-track railway.

C) PREVIOUS WORK

Investigations of the Molteno Formation in the north-eastern Cape were concerned primarily with the coal deposits. The earliest recorded investigation of this kind was carried out by A.J. Wylie (1856) who reported that the coal seams where economically unfeasable. E.J. Dunn (1873, 1878) suggested that coal deposits on the farm "The Camp" near Indwe were promising and that further exploration for workable coal deposits should be continued. Green (1883) first used the name Molteno to refer to a stratigraphic subdivision and investigated the origin of the coal and its economic potential. However, he expressed doubts as to whether it warranted a detailed exploration programme for economic purposes. In 1889 Galloway undertook an examination of the practicalities of a coal-mining venture in the Indwe area, and recommended the establishment of a colliery at Indwe. This led to the opening of the Indwe coal mine.

The most comprehensive survey of the coal deposits in the Indwe area up to that time was published by Du Toit in 1905. His report dealt at length with coal seams in the Indwe area and also lesser known seams in the vicinity of Elliot and Cala. He also recognized and named a number of distinctive lithological units of the Molteno Formation (including the Indwe Sandstone), and compiled several maps indicating the disposition of the coal seams.

In later years renewed interest in coal deposits between Dordrecht and Maclear by Federale Mynbou resulted in an intensive prospecting programme, so that a number of boreholes were drilled in the vicinity of Indwe between 1960 and 1961. An account of the quality and composition of the coal seams, their lateral extent, and a detailed description of the Molteno stratigraphy around Indwe by Ryan (1963) was based on this investigation.

A Geological Survey report by Turner (1971) described the geology and coal resources of the north-eastern Cape Province and dealt in detail with the quality and economic potential of coal deposits in the vicinity of Indwe.

A comprehensive investigation of the stratigraphy and geological history of the Molteno outcrop area was carried out by Turner (1975a). This was the first regional study of the Molteno Formation, and as a result of it a number of new stratigraphic members were recognized. His work also dealt with regional variations of thickness and lithology, an investigation into the causes of large-scale cycles identified in the succession, and a probable source area for the sediments. Turner also referred to the need for more detailed investigation to permit a more complete understanding of lateral facies variations and the depositional history of the Molteno Formation.

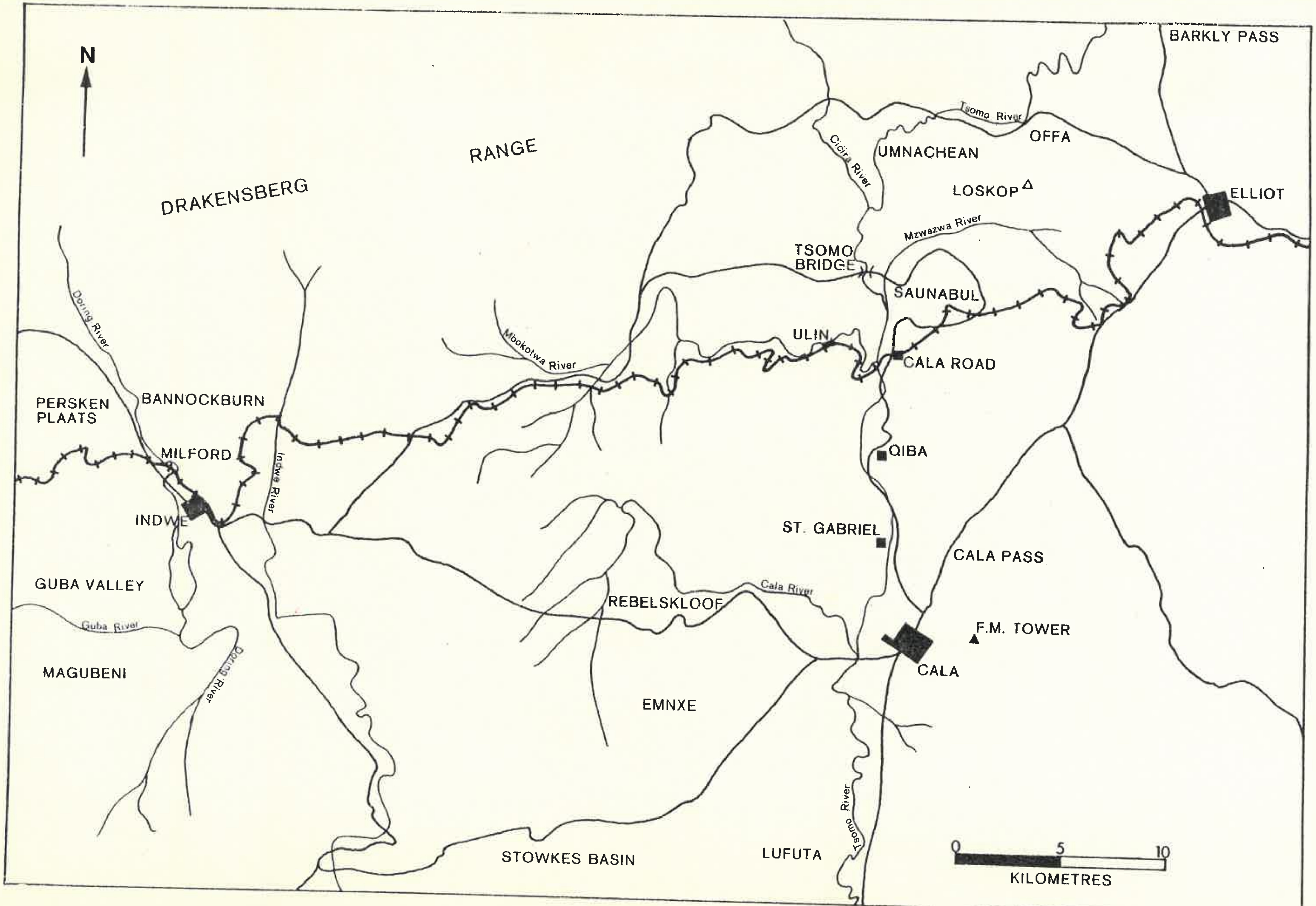


Figure 2. Locality map of the area investigated in this thesis.

CHAPTER 2

STRATIGRAPHY

The Molteno Formation comprises a northward thinning wedge of dominantly clastic sediments which form the base of the Stormberg Group (Fig. 3). Geographically, it crops out as a roughly oval-shaped feature in the main Karoo basin extending from the eastern Cape Province and Transkei northward into Lesotho, Natal and Orange Free State.

Before discussing stratigraphic subdivisions of the Molteno it is necessary to define the lower and upper limits of the formation in the light of previous work and of the present investigation. Although the conclusions reached will apply only to the Indwe, Elliot and Cala areas, the local stratigraphic succession (Fig. 4) is related to the stratigraphy of the Molteno Formation established by Du Toit (1904, 1905), Rust (1959), Ryan (1963), Smits (1967) and Turner (1966), and to regional relationships established by Turner (1975a). Names for members suggested by Turner (op. cit.) have been only partially retained because some of the stratigraphic subdivisions used by him could not be recognized in the present field area.

Formation	Group
Clarens Formation	STORMBERG GROUP
Elliot Formation	
Molteno Formation	
Burgersdorp Formation	BEAUFORT GROUP
Katberg Sandstone Formation	
Balfour Formation	
Middleton Formation	
Koonap Formation	

Figure 3. Stratigraphic subdivisions of the Beaufort and Stormberg Groups.

A) LOWER JUNCTION OF THE MOLTENO FORMATION

The lower junction of the Molteno in its southern outcrop area is traditionally defined by the base of the Bamboesberg Member (Turner, 1975a) which conformably overlies the Burgersdorp Formation (*Cynognathus* zone) of the Beaufort Group. Elsewhere the base of the Indwe Sandstone Member defines the lower junction of the Molteno. Du Toit (1905) and other early workers regarded the Guba and Indwe Seams and hence, by implication, the Bamboesberg Member as part of the Molteno Formation. Ryan (1963) was the first worker to describe the strata now known as the Bamboesberg Member as part of the Molteno Formation at Indwe. Before discussing the nature of the lower limit of the Molteno Formation, an examination of the lithological differences and stratigraphic relationships between the Beaufort Group and the Bamboesberg and Indwe Sandstone Members of the Molteno Formation is necessary.

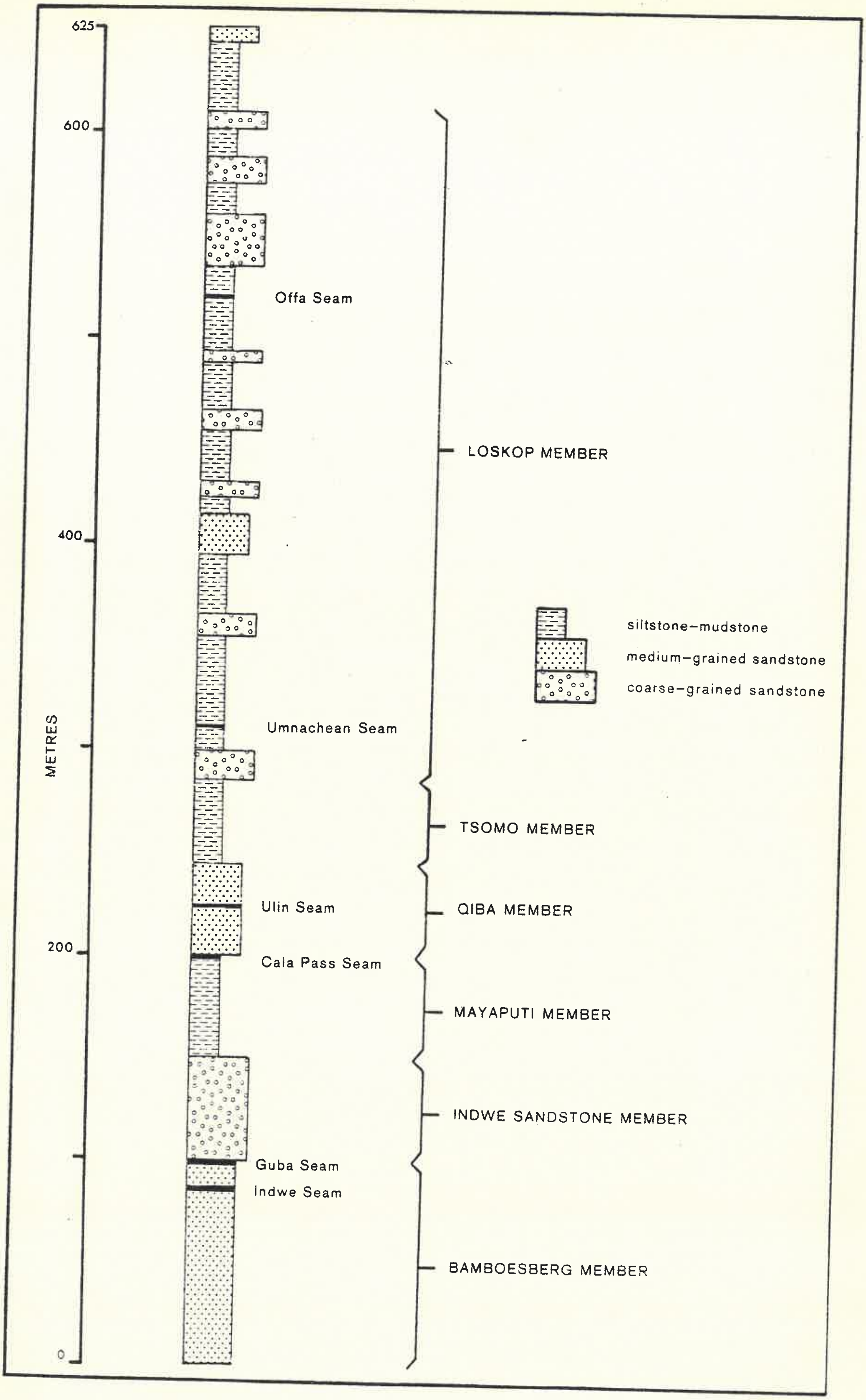


Figure 4. Composite stratigraphic section through the Molteno Formation of the north-eastern Cape Province.

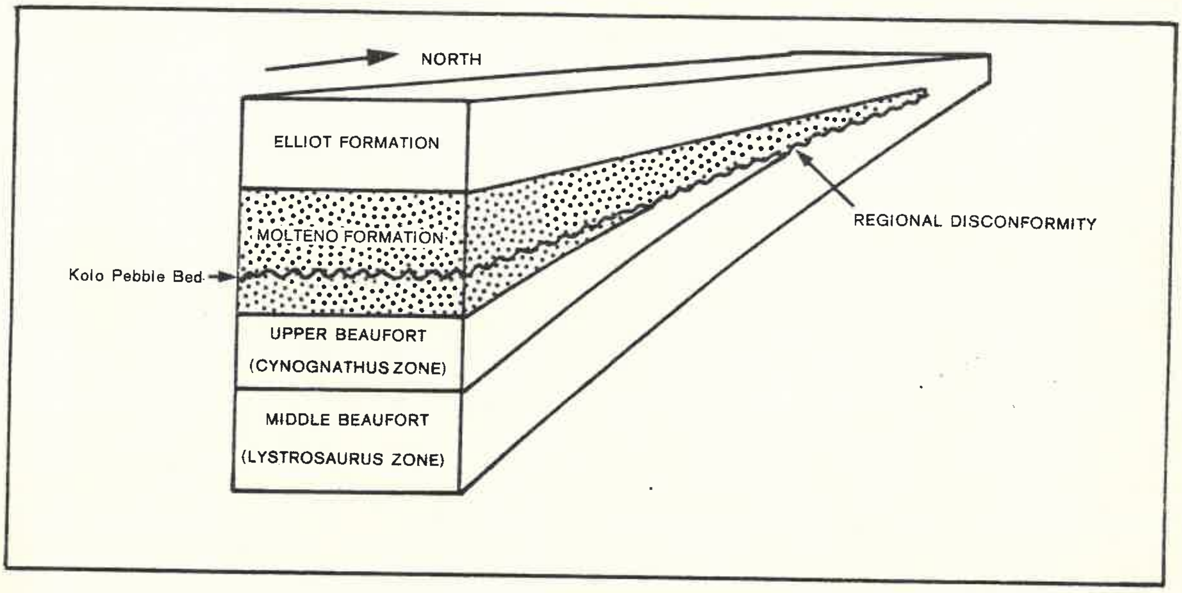


Figure 5. Block diagram showing regional stratigraphic relations of the Molteno Formation to the strata above and below (not to scale). After Turner, 1975a.

The upper Beaufort Group (Burgersdorp Formation) in the vicinity of Cala and Indwe comprises a monotonous maroon siltstone and mudstone succession with subordinate brown-grey, fine- to medium-grained sandstones. The argillaceous components may be up to 45 m thick and the sandstones are up to 20 m thick. Although it has commonly been reported (Du Toit, 1954; Haughton, 1969; etc.) that the Molteno is readily distinguished from the Beaufort by the absence of maroon sediments, in fact the maroon colouring is replaced by olive-brown, and light to dark grey rocks between 20 and 150 m below the base of the Bamboesberg Member as recognized during the present investigation. The colour change is abrupt and does not appear to be related to any lithological change.

Lithologically, the Bamboesberg Member is readily distinguished from the underlying Beaufort by its dominantly arenaceous nature. By volume it usually contains as little as

1 per cent argillaceous material in the vertical sections measured. This abrupt change in the proportion of arenaceous to argillaceous material results in a marked break in slope at the base of the Bamboesberg Member between the softer sediments of the Beaufort Group and the more resistant sandstones of the Bamboesberg. The Bamboesberg Member overlies the Beaufort Group conformably and the junction between the two is satisfactorily defined by an erosively based sandstone at the base of the former. Field observations strongly suggest that the base of the Bamboesberg is most conveniently defined by the horizon at which sandstone succeeds siltstone and mudstone as the dominant rock type.

From a regional point of view Turner (1975a, p23) found it more difficult to recognize the base of the Bamboesberg Member: "... east of the type section [Bamboesberg Mountains] facies changes and the interdigitation of shale and mudstone with sandstone complicate contact relations. Where sandstone replaces shale and mudstone in the section the contact can often be fixed on the basis of the predominantly coarser grain size of the Bamboesberg sandstones which also tend to be slightly paler in colour." No such lateral variations were observed at the base of the Bamboesberg in the area mapped by the writer. Although the Bamboesberg sandstones are more consistently medium-grained than those of the Beaufort which tend to be fine-grained, the two are commonly difficult to differentiate texturally in the field. It could thus be difficult to determine the boundary between the Bamboesberg (basal Molteno) and the Beaufort Group satisfactorily within an association of sandstones.

Turner's (1975a) regional investigation of the Molteno Formation showed that north of the present field area the Bamboesberg Member wedges out until the lower boundary of the Molteno is defined by an unconformity at the base of the succeeding Indwe Sandstone Member (Fig. 5). The latter is a coarse- to very coarse-grained pebbly sandstone, the base of which is defined by the distinctive Kolo Pebble Bed. The base of the Indwe Sandstone overlaps onto progressively older rocks of the Beaufort Group towards the north, but the unconformity is difficult to detect because of the essentially horizontal attitude of the strata and consequent lack of any obvious angular discordance (Turner, op. cit.).

From the above it might therefore seem more convenient and logical to place the boundary between the Molteno and Beaufort at the base of the Indwe Sandstone. There are, however, three reasons which make it seem more appropriate to regard the Bamboesberg Member as part of the Molteno Formation rather than of the Beaufort Group. These are:-

1) The Bamboesberg Member does not contain any vertebrate fossils. This may be due either to a considerable hiatus between the end of Beaufort times and the commencement of Bamboesberg deposition, or it may indicate that the environment prevailing during the Molteno was not favourable for vertebrate life.
2) The Bamboesberg Member contains numerous quartzite pebbles and cobbles, a characteristic feature of the Molteno Formation. There is no record of any such occurrences in the upper Beaufort.
3) The absence of coal locally in the upper Beaufort is in contrast with the coal seams found in the Molteno, and points to the existence of significant differences of palaeoenvironment between the two. The lowest coal seams are present in the Bamboesberg which therefore shows stronger affinities with the Molteno Formation than with the Beaufort.

B) UPPER JUNCTION OF THE MOLTENO FORMATION

The upper limit of the Molteno has been the subject of several attempts at definition due to its gradational relationship with the overlying Elliot Formation (Red Beds), and the lack of detailed knowledge concerning the latter. There is, consequently, a disparity in estimates of the thickness of the Molteno Formation in the southern part of the basin with which this thesis is concerned.

Emphasis has commonly been placed on grain size and colour in differentiating the Molteno from the Elliot. Du Toit (1954) and Haughton (1969) both regarded the prevalent red or purple colouration of the Elliot argillites as the chief means of distinguishing between the two formations, but gave different estimates for the thickness of the Molteno. Du Toit suggested a maximum thickness of 1600 feet (488 m) at Elliot, while Haughton reported a thickness of 2000 feet (610 m) between Glen Grey and Elliot. Ryan (1963) did not mention colour or grain size when he placed the upper boundary of the Molteno Formation in the Indwe area at the top of a coarse-grained pebbly sandstone (which he named the Upper Sandstone) about 98 m above the Kolo Pebble Bed. On that basis he calculated the formation to be 952 feet (290 m) thick.

Botha (1968, p103) examined exposures of the Elliot Formation in the Barkly Pass north of Elliot and commented that the upper boundary of the Molteno Formation "... is generally taken at the first purple mudstone occurring above the glittering Molteno sandstones, but serious anomalies can result from assuming that the first red mudstone always occurs at the same stratigraphic horizon."

Turner (1975a, p27) believed thickness estimates of the Molteno to have been exaggerated because of the incorporation of portions of the Elliot Formation within it. He suggested that, apart from grain size and colour, the most useful criteria for distinguishing the Elliot Formation from the Molteno are "... the abundance of reptile remains, and especially dinosaurs;

the persistent presence both laterally and vertically of red mudstone and shale; the absence of carbonaceous shale and coal; the lower sandstone/shale ratio; the almost complete absence of the Dicroidium flora; and the generally finer grain size of the sandstones and their often calcareous nature." It seems possible that Turner (op. cit.) used the same sandstone as Ryan (1963) - the Upper Sandstone - in defining the top of the Molteno Formation in his composite section, but used the criteria quoted above in placing the upper junction of the Molteno on his geological map.

The present writer is in agreement with the criteria used by Turner (op. cit.) to define the upper boundary of the Molteno, but nevertheless considers the colour and grain size of the sediments to be of prime importance. If the upper boundary of the Molteno is placed at the top of the highest coarse-grained sandstone unit in the Loskop Member then it coincides with the first appearance of persistently maroon coloured siltstone and mudstone of the Elliot Formation. Such an arrangement is also in agreement with the position of the junction as suggested by Botha (1968). The following features of the Loskop Member, which is described in greater detail later, argue for its inclusion in the Molteno Formation:-

1) Green and maroon coloured sediments occur sporadically throughout this member, but are nowhere extensively developed.
2) Thin and discontinous coal seams are present (e.g. the Offa Seam).
3) Although this is dominantly an argillaceous sequence, the sandstone components are generally coarse- to very coarse-grained and may contain quartzite pebbles and cobbles at their bases, whereas sandstones above the Loskop Member are fine- to medium-grained.

4) The plant fossil Dicroidium is moderately common.
5) The top of the Loskop Member is marked by a distinct topographic change due to the less resistant nature of the overlying Elliot Formation.

On the basis of the upper and lower junctions as defined above, the Molteno Formation is estimated to be 605 m thick in the Cala/Elliot area. At Indwe no reliable indication of the thickness can be given owing to poor outcrop and the presence of dolerite intrusions, but it is thought to be of the same order as in the eastern part of the field area. These thicknesses are not in agreement with those of Turner (1975a), namely 250 m between Indwe and Cala; nor with that of Ryan (1963), which was 290 m at Indwe. They are, however, in general accordance with Du Toit's (1954) estimate of 1600 feet (488 m) and Haughton's (1969) of 2000 feet (610 m). It is emphasised that the estimated thickness of the Molteno Formation given here relates only to the Indwe, Elliot and Cala areas.

C) SUBDIVISIONS OF THE MOLTENO FORMATION

On the basis of the upper and lower junctions referred to, six stratigraphic sub-divisions of the Molteno Formation are proposed (Fig. 4) :-

1) Bamboesberg Member;
2) Indwe Sandstone Member;
3) Mayaputi Member;
4) Qiba Member;
5) Tsomo Member;
6) Loskop Member.

These units have been named according to the usage contained in section 3.10 of the South African Code of Stratigraphic Terminology and Nomemclature (1977). The thickness of the Loskop Member ($\pm$300 m) may be considered excessive for a "member". However, the only criterion mentioned concerning the designation of a lithostratigraphic unit as a "member" is that it should be part of a formation (S.A.C.S., 1977).

Two scales of upward-fining sedimentary cycles are also recognized in the Molteno Formation:

1) First-order cycles (tens of metres thick) which may include one or more stratigraphic member.
2) Second-order cycles (metres thick) which are recognizable within individual stratigraphic members.

A geological map is presented in the back folder.

1) Bamboesberg Member

This is named after the Bamboesberg Mountains in the north-eastern Cape Province (Turner, 1975a). It crops out as a poorly defined cliff or as a steep, terraced slope which is commonly capped by the more resistant Indwe Sandstone (Fig. 6). The best exposures are on steep mountain slopes or in deeply incised river valleys as at Qiba and to the north of Cala.

The Bamboesberg Member is a composite succession of fine- and medium-grained sandstone beds and thin, lenticular intercalations of siltstone and mudstone. Two coal seams, the Indwe and Guba, are found at the top of the member in the vicinity of Indwe. The base of the member has been described in an earlier section dealing with the lower limit of the Molteno Formation. The top of the member is truncated by the erosively-based Indwe Sandstone, and at Indwe is defined by the Guba Seam. The contrasting lithologies of the Bamboesberg and Indwe Sandstone Members permit easy identification of the junction between them in the field.

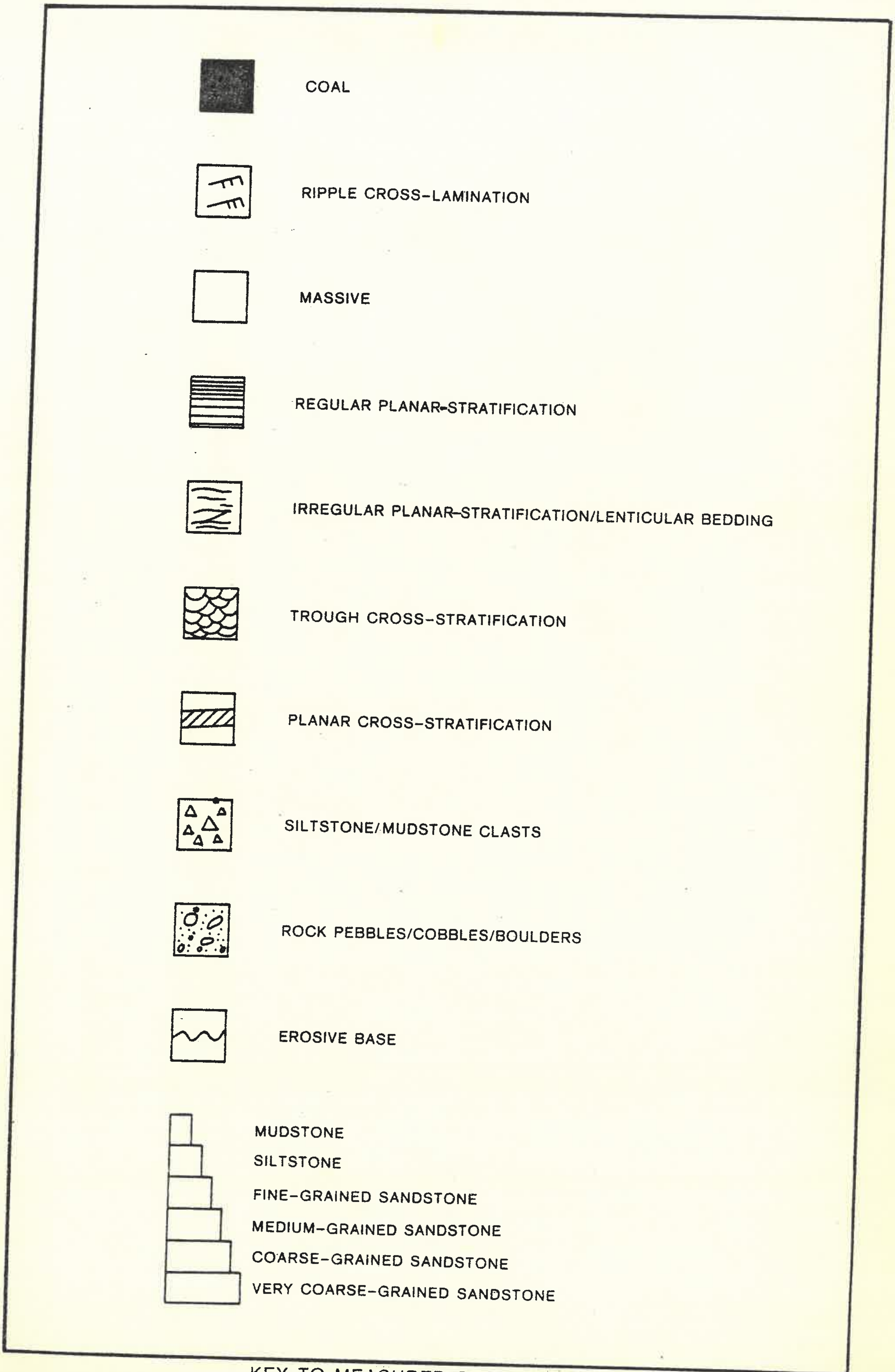
The northward-thinning nature of the Bamboesberg Member (due possibly to topographic or structural controls) combined with erosive effects at the base of the overlying Indwe Sandstone, have resulted in considerable variations in its thickness. The Bamboesberg thins from 115 m in the south of the area investigated

Figure 6. Characteristic topography associated with the outcrop of the Bamboesberg Member. The hill is capped by the more resistant Indwe Sandstone Member. This outcrop is approximately 4 km north of Cala.

to 70 m between Indwe and Cala. North of Cala it thickens abruptly again to 115 m, and at Maclear, to the east of Elliot, it is 128 m thick (Turner, 1975a). Reference sections (Fig. 7) from the Indwe and Cala localities illustrate the main sedimentary features and also the position of the coal seams at Indwe.

Sandstones of the Bamboesberg Member are generally yellow-brown to grey-brown, while the argillaceous components are light olive to dark grey. Secondary-quartz overgrowths on detrital grains of the coarser sandstones make them more resistant to weathering than finer grained ones. Iron and silica concretions commonly form rusty-brown deposits on sandstone bedding surfaces.

Planar stratification is the prevalent sedimentary structure of these sandstones, with trough and planar cross-stratification occurring to a lesser extent. Primary current lineation is to be seen at places on bedding planes. Individual beds display



KEY TO MEASURED SECTIONS

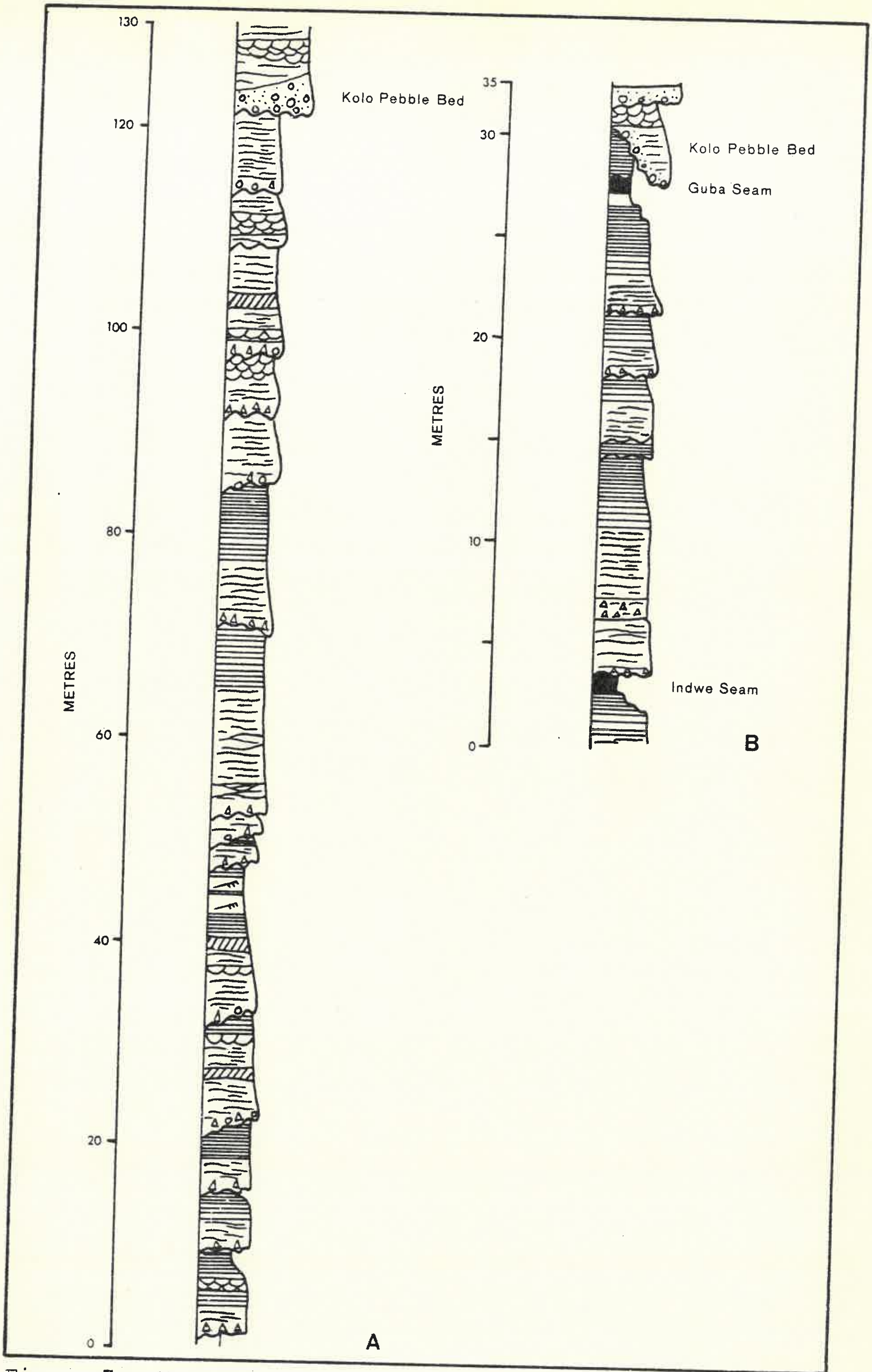


Figure 7. Measured sections through the Bamboesberg Member at (a) Cala Pass; (b) Bannockburn, near Indwe, where only the top 30 m are exposed.

considerable lateral variation in thickness. They are characteristically lenticular, ranging from 5 cm to 1,5 m in thickness. Channel structures are rare, and where present are in most cases deeply incised into the underlying sediments. Such a structure, exposed in a road cutting at Cala Pass, is 80 m wide and 7 m deep.

The proportion of argillaceous rock present in this member varies from about 1 per cent at Qiba to a maximum of 15 per cent below the F.M. tower about 2 km east of Cala. These fine sediments are commonly massive or planar laminated with a small amount of ripple cross-lamination.

The Bamboesberg Member is composed of a number of upward-fining cycles between 1 and 10 m thick (Fig. 7). Each has an irregular, erosive base with which may be associated an intra-formational, matrix-supported conglomerate up to 20 cm thick. Clasts are mostly siltstone and mudstone discs up to 12 cm long and 1,5 cm thick. Sparsely distributed, well-rounded quartzite cobbles and pebbles are also present within the conglomerates. The base of each cycle grades upward into sandstone which is commonly only slightly finer grained, and there may be no further substantial decrease in grain size before the cycle is truncated by the overlying erosively-based sandstone. Some cycles fine upward into siltstone and mudstone, and may culminate in a coal seam; the best examples of this are seen in the vicinity of Indwe.

In the Indwe district two coals, the Indwe Seam and the Guba Seam, are present. The Indwe Seam is developed between 24 and 28 m below the Guba Seam, which defines the top of the Bamboesberg Member in the Indwe vicinity. Each of these seams represents the culmination of an upward-fining cycle and comprises bands of bright coal interbedded with coaly shale, carbonaceous siltstone and carbonaceous mudstone. The Indwe Seam attains a maximum thickness of 4,5 m in the immediate vicinity of Indwe, and the

Guba Seam attains its maximum thickness (2,8 m) to the south-west of Indwe in the Guba Valley. The coal seams are more fully described in a later section.

2) Indwe Sandstone Member

The Indwe Sandstone derives its name from cliffs which it forms above the town of Indwe (Du Toit, 1905). The lower part of the member consists of resistant, cliff-forming sandstone which commonly caps high land and forms structural benches. Less resistant sandstones composing the upper part of the member are commonly eroded away but, where present, give rise to gentler, terraced slopes. The member is a dominantly coarse-grained, arenaceous unit comprising the basal part of a first-order upward-fining cycle, the Mayaputi Member being the upper component.

The lower junction of the Indwe Sandstone is defined by the base of the Kolo Pebble Bed which contrasts sharply with the top of the finer-grained underlying Bamboesberg Member. The junction is usually planar, but may be strongly erosive, as at Indwe, where up to 6 m of the Guba Seam have been removed over a distance of less than a kilometre. Regional studies of the Molteno Formation (Turner, 1975a) indicated the presence of an angular unconformity at the base of the Indwe Sandstone Member; in the south the member rests discordantly on the Bamboesberg Member but towards the north it oversteps onto progressively older rocks of the Beaufort Group. The medium-grained sandstones at the top of the member are replaced by siltstones of the Mayaputi Member either abruptly or gradationally over a vertical distance of less than a metre.

The member attains a minimum thickness of 10 m about 8 km south-west of Indwe, but increases progressively to a maximum of 60 m at the northern and southern boundaries of the field area. Thickness variations of the Indwe Sandstone are illustrated by

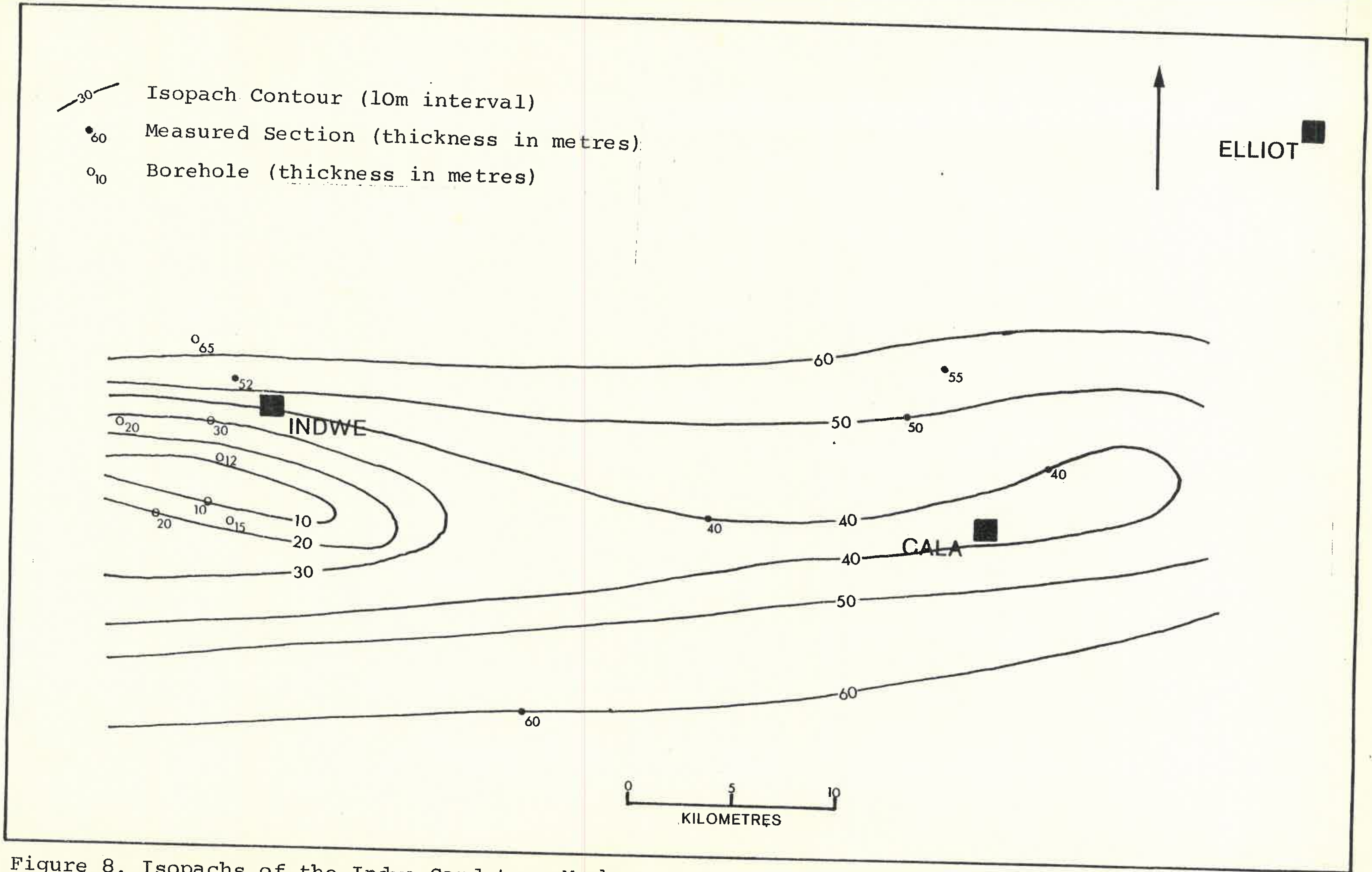


Figure 8. Isopachs of the Indwe Sandstone Member.

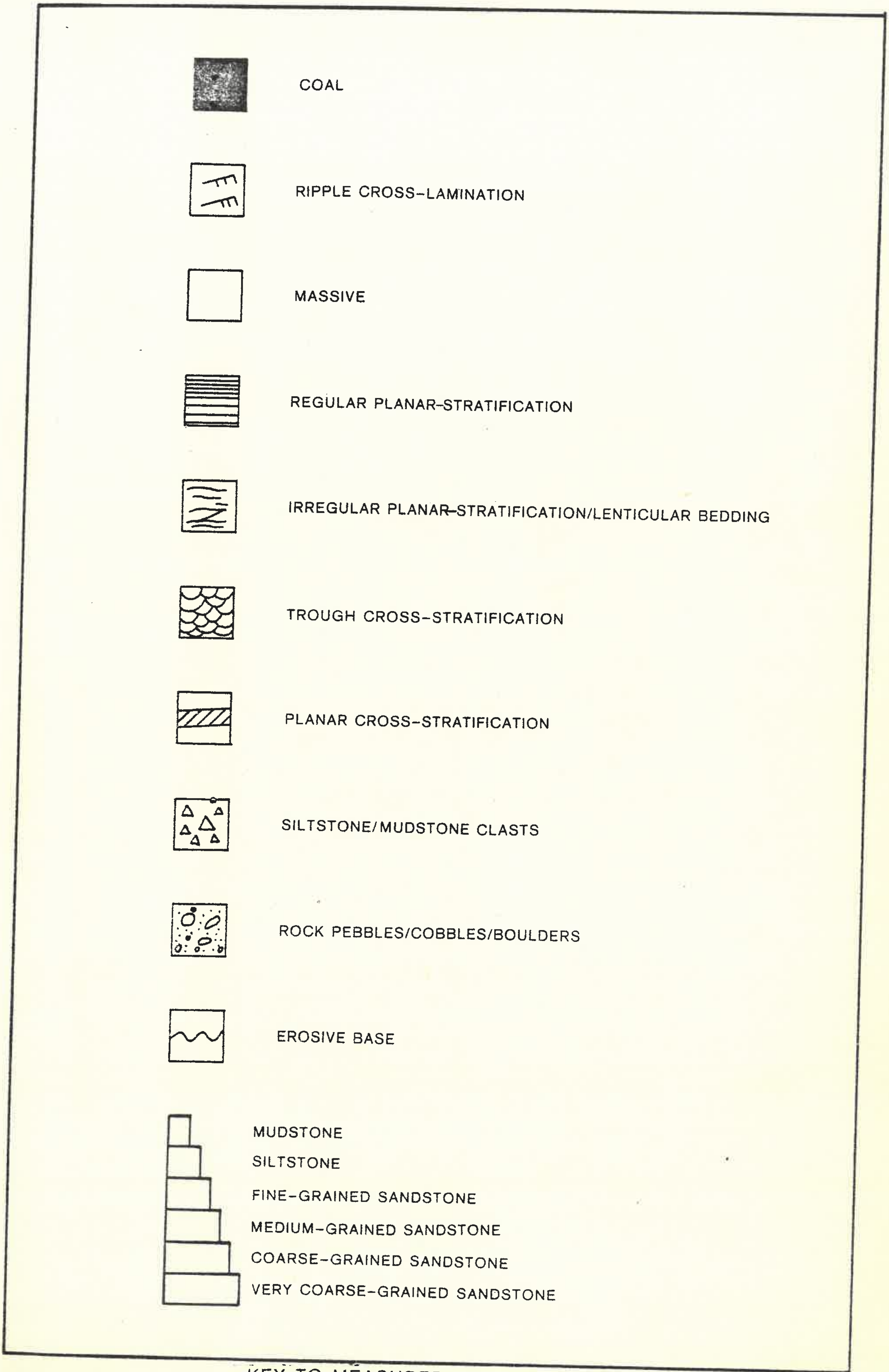
the isopach map (Fig. 8).

Instead of a single type section, four reference sections are used to illustrate the varied nature of the Indwe Sandstone within the field area (Figs. 9,10,11 and 12). The section measured at the town of Indwe by Turner (1975a) is not considered to be representative of the member as only the lower 28 m are preserved. The reason for this may be that the Guba Seam is not developed immediately north of Indwe, and the base of the Indwe Sandstone Member was set at the top of the Indwe Seam in error.

The Indwe Sandstone Member consists predominantly of yellow-brown to yellow-grey medium-, coarse- and very coarse-grained, pebbly sandstone with minor intercalations of fine-grained sandstone and siltstone. Pebbles, cobbles and boulders up to 60 cm in diameter are common in association with the coarser-grained sandstones. There is an overall decrease in grain size to medium-grained sandstone at the top of the member. Interstitial ferruginous cement and secondary-quartz overgrowths on detrital grains in the coarser sandstones have resulted in a rock which is highly resistant to weathering. Crystal faces of quartz overgrowths give these sandstones their characteristic glitter. In the absence of the cementing compounds referred to, the rocks are relatively soft and friable.

With regard to sedimentary structures: trough and planar cross-stratification and planar stratification are all commonly developed. Individual beds are between 5 cm and 3 m thick and display considerable lateral variation in lithology. Channel structures up to 80 m wide and 9 m deep are clearly defined by their discordant relationships with the underlying strata. Particularly good examples are present in the cliffs to the north-west of Indwe on the farms Bannockburn and Milford (Fig. 13).

The Kolo Pebble Bed, present at the base of the Indwe Sandstone Member, is a matrix-supported, polymictic pebble conglomerate varying in thickness between 20 cm and 4 m (Fig. 14).



KEY TO MEASURED SECTIONS

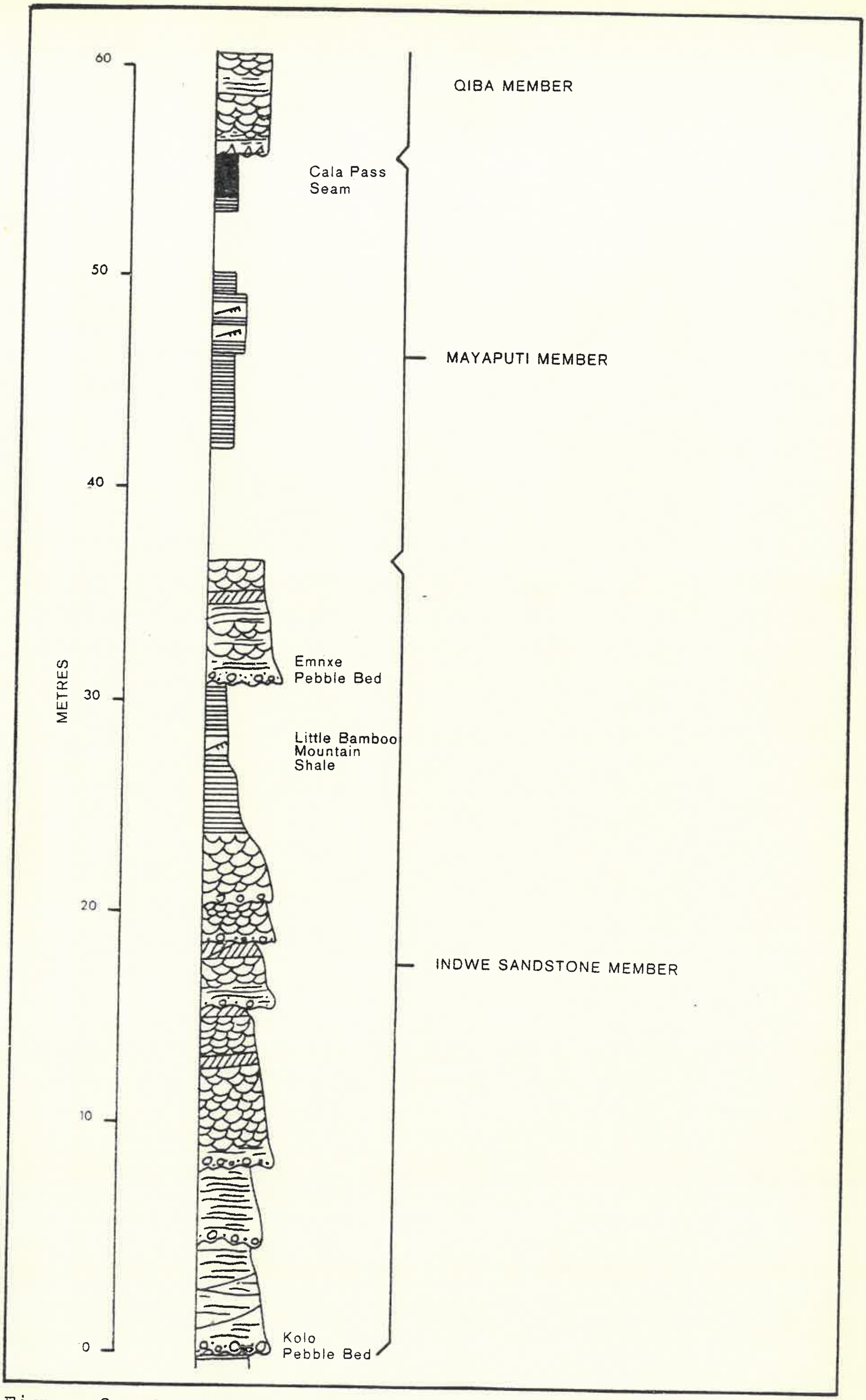


Figure 9. Measured section through the Indwe Sandstone and Mayaputi Members near the top of Cala Pass.

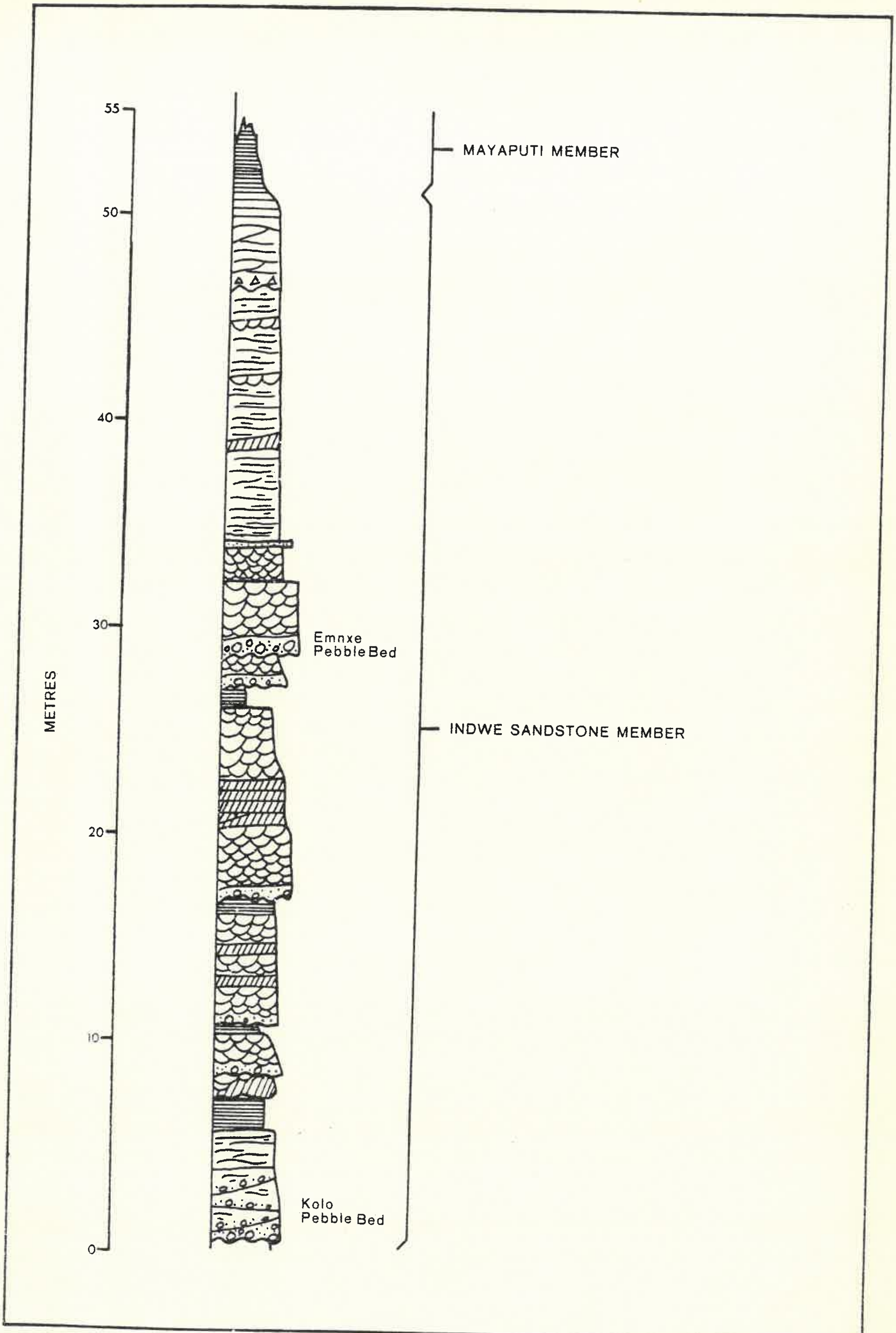


Figure 10. Measured section of the Indwe Sandstone Member. River valley about 1,5 km south of Qiba.

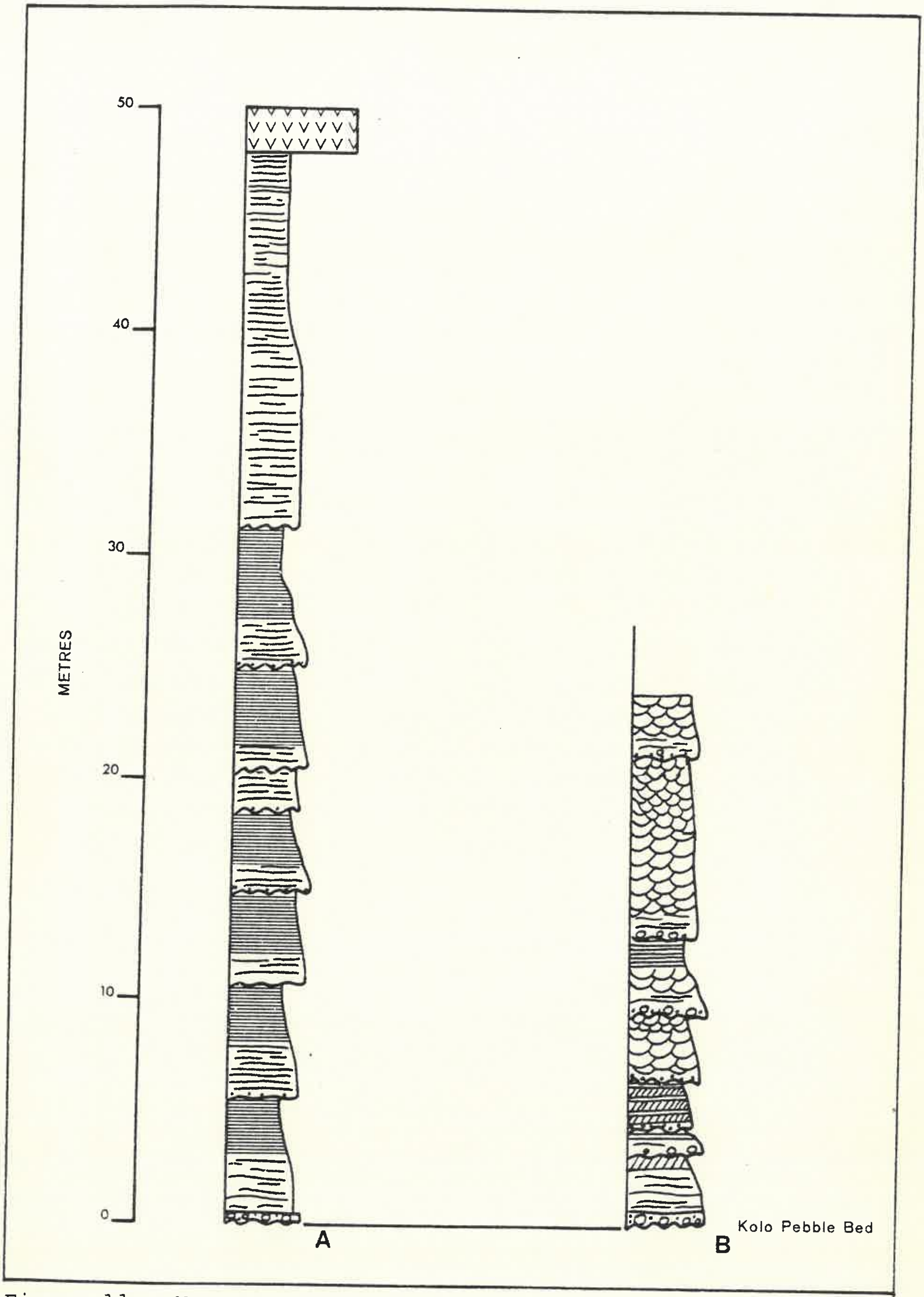


Figure 11. Measured sections through the Indwe Sandstone Member at Indwe: (A) Milford, (B) Indwe Commonage, directly north of Indwe.

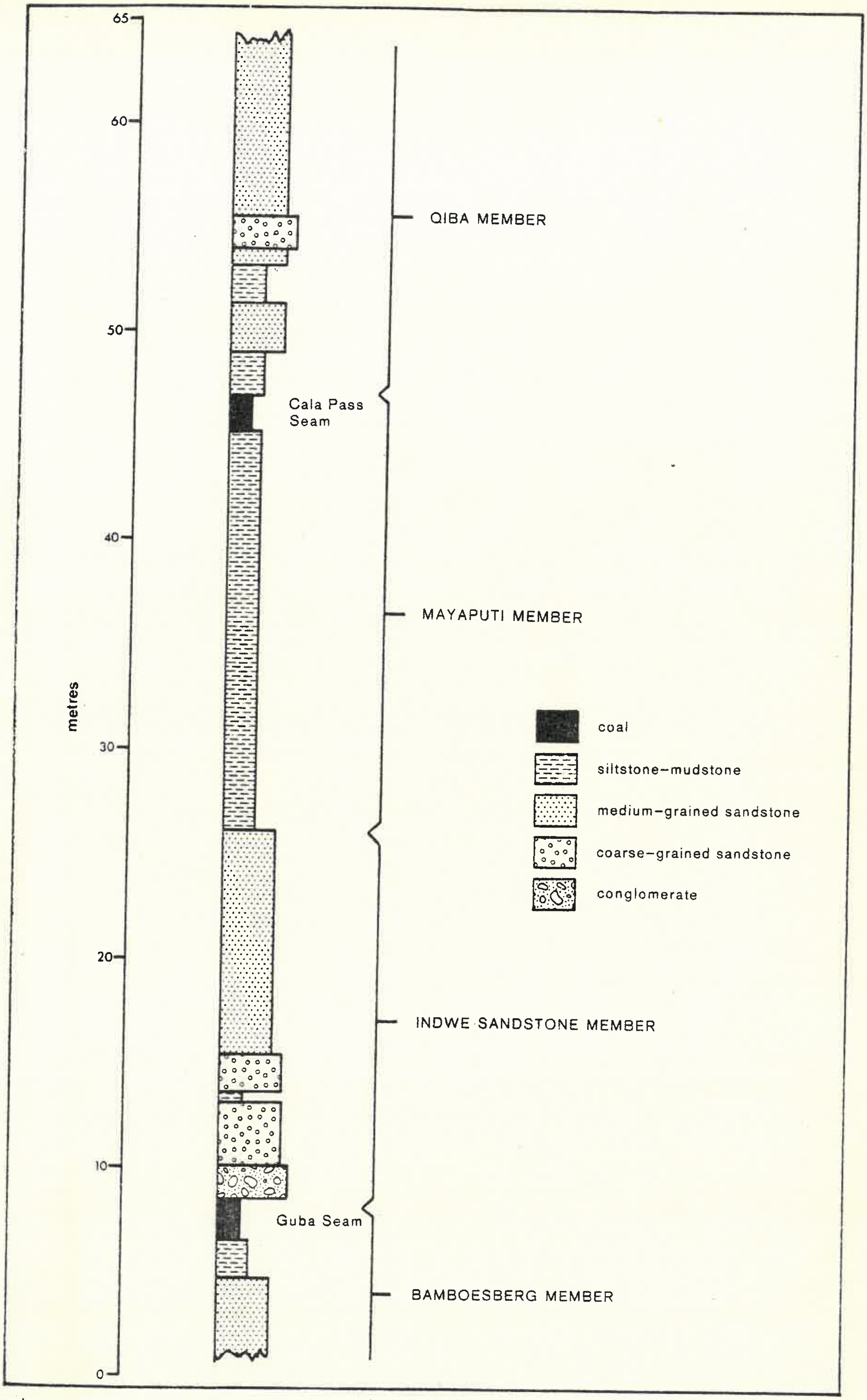


Figure 12. Borehole log of portion of the Molteno Formation showing the Guba and Cala Pass Seams. Note the reduced thickness of the Indwe Sandstone Member. Guba Valley, 8 km south-west of Indwe.

The matrix comprises clay to coarse-grained sandy material. A high secondary-iron content gives the bed a rusty red-brown colour and, in combination with secondary-quartz overgrowths on detrital grains, has resulted in a highly indurated rock. Quartz pebbles up to 2 cm diameter are the predominant clast type, though well-rounded, oval to ellipsoidal quartzite cobbles and pebbles between 2 and 60 cm in diameter are thinly but persistently dispersed at, or just above the base of the bed. Pebbles of vein quartz, polycrystalline quartz and feldspar are also present. Disc-shaped intra-formational silt clasts up to 15 cm long and coalified vegetal matter are also common. In the vicinity of Indwe the Kolo Pebble Bed may contain ferruginous concretions which Ryan (1963) described as resembling oysters. The concretions appear to be shale fragments which have been replaced by iron oxide. Where the bed overlies the Guba Seam it is crowded with clasts of shale and coal. Authigenic pyrite nodules up to 40 mm in diameter may also be present directly above the coal.

The Kolo Pebble Bed is a useful marker horizon as it is "... a distinct lithological unit that defines an erosional surface marking an important lithostratigraphic break or disconformity. The uniform thinness and lateral persistence of the superjacent pebbles and conglomerate make it one of the easiest contacts to pick out in the succession." (Turner, 1975a, p43).

At some localities a light grey, fine- to medium-grained, erosively based, planar bedded sandstone separates the Kolo Pebble Bed from the underlying Guba Seam. This sandstone may be up to 2 m thick, but is mostly much less due to erosion prior to deposition of the succeeding pebble bed.

A characteristic feature of the Indwe Sandstone is the presence of second-order upward-fining, lenticular sedimentary cycles between 2 and 8 m thick (Figs. 9,10,11 and 12). The lateral

Figure 13. Channel structure at the base of the Indwe Sandstone Member. Channel is about 10 m deep. On the farm Milford, Indwe.

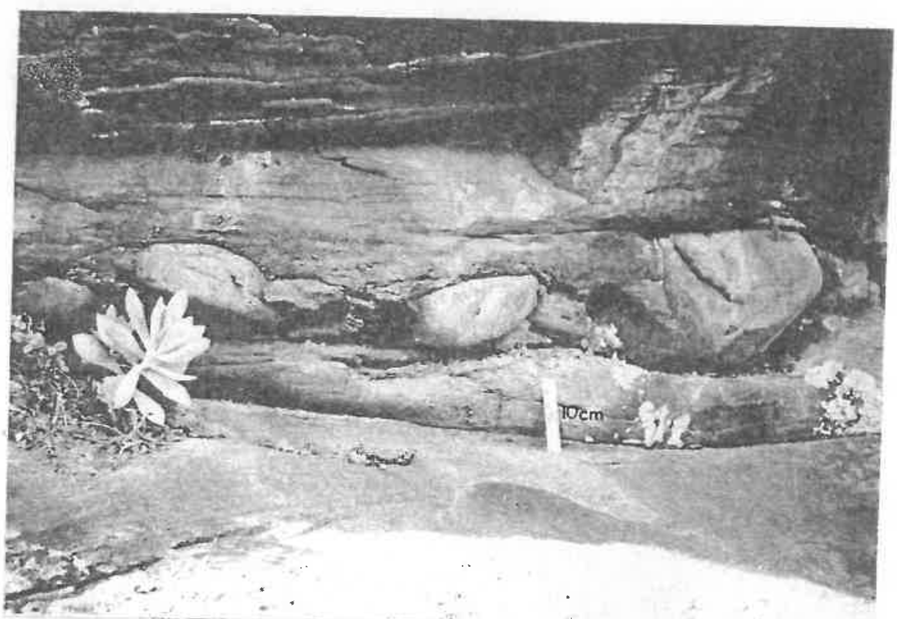


Figure 14. The Kolo Pebble Bed, showing quartzite cobbles. River valley 1,5 km south of Qiba.

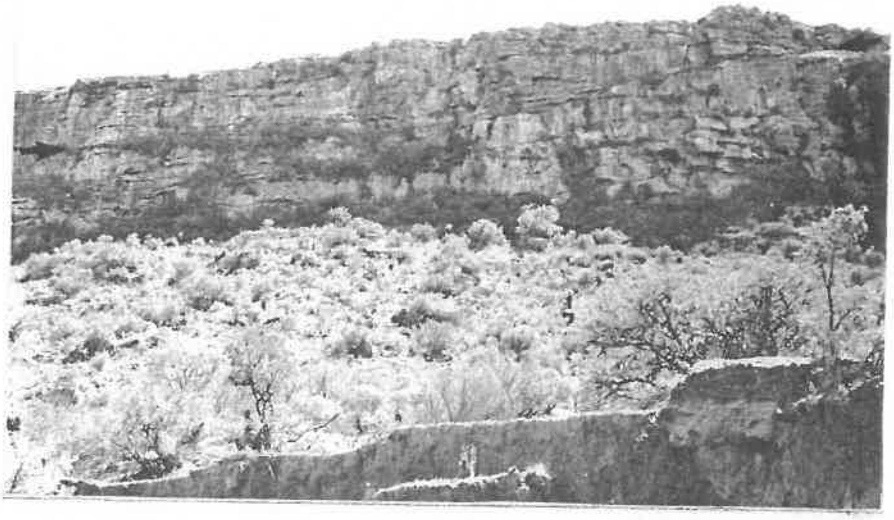


Figure 15. Cliff section showing the lenticular nature of second-order cycles in the Indwe sandstone Member. About 1 km north-west of Cala near the road to St. Gabriels Mission.

extent of the cycles could not be measured owing to insufficient exposure, but a cliff section at Cala shows this feature well (Fig. 15). The base of each cycle is defined by an irregular, erosive surface with relief up to 40 cm, overlain by a pebble conglomerate or a coarse-, felspathic sandstone which may contain quartzite pebbles, cobbles, boulders and intraformational silt clasts. Cycles decrease in grain size upward, but rarely do they culminate in sediment finer than medium-grained sandstone.

A second important cobble horizon occurs about 28 m above the base of the Kolo Pebble Bed and can be traced from Qiba to as far west as Rebels Kloof and Stowkes Basin (Figs.9 and 10). It is not, however, apparent at Indwe. This horizon has been designated the Emnxe Pebble Bed by the present writer, the name being derived from the southern portion of the field area in which its significance was first realized. The bed is up to 1,2 m thick and contains pebbles, cobbles and boulders up to 40 cm in diameter.

A lithologically distinctive grey-brown, medium-grained sandstone about 14 m thick is developed at the top of the Indwe Sandstone Member at Stowkes Basin, Rebels Kloof, Qiba and Cala Pass. It is irregularly planar-bedded with subordinate trough cross-stratification, contains abundant siltstone clasts, and lacks the characteristic glitter of sandstones at lower horizons in this member.

At Cala Pass a lens of olive, planar-laminated siltstone 8 m thick is present in the Indwe Sandstone Member directly below the Emnxe Pebble Bed. At Qiba, about 3 km to the north-west, this bed is represented by a metre of siltstone, but is not developed elsewhere. The base of the lens is rapidly gradational from sandstone into siltstone, and the top is overlain by the erosive base of the Emnxe Pebble Bed. A notable feature of this siltstone is its lateral persistence, which is in marked contrast to that of other siltstones within the member. The stratigraphic position of this lens suggests that it is the equivalent of the Little Bamboo Mountain Shale of Turner (1975a).

The Indwe Sandstone shows little lithological variation within the area investigated. However, towards the north-west and south-west of Indwe there is a marked decrease in grain size to generally medium-grained sandstones, and planar-bedding is developed to the exclusion of trough and planar cross-stratification. Sections measured in the cliffs above Indwe (Fig. 11) show the characteristic coarse-grained, gritty texture of this member, but 2 km north-west of the town, on the farm Milford, there are only minor amounts of gritty sandstone and no pebbles or cobbles are present above the Kolo Pebble Bed (Fig. 11a). The situation is the same to the south-west of Indwe, where there is also a decrease in thickness (Fig. 12).

The Indwe Sandstone Member proved to be of critical importance for purposes of correlation. Its distinctive characteristics and widespread occurrence make it one of the most useful members of the Molteno Formation for that purpose.

3) Mayaputi Member

Above the Indwe Sandstone Member is a thick, argillaceous unit which is considered to be the stratigraphic equivalent of the Mayaputi Shale Member of Turner (op. cit.). That author reported that the equivalent of the Mayaputi Shale Member "... can be traced just north of Cala in the Xalange district; beyond this point [i.e. westwards] the Indwe Sandstone is overlain by a thick unnamed siltstone unit and the shale lenses out." Although there may be very subordinate shales within the unit referred to, the rocks in the present field area are predominantly siltstone and mudstone with minor sandstone intercalations, so that use of the term "shale" to qualify this member in this particular area is misleading. Because Turner's Mayaputi Shale Member and the corresponding sedimentary unit in the Indwe and Cala areas are essentially argillaceous, it is suggested that the name Mayaputi Member be adopted for the whole of the Molteno outcrop. A coal seam (the Cala Pass Seam) is present at the top of the member at two localities: at Cala Pass (Fig. 9), where the seam is 1,3 m thick, and at Indwe, where the seam is 2 to 3 m thick (Fig. 12).

Soft, argillaceous rocks of this member give rise to gentle or moderately steep, grass-covered slopes yielding few exposures. The best outcrops are in dongas and deeply dissected stream valleys. The member is easy to identify in the field due to its position between the distinctive strata of the Indwe Sandstone and Qiba Members.

The Mayaputi Member rests upon the Indwe Sandstone with either a gradational or an abrupt junction. At Indwe and Cala Pass the top of the Mayaputi is defined by the Cala Pass Seam, but elsewhere it is directly overlain by erosively based sandstone of the Qiba Member. In the vicinity of Indwe the coal seam may be overlain by up to 9 m of siltstone or mudstone followed by the lowest sandstones of the Qiba Member.

The thickness of the Mayaputi Member varies from a maximum of 50 m at Qiba to a minimum of 15 m 10 km south-west of Indwe. At Cala Pass the member is only 18 m thick. South-west of Indwe the top of the Mayaputi Member, regardless of its thickness, is 33 to 38 m above the base of the Indwe Sandstone. This is significant, for both members combine to comprise a single, first-order upward-fining cycle. The combined thickness of the two members is shown in Fig. 16.

The Mayaputi Member is a dominantly argillaceous unit containing subordinate fine- to medium-grained sandstone (Fig. 17). Light olive-coloured siltstones are present in the lower part close above the Indwe Sandstone but, towards the top, light and dark grey siltstones and mudstones predominate. In proximity to coal the rock becomes fissile, carbonaceous, and dark grey in colour. The argillaceous rocks are generally massive or planar laminated with minor occurrences of ripple cross-lamination. The laminae are defined by alternating light and dark layers of coarser and finer material respectively. A small amount of mica is present. Sandstone beds are between 5 and 55 cm thick and typically a yellowish, grey-brown colour. Red-brown ferruginous concretions up to 40 mm in diameter are common. Planar stratification is the prevalent sedimentary structure of the sandstone, but sporadic sets of trough cross-bedding 10 to 30 cm thick may also occur.

Where sandstone overlies siltstone or mudstone the junction between the two is erosive and the base of the sandstone is crowded with angular siltstone and mudstone clasts up to 6 cm across. The upper junction of these sandstones is generally abrupt, but they may grade upward into siltstone over about 15 cm. There is no evidence of load casting where sandstone overlies

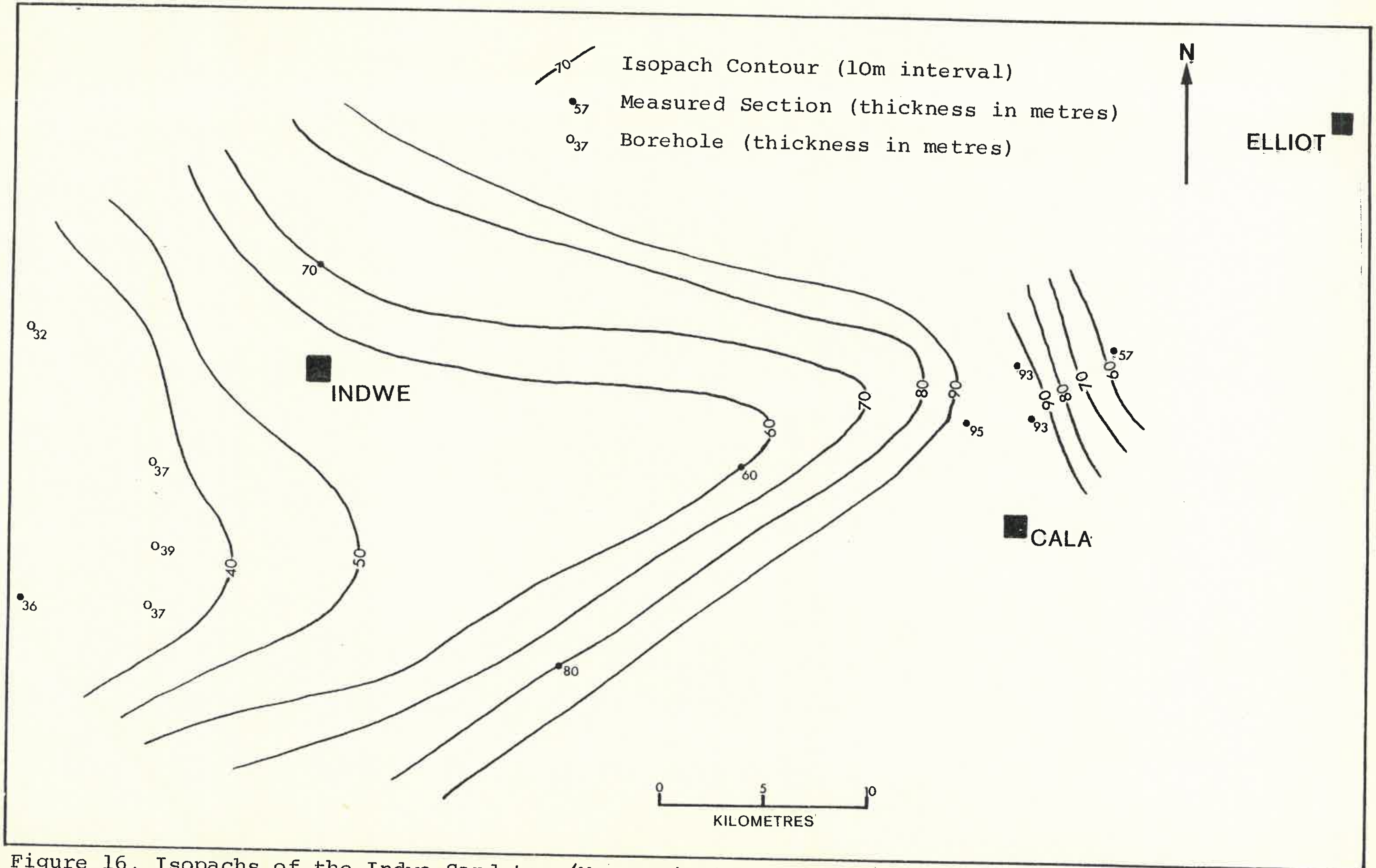


Figure 16. Isopachs of the Indwe Sandstone/Mayaputi first-order upward-fining cycle.

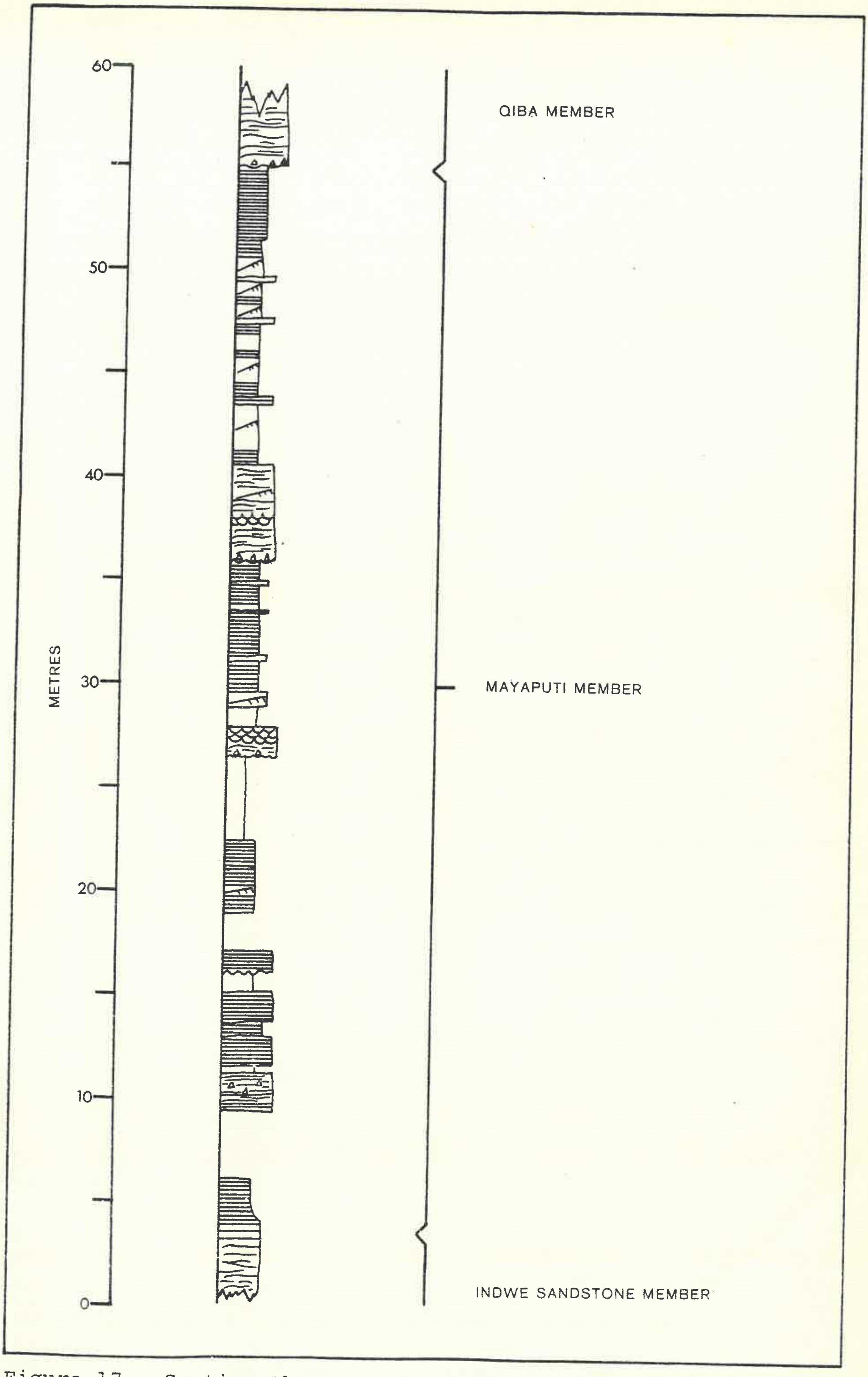


Figure 17. Section through the Mayaputi Member from a river gulley about 4 km south-west of Qiba.

siltstone or mudstone. Upward-fining, second-order cycles 2 to 8 m thick are present but not everywhere evident. They comprise relatively thin, erosively-based sandstones, between 40 cm and 4 m thick, overlain by a thick (up to 9 m) argillaceous component which may contain subordinate fine-grained sandstones up to 25 cm thick.

Turner (1975a) reported on the abundance of plant fossil material from his Mayaputi Shale Member, but in the area investigated plant fossils were found only in the upper part of the member at Qiba and within the Cala Pass Seam. They included leaves of *Baeira*, *Dicroidium*, *Phyllotheca* and *Taeniopteris*.

4) Qiba Member

The Qiba Member derives its name from exposures south of Qiba village in the Xalanga district of Transkei. A monotonous succession of yellow-grey, fine- to medium-grained sandstone beds with thin argillaceous intercalations characterises the member, which usually crops out as a poorly developed cliff feature. A shaly coal within the member, the Ulin Seam, is exposed on the farm Ulin, and in the road cutting adjacent to the new Tsomo River bridge on the road between Elliot and Indwe.

Ryan (1963) referred to a 60 m thick sequence of rocks overlying the Indwe Sandstone Member in the Indwe area as the Composite Zone. During the present investigation this was divided into the Qiba Member and overlying Tsomo Member. The Qiba Member appears to be the stratigraphic equivalent of the Glen Rosa Member, a coarse-grained, gritty sandstone identified by Turner (1975a) in the Zastron, Lady Grey and Albert districts. Turner (*op. cit.*) indicated that the Glen Rosa could be traced as far south as Kommandokop in the Albert district, and that "... there is a sudden decrease in the grain size of most of the sandstones in the upper part of the Molteno Formation which are predominantly fine-grained. Thus the finer-grained sandstone unit above the correlative of the Mayaputi Shale in the south may be the stratigraphic equivalent of the Glen Rosa Sandstone." The name Glen Rosa cannot be adopted in this study however, owing to apparent differences in thickness and lithological character between the two units concerned. There is also insufficient stratigraphic data to substantiate such a correlation. For these reasons the local name "Qiba Member" has been adopted for use in the present field area.

The Qiba Member is the basal component of a first-order, upward-fining cycle of which the argillaceous Tsomo Member comprises the upper part. The lower junction of the Qiba is commonly defined by a planar or slightly irregular erosional surface, and for 25 cm above this there may be abundant siltstone and mudstone clasts. The clasts are at some places of sufficient concentration to constitute a matrix-supported conglomerate. A few quartzite pebbles and cobbles are also present. In the Indwe area the base of the member may vary laterally from sandstone to siltstone or mudstone over distances of less than 3 km, and in these circumstances the top of the Cala Pass Seam assists in the recognition of the lower junction. The upper junction of the member may be abrupt, but is more commonly gradational into siltstone (over about 2 m) of the Tsomo Member.

The thickness of the member increases westward from 30 m at Cala to a maximum of about 58 m in the central part of the field area (Fig. 18). The member then decreases in thickness, and at Indwe it is between 20 and 40 m. Reference sections (Figs. 19, 20, 21 and 22) were measured at Qiba, Ulin, Rebels Kloof and the Tsomo Bridge.

Planar bedding, which may have a depositional dip of up to 6°, is the dominant sedimentary structure. Isolated sets of planar and trough cross-stratification are also present, and ripple cross-lamination and planar lamination occur in

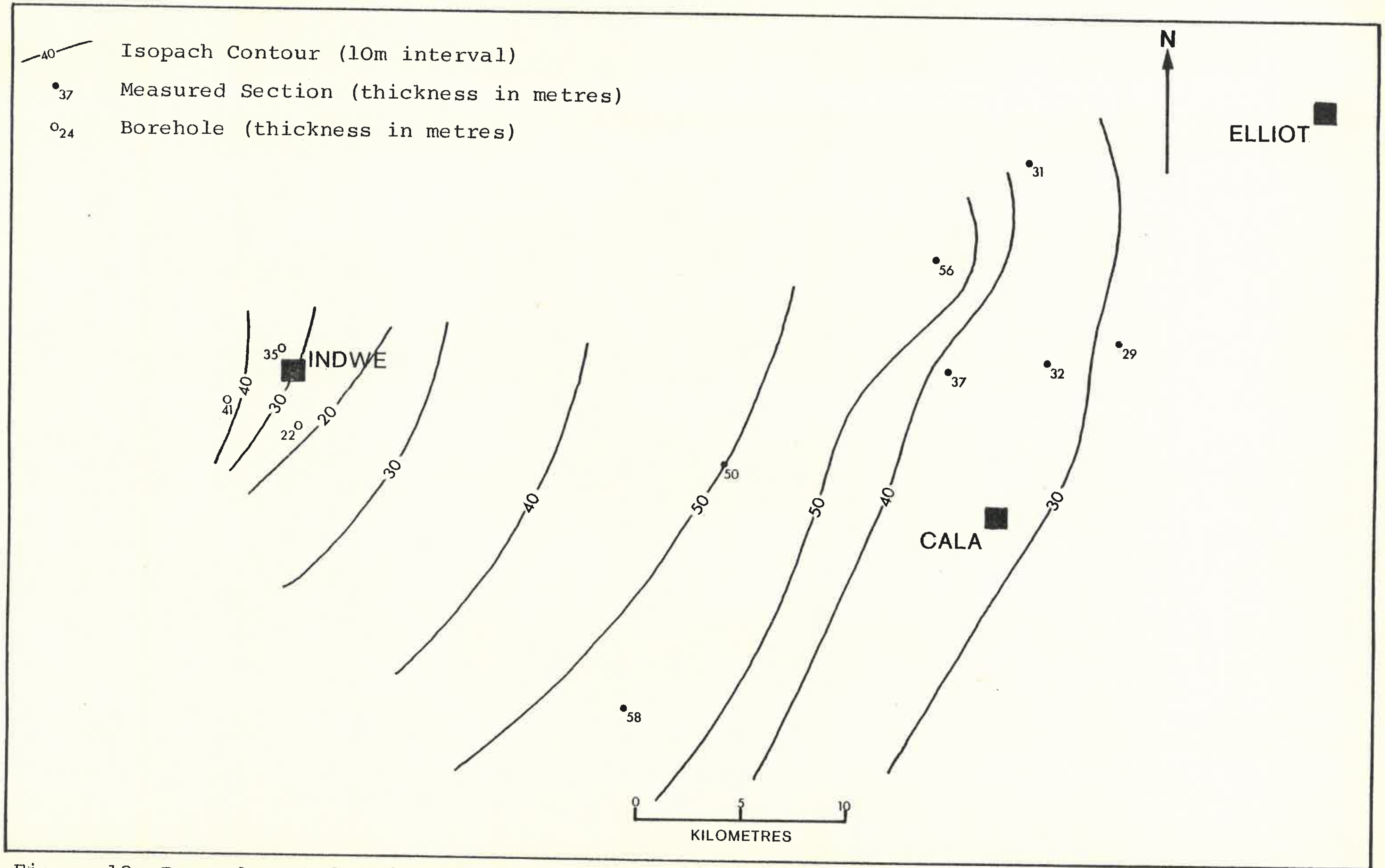
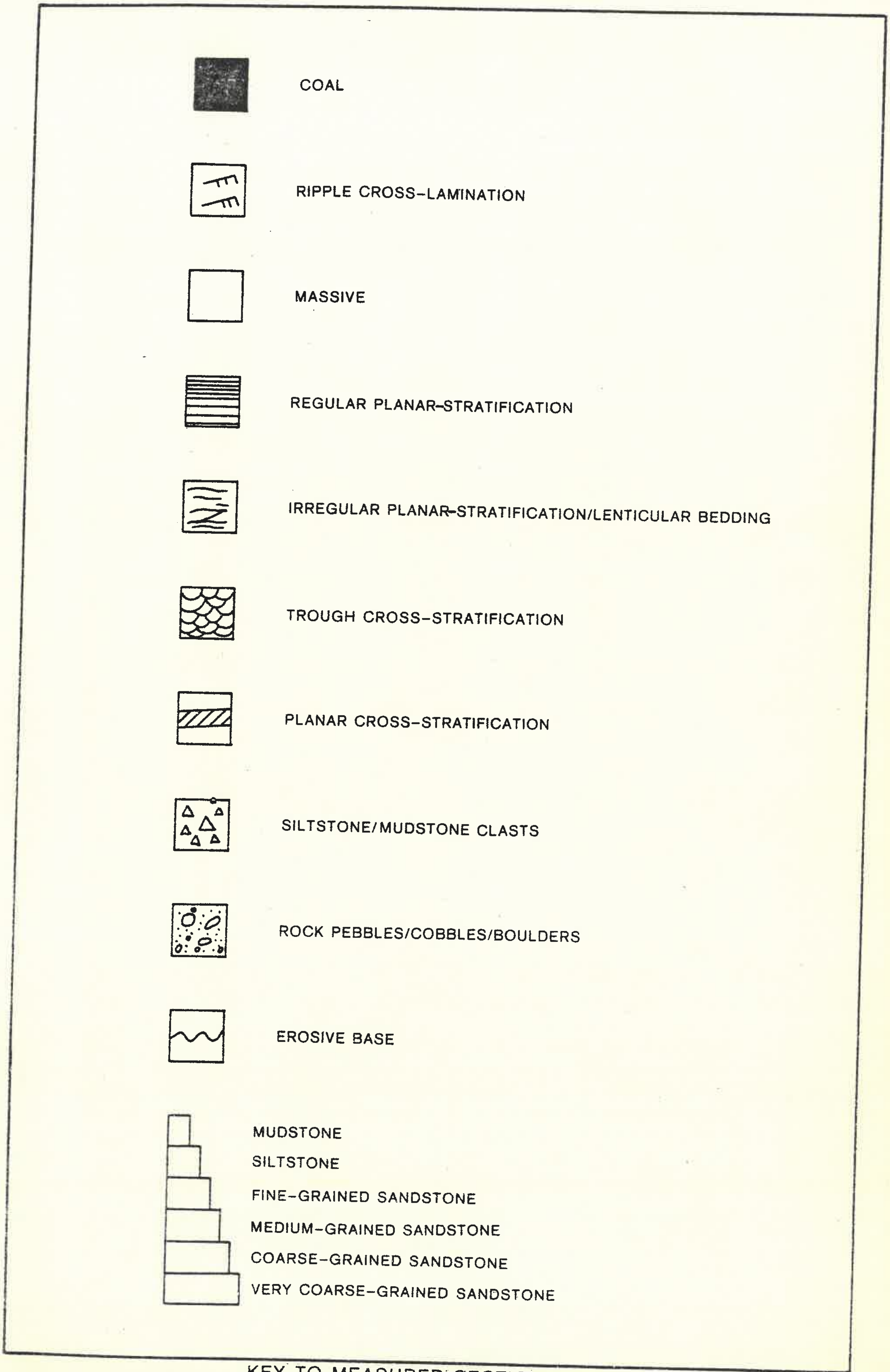


Figure 18. Isopachs of the Qiba Member.



KEY TO MEASURED SECTIONS

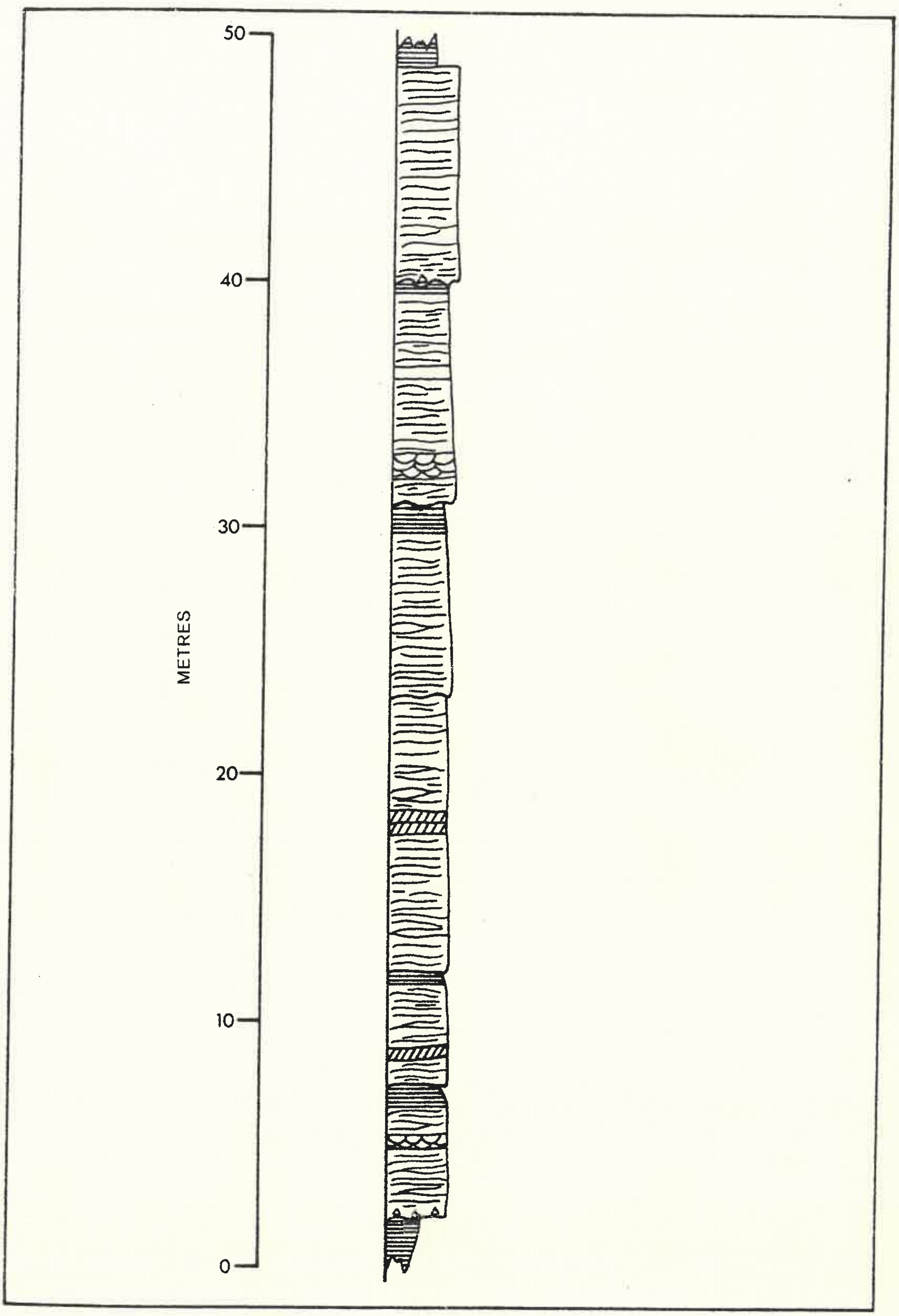


Figure 19. Measured section through the Qiba Member from a cliff section 0,5 km south-east of Qiba.

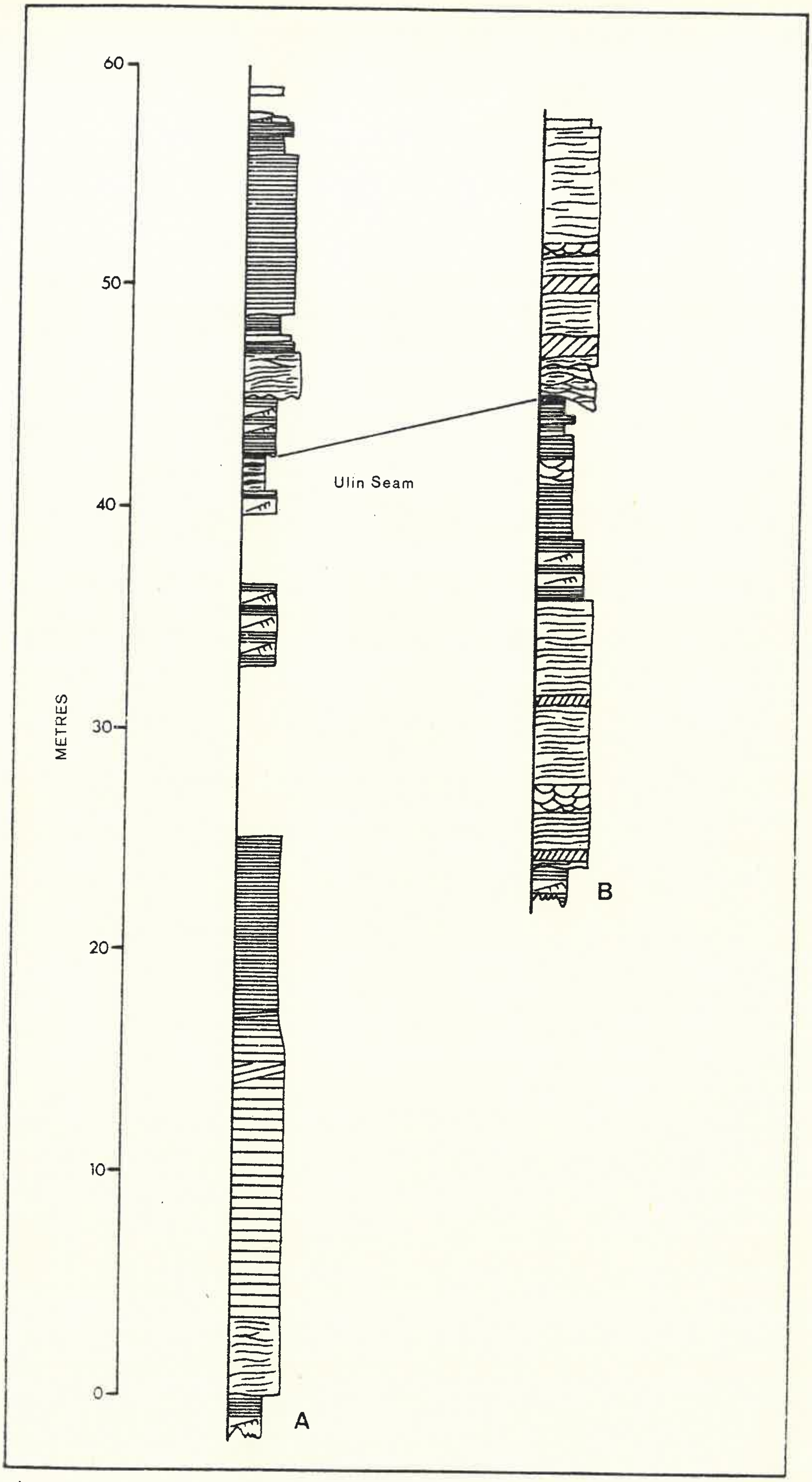


Figure 20. Measured sections through the Qiba Member from (A) the farm Ulin and (B) directly west of the new Tsomo River bridge.

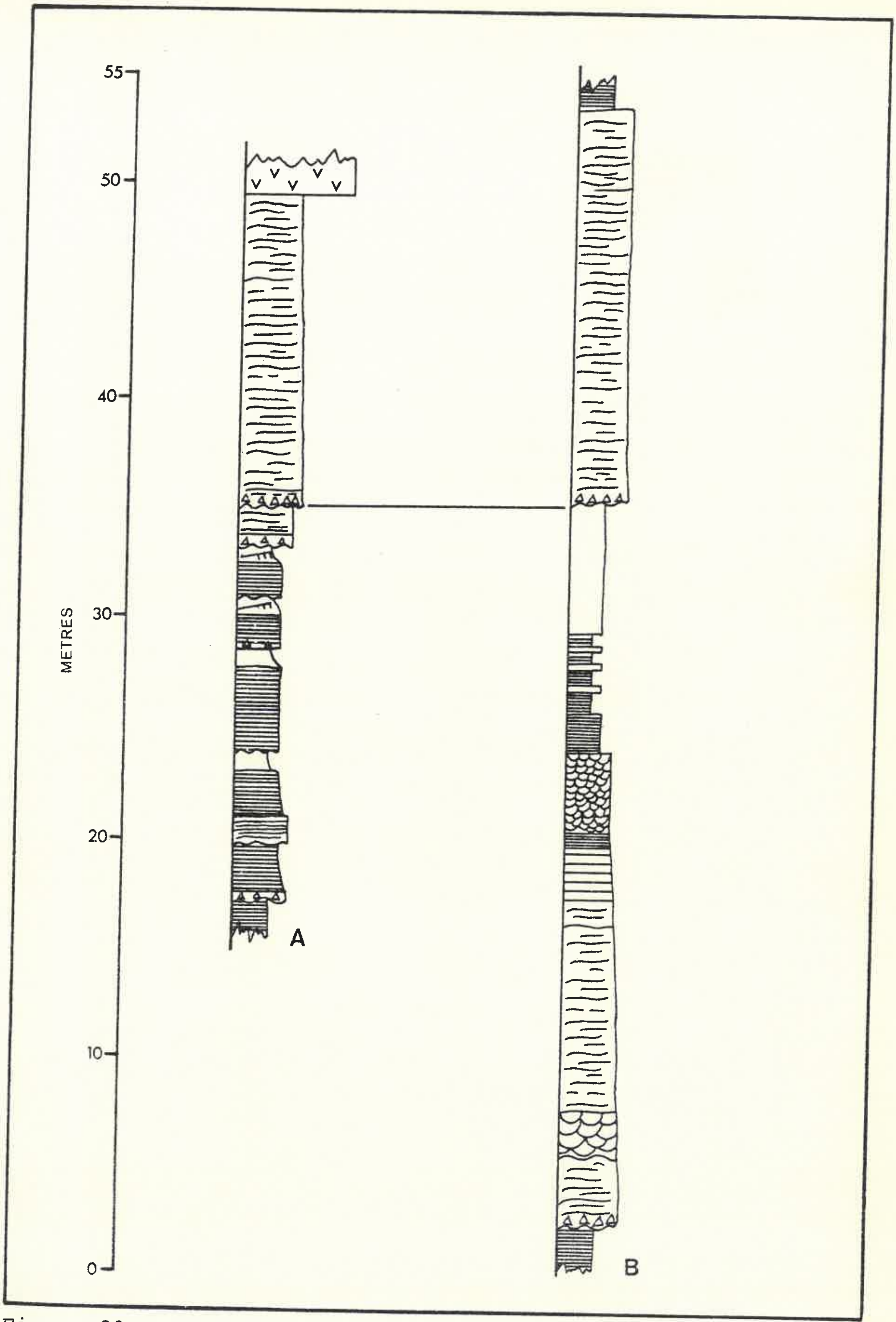


Figure 21. Measured sections of the Qiba Member at Rebels Kloof. Section (A) was measured 1,5 km to the south of section (B).

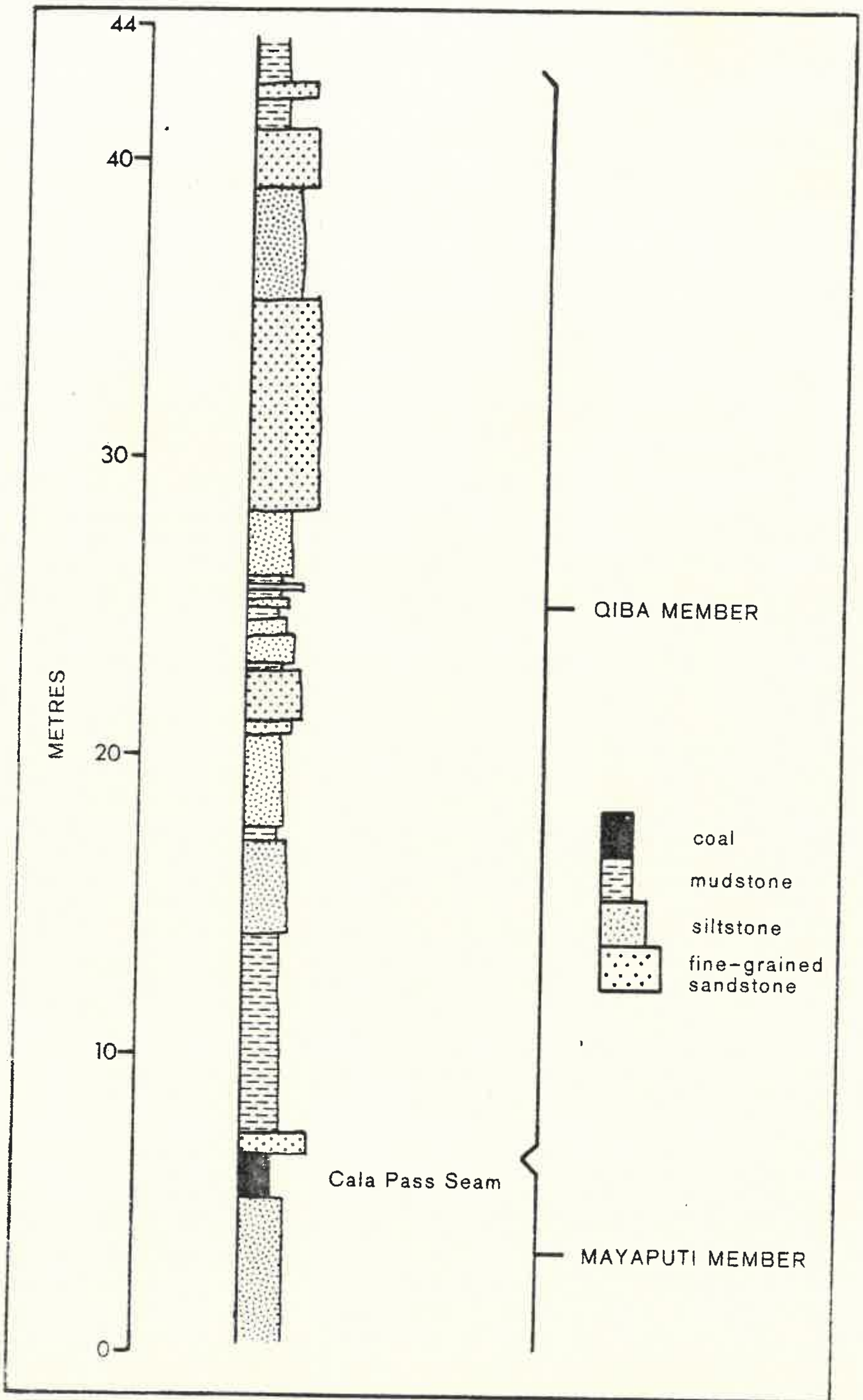


Figure 22. Borehole log of the Qiba Member 3,5 km south-west of Indwe in the Guba Valley.

siltstone and mudstone intercalations. North-west of Indwe, on the farm Perskenplaats, a channel structure 20 m wide and 2 m deep is exposed. Sand-volcanoes and extensively slumped sandstone beds occur 100 m north-west of the channel structure. The sand-volcanoes are about 80 cm below and 20 m away from the slumps, and appear to be developed on beds which have also slumped slightly.

On the basis of lithology, three differing facies of the Qiba Member were recognized:

1) At Qiba, Cala Pass, and on the farm Saunabul, north of Cala Road station, the member comprises an uninterupted sequence of medium- to fine-grained sandstone with thin, (less than 40 cm) discontinuous siltstone intercalations (Fig. 19). Matrix-supported intraformational conglomerate lenses up to 45 cm thick are common throughout the member. Clasts vary in length from 1 to 5 cm and consist mainly of siltstone. The homogenous nature of the rock at these localities makes it difficult to identify upward-fining cycles, which are undoubtedly present further west. The base of each of these cycles is defined by an erosional surface of low relief above which fine- to medium-grained sandstones show little or no upward decrease in grain size. There is, however, an upward change in the nature of the bedding within cycles. The lower portions of cycles show irregular and discontinuous planar-bedding between 5 and 30 cm thick and this becomes progressively thinner and more regular towards the top.

2) With increasing argillaceous content, second-order upward-fining cycles become better defined towards the west so that the member can there be divided into two parts, recognizable in sections measured at the new Tsomo River bridge, Ulin, Rebels Kloof and Stowkes Basin (Figs. 20 and 21). The lower component, between 15 and 42 m thick,

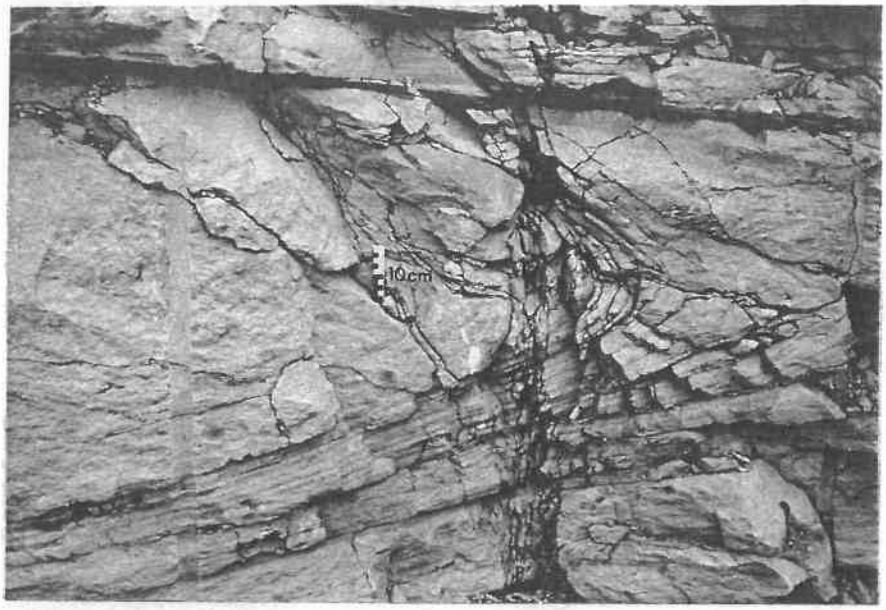


Figure 23. Recumbent-folded planar cross-bedded foresets. They have been overfolded in the direction of transport (towards the north-west) and are truncated by the base of an overlying set. Qiba Member, east side of the new Tsomo River bridge.

comprises a single, first-order upward-fining cycle. The cycle is defined at its base by an erosional surface of low relief, above which are siltstone and mudstone clasts up to 8 cm long. There is a distinct upward decrease from medium-grained sandstone at the base to fine-grained sandstone, siltstone or mudstone at the top. At Ulin and the new Tsomo River bridge the Ulin Seam is present at the top of a cycle which is 45 m thick at the former locality, and 20 m thick at the latter. At Rebels Kloof the lower component comprises six second-order, upward-fining cycles, each between 3 and 5 m thick (Fig. 21a).

The upper component of the Qiba Member is an erosively-based, planar bedded, medium-grained sandstone 11 to 15 m thick. It forms the base of an upward-fining first-order cycle, the argillaceous Tsomo Member comprising the upper part. Although the base of this cycle exhibits slight erosional relief, up to 7 m of the lower component, including the Ulin Seam, were removed by erosion over a distance of less than a kilometre at the new Tsomo River bridge.

In the road cutting on the eastern side of the bridge low-angle, planar cross-stratified foresets have undergone soft-sediment deformation in the form of recumbent slump folds. These have amplitudes of up to 80 cm. (Fig. 23).

3) In the Indwe area the Qiba Member is generally finer grained and comprises a higher proportion of mudstone and siltstone than further west (Fig. 22). Boreholes indicate the presence of two components, as above, but the strata chiefly comprise thick, argillaceous sequences with sandstone units up to 8 m thick. Where the upper component is recognizable it is an erosively based, planar stratified, medium-grained sandstone at least 8 m thick.

Silicified trunks of Dadoxylon are common within the Qiba Member throughout the field area. The trunks are mostly parallel to bedding, but at Rebels Kloof and Qiba upright, in situ specimens are present. The commoness of these fossils, and the fact that they are rare elsewhere in the Molteno, render them a valuable stratigraphic aid in identifying the Qiba Member where outcrop is poor.

5) Tsomo Member

This is named after the Tsomo River which flows through the field area, and not after any particular type locality. Poor exposure did not allow much lithological information to be obtained about these rocks, but reliable thickness measurements are possible because the member lies between two distinctive, generally well exposed sandstone units.

The Tsomo Member constitutes the top part of a first-order upward-fining cycle and overlies the Qiba Member with a sharp or gradational base. The top of the Tsomo is overlain by a very coarse-grained, erosively-based sandstone unit which defines the base of the Loskop Member. The Tsomo Member thins progressively towards the west from a thickness of 35 m at Qiba to 18 m west of Indwe.

The member is composed primarily of dark and light grey, horizontally laminated or structureless siltstones and mudstones. Thin (less than 30 cm) intercalations of fine-grained sandstone are present. At Indwe, on the farm Bannockburn, a very coarse-grained sandstone 3,8 m thick is transitional upward into medium-grained sandstone, and then into siltstone to form a 15 m thick upward-fining cycle near the top of the member.

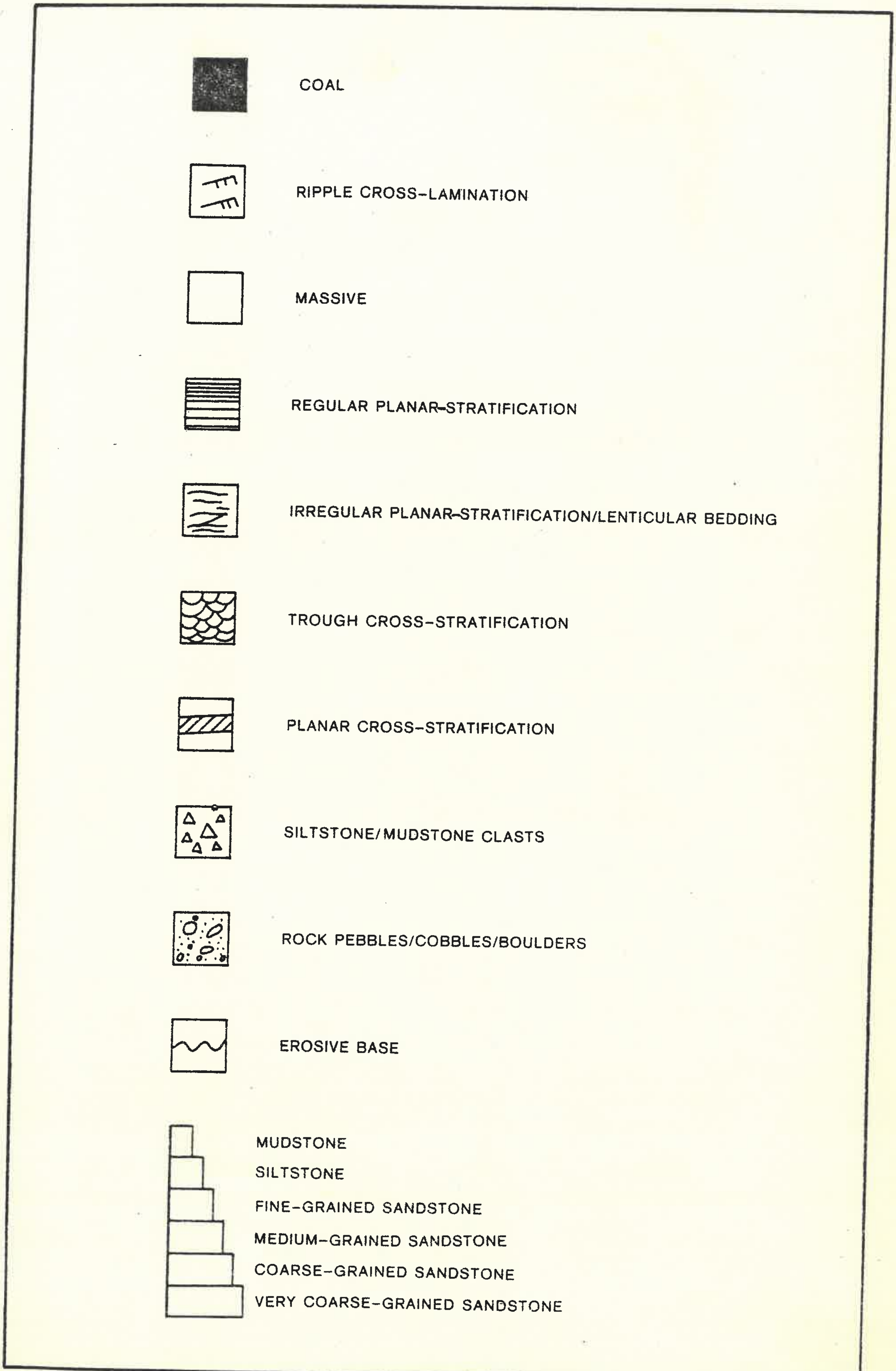
6) Loskop Member

The Loskop Member lies above what Turner (1975a) held to be the top of the Molteno Formation. There is therefore uncertainty about its stratigraphic status, but for the purposes of this project it is given the status of a separate member. The member is named after Loskop, a prominent hill to the west of Elliot where it is best exposed (Fig. 24). Further regional investigations are required to discover the true relationship of this unit with the Molteno and Elliot Formations.

Lithologically, this member comprises a repetitive pattern of resistant sandstones up to 25 m thick, alternating with argillaceous beds which may be as much as 60 m thick. The lower junction is defined by an erosively based, very coarse-grained sandstone overlying the Tsomo Member. Quartzite cobbles and pebbles up to 15 cm in diameter are commonly present at the base

Figure 24. Upper part of the Loskop Member exposed on the lower southern slopes of Loskop. The dotted line defines the upper boundary of the member and the change in outcrop pattern and slope between it and the overlying Elliot Formation.

Figure 25. Slumped foresets of planar cross-bedding. Loskop Member, Umnachean.



KEY TO MEASURED SECTIONS

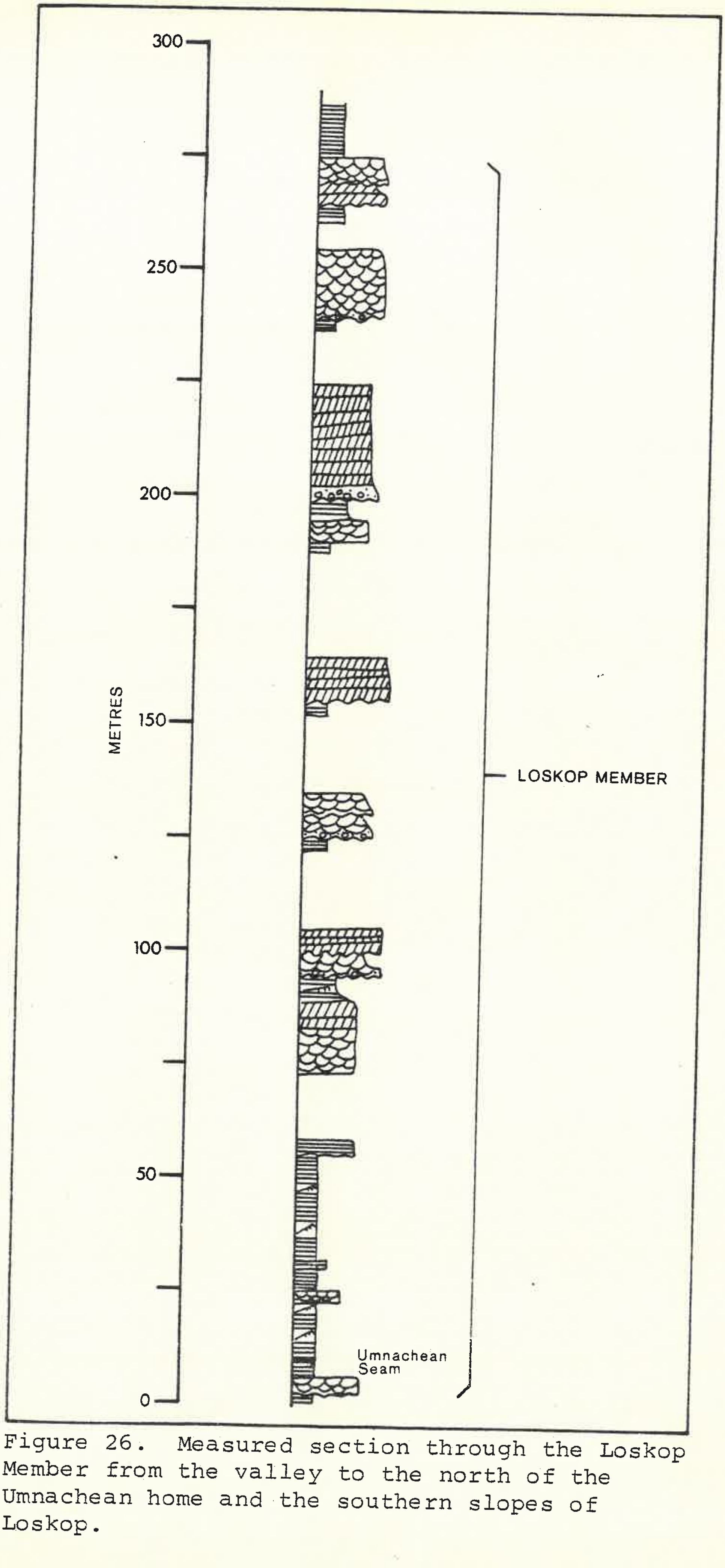


Figure 26. Measured section through the Loskop Member from the valley to the north of the Umnachean home and the southern slopes of Loskop.

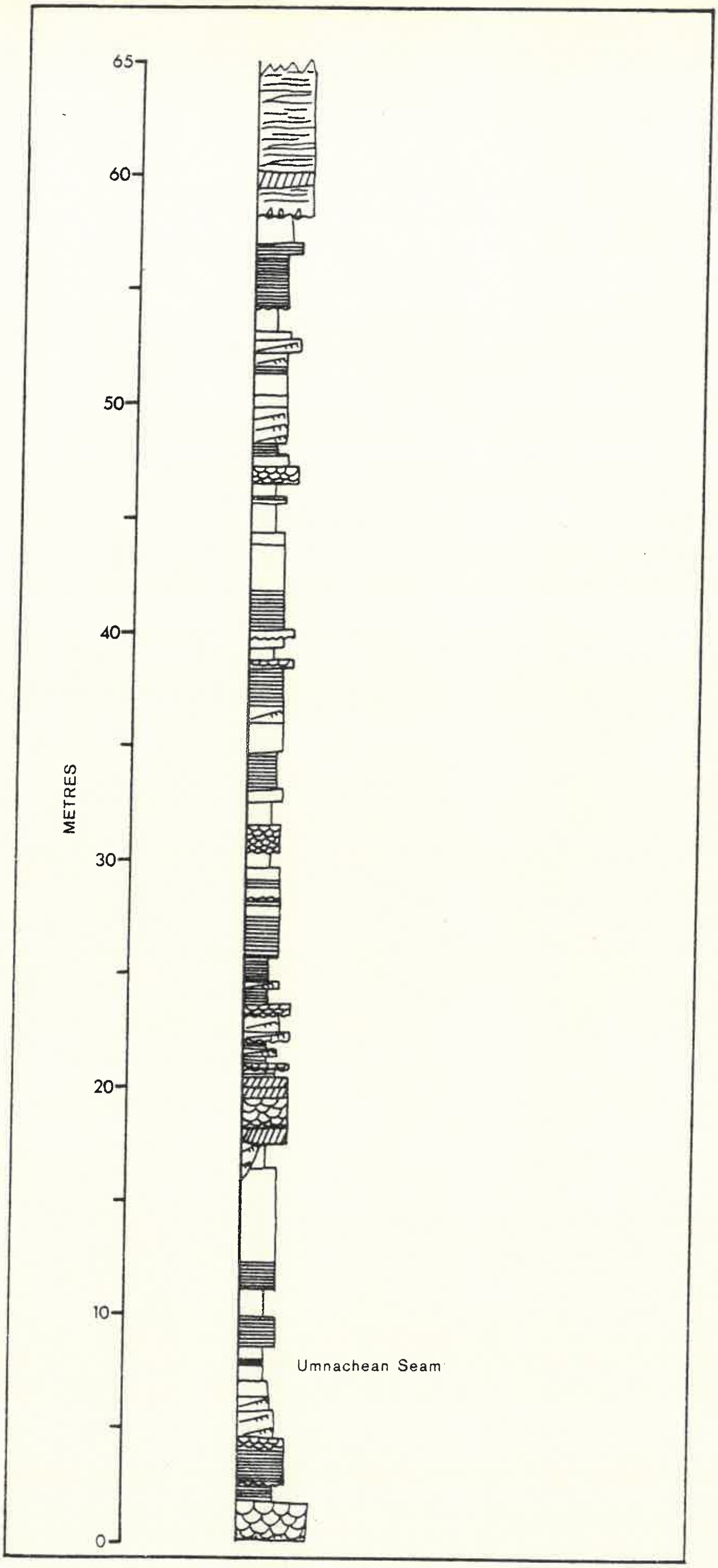


Figure 27. Section through the lower portion of the Loskop Member at Umnachean showing the detailed lithology of an argillaceous component.

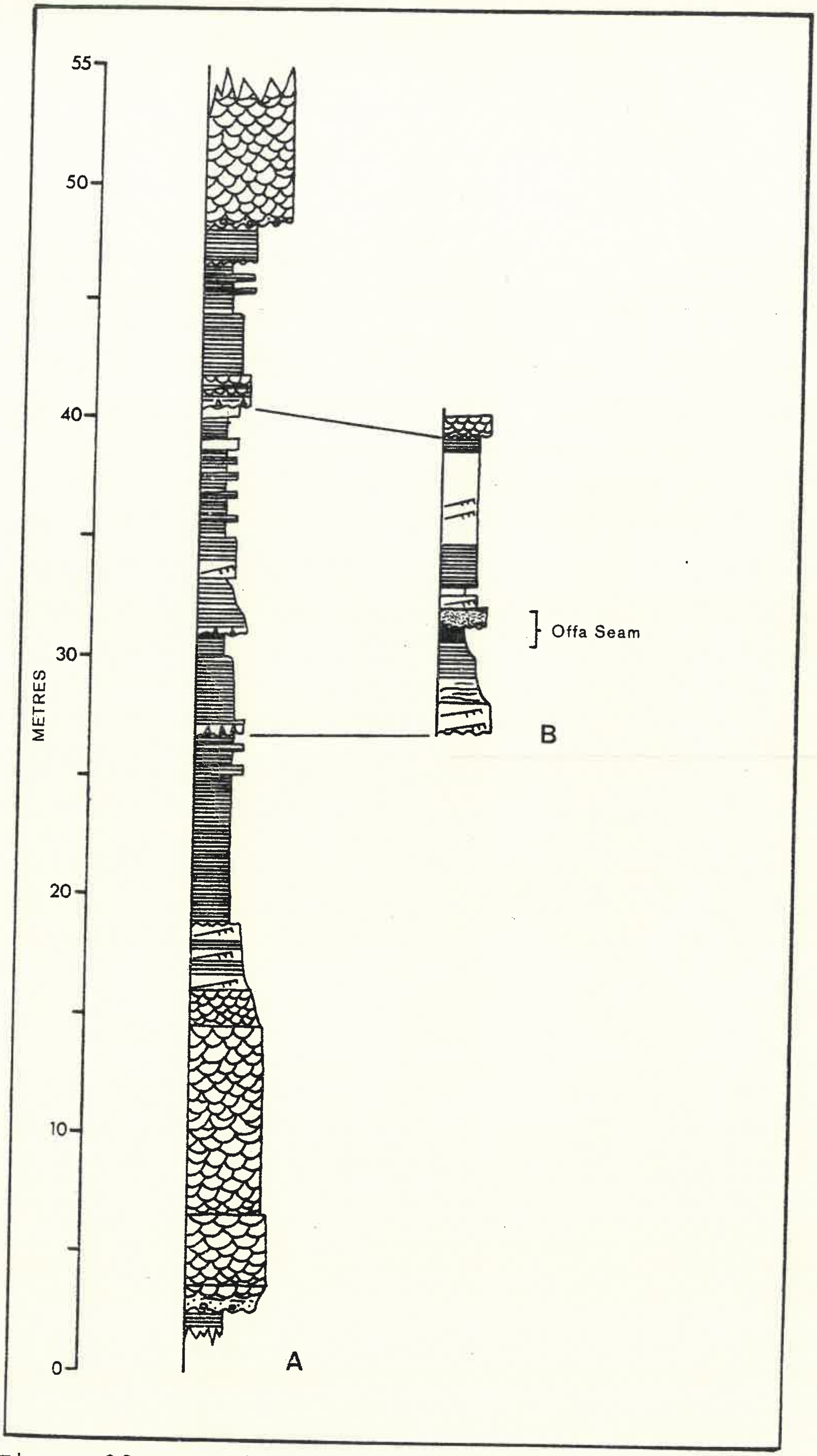


Figure 28. Section through portion of the Loskop Member on the farm Offa showing the Offa Seam. Section B occurs 200 m south of section A.

of this sandstone, which is probably the stratigraphic equivalent of the Gubenxa Sandstone (Turner, 1975a) present to the east of the area discussed here. The upper boundary of this member has been described in the section dealing with recognition of the top of the Molteno Formation.

It was only possible to measure the thickness of the Loskop Member with reasonable accuracy in the Elliot area where it is about 280 m. A thickness of about 250 m was measured at Indwe where the base appears to be faulted and is poorly exposed. This member seems to show little variation in thickness or lithology over the study area and so only one measured section is presented (Fig. 26).

A number of first-order cycles are recognized in this member, each comprising a basal sandstone 12 to 25 m thick which grades rapidly into an overlying argillaceous component with a thickness of between 15 and 60 m (Fig. 26). The sandstones are generally coarse- to very coarse-grained and pebbly, but may also be medium-grained, as at Umnachean. The base of each cycle is defined by an erosive surface displaying relief not exceeding 30 cm, with which is associated siltstone and mudstone clasts up to 25 cm across. Well-rounded quartzite pebbles and cobbles up to 15 cm in diameter may also be present. Only rarely does the concentration of clasts warrant the term conglomerate. The coarser-grained sandstone components became only slightly finer-grained upward and the medium-grained ones rarely show any tendency at all to become finer upward. The sandstone units commonly comprise two upward-fining second-order cycles, the lower one being truncated by the coarse-grained, pebbly base of the overlying cycle. The tops of sandstone components are marked by rapid gradation (generally over less than a metre) from sandstone into siltstone. These sandstones are continuous for distances of at least 5 km normal to the regional palaeoslope (i.e. towards the north-west).

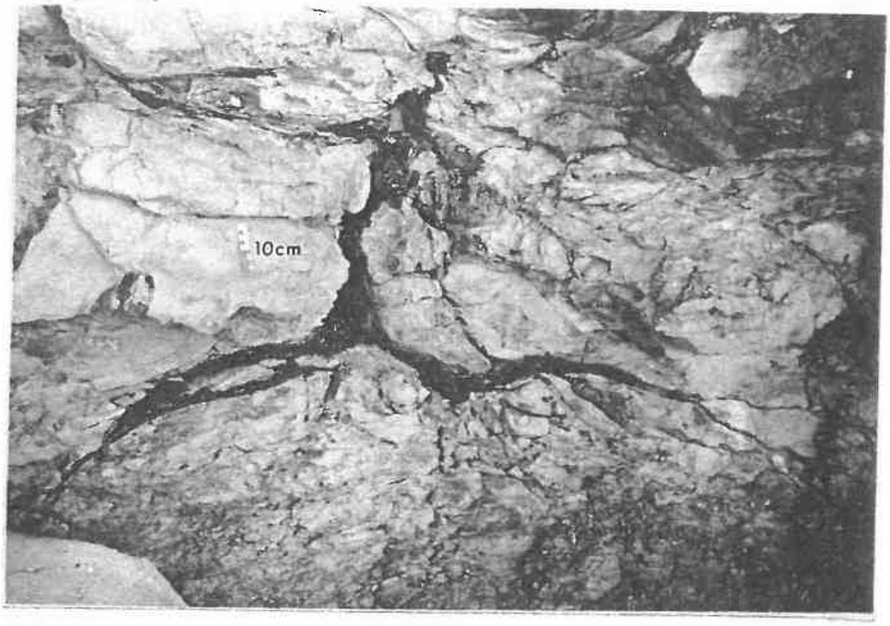


Figure 29. In situ tree trunk and root system in the Loskop Member about 600 m to the north-west of the home, Umnachean Farm.

The coarser-grained sandstone components are generally red- to yellow-brown and secondary quartz overgrowths on detrital grains have resulted in a rock which is highly resistant to weathering. Crystal faces of quartz overgrowths give the characteristic glitter which is typically seen in sandstones of the lower part of the Molteno Formation.

Trough and planar cross-stratification are the dominant sedimentary structures in the Loskop Member. Sets vary in thickness from 10 to 80 cm, commonly becoming thinner towards the top. Planar stratification is also common and may be the dominant sedimentary structure of certain sandstones, especially those that are medium-grained. This stratification varies from regular, thin bedding in fine- and medium-grained sandstones to irregular, poorly defined bedding in coarse or very coarse-grained ones.

A few lenses of siltstone up to 80 cm thick are present and in some instances siltstone fills scour channels in sandstone. Channel structures up to 5 m wide and 1 m deep are common at the base of sandstone components, and may penetrate completely through these into the underlying siltstone or mudstone. Water-escape structures in the form of sand volcanoes and fissures are common and slumped and overturned foresets of cross-beds were observed (Fig. 25).

The argillaceous components of first-order cycles mostly give rise to grass covered slopes and hence exposure is poor. However, a good idea of the detailed lithological composition of each component is given by three stream sections through part of the Loskop Member on the farms Umnachean and Offa (Figs. 27 and 28). Siltstone and mudstone are the dominant lithotypes with intercalations of fine- to medium-grained sandstone up to 1,1 m thick. Upward-fining second-order cycles, each comprising a thin, erosively-based sandstone passing upward into siltstone and mudstone, may be up to 4,5 m thick but are not always present. In these cycles the basal sandstone is commonly crowded with siltstone and mudstone clasts up to 4 cm long and 5 mm thick. Sandstones within the argillaceous beds are yellow-brown and show thin planar bedding, small scale trough cross-stratification or ripple cross-lamination. Siltstone and mudstone are generally light olive to dark grey, but red- and green-coloured rocks are also present. They are mostly massive, but may also be planar laminated or ripple cross-laminated. Thin, lenticular shaly coal seams are present at the tops of two of these cycles at Umnachean and Offa.

On the farm Umnachean, 12 km west of Elliot, an <u>in situ</u> trunk with roots attached is exposed at the top of the argillaceous component (Fig. 29). Vertical burrows, 5 mm in diameter and 2 to 3 cm deep, filled with fine-grained brown sandstone were found in light grey siltstone at Umnachean (Fig. 30). This was the only reliable indication of bioturbation that was seen within the Molteno Formation of the field area.

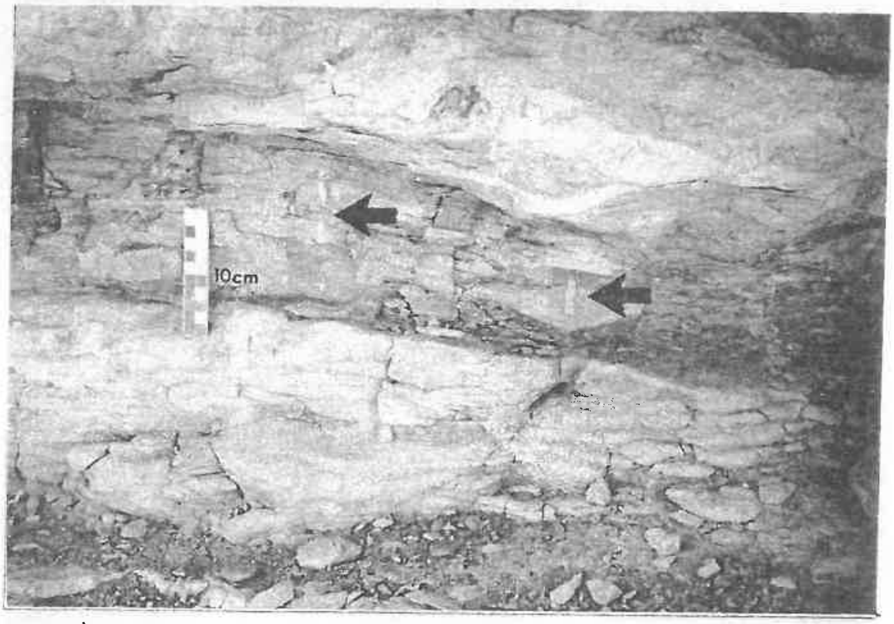


Figure 30. Vertical, sand-filled burrows in siltstone of the Loskop Member. Directly below the first sandstone ledge above the Tsomo River 600 m to the north-west of the home, Umnachean Farm.

D) COAL SEAMS

Coal seams of the Molteno Formation have been the subject of investigations since as early as 1856. Turner (1971) reviewed investigations carried out in the Indwe district between 1856 and 1948 with particular reference to the investigations conducted by Federale Mynbou (1960 and 1961) and the Geological Survey (1965 and 1967). The distribution, composition and quality of the coal seams was described in some detail by Turner (op. cit.), but confusion still exists as to the stratigraphic position they occupy. This section therefore presents a description of each seam and attempts to clarify the stratigraphic relationships.

During the present investigation it emerged that the most satisfactory method of correlating the coal seams is by considering their position with reference to first-order sedimentary cycles. Turner (1975a) realized this but, nevertheless, failed (in the opinion of the writer) to recognise the correct stratigraphic position of the coal seams, even though they had been correctly stated by Du Toit (1905), Ryan (1963) and Turner (1971). Conclusions reached in the course of fieldwork related to this investigation were later confirmed by borehole logs supplied by General Mining (Pty) Ltd.

The lowermost coal in the Molteno Formation is the Indwe Seam. This occurs between 24 and 30 m below the top of the Bamboesberg Member and is best developed to the north and north-west of Indwe. The Guba Seam occurs at the top of the Bamboesberg Member to the south and south-west of Indwe in the Guba Coalfield (Fig. 31).

A useful criterion used to differentiate between these seams is the nature of their respective hangingwalls: the Guba Seam is overlain by the distinctive Kolo Pebble Bed which is much coarser than the roof of the Indwe Seam. Both seams are rarely developed in close proximity to one another, but their true

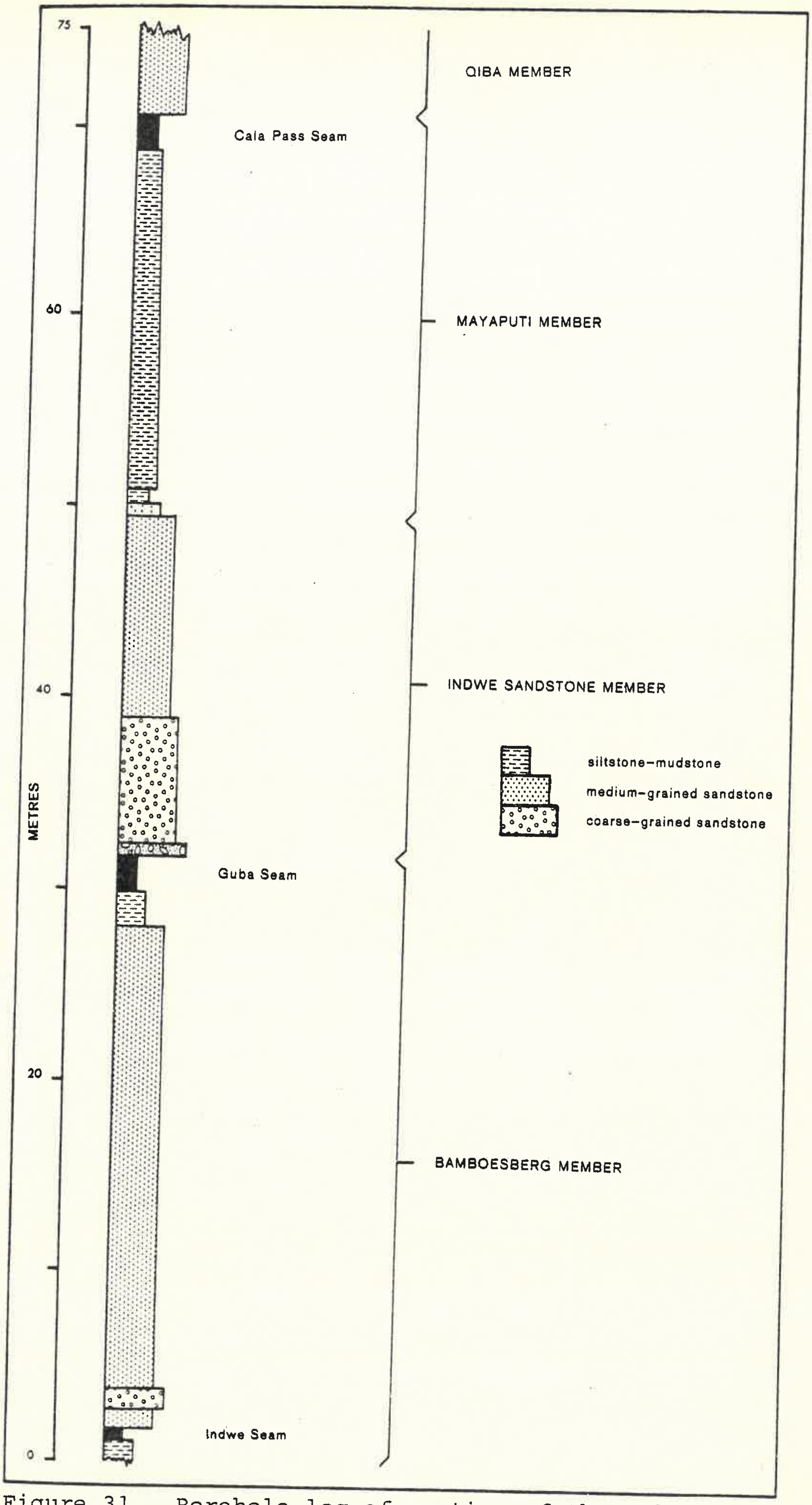


Figure 31. Borehole log of portion of the Molteno Formation in the Guba Valley showing position of the coal seams.

vertical relationship is shown by a measured section from Bannockburn (north-west of Indwe) (Fig. 7) and a borehole log from the Guba Valley (Fig. 31).

Turner (1975a , p12) stated that "... the Guba coal wherever it occurs is always located above the Indwe Sandstone and above the Cala Pass coal. Indeed, the presence of two coal seams below the Indwe Sandstone casts doubts on the true identity of the sandstone in the succession here." It appears that Turner regarded the Indwe and Guba Seams as being the same coal developed at the top of the Bamboesberg Member and the lateral equivalent of his Suurkop Seam to the west in the Bamboesberg Mountains. The fact that he regarded the Indwe Sandstone Member to directly overlie the Indwe Seam to the north of Indwe further substantiates this claim.

The Molteno and Cala Pass Seams may be readily correlated as both names have been applied to the first coal above the Indwe Sandstone Member. This seam is present at the top of the Indwe Sandstone/Mayaputi first-order upward-fining cycle (Fig. 31). Neither can be correlated with the Ulin Seam (cf. Turner 1975a) which is present in the Qiba Member. Due to the unsuitability of the name "Molteno Seam" (S.A.C.S., 1977), and the confusion that two names for the same coal horizon can cause, it is suggested that the name Cala Pass Seam should be used to refer to all coal seams at the top of the Mayaputi Member. Ryan (1963) referred to this seam as the Upper Seam, but this name does not comply with recommendations made by the S.A.C.S. (1977), and it has therefore not been used.

The Ulin Seam occurs within the Qiba Member as a thin, impersistent coal only seen in the area between Ulin and north of the new Tsomo River bridge. The relationship of this seam to that at Cyphergat, Molteno (Turner, 1975a) is not known to the writer. The highest coals in the Molteno are the Offa and

Umnachean Seams which occur in the Loskop Member. The Offa Seam, found about 8 km north-west of Elliot, is situated approximately 80 m below the top of the Molteno Formation, while the Umnachean Seam occurs within the first argillaceous unit above the base of the Loskop Member on the farm Umnachean. Both seams are thin and not laterally extensive.

Coal seams are important palaeoenvironmental indicators and a clear understanding of their stratigraphic position and associations is critical for an acceptable interpretation of the cyclic depositional pattern in the Molteno Formation. The apparently erroneous identification and correlation of the seams by Turner (1975a) inevitably casts some doubt on the validity of his hypothesis of cyclic sedimentation within the Molteno Formation, though his general conclusions are probably still valid.

1) Indwe Seam

This is a composite seam comprising bands of carbonaceous siltstone, mudstone, shale, shaly coal and coal. The seam occurs at the top of a second-order, upward-fining cycle. Its base rests abruptly on siltstone, and the roof comprises an erosively based, yellow-grey, coarse-grained sandstone. The seam dips at about 3^{o} towards the north-east. Prospecting and mining operations indicated that the thickness of the seam varies considerably, but a maximum thickness of 4,5 m was proved immediately north of Indwe at the Old Indwe Colliery. North-west of Indwe, at Bannockburn, the seam is only about 2 m thick. It thins to 0,75 m approximately 8 km south of Indwe, and pinches out altogether after a further 2 km. Ryan (1963) estimated the east-west diameter of the coal basin to be about 16 km but the northern limit is not known as the seam has been downthrown approximately 300 m to the north (Ryan, op. cit.).

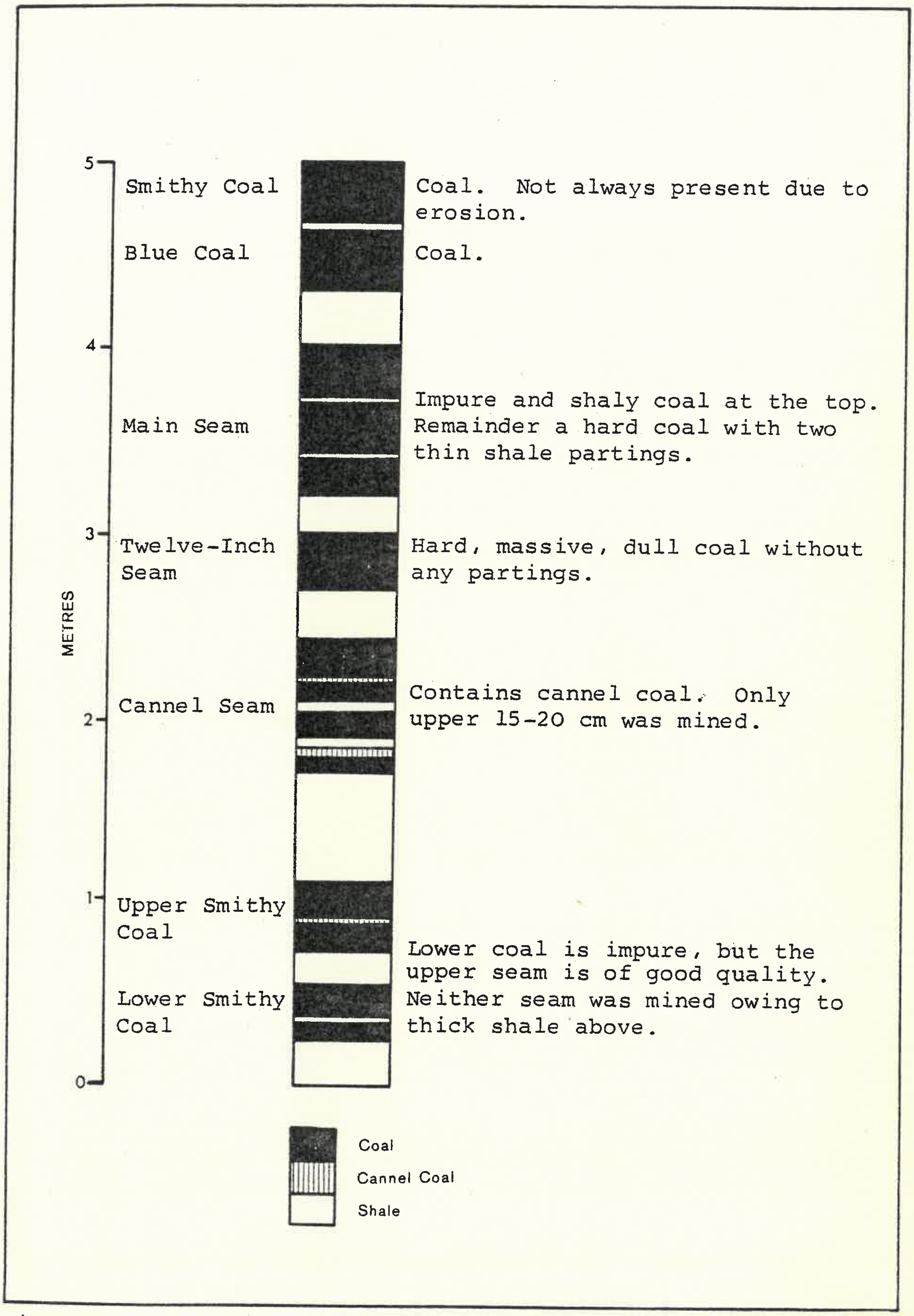


Figure 32. Detailed section of the Indwe Seam at the Dugmore Mine, Indwe (after Du Toit, 1905).

The Indwe Seam is best developed to the north and north-west of Indwe where it is subdivided by a number of shale and mudstone partings. A full description of the composition of the seam was given by Du Toit (1905), Ryan (1963) and Turner (1971) and is presented graphically in Fig. 32. A series of sections from east to west (Ryan, 1963) indicate that the seam contains a higher proportion of shale in the west than in the east. It becomes increasingly argillaceous towards the south. Thin and discontinuous lenses of shaly coal are present at approximately the same stratigraphic level as the Indwe Seam at Cala Pass and in the vicinity of Qiba.

The seam has undergone extensive erosion, and north of Indwe less than a metre remains in some places. Du Toit (1905) found the erosion of the upper part of the seam to be closely associated with the undulating nature of the seam floor: "The disappearing of the upper coals [of the Indwe Seam] can always be predicted by the falling level of the lower coals, while with the rising level of the latter, the upper coals reappear. Generally, when the dip of the roof is rapid the erosion is deep but the width of the denuded belt narrow and <u>vice versa</u>." A map of the Old Indwe Colliery (Fig. 33) made by Du Toit (<u>op</u>. <u>cit</u>.) indicating the denudation of the upper parts of the Indwe Seam, shows erosion channels orientated slightly west of north. Turner (1971) suggested that the irregularity of the seam floor was responsible for differential compaction which resulted in these erosion channels.

2) <u>Guba Seam</u>

This seam is developed at the top of the Bamboesberg Member between 24 and 30 m above the Indwe Seam but, as previously stated, it is rare for both seams to be developed in the same locality. The Guba Seam, which is best developed south-west of Indwe in the Guba Valley, is similar in character to the Indwe

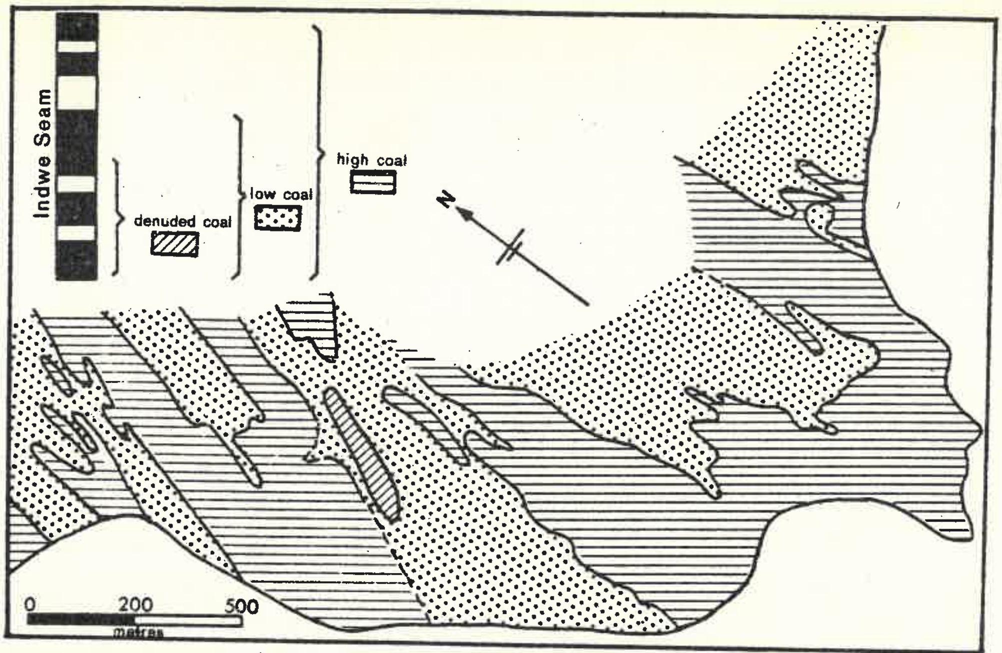


Figure 33. Plan of the Old Indwe Colliery showing the effects of contemporaneous erosion on the Indwe Seam (after Du Toit, 1905).

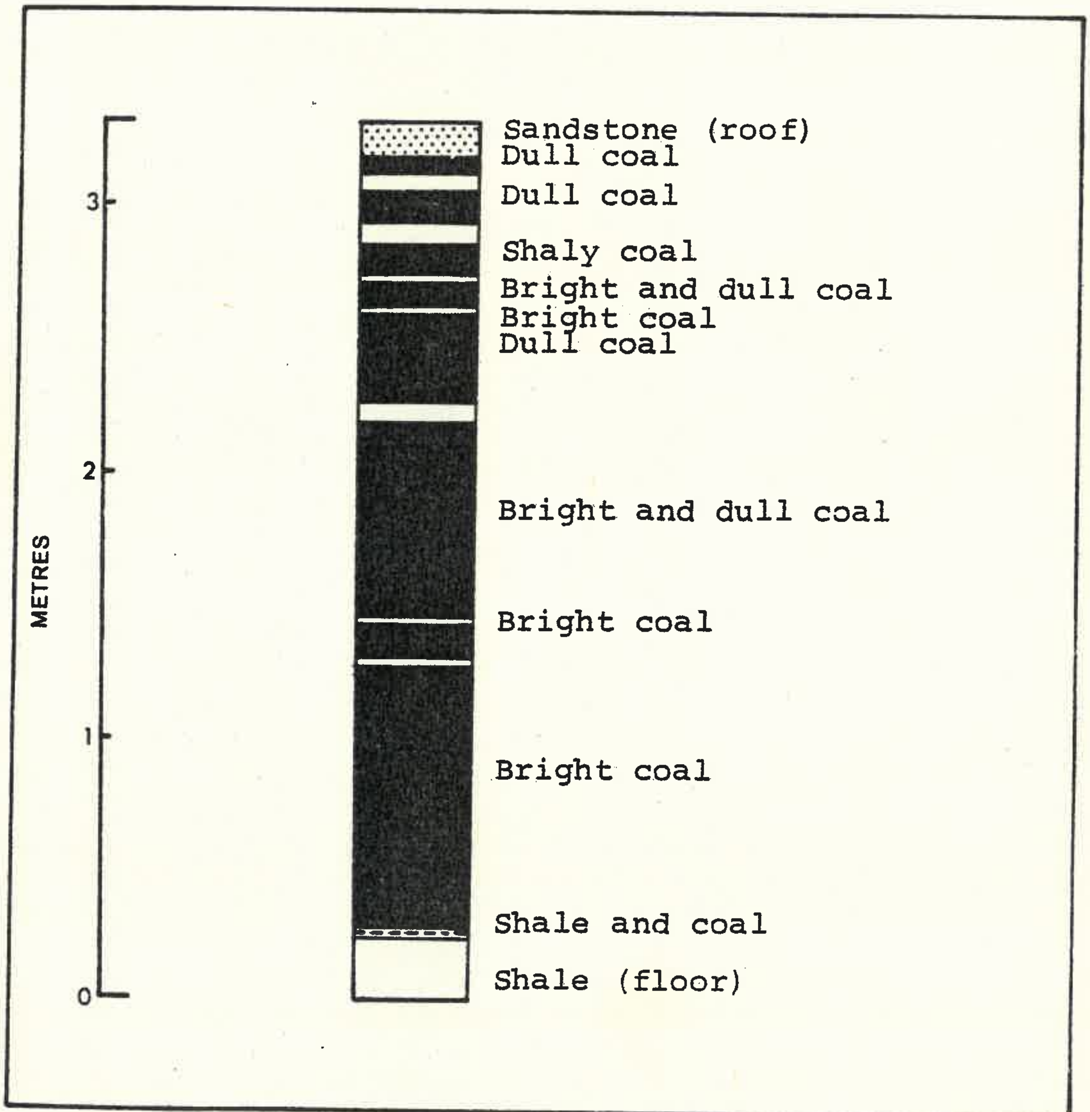


Figure 34. Section through the Guba Seam in the Guba Valley area (after Turner, 1971).

Seam, but contains less shale partings and is therefore economically more viable (Fig. 34).

The Guba Seam rests abruptly on dark grey to black mudstone and is overlain by the erosively-based Kolo Pebble Bed at the base of the Indwe Sandstone Member. The seam is thickest in the vicinity of the Guba Valley where it attains a maximum of about 2,8 m. Elsewhere the thickness varies considerably, and there is a general tendency to thin towards the south. There appears to be an inverse relationship between the thickness of the seam and that of the Indwe Sandstone Member; around Indwe, where the seam is thin or absent, the Indwe Sandstone is at its thickest, while in the Guba Valley the Indwe Sandstone is relatively thin. Furthermore, the Indwe Sandstone is generally medium-grained in the Guba Valley but predominantly coarse- to very coarse-grained in nature where the seam is absent. North-west of Indwe, on the farm Bannockburn, the Guba Seam is represented by a lens of coaly mudstone 50 cm thick. Two kilometres to the north-west, on the farm Perskenplaats, the seam is 1,6 m thick. In the extreme south of the Guba Coalfield the seam decreases in thickness to between 1 and 1,5 m.

Prospect adits and borehole logs indicate that the lower portion of the seam contains the better quality coal (Fig. 34). The basal part of the seam comprises between 60 and 110 cm of bright coal with thin vitrain bands, above which there is a dark grey, laterally continuous carbonaceous shale about 5 cm thick. This is followed by a seam about 1 m thick composed of alternating bright and dull coal bands. The upper portion of the seam, between 1 and 1,5 m thick, comprises thin bands of alternating bright and dull coal together with carbonaceous siltstone, mudstone or shale.

At other places in the field area thin, lenticular bands of bright coal occur directly below the Indwe Sandstone Member at the same horizon as the Guba Seam. These are never more than a few centimetres thick.

3) Cala Pass Seam

This is the culmination of a first-order, upward-fining cycle at the top of the Mayaputi Member at Cala Pass and in the vicinity of Indwe. The seam is laterally impersistent and generally of poor quality. It consists mainly of carbonaceous shale with thin bands of bright coal. The base is gradational from the underlying argillaceous sediments, and is recognizable by the first occurrence of thin bands of bright coal. In the Guba Valley the top of the seam may be abruptly overlain by dark grey, carbonaceous siltstone or mudstone but it is more commonly followed by medium-grained, erosively-based sandstone of the Qiba Member.

Around Indwe the seam is between 2 and 3 m thick, though generally contains an aggregate of less than 60 cm of coal as thin, discontinuous bands and lenses within carbonaceous shale. Borehole and outcrop information are insufficient to allow an estimate of the lateral extent of the seam in the Indwe area, suffice to say that it is present on the farm Perskenplaats to the north-west of Indwe and also for a distance of at least 15 km south-west of the same town.

A further occurrence of this seam is at the top of Cala Pass, after which this seam is named. It is visible in outcrop for a distance of only 800 m eastwards from the road to Elliot where it maintains a constant thickness of about 1,3 m, but becomes more shaly. There is no evidence of the seam to the west of the road or at Qiba. Adjacent to the Cala-Elliot road the seam comprises carbonaceous shale and mudstone with bands of dull coal up to 40 cm thick which may contain bright coal laminae (Fig. 35). Eastwards the seam becomes more shaly and plant fossils are abundant as carbonized impressions.

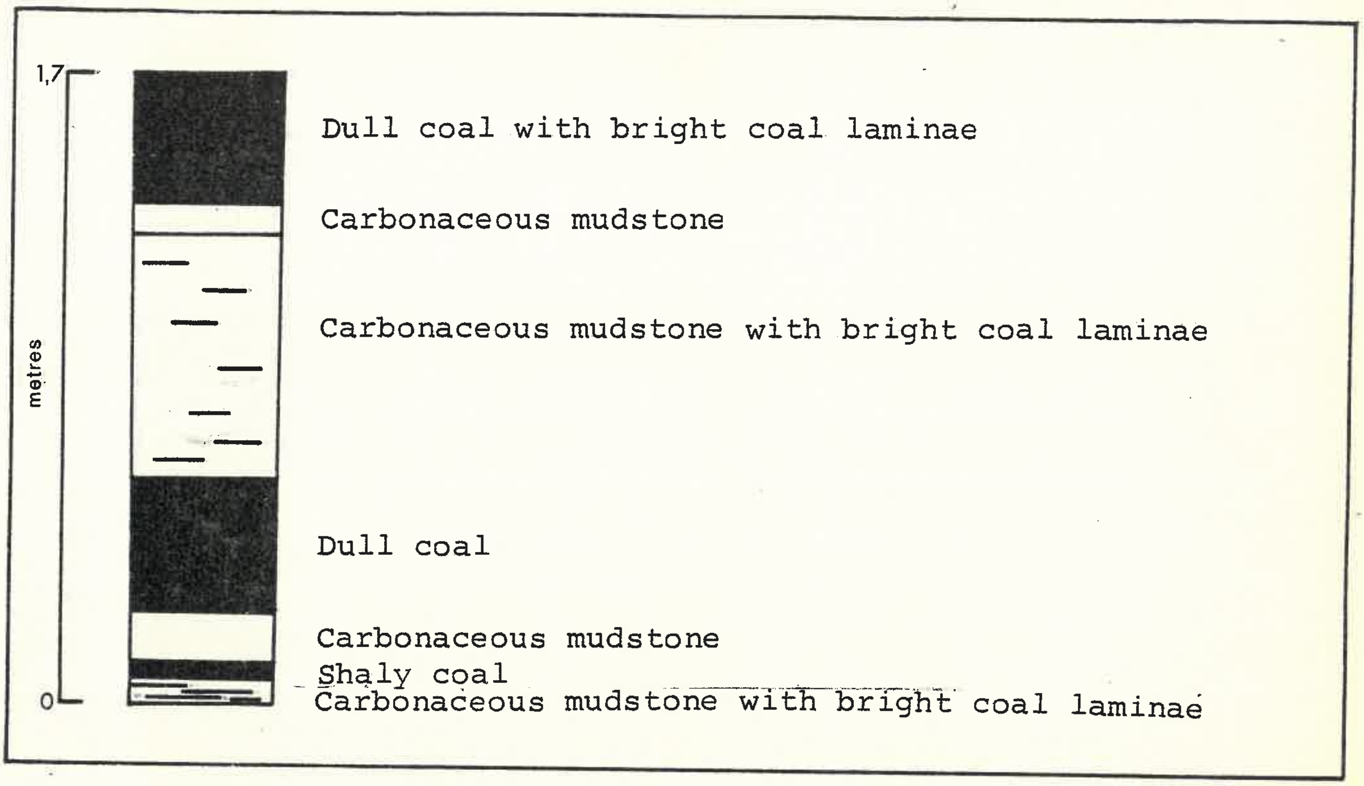


Figure 35. Section through the Cala Pass Seam alongside the road to Elliot at the top of Cala Pass.

4) <u>Ulin Seam</u>

The Ulin Seam is a laterally discontinuous band of coaly siltstone, mudstone and shale within the Qiba Member. It is exposed on the farm Ulin in a prospect adit, in the vicinity of the new Tsomo River bridge, and also near the junction of the Tsomo and Cicira Rivers north of the bridge. The seam occurs at the top of a first-order upward-fining cycle and is overlain by the erosively-based, medium-grained, upper sandstone of the Qiba Member. At Ulin, where the seam is exposed in a prospect adit, it is 1,7 m thick and comprises thin lenses of bright coal up to 2 cm thick in a matrix of brown to grey siltstone and mudstone. East of the adit the seam passes laterally into light olive siltstone and mudstone over a distance of less than 500 m.

At the Tsomo bridge the Ulin Seam is only 15 cm thick and comprises a friable, shaly coal with laminae of bright coal. It pinches out north of the bridge and reappears as a 10 cm thick coaly mudstone 3 km to the north, near the junction of the Tsomo and Cicira Rivers. Where the coal is not present between these three outcrops the Qiba Member comprises an uninterrupted succession of fine- and medium-grained sandstones. Leaf impressions found within this seam included _Dicroidium_, _Glossopteris_ and _Phyllotheca_.

5) _Coal Seams of the Loskop Member_

Coal seams within the Loskop Member are similar in character to the Ulin Seam in that they comprise only thin laminae or lenses of bright and dull coal and are of limited lateral extent. At Umnachean the seam reaches a maximum thickness of 20 cm and is visible along outcrop for no more than about 40 m. It consists of carbonaceous shale with numerous lenticular laminae of bright coal.

The Offa Seam (present on the farm Offa, 10 km north-west of Elliot) comprises two components (Fig. 28b). The lower one is developed at the top of a second-order upward-fining cycle and comprises a 90 cm band of dull, shaly coal with laminae of bright coal. This is overlain by a fine- to medium-grained, light grey, erosively based sandstone containing abundant fragments of bright coal between 5 and 30 mm thick and not more than 25 cm long, and fragments of charcoal (?pyrofusinite) which comprises the upper component. Lenses of mudstone and siltstone clasts up to 10 cm thick are also present. This part of the seam appears to be confined within a channel-shaped structure 35 m wide and 1,7 m deep and forms the base of a second-order upward-fining cycle. Two vertical tree trunks about 25 cm in diameter are present directly above the seam. Leaf impressions of _Baeira_, _Dicroidium_, _Ginko_, _Glossopteris_, _Phyllotheca_ and _Taeniopteris_ are also associated with this seam.

6) Quality of Coal

The economic properties of coal in the Indwe area were described by Ryan (1963) and included in Turner's (1971) report of coal in the north-eastern Cape. A summary of their results is appended as Table 1.

The coal is typically planar laminated, and composed of alternating bands or lenses of bright coal, dull coal and carbonaceous shale. The bright coal bands, composed of vitrain, are brittle and friable. Thin partings of fusian may also be present. Dull coal is commonly associated with carbonaceous shale and comprises fusian or durain. Cannel coal, present only in the Indwe Seam, is recognizable by its dull, greasy lustre, homogeneous nature, and conchoidal fracture when broken.

On the basis of volatile content, which is between 7,1 and 17 per cent (average 11,62 per cent), the rank of coal in the Indwe area ranges from low volatile bituminous to anthracite (Stach, 1975). The volatile content of the coals is generally inferior to that of other South African coals. It is apparent that the numerous dolerite intrusions present in the Indwe area have been responsible for increasing the rank of the coal.

Proximate analyses suggest that the high ash content of the coal is due to the introduction of extraneous mineral matter during peat formation. According to Turner (1971) the ash fraction comprises clay, calcium and magnesium carbonates, pyrite, marcasite and traces of chlorides, flourides and phosphorous.

TABLE 1. PROXIMATE ANLYSES OF COAL FROM THE INDWE AND CALA AREAS. (AFTER TURNER, 197I)

COAL SEAM	LOCATION OF SAMPLE	THICKNESS ANALYSED (CM)	S.G.	ANALYSIS OF FLOAT - AIR DRY BASIS				ASH YIELDS %		
				CALORIFIC VALUE (lb/lb)	H_2O %	VOLATILE MATTER %	FIXED CARBON %	FLOAT	SINK	RAW
INDWE	PERSEKENPLAATS	27,5	I,75	-	7,6	I7,0	47,3	28,I	54,7	48,7
"	"	50,0	"	-	4,2	I2,8	57,3	25,7	6I,9	39,9
"	"	42,5	"	-	2,7	9,7	56,8	30,8	59,I	42,2
"	BANNOCKBURN	40,0	"	I0,6	2,2	II,7	58,7	27,4	62,6	32,5
"	"	30,0	"	I0,6	I,7	II,8	58,2	28,3	57,4	32,5
"	"	55,0	"	I0,0	I,6	I2,0	55,I	3I,3	62,6	5I,2
"	"	47,5	"	I2,I	I,4	I2,0	64,7	2I,7	67,8	44,I
"	"	52,5	"	I0,8	3,4	I2,8	60,3	23,5	62,9	38,I
GUBA	GUBA FIELD	60,0	I,75	I0,3	2,4	7,I	60,9	29,6	64,5	58,7
"	"	50,0	"	9,7	I,5	I2,8	50,2	35,5	68,I	58,5
"	"	80,0	"	I0,2	I,3	I5,I	52,5	3I,I	64,4	47,5
"	"	85,0	"	II,7	I,3	I6,2	56,3	26,2	68,6	38,3
"	"	32,5	"	II,5	I,6	II,9	6I,8	24,7	59,4	32,2
"	"	I7,5	"	II,0	I,5	II,2	59,7	27,6	63,8	50,5
"	"	57,5	"	I0,9	I,6	II,9	57,9	28,6	7I,9	35,7
CALA PASS*	CALA PASS	±30,0	I,75	-	±I,8	±I0,4	±68,I	±I,9	-	-

*Values of Cala Pass Seam calculated from Turner (197I, Fig I4).

CHAPTER 3

COMPOSITION AND TEXTURE OF SANDSTONES

Petrographic analyses were carried out to establish the composition of the sandstones and to investigate the possibility of compositional variations within the Molteno Formation. Light and heavy mineral assemblages were examined to assess the nature of the source terrain. Textural analyses of the sandstones were mainly concerned with detrital grain sizes.

A) GENERAL PETROGRAPHY

1. Petrographic Description

i) Quartz

Quartz is the principal constituent of all the sandstones. The grains are generally subrounded to subangular, though a few well rounded ones are present. A large proportion of grains are strained and display undulatory extinction. Polycrystalline quartz grains occur, but these are regarded as rock fragments.

The detrital character of quartz grains is commonly modified by diagenetic overgrowths which may comprise up to 12 per cent

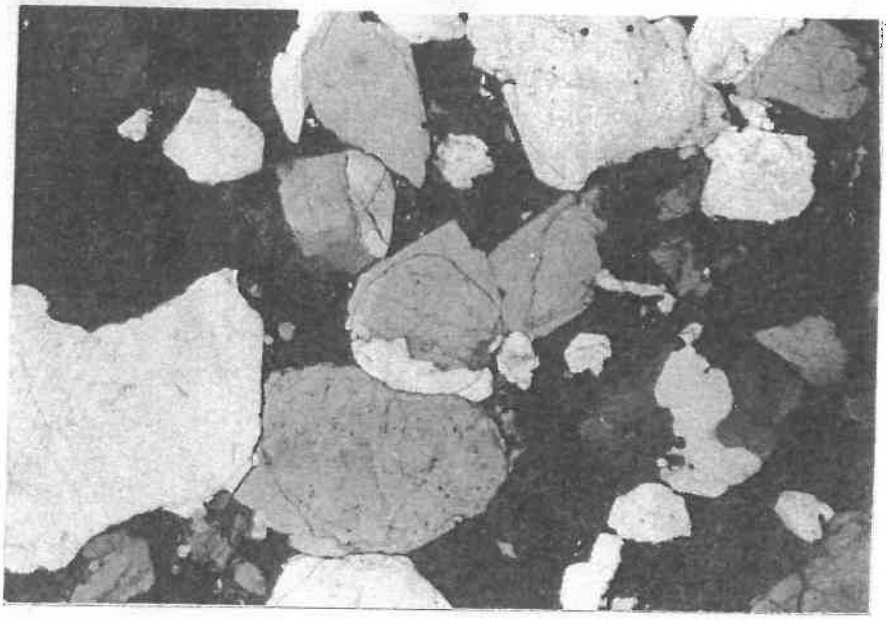


Figure 36. Secondary-quartz overgrowths on detrital quartz grains. Boundaries between detrital grains and quartz overgrowths are defined by lines of dark inclusions. Note the well rounded detrital grain in centre of micrograph in contrast to the subrounded to subangular character of the others. Indwe Sandstone Member, Qiba. (crossed nicols-x40).

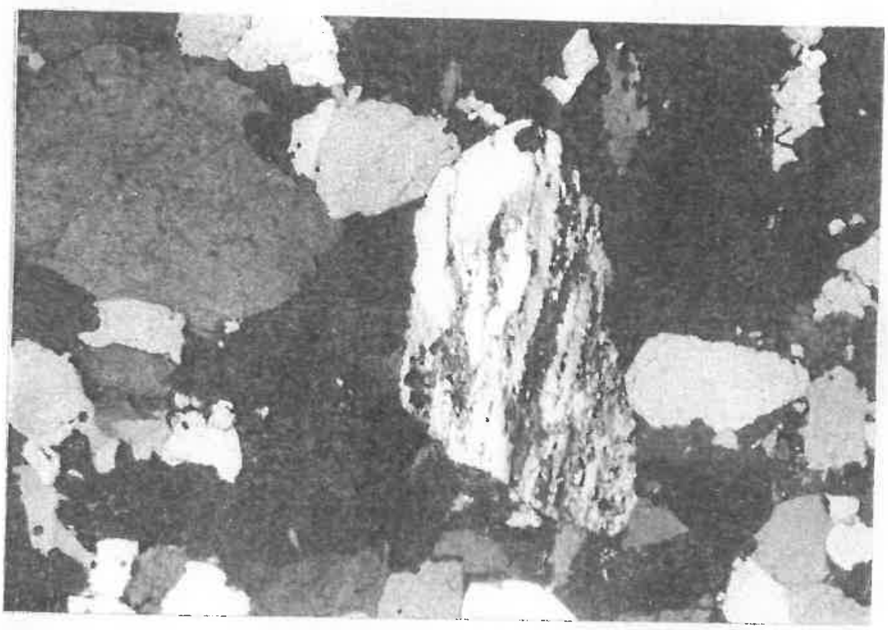


Figure 37. Elongate rock fragment showing undulose extinction and sutured intercrystalline boundaries. Loskop Member, Loskop. (crossed nicols-x40).

of the sandstone (Fig. 36). The quartz overgrowths commonly result in the formation of euhedral crystal faces and in mosaics of interlocking grains. Overgrowths are in optical continuity with detrital grains, even when the latter show undulose extinction or are polycrystalline. The contact between a detrital grain and its overgrowth is commonly marked by a distinct line of small, dark inclusions.

Long, point and floating contacts are most commonly developed between detrital grains, though a moderate number of sutured and concavo - convex ones were also observed. Contacts between grains with quartz overgrowths are generally concavo - convex or planar. Small acicular rutile needles may be present within quartz grains.

ii) Feldspar

Plagioclase and potassium feldspars are present in varying proportions in Molteno sandstones, the former being generally more abundant. Determinations of plagioclase composition were made using the Michel-Levy method (Kerr, 1959) whereby extinction angles of albite twins in sections normal to (010) are measured. The anorthite content was obtained using the Michel-Levy graph included in the above publication. The maximum anorthite content was An_{46} but the average was between An_6 and An_{34}. (i.e. albite to andesite). Fresh, partially and totally decomposed grains are present, the latter being difficult to distinguish from the clay matrix or siltstone clasts. Fresh and completely weathered grains are commonly present in the same thin sections, and may even be adjacent to one another.

Plagioclase feldspars show albite-, carlsbad-, and less frequently, pericline-twinning and are typically lath shaped. Potassium feldspar is usually associated with coarser-grained sandstones. Both microcline and orthoclase were present;

microcline being the commoner of the two. Very few microcline grains were weathered or decomposed.

iii) Rock fragments

Rock fragments are capable of providing an important indication of source rock composition. They are commonest in the coarser sandstones, particularly those of the Indwe Sandstone and Loskop Members. The fragments show little variation in composition and generally comprise polycrystalline quartz, though small amounts of potassium and plagioclase feldspar and muscovite may also be present. Some fragments contain elongate, semi-aligned quartz crystals with sutured intercrystalline boundaries (Fig. 37). Crystals range from very fine to medium sand size, and frequently display a bimodal size distribution. A second type of rock fragment contains undeformed crystals and has a welded texture. Lithic fragments are generally larger in size than monocrystalline grains.

iv) Mica

Mica is not a common constituent of the sandstones, muscovite being more common than biotite which is rarely present. Mica generally occurs as small, lath-shaped grains with ragged edges, deformed around adjacent quartz or feldspar grains and is considered to be detrital.

v) Matrix

Much of the matrix is composed of clay minerals, though carbonaceous material may also be present. Most of the matrix appears to be of detrital origin with only a small quantity being due to authigenic alteration of potassium and plagioclase feldspar. No X-ray diffraction, microprobe or chemical analyses were carried out to determine the composition of the clays. X-ray diffraction analyses carried out by Turner (1969) on Molteno sandstones from the Aliwal North district showed the matrix to consist mainly of quartz and feldspar, with illite and montmorillonite as the main clay minerals.

2. Quartz Overgrowths

Weyl (1959) suggested that a pressure solution mechanism might account for the presence of quartz overgrowths on detrital grains. He thought that high effective pressures between the point contacts of quartz grains could increase solubility and result in the release of SiO_2 to the pore water. When the pore water became supersaturated with respect to SiO_2, quartz would be precipitated as overgrowths on the quartz grains. Pettijohn et al. (1972) interpreted well defined boundaries between detrital grains and overgrowths as evidence for pressure solution. Boundaries of this kind as well as the presence of sutured boundaries between detrital grains suggests pressure solution as a mechanism for inducing secondary quartz-overgrowth. This does not, however, preclude the possibility that authigenic quartz may have formed by the introduction of silica supersaturated pore waters (Siever, et al., 1965). Quartz overgrowths on floating detrital grains may attest to such a mechanism.

Matrix content and grain size play an important role in authigenic quartz growth in sandstones of the Molteno. The relative scarcity of quartz overgrowths in fine- to medium-grained, matrix-rich sandstones may possibly be due to the lower porosity of such sediments, which would no doubt have inhibited pore-water circulation. Furthermore, a high matrix content would tend to decrease the number of direct grain contacts and act as a cushion against pressure effects.

3. Modal Analysis

Modal analyses were carried out to determine the primary mineralogical composition of sandstones in each member, and to discover whether any upward variation in composition existed.

A total of approximately 500 grains were counted in each thin section using a Swift point counter. The proportions of quartz, plagioclase feldspar, potassium feldspar, rock fragments, secondary quartz-overgrowths, hematite cement and matrix were computed (Table 2).

i) Classification of sandstones

Turner (1975a) experienced difficulty in classifying the Molteno sandstones using conventional classification schemes because of the large amount of matrix present and the variable feldspar content. A similar difficulty was experienced during this investigation. Modal analyses resulting from this study seem to be in satisfactory agreement with those given by Turner (op. cit.), though he failed to give any indication of the exact stratigraphic horizons from which his samples were collected.

In this thesis the sandstones were classified using the scheme of Pettijohn et al. (1975) which is based on frame-work grains of quartz, feldspar and rock fragments. Matrix content is used to assign the sandstones to either the arenite or wacke (greater than 15 per cent matrix) subdivisions. The matrix content of sandstones from the Bamboesberg and Qiba Members and from the upper part of the Indwe Sandstone places them within the wacke subdivision and, depending on the relative proportions of feldspar and rock fragments, these rocks would be described as feldspathic or lithic wackes. The high feldspar content of the Qiba Member identifies it as an arkosic wacke. Sandstones from the lower part of the Indwe Sandstone Member and the Loskop Member are classified as arenites because of their relatively low matrix content. On the basis of their relative feldspar and rock fragment content they would be either subarkoses or sublith-arenites.

Table 2: MEAN MODAL ANALYSIS OF MOLTENO FORMATION SANDSTONES

MEMBER	Q	PF	KF	RF	M	QO	HC	n
BAMBOESBERG	68	7	1	2	21	2	Tr	6
INDWE SANDSTONE	62	2	7	10	12	4	3	6
INDWE SANDSTONE (Upper)	70	5	Tr	2	22	Tr	Tr	3
QIBA	51	27	1	2	18	1	Tr	6
LOSKOP	63	1	5	10	11	8	2	8

Q : Quartz.

PF : Plagioclase feldspar.

KF : Potassium feldspar.

RF : Rock fragments.

M : Matrix.

QO : Quartz overgrowths.

HC : Hematite cement.

n : Number of slides analysed.

Tr : Trace amount. (< 0,5%).

4. Grain Size Analysis

Thin section grain-size analyses were initially carried out to provide textural information concerning the Molteno sandstones. However, other than confirming that grain size variations between members exist, a fact which was already apparent from the field data, nothing further was gained. Mean grain diameters were calculated (Table 3) in order to provide a quantitive basis on which to establish the relationship between grain size and composition. Mean grain diameters obtained from thin-section data were converted to equivalent sieve sizes using Friedman's (1958) correction factor. These measurements were converted to phi-notation and plotted as cumulative frequency curves. Mean diameters were calculated using the formula of Folk and Ward (1957).

Table 3: MEAN GRAIN DIAMETERS OF SANDSTONE

MEMBER	n	Mean grain diameter range for a sample (Ø)	Composite mean grain diameter (Ø).
Bamboesberg	5	1,5 - 2,4	1,9
Indwe Sandstone (Lower)	4	0,4 - 1,1	0,6
Indwe Sandstone (Upper)	2	1,8 - 2,5	2,2
Qiba	4	1,4 - 2,2	1,8
Loskop	6	0,5 - 1,44	0,8

Mean grain sizes computed on the basis of thin-section data are slightly smaller than those estimated from hand specimens. This may be due to the presence of secondary quartz-overgrowths (not taken into account in hand specimens), to a bias towards the selection of slightly finer samples for thin section analysis, or even to Friedman's (1958) statistical technique for converting thin-section diameters into equivalent sieve-size diameters.

5. Compositional Trends

From the foregoing, certain relationships become apparent:

1) Rock fragments and potassium feldspar are more common in the coarse-grained units (Indwe Sandstone and Loskop Members).
2) Plagioclase is more abundant in the Qiba Member than in other parts of the Molteno.
3) Secondary quartz-overgrowths are commonest within sandstones of coarser mean grain size and lower matrix content.
4) There is a marked difference in mineral composition between fine- to medium-grained sandstones in the upper part of the Indwe Sandstone and those of the lower, coarser part.

B) HEAVY MINERAL ANALYSIS

Heavy mineral analyses were carried out on eighteen hand specimens collected from each sandstone member of the Molteno Formation in the field area. Following crushing, using a mortar and pestle, the heavy minerals were separated using the standard bromoform technique and examined under the microscope.

The four minerals present were identified as garnet (colourless and pale pink/red), zircon (colourless), rutile (yellow-brown) and tourmaline (colourless and pale green). No systematic , or even significant variation in heavy mineral suites was found among the specimens.

i) Garnet

This is the most abundant heavy mineral and it usually occurs as anhedral to subhedral, angular to subangular grains, commonly showing conchoidal fracture. Reynolds (1980), assigned most garnets he collected from the Molteno Formation to the almandine-pyrope class, on the basis of chemical analyses, though some had a small grossularite component.

ii) Zircon

Most grains showed a conspicious zoning and commonly contained black inclusions. The zircons were subhedral to euhedral and generally subrounded.

iii) Rutile

Rutile is not common, and occurs as subhedral, subrounded to subangular grains.

iv) Tourmaline

Tourmaline was the least abundant heavy mineral present, as Turner (1975a) also found. A few euhedral basal prisms of tourmaline were observed, but this mineral generally occurs as subhedral to anhedral, subangular to subrounded grains.

v) Opaque heavy minerals

Thin section analysis confirmed that this class of heavy minerals is more common than the non-opaque variety. Magnetite and ilmenite are the commonest and are associated with minor amounts of leucoxene.

C) PROVENANCE

Owing to the common occurrence and durable nature of quartz, it is not indicative of any particular provenance. Quartz showing undulose extinction is common in both igneous and metamorphic terrains. Acicular rutile inclusions are common in quartz of granitic derivation.

The varying degrees of decomposition shown by plagioclase feldspar in the sandstones examined present an interesting problem as to whether pre- or post-depositional alteration is represented. Although calcic plagioclase is generally more altered than sodic plagioclase, all feldspars show the same range of weathering. Some plagioclase feldspars, particularly those in the Bamboesberg and Qiba Members, are extensively altered and it is unlikely that they would have survived transport in such a state. Nevertheless, evidence suggesting weathering at source or during transport is provided by the absence of authigenic kaolinite (Turner, 1969) and by the absence of any difference in the degree of weathering between surface and borehole-core samples from Indwe (Ryan, 1963). Turner (1975a) suggested that the absence of kaolinite as an alteration product of feldspar may be interpreted as an indication of high relief, low temperature and seasonal rainfall. Low temperatures associated with high relief suggests that mechanical would be more important than chemical weathering.

The variation in feldspar content between members in the Molteno (Table 2) may be a function of the distance of the depositional site from the source area, or of variation in the composition of the source rocks. According to Krynine (1936) and Pettijohn et al. (1972) the amount of feldspar eventually deposited is a function of relief, rate of erosion and the ratio of mechanical to chemical weathering. Blatt et al. (1972) suggested that due to the well-developed cleavage, abundant twinning and partially hydrolized state of feldspar, its mechanical strength is not great and it is rapidly destroyed in turbulent environments. It therefore appears that the amount of feldspar eventually deposited may be only a small proportion of what was initially available in the source area, so that it is not an accurate indication of source-rock composition. This complication is compounded by the higher stability of quartz and microcline which would thus be proportionately better represented than plagioclase feldspar in the depositional basin.

The exclusive presence of alkali feldspars may be a reflection of their higher stability compared with calcic ones, but may also be indicative of a source area comprising acid to intermediate plutonic igneous rocks or gneisses (Pettijohn et al., 1972). The higher potassium: plagioclase feldspar ratio in the Indwe Sandstone and Loskop Members implies derivation from granitic source rocks, while the anomalously high plagioclase feldspar content of the Qiba Member may reflect high relief and rapid erosion in the source area (Krynine, 1936). The relatively fine-grained nature of that member, however, suggests a more distal environment than that envisaged for the Indwe Sandstone, so that the feldspar content would be expected to be correspondingly reduced. This seems to present a substantial argument favouring the derivation of sediment from provenance areas of differing composition.

Lithic fragments supply valuable information concerning the lithology of provenance areas (Blatt et al., 1972) and are therefore important. As Turner (1975a) suggested, the rock fragments present in the Molteno imply the existence of two different source lithologies. Rock fragments comprising elongate, sutured quartz grains with a bimodal size distribution imply a metamorphic provenance (Blatt and Christie, 1967), while those grains which do not show elongation and comprise two to five quartz crystals are indicative of quartz from granitic rocks (Blatt et al., 1972). Both types of rock fragment may have been derived from a similar source area, for granitoid intrusions into metamorphic assemblages are common in the Basement Complex (Truswell, 1977).

The clear relationship between sandstone grain-size and rock-fragment content reflects the succeptibility of polycrystalline grains to disaggregation during transport (Pettijohn et al., 1972). This is in keeping with the hypothesis that the coarser sandstone units were derived from an area undergoing rapid erosion, and were subjected to a relatively short period of transportation prior to deposition.

Quartzite pebbles and cobbles within the Molteno Formation include large numbers of polycrystalline quartz fragments similar to those grains considered to have a metamorphic derivation. This similarity prompted Turner (1975a) to suggest that the quartzite pebbles and cobbles were derived from the Witteberg quartzites of the Cape Supergroup (Rust, 1959) and that the metamorphic rock fragments were derived from a similar source.

The mica content of the sandstones is generally too low to have significance in provenance studies. Pettijohn et al. (1972) stated that detrital mica is mostly derived from schists, gneisses and plutonic igneous rocks. It has also been reported that muscovite may survive a second cycle of sedimentation (Kerr, 1959).

Visual comparison of the degree of roundness of detrital grains with the roundness scale of Powers (1953) shows that most of the grains are in the subangular to subrounded range, while a small proportion are rounded or even well-rounded. Rounding is known to be a slow process, and becomes progressively slower with decreasing grain size (Pettijohn et al., 1972). Calculations by Kuenen (1959) showed that 20 000 km of transport is required for a 1 per cent weight loss of an angular, medium-grained sand quartz grain. The subangular to subrounded shape and immature nature of the detrital grains suggests no more than a single cycle of sedimentation and a depositional site that was not far removed from the source area.

Evidence for a sedimentary source is provided by the presence of well-rounded quartz grains. These constitute only a small proportion of the total sandstones sampled, and the implied sedimentary source area is considered to have been of correspondingly minor importance.

Although heavy minerals are generally considered a valuable aid in assessing source-area lithology, the ultra-stable assemblage yielded by the Molteno samples does not provide any useful evidence. The absence of less stable heavy minerals may be indicative of either extensive weathering of the source rocks in situ or derivation from a sedimentary source area. The variation in degree of rounding of non-opaque mineral particles was thought by Turner (1975a) to be indicative of variations in source-rock composition. Reynolds (1980) suggested that almandine-pyrope garnets were derived from amphibole-bearing metamorphic rocks and grossularite from contact metamorphic rocks. It is also possible that the rounded nature of some of the grains reflects a second cycle of sedimentation. Tourmaline is generally associated with acid igneous and metamorphic rocks.

D) SUMMARY

The most dependable directional evidence for the location of the source area of the Molteno strata is provided by palaeocurrent data which indicate derivation from the south-east, south and south-west (Chapter 8). The heterogeneity of sandstone composition suggests a varied source terrain. The quartz component may have come from a granitic or granitoid terrain. Evidence for a limited sedimentary source is provided by the well-rounded shape of some of the detrital quartz grains. The presence of undeformed, polycrystalline quartz suggests derivation from a granitic environment, while the deformed variety with elongate and recrystallized grains indicates contributions (probably minor) from a metamorphic terrain. The sodic-rich plagioclase feldspars were probably derived from acid igneous or metamorphic rocks, while microcline usually occurs in granites, syenites and gneisses Muscovite is a common constituent of pegmatites, more acidic granites, and metamorphic rocks such as phyllites, schists and fine-grained gneisses. The limited heavy mineral assemblage provides no conclusive indication of derivation from an acid terrain.

In conclusion, it appears likely that the Molteno was derived from a source area of predominantly acid-plutonic rocks, with lesser amounts of material from metamorphic rocks. Turner (1975a) suggested that the low grade quartzose metasediments of the Witteberg also contributed to the Molteno. A further possibility is that a small proportion of the sand may have been derived by reworking from sandstones of earlier Karoo strata (Ecca or Beaufort Groups).

CHAPTER 4

SEDIMENTARY FACIES

A) INTRODUCTION

A sedimentary environment is generally understood to refer to the place of deposition of sediments and to the "... physical, chemical and biological conditions which characterize the depositional setting" (Gould, 1972, p 1). The hydrodynamic conditions under which a sedimentary rock is deposited are reflected in its texture and composition, the geometry and scale of sedimentary structures, and the absence or presence of biological activity. It is the sum total of these primary characteristics imprinted on a rock which define a sedimentary facies. However, a facies in isolation gives comparatively little information regarding the palaeoenvironment of a sedimentary sequence; it is the association and mutual relationships of facies that are of greatest significance.

In order to reconstruct the palaeoenvironment during Molteno times, observed field characteristics and relationships of facies are compared with results obtained from laboratory studies and with models based on processes and their results in present day depositional environments.

On the basis of the field work seven sedimentary facies were recognized:-

1) Facies Cp - rock pebble conglomerate.
2) Facies Cm - siltstone and mudstone clast conglomerate.
3) Facies St - trough cross-stratified fine- to very coarse-grained, pebbly sandstones.
4) Facies Spc - planar cross-stratified fine- to very coarse-grained sandstone.
5) Facies Sp - planar stratified fine- to very coarse-grained sandstone.
6) Facies F - mudstone and siltstone.
7) Facies C - coal.

Following the principle that sedimentary facies may be regarded as the building blocks of which stratigraphic sequences are composed (Harms et al., 1975), the method of Cant and Walker (1976) was used to construct a palaeoenvironmental model for each stratigraphic member. Each facies is defined with respect to its lithological, structural and organic properties and then interpreted in terms of the conditions under which it was deposited. Following this a general vertical facies sequence for each member is derived and the facies are interpreted in terms of their mutual associations and the physical environments from which they are thought to have originated. Owing to the particular importance of coal as a palaeoenvironmental indicator, it is dealt with separately following the environmental interpretation of each member of the Molteno Formation.

B) FACIES DESCRIPTION

1) Facies Cp: Rock pebble conglomerate.

Both matrix- and clast-supported conglomerates are present, the former being commoner in the Indwe Sandstone Member and coarse-grained sandstone components of the Loskop Member. The conglomerates range in thickness from a single pebble layer to 3,1 m. Clasts are of colourless and white quartz, potassium and plagioclase feldspar, and quartzite. Mudstone and siltstone clasts are also present, though subordinate in amount.

Within the matrix-supported conglomerates clasts consist of subangular to rounded pebbles 2 to 20 mm in diameter. Larger, well-rounded ellipsoidal quartzite pebbles, cobbles and boulders with long-axis lengths up to 60 cm, though more generally between 4 and 18 cm, are thinly scattered through the conglomerate. Intermediate-: long-axial ratios of between 0,65 and 0,85 and short-: intermediate-axial ratios of between 0,40 and 0,75 place these larger clasts predominantly in the oblate and equant fields of the Zingg (1935) shape classification diagram. These larger clasts may be roughly imbricated, with long axes approximately normal to the current direction as indicated by overlying trough cross-stratification. The matrix comprises only a small proportion of clay and silt; fine- to coarse-grained, generally poorly sorted sand size material being most common.

Clast-supported conglomerates are not as well represented as matrix-supported ones, but are similar to them in most respects. The clasts are generally slightly smaller, ranging from 5 to 15 mm in diameter. Larger ones (greater than 20 mm in diameter) are rarely present. The matrix consists of clay to fine-grained sand size material, and is moderately well sorted.

Both types of conglomerate are massive or crudely planar stratified, but may also display crude trough and planar cross-stratification. They are commonly at the base of upward-fining second-order cycles which overlie erosional surfaces. The conglomerate may exhibit either a gradual upward decrease in pebble size or have an abrupt upper junction. Clast-supported conglomerates generally occur as lenses within the matrix-supported conglomerates, or are laterally gradational into them.

2) Facies Cm: Siltstone and mudstone clast conglomerate.

Matrix-supported intraformational conglomerates are developed throughout the Molteno Formation, but are commonest within the Bamboesberg and Qiba Members and in the finer sandstone units of the Loskop Member. They range from less than 2 cm to 45 cm in thickness. Clasts are generally angular to subangular, disc-shaped fragments of mudstone, siltstone and shale up to 30 cm across and 2 cm thick. Solitary quartzite pebbles and cobbles, plant debris, and sandstone fragments may also be present, but are subordinate in amount.

Some conglomerates show siltstone and mudstone clasts with the primary sedimentary structure deformed. In one exposure along the Tsomo River, on the farm Umnachean, clasts with deformed lamination (Fig. 38) are visible only centimetres away from the bed from which they were derived, and the latter was also intensely deformed. This is significant with respect to the genesis of these intraformational conglomerates as it provides an indication of the degree of cohesion of the substrate prior to it being ripped up.

Matrix grain size varies from medium- to coarse-grained sand and appears to become coarser with increasing clast size. The conglomerates are mainly massive, but crude planar bedding and trough cross-stratification were also seen. These conglomerates also occur at the base of upward-fining second-order cycles overlying erosional surfaces. The upper boundary of the conglomerate may be either abrupt or there may be a

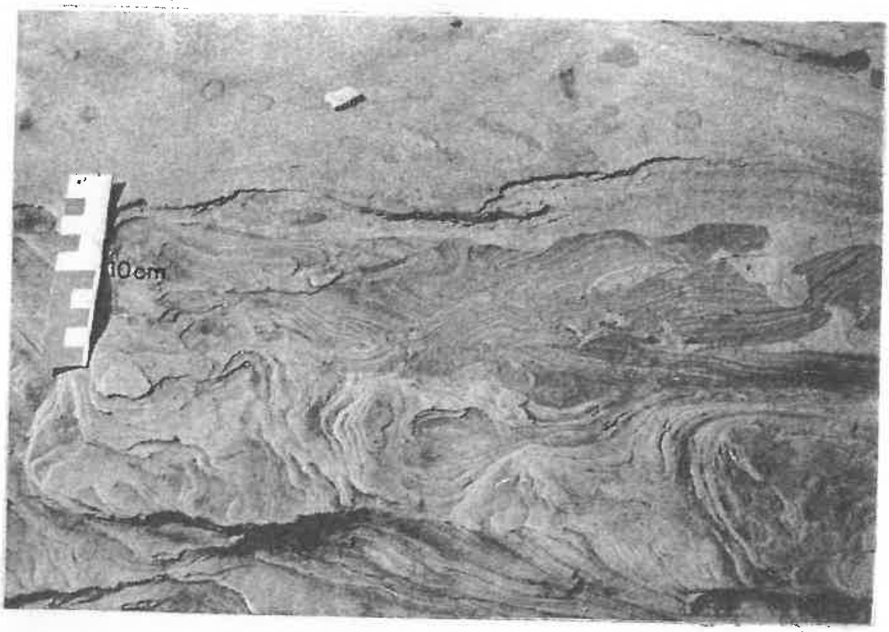


Figure 38. Deformed laminae in siltstone clasts. Loskop Member, on the western boundary of the farm Umnachean. (Scale 10 cm).

Figure 39. Small scale trough-cross stratification. Loskop Member, on the eastern bank of the Tsomo River near the western boundary of the farm Umnachean.

gradual upward decrease in clast concentration and a gradational junction with the succeeding bed. In the Qiba Member intra-formational conglomerates occur in the upper part of cycles as lens-shaped bodies up to 12 m wide and 60 cm thick.

3) Facies St: Trough cross-stratified sandstone.

Trough cross-stratification is one of the most common sedimentary structures within the Molteno Formation and is particularly well developed within the Indwe Sandstone Member and sandstone units of the Loskop Member but is relatively rare in the Bamboesberg and Qiba Members. This facies is composed of well defined wedge-, tabular-, and trough-shaped sets generally between 15 and 80 cm thick. Troughs may be up to 10 m wide, (average 1,5 m), and are traceable in the downcurrent direction for up to 15 m. Cosets are between 1,5 and 7 m thick. The lower surfaces of sets are commonly erosive, with an accompanying thin pebble wash immediately above. In some outcrops set bases dip upcurrent at angles of between 5° and 12° to the main bedding.

Trough cross-stratification is present in medium- to very coarse-grained, pebbly sandstones, but is commonest in sandstones that are coarse- to very coarse-grained. Discontinuous mudstone and siltstone drapes occur between successive sets. In the Indwe Sandstone Member trough cross-stratification is present in upward-fining, second-order cycles above massive to crudely-stratified pebbly sandstones or conglomerates. There may be a minor decrease in set thickness and grain size towards the tops of cycles. Within the Bamboesberg and Qiba Members trough cross-stratification is usually associated with coarse-grained sandstone, and developed as solitary sets.

Included in this facies, because of its uncommon development, is small scale trough cross-stratification (Fig. 39). Sets of this kind are similar to the larger scale structures but are only up to 5 cm thick and restricted to fine- or medium-grained sandstone. Small scale trough cross-stratification occurs at or near the top of the sandstone component of upward-fining cycles, where there is generally a rapid decrease in set thickness and grain size. It also occurs in thin sandstone beds within the dominantly argillaceous sequences.

4) Facies Spc: Planar cross-stratified sandstone.

This facies is developed throughout the Molteno but is not as common as trough cross-stratified sandstones. Set thickness ranges from 8 cm and 2,5 m but averages between 20 and 80 cm. Although solitary sets are fairly common, cosets up to 8 m thick are present. Sets are usually tabular- or wedge-shaped, the base of each being either slightly erosional with low relief or non-erosional planar. Some sets persist in the downcurrent direction for up to 30 m and laterally along strike for 60 m.

Planar cross-stratification occurs in the Bamboesberg and Qiba Members in sandstones that are fine- to medium-grained and in medium- to very coarse-grained sandstones in the Indwe Sandstone and Loskop Members. The sandstones are moderately to well sorted and normally-graded foresets are common.

Most tabular-shaped sets are interrupted by reactivation surfaces. Another common occurrence is the convergence of smaller sets of planar cross-strata (up to four) to form a single large set in the downstream direction. Thin intercalations (up to 12 cm) of planar-laminated or thinly-bedded sandstones, or less commonly ripple cross-lamination, may be developed between successive sets.

Three types of planar cross-stratification were recognised in the Molteno Formation on the basis of the relationship between the foresets and the lower bounding surfaces of the set. (Crook, 1965; Kelling, 1969). The most common type, planar A, consists of straight, tabular foresets discordant to the lower bounding

Figure 40. Planar A-type cross-stratification. Indwe Sandstone Member, river valley 1,5 km south of Qiba.

Figure 41. Planar B-type cross-stratification. Loskop Member, on the southern slope of Loskop.

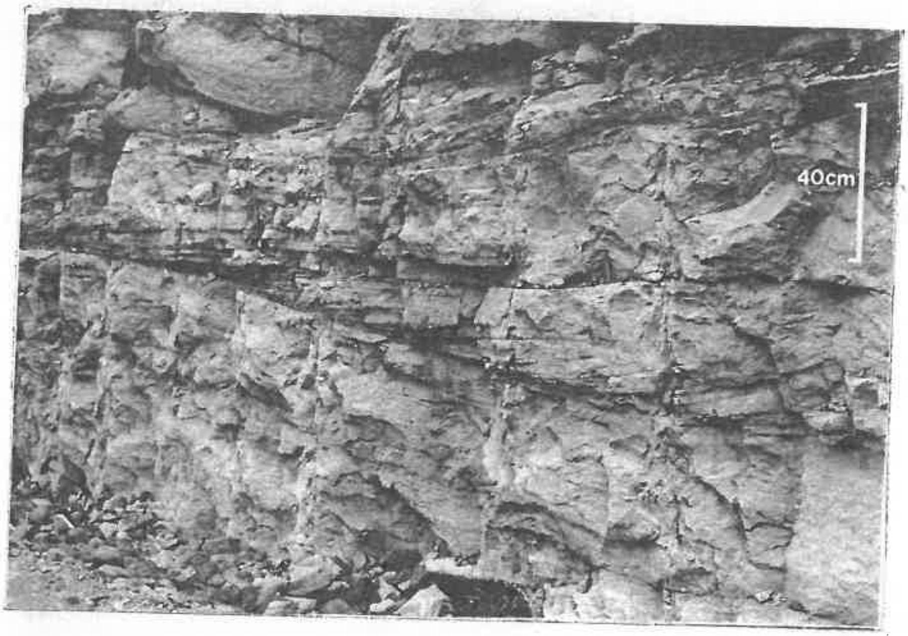


Figure 42. Planar C-type cross-stratification filling a shallow scour. Qiba Member, Tsomo Bridge.

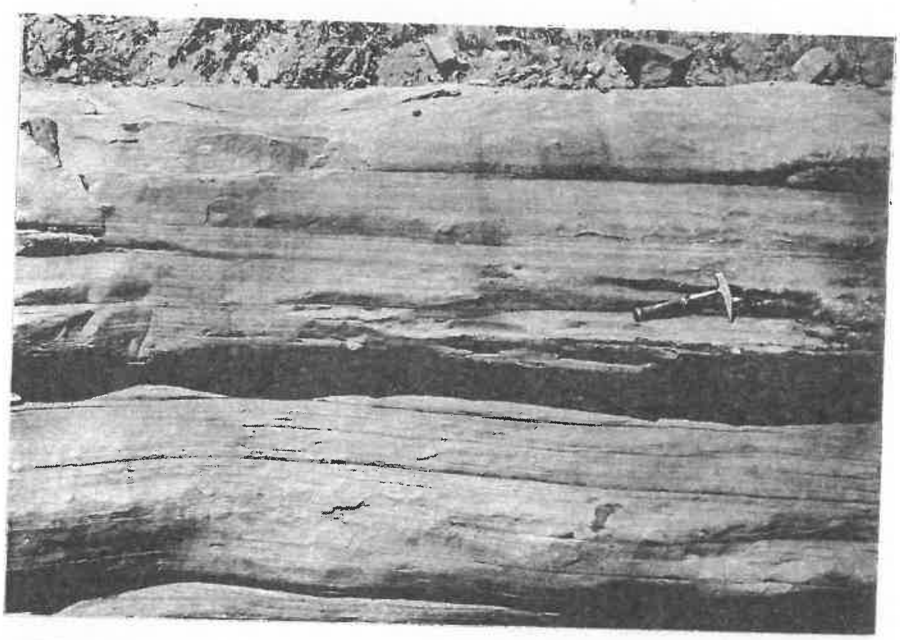


Figure 43. Regular planar-bedding. Bamboesberg Member, river valley 1 km south of Qiba.

surface of the set (Fig. 40). Sets are usually tabular, but pronounced wedging is also present in places. Foresets of planar B-type change slope near the lower bounding surface of the set and develop into tangential or asymptotic bottom sets which may persist laterally for some distance (Fig. 41). The foresets are not as steeply inclined as those of the planar A-type. A third type of cross-stratification, planar C, is similar to Facies G of Cant and Walker (1976) and Facies Sl of Rust (1978). In this type, foresets dip at a maximum angle of about 10^{o} and are laterally transitional into horizontally-stratified sandstone (Fig. 42). Occurrences of planar C-type cross-stratification are restricted to the fine- and medium-grain sandstones of the Qiba Member and, to a lesser extent, the Bamboesberg Member. Downstream increase in foreset inclination from planar B- or planar C-type into planar A-type cross-stratification may commonly be observed.

5) Facies Sp: Planar stratified sandstones.

Planar stratification is the term used to describe stratification that is essentially horizontal, but may dip at up to 6^{o} in various directions. This facies is extensively developed within the Molteno Formation and is the most common sedimentary structure present in the Qiba and Bamboesberg Members. Two sub-facies are recognised, each of which is subject to a different hydrodynamic interpretation.

i) Facies Spr: Regular planar-stratified sandstone.

Stratification of this sub-facies comprises parallel, fine- to medium-grained sandstone laminae and beds 2 mm to 10 cm thick which occur in units up to 2,5 m thick. The characteristic feature of stratification in this facies is their essentially horizontal attitude and lateral continuity (Fig. 43). Thicker beds may commonly be followed laterally over entire outcrop

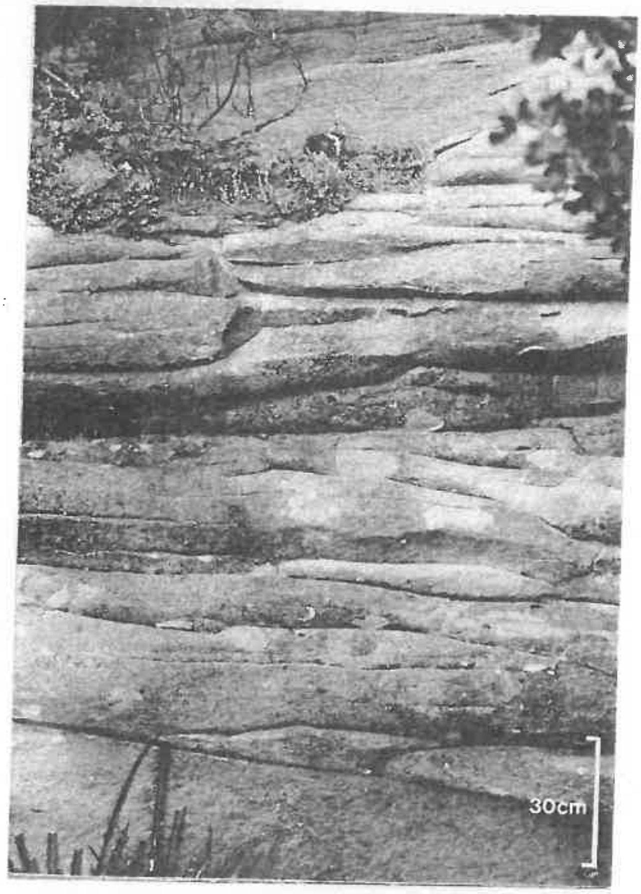


Figure 44. Irregular planar-stratification. Bamboesberg Member, 1,5 km north of Cala.

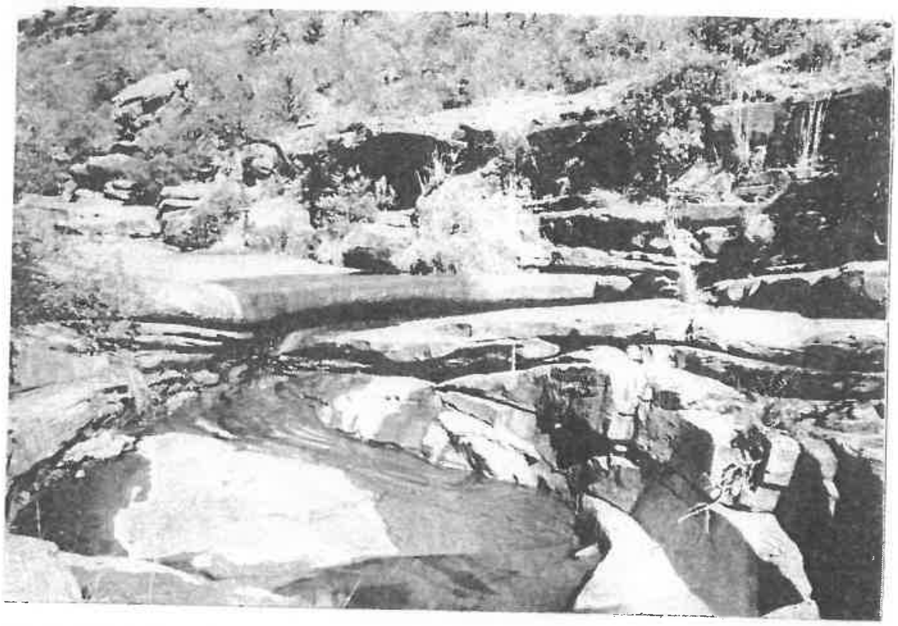


Figure 45. Lenticular bedding. Bamboesberg Member, river valley 1 km south of Qiba.

widths, while laminae are continuous for distances of at least 90 cm. Only a few examples of primary current lineation were found, but the nature of the outcrops did not generally allow examination of bedding surfaces. This facies usually occurs at or near the top of second-order upward-fining cycles or as thin (5-15 cm) intercalations between planar cross-stratified sets.

ii) Facies Spi: Irregular planar-stratified sandstone.

This facies includes beds which contain slightly undulating, laterally discontinuous bedding planes and beds which are lenticular in shape. Discontinuous planar-stratification may dip at angles of up to 6° and the beds are generally between 10 and 60 cm thick. They can rarely be traced laterally for distances exceeding 6 m and contain poorly defined internal laminations which are also discontinuous (Fig. 44). Lenticular beds are up to 60 cm thick and about 15 to 20 m wide. They may be massive, or show internal laminae which are horizontal and parallel, or laterally discontinuous and dip at low angles. The lenticualr nature of these beds may have been due to an irregular surface of underlying strata or to erosion prior to deposition of the overlying strata (Fig. 45).

Lenticular bedding is particularly well developed within the Bamboesberg Member and is usually present in medium- to coarse-grained sandstones occupying the lower portions of second-order upward-fining cycles. With an upward decrease in grain size the stratification becomes more regularly developed and grades into Facies Spr (Fig. 46).

6) Facies F: Siltstone and mudstone.

Siltstone and mudstone comprise a very small proportion of the Bamboesberg, Indwe Sandstone and Qiba Members, but are major constituents of the Mayaputi, Tsomo and Loskop Members. The

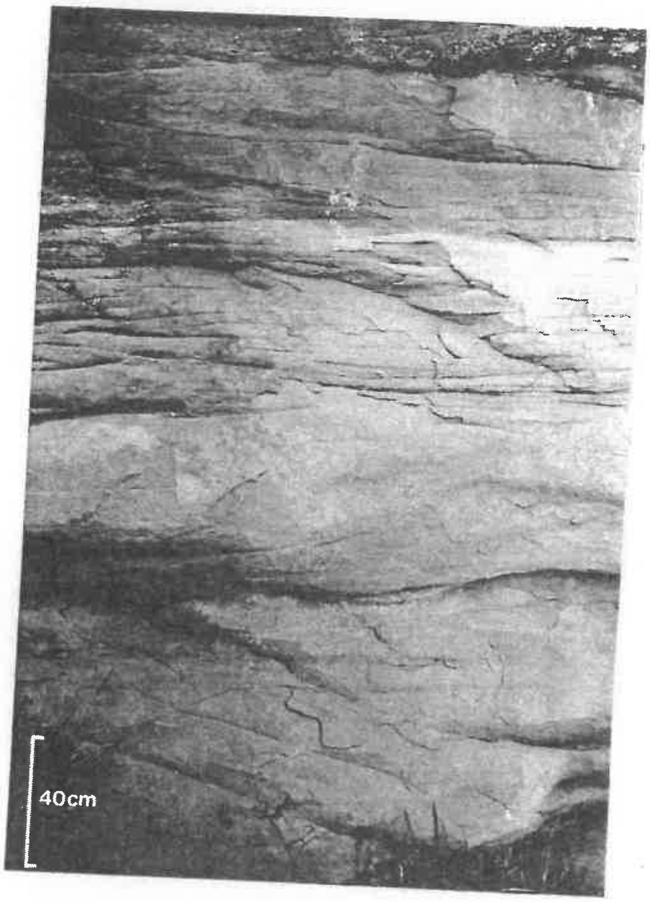


Figure 46. Upward gradation from thick, irregular bedding into more regularly and thinly developed planar bedding. Bamboesberg Member, 4 km north-west of Cala.

mudstones and siltstones are generally light to dark grey and brown in colour. In the upper part of the Loskop Member small amounts of red and green coloured sediment are present.

i) Facies Fm: Mudstone.

Mudstones are predominantly grey and light brown, but some alternating white and light grey beds are also present. The facies is predominantly massive, but may show delicate cross and horizontal laminations with alternate colour banding. Plant impressions are common on partings, and penecontemporaneous deformation in the form of water-escape and flame structures, and small recumbent folds are present. A few examples of polygonal mud cracks directly beneath sandstone beds were seen in the upper part of the Loskop Member.

ii) Facies Fp: Planar stratified and massive siltstone.

Siltstones in the Molteno are mostly planar stratified, though some are massive. Stratification is regular and varies in thickness from laminae less than 2 mm thick to thin beds of up to 3 cm (Fig. 47). Some exposures show small recumbent folds with amplitudes of up to 3 cm.

iii) Facies Fr: Ripple cross-laminated siltstone.

Asymmetric straight-crested, sinuous-crested, or lingoid ripples with or without climbing-ripple lamination are less common than planar stratified siltstone, but constitute an important component of the argillaceous sediments. The ripples have amplitudes of up to 2 cm and occur in cosets rarely thicker than 35 cm (Fig. 48). Where this facies overlies mudstone it has a slightly erosive base.

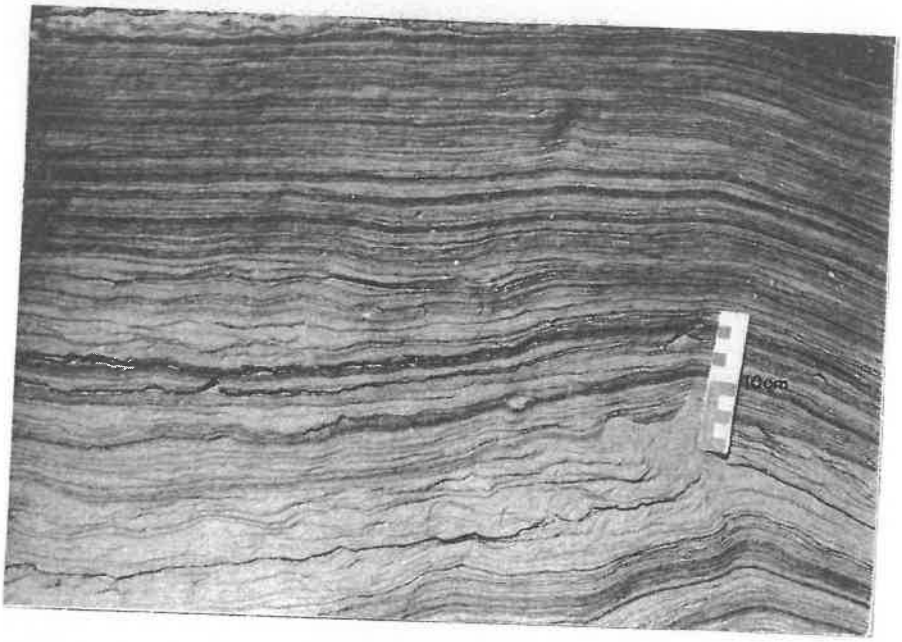


Figure 47. Planar laminated siltstone with symmetric ripples developed near the top of the photograph. Loskop Member, gulley west of homestead on the farm Offa, near Elliot.

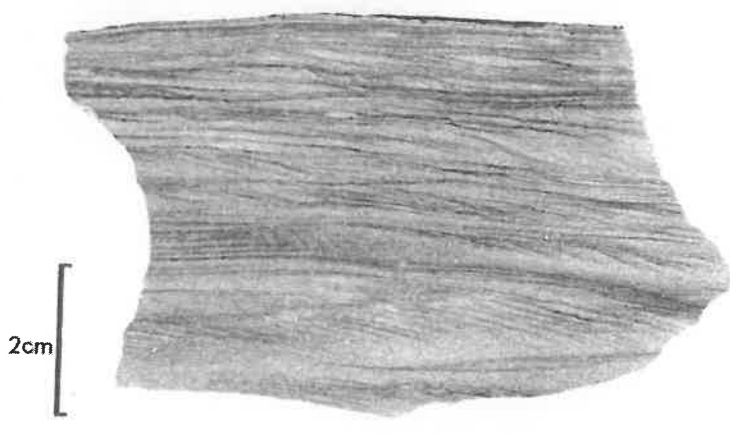


Figure 48. Ripple cross-laminated siltstone. Note climbing ripple at base of specimen. Current direction was from left to right.

C) FACIES INTERPRETATION

1) Facies Cp: Rock pebble conglomerate.

Pebbles, cobbles and boulders are moved only during high energy discharge in the extreme upper flow regime (Simons et al., 1965). The poor sorting, general absence of sedimentary structures and coarse texture of this facies resembles that of debris flows described by Bull (1972) and Walker (1975). However, the arenaceous and generally upward-fining nature of these deposits and presence of crude stratification argues against a debris flow origin. Boothroyd and Ashley (1975) observed that stream power, and therefore stream competence, is greatest in deep channels, and this is where the coarsest load is carried (Miall, 1977a). The position of these conglomerates at the base of upward-fining second-order cycles overlying an erosive base suggests generation as coarse, bedload deposits under upper flow regime conditions.

The close association of matrix- and clast-supported conglomerates suggests a common origin, and that the matrix-supported conglomerates were initiated by a decrease in energy regime and deposited as lags in a river channel (Rust, 1972). The clast-supported nature of the conglomerates is due to the winnowing out of finer particles during high discharge; the matrix being deposited during waning flow (Walker, 1975).

Lag gravels act as nuclei in the development of longitudinal bars (Hein, 1974; Walker, 1975; Miall, 1977a). The crude planar stratification displayed by some of the clast-supported conglomerates may indicate the existence of such a bedform, but there is no corroborating evidence in the form of conglomerate morphology or clast imbrication.

2) Facies Cm: Siltstone and mudstone clast conglomerate.

Intraformational conglomerates following surfaces of erosion at the base of upward-fining cycles were formed by high energy flood waters ripping up and reworking an argillaceous substrate. The existence of high energy conditions is confirmed by the presence of scattered quartzite pebbles and cobbles within this facies. The composition and angular to subrounded shape of the clasts indicates that they were of local derivation, and represent cohesive, semi-consolidated mud and silt. Deformed stratification within clasts, particularly at Umnachean, further confirms their low degree of consolidation and local derivation. In most cases within the Bamboesberg and Qiba Members siltstone and mudstone clasts are the only evidence of prior argillaceous deposits.

In summary, intraformational conglomerates indicate three significant facts, namely:

1) they do not represent any great time break in the process of sedimentation (Pettijohn, 1957);
2) high energy conditions are implied;
3) the clasts have undergone little transportation.

3) Facies St: Trough cross-stratified sandstone.

The origin and formation of trough cross-stratification is still open to some controversy. Allen (1963) believed trough cross-stratification to be related to migrating lingoid or lunate dune-forms. However, McKee (1966) found trough cross-stratification to be rare in dunes. Harms and Fahnestock (1965) agreed with Matthes (1947) that relatively deep, localized scours within a dune field are filled by irregularly shaped migrating dunes. The scours are not a result of the dune lee-face eddy, but were formed by jets of water flowing over or between dune crests. Preservation of trough cross-sets occurs only when dunes fill depressions below the local depth of scour.

Trough cross-stratification is formed by currents in the upper part of the lower flow regime (Simons *et al*., 1965; Harms and Fahnestock, 1965). Harms et al. (1975) stated that the depth of flow at which dunes form is approximately twice the thickness of individual sets, but warned that dunes can exist at greater depths. Harms and Fahnestock (1965) suggested that they form where water depth exceeds 30 cm. It seems likely, therefore, that decreasing thickness of sets in the upper parts of cycles suggests decreasing depth of water.

The comparative lack of trough cross-stratification in the Bamboesberg and Qiba Members is considered to be a function of current velocity, water depth, and the mean sediment size available for deposition. It is suggested that the generally finer grain size of sand and shallower depth of water under which these members were deposited helped to promote upper flow regime conditions in which trough cross-stratification is not a stable bedform.

4) Facies Spc: Planar cross-stratified sandstone.

Planar cross-stratification was the internal sedimentary structure of Jopling's (1965) "laboratory deltas". The same structure has been reported from lingoid or transverse bars (Ore, 1964; Smith, 1970, 1971, 1972; Collinson, 1970; Cant and Walker, 1978). Transverse bars are similar to lingoid bars but tend to have straighter crests. Other terms used to describe similar types of bars are cross-channel (Cant and Walker, 1978), migratory bar avalanche faces (Williams and Rust, 1969) and sand waves (Harms and Fahnestock, 1975).

The origin and growth of transverse bars was explained by Smith (1970, 1971) who agreed with the mechanism described by Jopling (1965). According to these authors a bar is initiated when bedload sediment encounters a depression of sufficient depth to lower the stream velocity below the critical value needed for traction transport. The bar forms by downstream and lateral aggradation of slip faces into the depression until equilibrium is established and the critical depth and velocity are attained. The bar top then becomes the channel floor over which sediment is once more transported. The main factor controlling the formation of bars in the South Saskatchewan River (Cant and Walker, 1978) is flow expansion (i.e. relative decrease in stream competency) controlled by the topographic variation induced by channels, banks and islands.

Planar A-type cross-stratification is considered by Harms and Fahnestock (1965) to be formed by currents in the middle part of the lower flow regime where the lee side of the bar has a well developed eddy. The steep angle of foreset inclination suggests that a large amount of sediment was transported as bedload by weak currents causing avalanching down the bar face close to the angle of repose. Currents in the transitional flow regime (between low and high regimes) form planar B-type cross-stratification (Harms and Fahnestock, 1965). The lower angle of inclination and progressive downstream decrease in foreset dip indicate that the bar face rarely attained the maximum angle of repose before avalanching took place, as sediment was deposited from suspension as well as from bedload or avalanching (Williams, 1966). Low angle planar C-type cross-stratification was interpreted by Rust (1978) to be the result of shallow, high velocity flow into low relief scours.

In terms of the foregoing argument, observed downstream transitions from low angle cross-stratification into planar A- or planar B-type cross-stratification appear to suggest a progressive decrease in current velocity. Reactivation surfaces indicate changes in process or flow direction following low river stages (Collinson, 1970), and may also be indicative of variations in flow depth and strength. The lateral convergence of smaller sets of planar cross-stratification into a larger single set indicates waning flow and the merging or overriding of smaller transverse bars (Smith, 1971).

Upstream surfaces of transverse bars in the South Saskatchewan River (Cant and Walker, 1978) and the Rio Grande (Harms and Fahnestock, 1965) were observed to contain either lower flow regime structures (ripples of small-scale dunes) or upper flow regime planar stratification (Facies Spr). Smith (1971) found that there was a gradational decrease in dune size from the deeper upstream portion of a bar into shallower water near the bar margin where lingoid ripples or planar stratification (if median grain size greater than 0,5 or 0,6 mm) formed due to the decrease in flow velocity and depth.

5) Facies Sp: Planar stratified sandstone.

Sedimentary sequences showing predominantly planar stratification are uncommon, but not unknown (McKee *et al.*, 1967; McLean and Jerzykiewicz, 1978). The large proportion of planar stratification present in the Molteno Formation makes the interpretation of this facies particularly significant.

Irregular planar-stratification is formed by high velocity currents in the upper flow regime (Picard and High, 1973a), and the upward decrease in strata thickness suggests a progressive decrease in water depth. Upward decrease in grain size and gradation into more regularly bedded sandstones of facies Spr may be indicative of decreasing flow velocities and deposition under lower flow regimes. Upper flow regime conditions may, however, still have prevailed due to shallow water and fine grain size. Planar laminated, very fine-grained sandstone is formed at low current velocities in the lower flow regime (Harms *et al.*, 1975). The rare occurrence of this facies is perhaps a function of a low preservation potential rather than non-deposition.

Lenticular bedding, usually associated with irregular planar-stratification in the lower part of second-order upward-fining cycles, is thought to form as a result of shifting depositional centres. It is considered to be especially characteristic of the braided-stream environment (Picard and High, 1973a).

6) Facies F: Siltstone and mudstone.

i) Facies Fm: Mudstone.

The predominantly massive nature of this facies is probably indicative of the uninterrupted settling of suspended fine sediment under very low energy conditions over a long period of time (Pettijohn, 1975). Planar lamination displaying colour alternations may be due to small changes in grain size (Reineck and Singh, 1973) brought about by weak and fluctuating currents. Although the massive nature of these rocks may be indicative of intense bioturbation (Dapples, 1942; Moore and Scruton, 1957) rather than a primary depositional feature, the lack of biogenic structures throughout the Molteno make it unlikely that this was the cause. Mud cracks were formed by the shrinkage of argillaceous sediment as it dried on exposure to air (Picard and High, 1973).

Indications are that this facies was deposited under low energy conditions: either in essentially still water, or by weak currents in the lower part of the lower flow regime.

ii) Facies Fp: Planar stratified and massive siltstone.

Siltstone of this facies is indicative of a flow regime too low to promote tractional movement of sediment (Harms and Fahnestock, 1965). Massive siltstones reflect uninterrupted deposition from suspension where flow turbulence was insufficient for the formation of planar lamination or ripple cross-lamination. As in the case of the mudstone facies, it is not suspected that bioturbation was the cause of the unstructured nature of the sediment. The presence of planar lamination suggests periods of fluctuating sediment supply due to slight changes in current strength or periods of rapid settling (Reineck and Singh, 1973; Pettijohn, 1975).

iii) Facies Fr: Ripple cross-laminated siltstone.

Asymmetric ripple cross-laminated siltstones are indicative of currents in the lower part of the lower flow regime (Harms and Fahnestock, 1965; Harms *et al.*, 1975). Straight-crested ripples are formed at slightly lower flow velocities than lingoid ripples, while sinuous-crested ripples are considered to be an intermediate bedform. Climbing-ripple lamination is formed by the migration and simultaneous upward growth of ripples where abundant sediment, especially in suspension, is available. (Reineck and Singh, 1973).

CHAPTER 5

ANALYSIS OF VERTICAL FACIES SEQUENCES

A) INTRODUCTION

The environmental significance of each sedimentary facies depends to a considerable extent on its position in the stratigraphic sequence. Observations in the field suggested some degree of vertical ordering in the measured sections and also the presence of conspicuous second-order upward-fining cycles within the Bamboesberg and Indwe Sandstone Members. Cyclicity in the Qiba Member is only apparent between Rebels Kloof and the Tsomo River bridge, elsewhere the lithological homogeneity of the succession makes it obscure. Readily identifiable first-order cyclicity is present within the Loskop Member. Within the argillaceous dominated sequences of the Molteno Formation, second-order upward-fining cycles are commonly apparent, but not always present.

The techniques used to analyse vertical facies sequences in the Molteno Formation were dictated by the thickness and complexity of the measured sections available. The simple lithological succession shown by the Qiba Member and sandstone units of the Loskop Member permits visual recognition of the vertical facies sequence. The thicker and more complex facies assemblages of the Bamboesberg and Indwe Sandstone Members required a more detailed and rigorous analysis to recognize the vertical facies sequence. The argillaceous units of the Loskop Member were not analysed owing to the paucity of outcrop data and the questionable validity of pooling data from different stratigraphic positions. The Markov chain technique was therefore used to appraise the vertical facies sequences of the Bamboesberg and Indwe Sandstone Members statistically and the approach used by Miall (1973) was followed with minor modifications.

A Markov chain is "... a sequence or chain of discrete states in time (or space) in which the probability of the transition from one state to a state in the next step in the chain depends on the previous state." (Harbaugh and Bonham-Carter, 1970, p98). A sedimentary sequence is therefore analysed to determine whether it is random or whether it is ordered and possesses a "memory".

B) ANALYTICAL PROCEEDURE

A first-order embedded Markov chain is assumed to exist in computing the transition count-matrix which is the starting point for any Markov chain analysis. In a first-order Markov process the position of any facies depends only on the facies that immediately precedes it, and the process is said to have a one-step memory. An embedded Markov chain records only transitions between different facies, regardless of the thickness of any single facies or individual bed.

The transition-count matrix is a two-dimensional array which records the number of transitions within a given stratigraphic sequence and is composed of elements, each of which is designated f_{ij}, where i = row number and j = column number. From this matrix two probability matrices may be derived. The first is an independent-trials probability matrix composed of elements designated r_{ij} and assumes a random vertical sequence of facies. Given any state i, the probability of it being succeeded by any other state j is dependent only on the number of other states present. For the embedded chain method, i = j transitions are not permitted, and the probability of these occurring must therefore be excluded:-

$$r_{ij} = s_j/(t-s_i) \qquad (1)$$

where s_j is the sum of the f_{ij} for the jth column of the f matrix.

s_i is the sum of the f_{ij} for the ith row of the f matrix.

$t = \sum_{ij}^{n} f_{ij}$ = total number of states.

n = rank of matrix.

A second matrix, which contains elements p_{ij}, gives the actual probability or relative frequency of a given transition occurring in the sequence:-

$$p_{ij} = f_{ij}/s_i \qquad (2)$$

This matrix reflects Markovian tendencies, but it does not prove the presence of any Markov dependency. A difference matrix, d_{ij}, is constructed by subtracting the random-transition probability matrix from the observed transition actual-probability matrix:-

$$d_{ij} = p_{ij} - r_{ij} \qquad (3)$$

A positive value in the difference matrix indicates that any particular upward transition occurs more frequently, and a negative value less frequently, than if the sequence was a result of random ordering. The positive values emphasise the Markov property, but may themselves be due to random processes, and thus it is necessary to test the significance of the results. A chi-square test using the formula recommended by Davis (1973) was used for this purpose:-

$$\chi^2 = 2 \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \cdot \log_e \frac{p_{ij}}{p_j} \qquad (4)$$

where p_j = marginal probability in the jth column = $\frac{s_j}{t}$

Number of degrees of freedom = $(n-1)^2$

The null hypothesis (H_o) is that the vertical succession of strata was derived by random variation of depositional mechanisms and environments.

A basic assumption in Markov chain analysis is that the vertical transition probabilities are approximately constant throughout a given succession. Such a succession is said to exhibit "stationary" Markovian dependency. A chi-square test is available to test for stationarity but is not utilized in this thesis for reasons explained below. It is clear from the measured vertical sections (Chapter 2) that each member is lithologically distinct from those above and below it. A visual check reveals that the kind of cyclicity and vertical facies ordering differs between the Bamboesberg and Indwe Sandstone Members. It is intuitively evident that strata of the Molteno Formation were deposited in environments which differed through time, and the prerequisite of stationarity will therefore not be met. For this reason each of the above two units is analysed separately.

Although nine facies were intially described, some are present too rarely for them to be considered as separate facies for purposes of statistical analysis. They are therefore pooled with related facies. An exception to this is Facies Sp which has been subdivided into two discrete facies states because each represents a recognizably different hydrodynamic environment.

Coal, although an important sedimentary facies, has been grouped with the mudstone-siltstone facies as it occurs relatively rarely and is always associated with that facies. The grouping of facies for both the Bamboesberg and Indwe Sandstone Members is the same. Miall (1977a) suggested that the ideal number of states for Markov chain analysis, is between four and six; five were used for present purposes.

C) RESULTS OF STATISTICAL ANALYSIS

1) Pooling of Facies for Statistical Analysis.

Facies Described	States used for analysis of the Indwe Sandstone and Bamboesberg Members.
Facies Cp, Facies Cm	STATE A
Facies St, Facies Spc	STATE C
Facies Sp - Spr	STATE D
Spi	STATE B
Facies F, Facies C	STATE E

2) Matrix Analysis of Bamboesberg Member

TRANSITIONAL-COUNT MATRIX

STATE	A	B	C	D	E		
A	-	36	6	6	-	48	
B	8	-	11	23	3	45	
C	2	10	-	7	3	22	$=f_{ij}$
D	24	1	5	-	5	35	
E	10	-	-	-	-	10	
						160	

TRANSITIONAL-PROBABILITY MATRIX

STATE	A	B	C	D	E	
A	-	0,75	0,13	0,13	-	
B	0,18	-	0,24	0,51	0,07	
C	0,09	0,45	-	0,32	0,14	$=p_{ij}$
D	0,69	0,03	0,14	-	0,14	
E	1,00	-	-	-	-	

INDEPENDENT-TRIALS PROBABILITY MATRIX

STATE	A	B	C	D	E	
A	-	0,42	0,20	0,32	0,10	
B	0,38	-	0,19	0,31	0,10	
C	0,32	0,34	-	0,26	0,08	$=r_{ij}$
D	0,35	0,38	0,18	-	0,09	
E	0,29	0,31	0,15	0,24	-	

DIFFERENCE MATRIX

STATE	A	B	C	D	E
A	-	0,33	-0,07	-0,19	-0,10
B	-0,20	-	0,05	0,20	-0,03
C	-0,23	0,11	-	0,06	0,06
D	0,34	-0,35	-0,04	-	-0,05
E	0,71	-0,31	-0,15	-0,24	-

$= d_{ij}$

3) Matrix Analysis of Indwe Sandstone Member

TRANSITIONAL-COUNT MATRIX

STATE	A	B	C	D	E	
A	-	24	14	-	-	38
B	4	-	14	9	-	27
C	14	3	-	7	5	29
D	12	-	5	-	-	17
E	4	-	-	1	-	5
						116

$= f_{ij}$

TRANSITIONAL-PROBABILITY MATRIX

STATE	A	B	C	D	E
A	-	0,63	0,37	-	-
B	0,15	-	0,52	0,33	-
C	0,48	0,10	-	0,24	0,17
D	0,71	-	0,29	-	-
E	0,80	-	-	0,20	-

$= p_{ij}$

INDEPENDENT-TRAILS PROBABLITY MATRIX

STATE	A	B	C	D	E
A	-	0,35	0,42	0,22	0,06
B	0,38	-	0,37	0,19	0,06
C	0,39	0,31	-	0,20	0,06
D	0,33	0,27	0,33	-	0,05
E	0,31	0,24	0,30	0,15	-

$= r_{ij}$

DIFFERENCE MATRIX

STATE	A	B	C	D	E
A	-	0,28	-0,05	-0,22	-0,06
B	-0,23	-	0,15	0,14	-0,06
C	0,09	-0,21	-	0,04	-0,11
D	0,38	-0,27	-0,04	-	-0,05
E	0,49	-0,24	-0,30	0,05	-

$= d_{ij}$

Table 4. Tests of Significance at the 95% Confidence Level.

MEMBER	χ^2 CALCULATED	d.f.	CRITICAL VALUE
Bamboesberg	144,97	16	26,30
Indwe Sandstone	118,08	16	26,30

4) Facies Relationship Diagrams

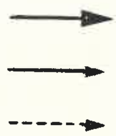
Only transitions that occur more commonly than random are shown. Data were derived from difference matrices.

TRANSITION PROBABILITY

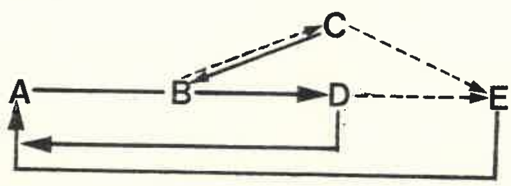
$\geq 0,20$

$\geq 0,10$

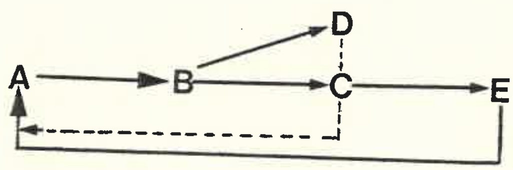
$< 0,10$



BAMBOESBERG MEMBER



INDWE SANDSTONE MEMBER



CHAPTER 6

DEPOSITIONAL ENVIRONMENTS OF THE MOLTENO FORMATION

A) BAMBOESBERG MEMBER

Markov analysis permits certain tentative conclusions to be reached, namely:-

1) there is a well developed second-order cyclicity within the Bamboesberg Member;
2) the general upward-fining facies sequence is Cm-Spi-Spr-Cm;
3) Facies St and Spc are not common and are usually associated with Facies Spi;
4) Facies F is rarely developed, but where present always occurs at the top of a cycle.

The presence of scoured basal surfaces and associated intraformational conglomerate, the large amount of planar stratification, and the comparative rareness of argillaceous material are features in which cycles of the Bamboesberg Member resemble the Bijou Creek ephemeral stream deposits described by McKee _et al_. (1967) and also sandstone components of the

Brazeau-Paskapoo Sequence (McLean and Jerzykiewicz, 1978).

The occurrence of a basal scoured surface, followed by an intraformational conglomerate at the base of second-order upward-fining cycles is due to erosion in a river channel and the deposition of eroded material as a lag conglomerate (Allen, 1965a, 1970a). Irregular planar-stratification is indicative of high energy flow regimes and the wide distribution of this structure in what are interpreted as fluvial channel deposits implies that these high energy conditions were of common occurrence. Cycles of this kind are thought to have been generated by high energy flows in channels with steeper gradients and lower sinuosity than those in which deposits composed predominantly of trough cross-stratification were formed (Allen, 1970a). Channels with massive fills were probably formed and filled by essentially the same process, with strong, turbulent currents dropping their suspended load rapidly. Lenticular stratification is reported to be especially prevalent in braided streams where it is indicative of a fluctuating sedimentary regime (Picard and High, 1973a).

Regular planar-stratification developed in the upper parts of second-order cycles was also recorded as thin sheets spreading about 800 m (0,5 mile) across the flood plain in the Bijou Creek deposits (McKee et al., 1967). Not only do such deposits indicate decreasing current velocity and turbulence, but also shallower water (Harms and Fahnestock, 1965) brought about by channel flood-waters spreading over the flood plain at and after the peak of the flood. Late stages of flooding and sediment infilling within the confines of a channel would produce similar deposits.

A feature of the Bamboesberg Member is the thin, lenticular nature of the argillaceous intercalations. Little argillaceous material was also recorded from the Bijou Creek deposits, and it therefore seems probable that the limited quantity of mudstone and siltstone preserved is a primary depositional feature and not due to subsequent erosion. The lenticular, and commonly massive or planar stratified nature of these deposits suggests deposition in restricted areas of a flood plain under low energy conditions. Abandoned channels or depressions in the flood plain would have offered possible sites of deposition. The formation of coal seams in the Indwe area required stable, quiet environmental conditions away from the influence of flood events for a relatively long period of time. Relatively thick accumulations of silt and mudstone below each seam indicate the presence of such an environment prior to the establishment of peat swamps.

The upward decrease in current velocity and water depth indicated by second-order cycles suggests high energy flood events which deposited large amounts of sediment during periods ranging from a few hours to a few days as was the case with the Bijou Creek (McKee et al., 1967) and the western Lake Eyre basin floods (Williams, 1971). The low ratio of channel to overbank deposits characteristic of the Bamboesberg cycles is considered to be typical of braided-stream deposits (Allen, 1965a, 1970a; Visher, 1972; Miall, 1977a,b; Cant and Walker, 1976). Miall (1977b) proposed that the Bijou Creek section should constitute one of six generalised vertical profile models for braided streams, and that it should relate in particular to shallow ephemeral sandy streams.

In the light of the available evidence it would appear that the Bamboesberg Member was deposited by ephemeral flood events of great intensity and short duration. Evidence supporting the existence of high flow velocities is the presence of sporadic quartzite pebbles and cobbles at the base of cycles. This suggests that the flow competence was greatly in excess of that required to transport fine- to medium-grained sand, and that sediment of this grain size was all that was available for transport and deposition.

B) INDWE SANDSTONE MEMBER

Markov chain analysis confirms the existence of a well developed, upward-fining second-order cyclicity within this member. The vertical facies sequence, coarse-grained nature of the sandstones, lack of substantial argillaceous deposits, and unimodal palaeocurrent dispersal patterns of individual cycles (Chapter 8) are indicative of a low sinuosity or a braided-stream depositional environment (Miall 1977a, 1978). A comparison with braided-stream models described by Miall (1978) indicates the Indwe Sandstone Member to resemble the South Saskatchewan model of Cant and Walker (1976).

Matrix-supported conglomerates at the base of sedimentary cycles are interpreted as channel lags deposited by high current velocities in the early stages of flooding. Longitudinal bars are thought to be represented by poorly stratified, clast-supported pebble conglomerate lenses. These bars were initiated by the dumping of the coarser fraction of the channel load due to a local decrease in flow velocity or depth. The lack of well-developed longitudinal bars, usually considered characteristic of braided streams (Smith, 1970, 1972; Miall, 1977a), is attributed to the relatively fine grain of sediment available for deposition. Campbell (1976) observed that preservation of bar morphologies in ancient braided streams was not to be expected owing to the constant shifting of channels and the coincident formation and destruction of bars.

Poorly defined planar stratification in coarse-grained, pebbly sandstone or pebble conglomerate may have been formed under slightly lower flow regime conditions and reflects a decrease in the grain size of the bedload. The commoness of trough cross-stratification suggests that downstream migration of dune-fields was active during the high water stage within channels.

Planar cross-stratification is interpreted as a result of the downstream migration of transverse bars extending partly or completely across the river channel. The direction of advance of these is commonly oblique to the main channel of the river (Cant and Walker, 1976). Solitary planar cross-stratified sets within a dominantly trough cross-stratified sequence are thought to represent the downstream migration of transverse bars within channels of the river system. Further channel aggradation resulted in dunes migrating over the transverse bars. Planar cross-stratification in the upper sandstone components of second-order cycles overlain by planar-stratified sandstone (Facies Spr) may reflect deposition under shallow water conditions on a sand flat (Cant & Walker, op. cit.) Sedimentary structures in such a situation are generally of low amplitude and related to waning flow. Planar stratified fine- to medium-grained sandstones of Facies Spr developed directly above trough cross-stratification may imply upper flow regime conditions in response to a decrease in flow depth or grain size.

Siltstone and mudstone were deposited under very low energy conditions either in abandoned channels or as a result of overbank sedimentation on abandoned braided alluvial plains.

Completely planar-stratified upward-fining sandstone cycles at Milford north-west of Indwe, in the Guba Valley south-west of Indwe, and elsewhere in the field area resemble those described by Allen (1970a) which are attributed to upper flow regime conditions. The persistently finer-grained nature of the Indwe Sandstone in the vicinity of Indwe together with dominantly planar-stratified cycles is probably indicative of shallow rivers away from the influence of the main river channel. The presence, and perhaps even the preservation, of the Guba Seam south-west of Indwe lends support to this hypothesis. Nevertheless, the Guba Seam is also present on the farm Perskenplaats, where the Indwe Sandstone is characteristically coarse grained.

The dominantly planar bedded, medium-grained sandstone (Facies Spi) at the top of the Indwe Sandstone in the eastern part of the field area resembles the lithology of the Bamboesberg Member. The decrease in grain size, absence of extra-basinal clasts and recognizable upward-fining nature of the cycles seems to reflect a decrease in energy conditions and water depth prior to the deposition of the Mayaputi Member.

Work by Smith (1970, 1971, 1972), Cant and Walker (1976) and Miall (1977a) has shown vertical accretion to be a significant process during the deposition of fluvial sediments, especially braided stream deposits. The presence of thick sequences of trough cross-stratification and indications of progressively decreasing flow depth suggest that vertical accretion was an important process of sediment accumulation during the formation of the Indwe Sandstone. Nevertheless, lateral migration also plays an important role. Cant and Walker (1976) observed that channels of the South Sakatchewan River migrated laterally or aggraded in one reach and simultaneously degraded in another. Lateral migration of the Kosi River of up to 30 km per year has been reported by Fahnestock (1963).

Lateral migration of any channel, even in excess of 30 km per year, seems unlikely to be able to account for the regional extent of the Indwe Sandstone Member which Turner (1975a) regarded as a sheet or blanket sand. The extent and sheet-like nature of the member can only be explained in terms of a regional braided-stream environment which must have prevailed throughout its deposition. The lenticular nature of second-order cycles suggests that the alluvial plain was dominated by a number of braided-river systems and the Indwe Sandstone Member is therefore interpreted as a sheet-sandstone comprising coalescing braided-stream deposits.

C) MAYAPUTI MEMBER

The lithology of this member is indicative of lower energy conditions than those experienced during Bamboesberg and Indwe Sandstone times. The sedimentary facies assemblage is similar to that of flood-basin deposits described by Allen (1965a), Turner (1978), and Friend (1978). The second-order upward-fining cycles differ markedly from those of the Indwe Sandstone in that the basal sandstones are thinner and of considerably finer grain size and there is a thicker argillaceous component. These cycles contain sedimentary structures indicative of generally short-lived high-energy events followed by prolonged deposition under low-energy conditions. Erosively-based sandstones containing minor siltstone and mudstone clast conglomerates indicate the influx of sediment-laden waters which ripped up the argillaceous substrate. The predominance of planar stratification suggests shallow, upper flow regime conditions in the early stages of flooding followed by progressively decreasing flow velocity and water depth as reflected by the presence of small scale trough cross-stratification, ripple cross-lamination and finer grain sizes. The thick siltstone and mudstone at the top of these cycles implies deposition by low-energy currents or from suspension in ponds or small lakes of still-standing water.

Although the character of these cycles suggests deposition by meandering streams (thin sandstone base and thick argillaceous component at top), there is no evidence of lateral accretion or point bar deposits. The relative thinness of the sandstone components and the implied high energy of the floodwaters suggest a sheet deposit, perhaps of the kind associated with a large-scale crevasse splay following a major flood event. The thin sandstone intercalations with abrupt lower and upper junctions in the upper parts of the thick argillaceous sequences are indicative of short-lived, minor events away from the immediate influence of a major river channel. These are thought to have formed as a result of minor crevasse splays (Leeder, 1973).

A further possiblity as to the depositional environment of these deposits is explored below. The dominantly argillaceous nature of the Mayaputi member suggests an almost complete cessation of fluvial channel activity, especially when compared with the high-energy environments represented by the Indwe Sandstone Member. The deposition of the Mayaputi seems to have been generally unaffected by major fluvial activity and it would therefore appear that the depositional environment was not an orthodox flood plain. Possibly it was some kind of distal depositional basin into which the rivers drained. A hypothetical inland sea, or large lake fails to constitute a satisfactory explanation owing to the relatively coarse-grained nature of the Mayaputi sediments and their implied shallow water environment (Picard and High, 1973b). These deposits may therefore have formed in a depositional environment similar to that of the present Okavango Swamp of Botswana. Turner (1975a) believed that the Molteno rivers drained into such a centripetal basin. The streams of the Australian Riverine Plain dissipate in a similar manner (Butler, 1961). The sandstone components are thought to represent an influx of sediment-laden water from more proximal sources which entered the plain as sandy, shallow streams. The streams were possibly ephemeral in nature and formed thin, sheet-like deposits over the plain. Following such floods small ponds and lakes provided sites for the deposition of finer sediment from suspension.

The vertical repetition of upward-fining cycles suggests repeated flood events. Where the whole member comprises an uninterrupted sequence of mudstone and siltstone, the site may have been beyond the influence of active river channels and high energy flood deposits.

Climate always exerts an important influence on the characteristics of terrestrial sediments. Flood deposits formed in dry climates are normally brown or red and lack organic detritus (Allen, 1970b). Dark grey, carbonaceous rocks obtain their colour from finely disseminated organic matter. The tendency for the Mayaputi Member to become darker upward, and the presence of the Cala Pass Seam at its top suggests a climate and depositional environment which were, locally at least, conducive to the establishment of vegetation.

D) QIBA MEMBER

The lithology of the Qiba Member suggests a progressive westward change of depositional environment. In the east, around Qiba itself, the predominance of planar stratification, fine- to medium-grained sandstones and the low argillaceous content (similar in this respect to the Bamboesberg Member) suggests deposition by high energy ephemeral streams of Bijou Creek type (McKee et al., 1967). Planar stratification and the presence of sporadic cobbles and fossilized tree trunks suggest shallow water conditions in the upper flow regime. The high energy level would have prevented large quantities of fine-grained material being deposited or preserved.

Further westward, at Stowkes Basin, Rebels Kloof and in the Ulin area, the increased agillaceous content and well defined first- and second-order cycles reflect progressively decreasing stream power rather than the ephemeral flow which seems to have been responsible for deposition at Qiba. The basal scours and associated siltstone- and mudstone-clast conglomerates with sporadic cobbles represent channel lag deposits (Allen, 1965a). The gradation from Facies Spi upward into Facies Spr and small scale trough cross-stratification and ripple cross-lamination indicates gradually decreasing flow strength and water depth (Harms et al., 1975; McKee et al., 1967). A significant difference between the sandstone component of these cycles and those of the Bamboesberg Member is the larger proportion of trough and planar cross-stratification in the former which may signify slightly greater water depths. The thick argillaceous components with sedimentary structures indicative of low energy currents are analogous to modern overbank and flood-plain deposits (Picard and High, 1973a; Allen, 1965a; Blatt et al., 1975).

At Stowkes Basin the six successive second-order upward-fining cycles probably formed some distance from the main fluvial channel. It is suggested that the larger, first-order cycles indicate more or less continuous flow, whereas the smaller ones reflect deposition in the less active parts of the alluvial plain during flood events only. The fact that the lowermost of these cycles is developed about 15 m above the base of a first-order cycle situated to the west may be due to the formers isolation from the main channel, as it may have been initiated only some time after the first influx of flood waters. Each of these second-order cycles represents deposition under high energy, shallow flow conditions of progressively decreasing strength, followed by a quiet period during which siltstone and mudstone were deposited, perhaps in abandoned channels or shallow depressions.

Doubt exists as to the type of river that was responsible for the deposition of this member in the central part of the field area. The prevalence of planar stratification (Facies Spr and Spi) suggests deposition within a high energy river system, perhaps similar to the Bijou Creek model (McKee et al., 1967). However, the thick argillaceous component resembles that normally characteristic of a meandering river system (Allen, 1965a, 1970a). Collinson (1978) considered it naive to invariably attribute a thick argillaceous component of a fluvial cycle to high sinuosity (meandering) rivers; the chief factor governing the preservation of the overall sedimentary sequence would have been the nature and frequency of channel migration over any given point on the alluvial plain, together with the overall subsidence rate. The indication that upper flow regime conditions prevailed lends some support to the idea that deposition took place in a braided fluvial environment. In addition, the lateral extent of the Qiba Member in relation to the inferred north-westerly direction of palaeocurrent flow (Chapter 8), and the lack of evidence of channel incision into the underlying flood-plain deposits suggests sheet-flood events characterised by poorly defined channels (Friend, 1978). In a general sense the sedimentary sequence exposed within this part of the field area is therefore thought to have been the result of high energy, periodic flood activity followed by flood-plain conditions with colonization by vegetation and the formation of peat swamps in locally favourable situations.

The higher proportion of siltstone and mudstone in the Qiba Member around Indwe seems to be indicative of a more distal fluvial environment than that further eastward. The sandstone deposits indicate that this part of the basin was still influenced by a number of major river channels capable of transporting and depositing a substantial amount of sand. The argillaceous sediments were probably laid down between major floods by suspension settling in ponds and shallow lakes.

The lithology of the upper part of the Qiba Member reflects the influx of high energy, sediment-laden currents. They appear to have been of a similar nature to those responsible for the basal part of this member around Qiba. These deposits are interpreted as low sinousity, high energy sheet-flood sediments, and are situated at the base of an upward-fining first-order cycle of which the Tsomo Member comprises the upper, argillaceous component.

The thick sandstone deposits at Qiba reflect influxes of sediment transported by high energy ephemeral streams, while at Indwe the alluvial plain was subject to periodic high energy floods. The change in sedimentary character of the Qiba Member, from approximately east to west, is related to the north-westerly flow direction and suggests a proximal-distal depositional setting. A second major event is indicated by the upper sandstone part of the member which is present throughout the field area. Significantly, the isopach map shows that the thickness of the member increases down the palaeoslope towards that part of the area where cyclicity is best developed. In the Indwe direction, where the sedimentary aspect is more distal, the member thins again.

Foreset slumping and overturning are thought to have occurred while the sediment was water saturated (Allen and Banks, 1972), and may have been initiated by mild seismic activity or, more likely, by gravitational adjustment of the foreset angle following a change in the direction and velocity of the prevailing current. Recumbent folding is attributed to shear from current drag induced by the build-up to a higher flow regime (Allen and Banks, op. cit.). The association of slumps and sand volcanoes at Perskenplaats suggests a similar mechanism of formation to that described by Neumann-Mahlkou (1976). That author considered sand-volcanoes to have resulted from dewatering due to an increase in pore-water pressure promoted by overburden pressure. In the Qiba Member this probably resulted from the slumping of adjacent sediments. An alternative mechanism was formulated by Gill and Kuenen (1958) who suggested that sand volcanoes on slumps were formed subaqueously by the extrusion of sediment-laden water from the slumped masses. Extensive slumping of sandstones above the sand volcanoes may have initiated slumping of the lower sandstone on which the sand volcanoes were found, and resulted in an increase in pore-water pressure and dewatering.

E) TSOMO MEMBER

The depositional environment of this member is considered to have been the same as that described for the Mayaputi Member. The presence of a coarse-grained sandstone unit near the top of the member at Bannockburn confirms the presence of major river channels dissecting a generally low energy flood-plain or centripetal basin environment.

F) LOSKOP MEMBER

First-order cycles in the Loskop Member are similar to the Tsita River cycle of Turner (1975a) and also to modern alluvial flood-plain sequences described by Allen (1974). The interpretation of the depositional environment given by Turner (op. cit.) is basically accepted here, but some variations are proposed, based on the larger number of cycles examined.

The erosive base and associated conglomerate of sandstone components in these cycles reflects high energy currents which scoured the floor and sides of channels. This resulted in the accumulation of lag-pebble conglomerates (less commonly longitudinal bars) as the channel migrated across its flood plain. Coarse-grained to very coarse-grained, massive to poorly-defined, irregularly planar-stratified sandstone of Facies Spi suggests the dumping of sediment by slightly less powerful currents than those which initiated the cycles, but still within the upper flow regime. Thick sequences of coarse- to very coarse-grained trough cross-stratified sandstone reflect flow conditions within the upper part of the lower flow regime (Harms and Fahnestock, 1965; Harms et al., 1975) and the development of extensive migrating dune fields. Small scale trough cross-stratification, ripple cross-lamination and planar lamination at the top of the sandstone components are all indicative of low flow regime conditions associated with a decrease in stream power and water depth.

The presence of medium-grained, planar cross-stratified sandstone with thin intercalations of Facies Spr suggests deposition under a lower flow regime than that associated with trough cross-stratification. The rareness of coarse-grained sandstones and pebble conglomerates is reminiscent of deposits of the Platte River (Smith, 1970, 1971, 1972) which has a shallow, sandy braided channel with a high proportion of transverse bars.

The third type of sandstone, composed mainly of medium-grained planar-stratified beds (Facies Spr and Spi) with minor sets of planar cross-stratification, represents upper flow regime conditions acting on relatively fine sediment in shallow water. (Picard and High, 1973a; Simons et al., 1967).

The facies association, relatively coarse texture, unimodal palaeocurrent patterns (Chapter 8), and high proportion of planar cross-stratification in sandstones of the Loskop Member suggests deposition by low sinuosity (braided) rivers (Smith, 1970, 1971; Miall, 1977a,b, 1978). The vertical sequence of textures and sedimentary structures in sandstones of the Loskop Member and its high width to thickness ratio are reminiscent of fluvial sheet-sandstone deposits such as the Westwater Canyon Member, Morrison Formation (Jurassic), New Mexico (Campbell, 1976). The presence of multistorey sandstones incorporating incomplete sedimentary cycles suggests that the sheet sandstone was deposited by aggrading and coalescing braided-stream systems. (Campbell, op. cit.). The abrupt upward transition from what appears to have been coarse-grained braided-stream deposits to argillaceous flood-plain sediments above each channel sandstone may have resulted from sudden abandonment of the channel rather than its gradual infilling. This feature is discussed more fully in Chapter 9 dealing with cyclicity in the Molteno.

The depositional environment of the argillaceous components is considered to be similar to that postulated for the Mayaputi Member. Upward-fining cycles suggest the introduction of sediment-laden water followed by gradually decreasing current flow in a distal flood-plain environment. The reason for the varied colouration of argillaceous sediments in the Loskop Member is considered below in the light of the investigations of Blatt, et al. (1972) and McBride (1974). The red colouration is due to the presence of finely divided iron oxide (hematite) as grain coatings and intergrown crystals. Hematite is formed by the early post-depositional oxidation of ferrous iron exposed to air. The green colouration is due to the ferrous iron content of chlorite and illite and indirectly to the lack of hematite, iron sulphide and vegetal matter. The ratio of ferrous to ferric iron for red mudstones averages 0,5, while that for green mudstone averages 2,8. An increase in organic material content results in olive to light grey rocks.

As in the Difunta Group, Mexico (McBride, 1974), the contact between red and green zones in the Loskop Member commonly transgresses bedding, and is therefore diagenetic. The green beds may have formed during early diagenesis following the reduction of ferric iron in red beds by migrating ground water (McBride, op. cit.). Plant debris, though relatively scarce, may have provided the necessary reducing conditions. The presence of green tubes and nodules in the predominantly red sediments is further evidence for diagenetic reduction. Where the boundary between red and green coloured mudstones coincides with bedding, a depositional control is suggested. In such circumstances the green mudstones may have formed by deposition under reducing conditions in standing water with restricted oxygen circulation. Desiccation cracks confirm the sub-aerial exposure of some of the mudstones.

The paucity of dark grey, carbonaceous rocks and coal, and the appearance of green and red mudstones associated with dominantly brown and olive coloured sediments reflects a climate becoming increasingly warm and arid. (Allen, 1970; McBride, 1974; Winston, 1978). This appears to have culminated in the overlying Elliot Formation (Botha, 1968).

Slumped foresets and water-escape structures probably originated by the same mechanism as has been suggested for the Qiba Member. The structures believed to have resulted from water-escape fissures may have formed as water-saturated sediment forced its way up soft-sediment shear planes. Certainly, their linear mode of formation suggests control by a planar structure, but there appear to be no accounts of such structures in the literature.

In summary, the major sandstone units are interpreted as fluvial-sheet deposits formed by coalescing braided streams. Following the deposition of these sheet sandstones, sporadic floods inundated the alluvial plain and it is to this kind of activity that the presence of second-order upward-fining cycles within the argillaceous component are attributed.

G) COAL SEAMS

1) Indwe and Guba Seams

The depositional setting of these poses the perennial question as to whether the coal is of autochthonous or allochthonous origin. The absence of seat earths has for long been considered an indication of the allochthonous nature of Gondwana coals. (Fox, 1931; Hoffman and Hoehne, 1960a,b.). Duff (1967), however, suggested that seat earths, formerly regarded as leached fossil soils, may represent the accumulation of intensely weathered clay which had already assumed its peculiar chemical and mineralogical properties before being colonized by vegetation. The fact that both seams rest on carbonaceous siltstone and mudstone at the top of upward-fining cycles suggests deposition of fine sediment by weak currents and by suspension settling in a back-swamp environment prior to the establishment of stagnant, peat-forming conditions. Isopach maps (Ryan, 1963) indicate that peat accumulation reached a maximum along narrow, elongate depressions which were considered to represent abandoned drainage channels. It is suggested that extensive vegetal growth and peat formation followed the isolation of a formerly active portion of the alluvial plain as a clearly defined swamp. This, by implication, suggests an autochthonous origin for the coal. Furthermore, the well defined laminations of both seams implies autochthonous or hypautochthonous deposition (Stach, 1975).

The formation of swamps or lakes on an alluvial plain following seasonal flooding is common, but such episodes are usually only local and of temporary occurrence. An appreciation of the time required for the formation of the coal seams can be gained from Stach's (1975) estimate that 6000 - 9000 years are required for the accumulation of peat to form 1 m of bituminous coal. It is therefore probable that prolonged establishment and maintenance of peat-forming sites must have occurred within a generally high energy, ephemeral stream environment.

The presence of thin bands of carbonaceous shale, mudstone and siltstone in combination with the generally high ash content of the coal (Table 1) suggest that the swamps were subject to periodic inundations by sediment-laden waters. The thick accumulation of shale on the margins of the basin is indicative of streams dumping most of their coarser suspended load on entering the swamp. Cannel coal, which forms under anaerobic conditions in quiet, open water (Stach, 1975) is restricted to the Indwe Seam, and supports Ryan's (1963) theory that the most extensive and thickest coal swamps occurred in the vicinity of Indwe. On compaction the relief of the coal-seam floors was perpetuated upwards, and later currents were directed along these depressions.

A cool climate during the deposition of the peat is suggested by the presence of fresh feldspar grains in associated sandstones and the absence of leaching or intense weathering of seam footwall strata. The presence of Dadoxylon trunks with well defined growth rings in the coal measures (Turner, 1971) indicates seasonal growth, thus offering further support for a temperate climate. Coal does, however, require a humid climate and sunshine sufficient to promote the luxuriant growth of vegetation to form peat. The stagnant, anaerobic reducing conditions essential for peat formation (Stach, 1975) are provided by a water table sufficiently high to prevent oxidation and the total decomposition of vegetal matter, yet not so high as to prohibit the growth of vegetation. For a suitable relationship between the height of the water table and the surface of the peat swamp,either subsidence (compactional, isostatic or tectonic) equal to the vegetal accumulation rate was taking place, or else the water-table was slowly rising (McLean and Jerziekywicz, 1978). The common presence of thin bands and lenses of fusain in the coal indicates periods of subaerial exposure (i.e. oxidation).

2) Cala Pass Seam

The sedimentary facies associated with this seam suggest a flood-plain environment with deposition under low energy conditions. The presence of coal at both Indwe and Cala Pass shows that peat forming conditions existed simultaneously over a wide area. Numerous well preserved leaf fossils, macrobanding and the implied low energy environment are taken to indicate autochthonous deposition (Stach, 1970). The poor quality of the coal, due to high ash content and presence of numerous shale partings, suggests that the peat swamp was frequently inundated by sediment-laden waters.

3) Ulin Seam

The stratigraphic and sedimentological context suggest that the Ulin Seam was deposited in a similar environment to that of the Guba and Indwe Seams, but in surroundings of slightly lower energy levels. The thicker argillaceous footwall sediments indicate deposition by weak currents or by suspension settling for an extended period prior to deposition of the peat. The presence of three discrete and separate coal lenses at this horizon suggests deposition in shallow depressions on the flood plain. However, uncertainty exists as to whether the Ulin Seam is of autochthonous or allochthonous origin. The large number of Dadoxylon trunks dispersed throughout the Qiba Member shows that vegetation flourished at least locally on the flood plain. The low energy environment in which the coal seams originated makes it improbable that tree trunks could have been transported there. Fossil leaf impressions present below the seam at Ulin and along the banks of the Tsomo River suggest *in situ* deposition with minimal transport. At Ulin much of the seam comprises lenses of coal up to 2 cm thick in a carbonaceous siltstone and mudstone matrix. Such an assemblage, however, points to the introduction of fragments of vegetation by weak currents.

Growth rings shown by Dadoxylon trunks suggest a seasonal variation in climate, perhaps accompanied by alternating wet and dry periods. The poor quality of the coal may be a direct result of only partially favourable climatic conditions.

4) Coal Seams of the Loskop Member

The thin and discontinuous nature of the two seams developed in the Loskop Member serve to emphasise the increasingly unfavourable conditions for peat formation during upper Molteno times, probably due to the increasing aridity of the climate. Sedimentological associations suggest deposition in a flood-plain environment similar to that of the Cala Pass Seam. The thinness and local development of these coals implies a short-lived period of peat formation.

The Offa Seam is the highest coal in the Molteno Formation and is perhaps one of the most interesting in the area investigated. It is not traceable for more than 30 m along outcrop and appears to reflect the presence of two distinct depositional environments. The earlier one, represented by alternations of coal with carbonaceous mudstone and siltstone may be autochthonous, considering its regular lamination, the presence of leaf impressions and its position above finely laminated mudstone. The overlying fine to medium-grained sandstone representing the base of an upward-fining cycle and crowded with coal clasts implies a relatively high energy environment. It seems certain that this deposit is allochthonous for it represents flood waters ripping up fragments from the underlying peat and incorporating them as clasts in the sand deposit. The seam overlies small amounts of red and green coloured sediment thus hinting at increasingly arid climatic conditions.

In general, the climatic conditions seem to have favoured the formation of peat during early Molteno times. Above the Indwe Sandstone the nature of the seams indicates a progressively less favourable coal-forming environment; perhaps due to the increasing aridity of the climate.

CHAPTER 7

URANIUM MINERALIZATION

The discovery of uranium in the Beaufort Group around Beaufort West during 1974 prompted further exploration for uranium in the Karoo Supergroup. Although uranium occurs in a variety of lithological settings, particular interest has centered on the Molteno Formation owing to its continental depositional setting, for about 95 per cent of known United States uranium reserves are in sandstones of terrestrial origin.

During the present investigation use was made of Chemtron G-12 gamma-ray scintillometer. A scintillometer does not discriminate between U, Th and K, but measures gamma radiation over virtually the entire spectrum. For this reason selected rock samples were also chemically analysed to ascertain the uranium content.

Although some of the Molteno strata tested showed uranium concentrations of between 12 and 30 ppm, the average was between 3 and 8 ppm. Notwithstanding these generally low uranium concentrations, the following facts emerged from the investigation:

1) Although uranium values measured in the field area were generally low (3-8 ppm), marginally higher values were encountered in the Loskop Member (3-30 ppm).
2) Uranium values approximately 4 to 6 times above background occurred in coal seams at Umnachean and Offa (30 ppm). The Indwe, Guba and Cala Pass Seams showed values equal to, or only slightly higher than, adjacent argillaceous rocks (8-12 ppm).
3) Argillaceous rocks generally have higher uranium concentrations than sandstones.
4) Second-order upward-fining cycles in the Loskop Member showed an abrupt decrease in uranium content from the argillaceous top of a cycle into the siltstone or fine-grained sandstone base of the overlying cycle (Fig. 49).

These observations suggest a strong lithological control on uranium distribution. A somewhat weaker stratigraphic control exists in that the uranium concentration is marginally higher in the Loskop Member.

The generally low uranium content of the Molteno strata may be attributable to:

1) The absence of a uranium source rock during or immediately after deposition of the Molteno.
2) The absence of suitable ground-water solutions to leach and transport uranium ions from the source rock.
3) Gabelman (1971) suggested that an interruption of flow is essential to allow time for uranium to precipitate from groundwater. The apparent absence of any structural or lithological barrier may have caused uranium-bearing groundwaters to be flushed northward through the southern part of the formation. This may

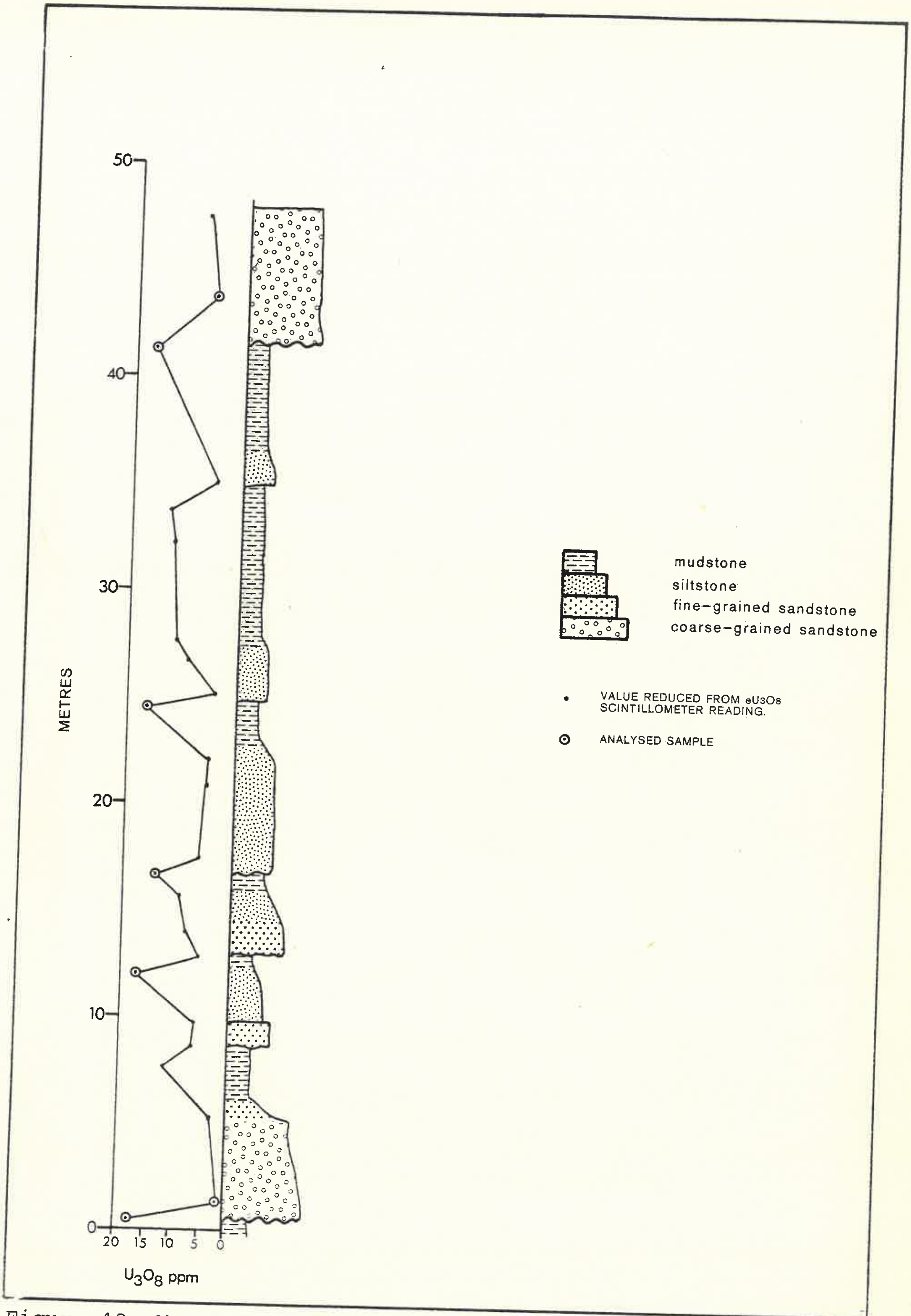


Figure 49. Measured section of portion of the Loskop Member on the farm Offa showing the relationship between grain size and uranium content.

perhaps suggest the possibility of uranium precipitation in the distal, northerly parts of the basin.

4) The field area is situated in a high summer rainfall area. It is therefore possible that if uranium was originally present, much of it was leached out of the strata, particularly from the sandstones. On the whole, however, this seem unlikely because of the generally highly indurated and impermeable nature of these strata.

In the Beaufort Group uranium mineralization is commonly associated with sandstone or conglomerate beds (Kübler, 1977; Turner, 1978). This is contrary to the situation observed in the Molteno Formation where the highest uranium concentrations are found in argillaceous rocks. It is suggested that the more permeable fine- to medium-grained sandstones acted as aquifers through which groundwater solutions were flushed, while the argillaceous sediments acted as host rocks. If, as in the Beaufort Group, uranium was transported as uranyl carbonate complexes in oxidizing or mildly reducing solutions with a neutral to alkaline pH and high CO_2 content (Turner, 1978), a reductant in the form of H_2S (derived from anaerobic bacteria acting on organic matter) would have been required to precipitate any uranium present. Not only do the argillaceous rocks have a higher content of disseminated carbonaceous matter than the sandstones, but they are also less permeable, and would therefore have provided the necessary environment for the uranium to precipitate. It is apparent from the detailed vertical sections of argillaceous components in the Loskop Member (Fig. 49) that the thin sandstone units have a higher uranium content than the major coarser-grained sandstone units. This might be the result of lower permability in the enclosing argillaceous strata.

If uranium-charged groundwaters were flushed through the Molteno, the coal seams might have been expected to act as potential reductants and fixatives for the uranium. The Indwe, Guba and Cala Pass Seams show very little uranium mineralization, but those in the Loskop Member (at Offa and Umnachean) contain significantly higher uranium concentrations than other strata in the formation. This may be indicative of uranium-charged groundwaters passing through only the upper part of the Molteno Formation.

CHAPTER 8

PALAEOCURRENT ANALYSIS

A) INTRODUCTION

Some modern authors interpret palaeocurrent distribution patterns by means of a palaeocurrent map based on all available directional data. A limitation of this approach if it is a thick sedimentary sequence is that it does not permit any indication of vertical variability in current directions. In this thesis palaeocurrent measurements were recorded at selected stratigraphic levels, and in some instances measurements were refined sufficiently to differentiate between specific second-order cycles within a single stratigraphic unit.

Palaeocurrent directions were determined by measuring the orientation of foreset dip directions of planar cross-stratified sets and axial directions of trough cross-stratification. Palaeocurrent readings were recorded in classes of 10° of arc. Ripple cross-lamination, primary current lineation and fossil tree trunks were not present in sufficient quantity or concentration to provide assistance in determing mean flow azimuths. The Bamboesberg and Qiba Members contain relatively few directional data, and therefore statistical and analytical proceedures are biased towards the Indwe Sandstone and Loskop Members in which cross stratification is common.

It was found that considerable variability existed within the Indwe Sandstone Member, and measurements were therefore separated into data sets on the basis of second-order cycles. At Qiba, not only was variability of current direction analysed with respect to successive stratigraphic levels of this member, but reference was also made to geographic variations in palaeocurrents within cycles.

B) ANALYTICAL PROCEEDURE

The method used in analysing palaeocurrent data was that employed by Sanderson (1973) and Till (1974). Mean azimuth ($\bar{\Theta}$) is the direction of the resultant vector of directional data assuming a circular normal distribution. The angular dispersion about $\bar{\Theta}$ can be expressed as a vector strength, r, which is the magnitude of the resultant vector, R, normalized for sample size, n.

Equations are:

$$\text{Tan } \bar{\Theta} = \frac{\sum_{i=1}^{n} \sin \Theta_i}{\sum_{i=1}^{n} \cos \Theta_i} \qquad (5)$$

$$r = \frac{R}{n} = \frac{\left[(\Sigma \cos \Theta)^2 + (\Sigma \sin \Theta)^2 \right]^{\frac{1}{2}}}{n} \qquad (6)$$

The value of r approaches 1 for increasing density or cluster of points. The mean angular deviation, S, which is similar to the standard deviation, is:

$$S \text{ (radians)} = 2\sqrt{(1-r)} \qquad (7)$$

Although visual inspection indicates that a preferred orientation of the data does exist, randomly selected sample populations were used to test for this property prior to the calculation of mean azimuths. A modification of the Rayleigh test was used to evaluate the null hypothesis of uniformity of direction. $Z = R^2/n$ is calculated, for which at the 0,05 significance level the critical value, Zc, is approximately $\frac{1}{2} X^2_{(2;0,05)}$ (Sanderson, 1973). Zc changes only slightly with increasing n: n=5, Zc=2,8; n=10, Zc=2,92; $n \rightarrow \infty$, Zc=2,996. (Greenwood and Durand, 1955). A general statement therefore is that $Zc \doteq 3,0$. This method is both simple and rapid and does not require additional complicated calculations. The null hypothesis of uniformity is rejected in all samples, in other words all samples showed a preferred orientation at the 95% confidence level (Table 5).

Where bimodal palaeocurrent distributions were present the mean azimuth of each group was calculated separately. Overlapping distributions were separated by dividing the two groups of data about the midpoint of the lowest common frequency interval (Kelling, 1969).

C) PALAEOCURRENTS AS INDICATED BY CROSS STRATIFICATION

Studies of modern river systems (High and Picard, 1974; Cant and Walker, 1976; Miall 1977a,b) have shown the orientation of planar cross-stratification to have a higher variability than that of trough cross-stratification. Trough cross-stratification is a result of downstream migration of dunes within the river channel, and due to its low mean angular deviation provides a relatively accurate indication of flow direction. Cant and Walker (1978) measured an average deviation of 69° from the mean flow direction in planar sets in the South Saskatchewan River, while Miall (1976) calculated a 186° range in variation between planar cross-stratification in transverse bars of a Cretaceous braided-stream deposit in the Isachsen Formation, Banks Island, Arctic Canada.

Only a few planar cross-stratified sets showed orientation at high angles to the mean current direction as indicated by trough cross-stratification in the Molteno. Analyses of planar cross-stratification in the Indwe Sandstone indicated that their mean angular deviation generally lies within the range calculated for trough cross-stratification. A possible reason for the low directional variability of planar cross-stratification in this instance was offered by Miall (1976) and also by Banks and Collinson (1974). They suggested that the preservation potential may be higher for structures formed in mid-channel whose foreset azimuths are closer to the mean flow direction of the river than for ones nearer the lateral margin and lying at oblique angles to the channel.

D) RESULTS

The mean flow azimuth derived from measurements from the whole of the field area (Fig. 50) shows a dominant transport direction towards the north-west ($\bar{\theta} = 329°$). Inspection of palaeocurrent data from individual members (Table 6) indicates only minor local deviations from the mean palaeoflow direction towards the south-east, south-west and north-east.

The results of palaeocurrent analyses for each member of the Molteno Formation are described below and illustrated in Figs. 51 and 52.

Table 5: TEST FOR UNIFORMITY

MEMBER	LOCALITY	n	R^2/n	d.f.	$\frac{1}{2}\chi^2_{,05}$
BAMBOESBERG	INDWE	31	20,76	2	3,0
INDWE SANDSTONE	CALA	36	34,20	2	3,0
	ST. GABRIEL	46	28,76	2	3,0
QIBA	TSOMO BRIDGE	27	16,30	2	3,0
LOSKOP MEMBER	LOSKOP (1)	10	5,78	2	2,92
	OFFA (6)	284	235,18	2	3,0
	INDWE (1)	30	26,72	2	3,0

Table 6: PALAEOCURRENT DATA

STRATIGRAPHIC UNIT	LOCALITY	n	R	r	S (degrees)	$\bar{\theta}$ (degrees)
BAMBOESBERG MEMBER	CALA AREA	87	70,15	0,81	36	330
	INDWE	31	25,37	0,82	37	342
INDWE SANDSTONE MEMBER	CALA PASS	148	127,04	0,86	30	344
	CALA	36	35,09	0,97	13	50
	F.M. TOWER	31	27,71	0,89	27	304
	REBELS KLOOF	30	14,38	0,48	58	316
	ST. GABRIEL	46	36,37	0,79	37	319
	INDWE	79	65,09	0,82	34	337
QIBA MEMBER	INDWE	14	13,17	0,94	20	294
	TSOMO BRIDGE	27	21,03	0,78	38	284
	CALA PASS	18	16,62	0,92	22	358
	REBELS KLOOF	22	28,12	0,91	25	324
LOSKOP MEMBER	LOSKOP (1)	10	7,60	0,76	40	41
	(3)	48	40,13	0,84	33	29
(major sandstone units are numbered from the base of the sequence)	(4)	44	42,13	0,96	17	311
	(6)	71	65,06	0,92	24	332
	(7)	28;24	27,01;22,39	0,96;0,93	15;21	67;193
	(8)	31	28,12	0,91	25	267
	OFFA (3)	143;42	113,58;40,64	0,79;0,97	37;14	346;198
	(4)	24	22,89	0,95	17	310
	(6)	284	258,49	0,91	25	305
	(7)	29	27,03	0,94	20	352
	CALA PASS (1)	46	38,09	0,83	37	100
	ULIN (1)	62	58,50	0,94	19	322
	(2)	16	15,51	0,97	14	339
	TSOMO BRIDGE (1)	19	17,30	0,91	24	101
	(2)	29	27,69	0,95	17	106
	INDWE (1)	30	28,31	0,94	19	325
	(2)	17	16,43	0,97	15	322
	(3)	11;11	10,69;10,39	0,97;0,94	13,59;19,06	326;169

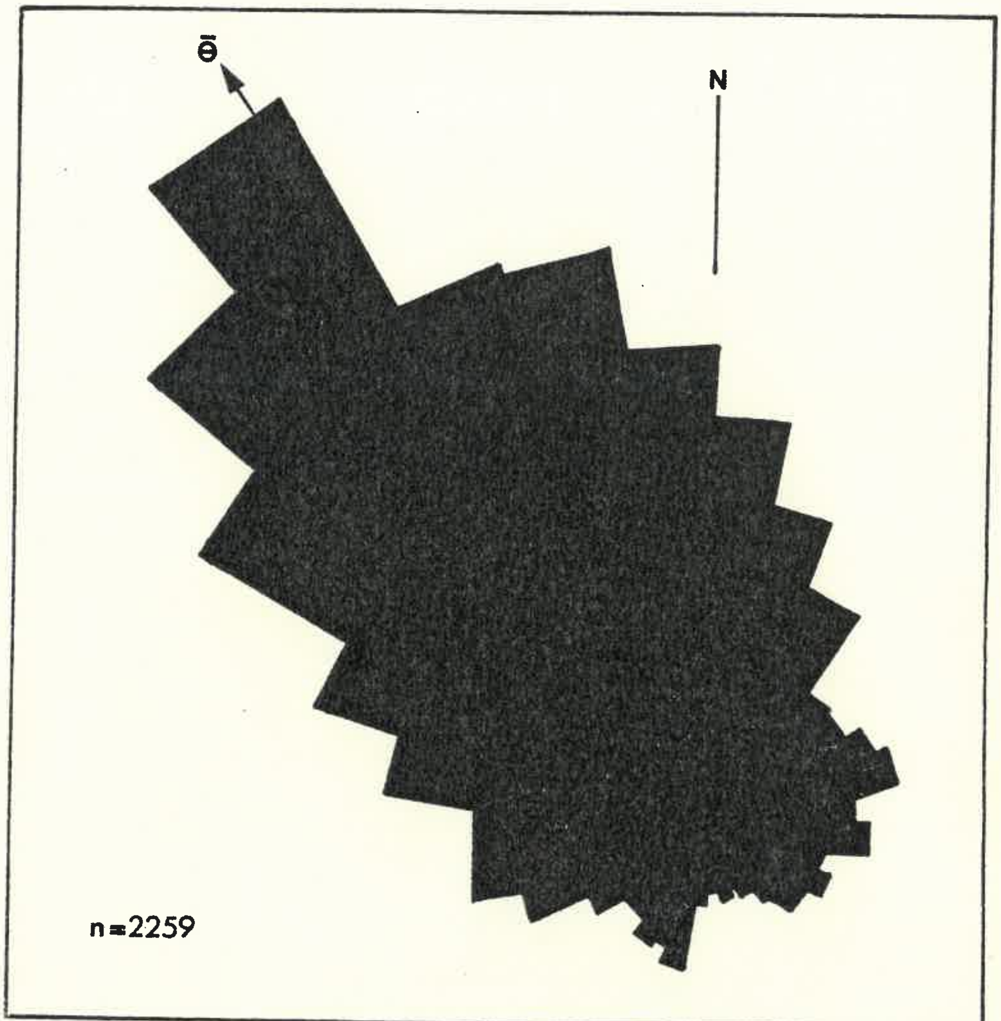


Figure 50. Rose diagram illustrating palaeocurrent distribution of the total field area.

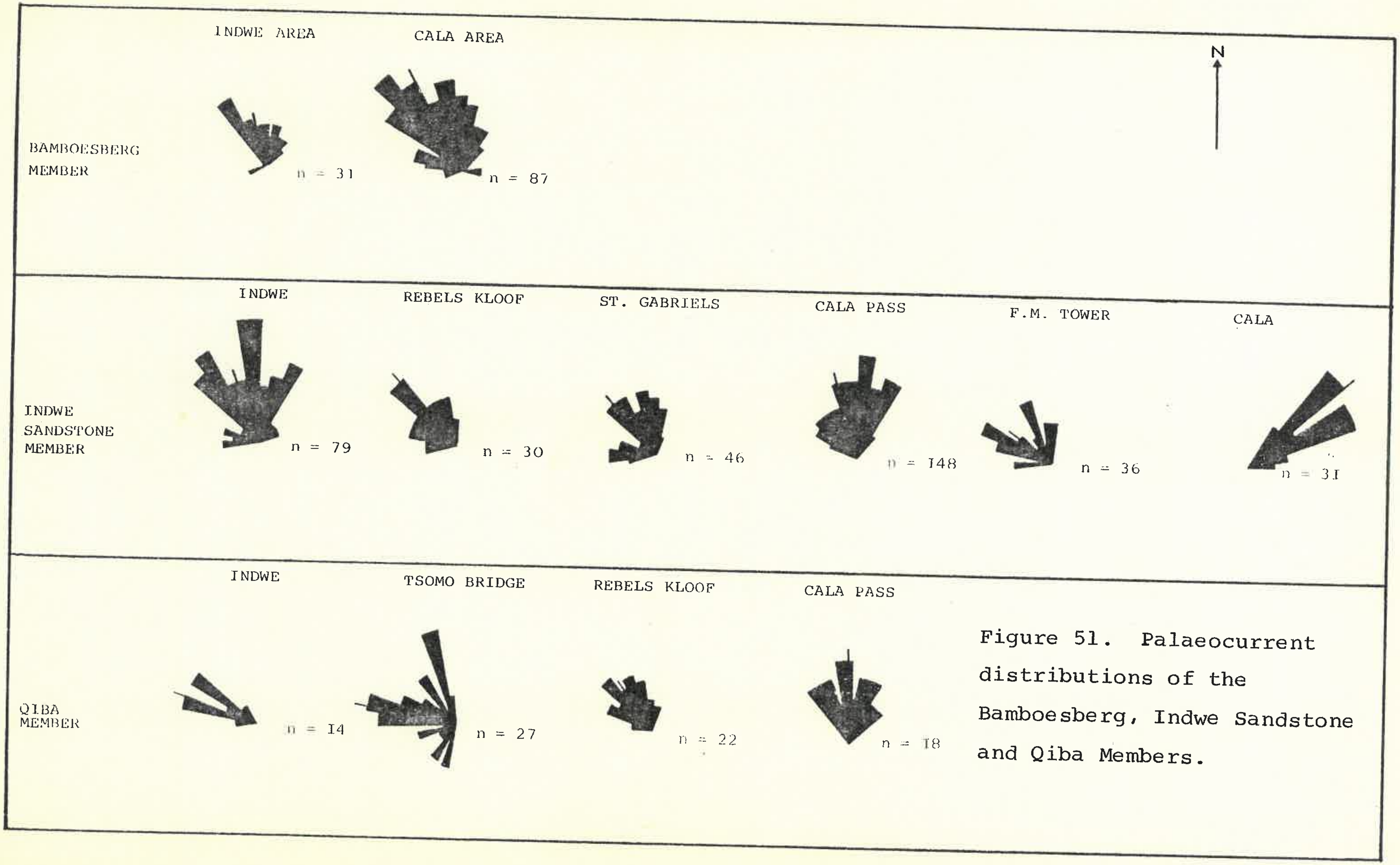


Figure 51. Palaeocurrent distributions of the Bamboesberg, Indwe Sandstone and Qiba Members.

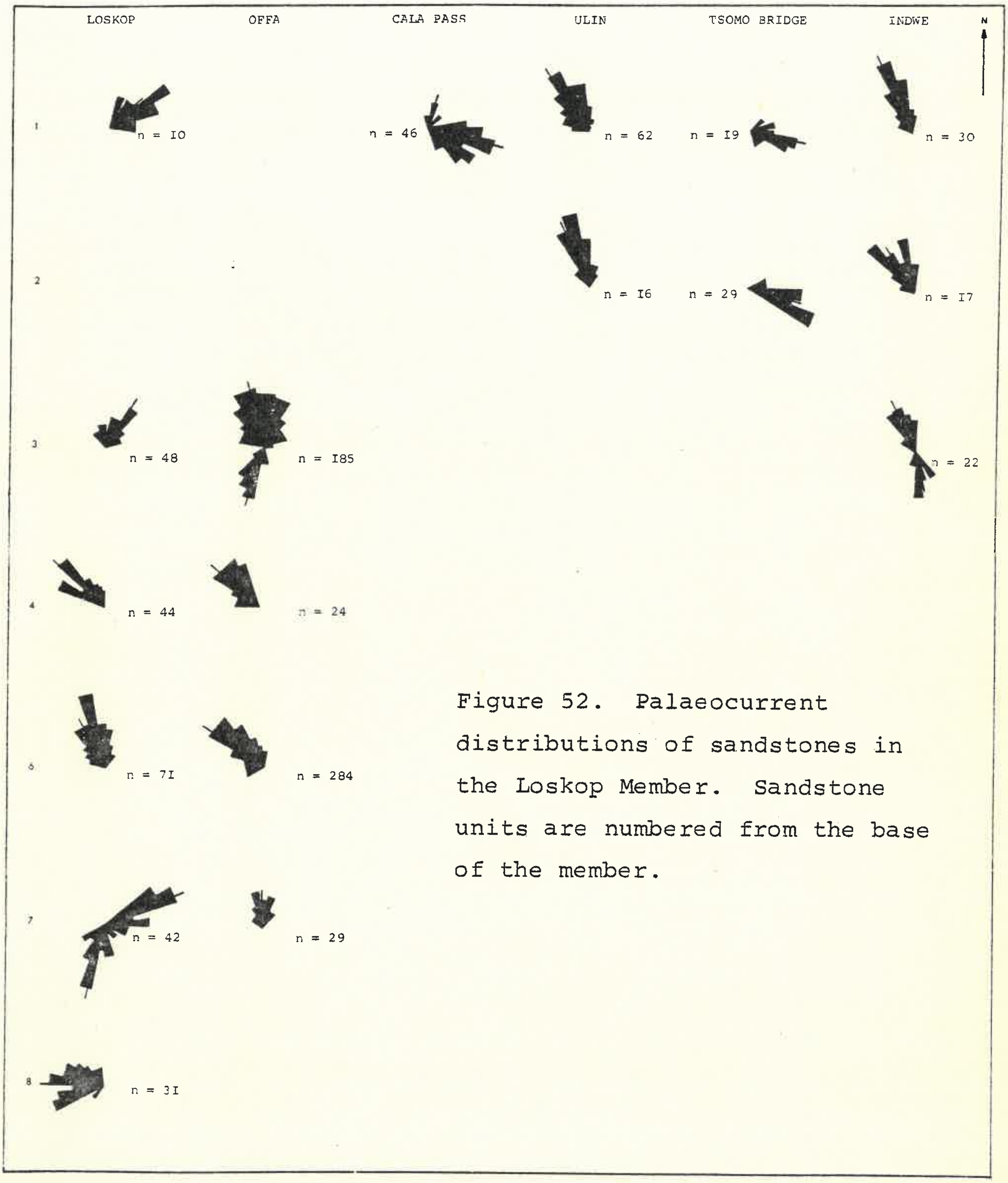


Figure 52. Palaeocurrent distributions of sandstones in the Loskop Member. Sandstone units are numbered from the base of the member.

1) Bamboesberg Member

Lack of cross-stratification data from this member made it necessary to pool the available palaeocurrent readings into two groups, one for the Indwe vicinity and the other for the vicinity of Cala. The dominant flow direction in both areas was towards the north-west (Fig. 51).

2) Indwe Sandstone Member

Owing to excellent outcrop quality and the common occurrence of cross-stratification, the Indwe Sandstone Member provided abundant palaeocurrent data throughout the field area. The dominant flow direction was towards the north-west, though there was minor sediment transport towards the north-east, south-west and south-east (Fig. 51).

Detailed measurement of five sections in the Qiba area permitted vertical and lateral variation in mean palaeocurrent direction within the Indwe Sandstone Member to be analysed (Fig. 53). Measurements from individual second-order cycles were not only unimodal, but also had r values approaching 1 and mean angular deviations not greater than 27^{o}, the average being about 18^{o} (Table 7). The mean azimuth for each cycle was plotted with respect to the stratigraphic interval it occupies above the base of the Indwe Sandstone. Lateral comparison of mean current azimuths was carried out visually. Initially, the F-test (Sanderson, 1973) was employed to explore further the apparent similarity between mean palaeocurrent directions at the same horizon but at different localities, and in some cases the difference in lateral current variation between cycles was found to be statistically significant. However, in terms of present-day braided rivers, the variations between cycles in the Indwe Sandstone Member seem in general to be insignificant and

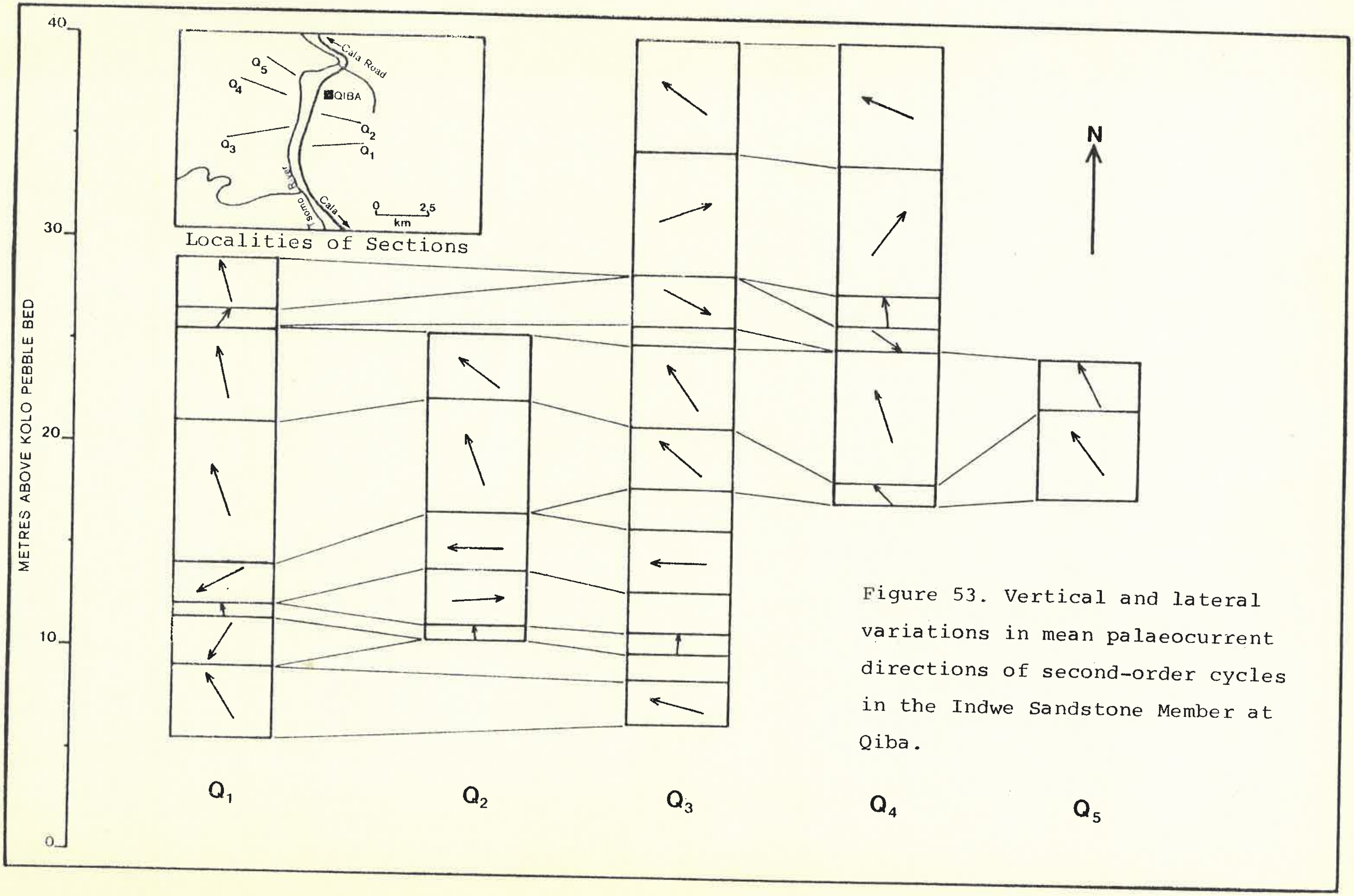


Figure 53. Vertical and lateral variations in mean palaeocurrent directions of second-order cycles in the Indwe Sandstone Member at Qiba.

Q_1	Q_2	Q_3	Q_4	Q_5
		$\bar{\theta} = 326^{\circ}$ $r = 0{,}95$ $s = 18^{\circ}$ $n = 10$	$\bar{\theta} = 308^{\circ}$ $r = 0{,}96$ $s = 16^{\circ}$ $n = 4$	
		$\bar{\theta} = 86^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 9$	$\bar{\theta} = 77^{\circ}$ $r = 0{,}96$ $s = 16^{\circ}$ $n = 24$	
$\bar{\theta} = 339^{\circ}$ $r = 0{,}99$ $s = 8^{\circ}$ $n = 10$			$\bar{\theta} = 350^{\circ}$ $r = 0{,}93$ $s = 21^{\circ}$ $n = 15$	
$\bar{\theta} = 30^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 35$		$\bar{\theta} = 153^{\circ}$ $r = 0{,}96$ $s = 16^{\circ}$ $n = 9$	$\bar{\theta} = 146^{\circ}$ $r = 0{,}97$ $s = 14^{\circ}$ $n = 8$	
$\bar{\theta} = 348^{\circ}$ $r = 0{,}95$ $s = 18^{\circ}$ $n = 17$	$\bar{\theta} = 339^{\circ}$ $r = 0{,}84$ $s = 32^{\circ}$ $n = 18$	$\bar{\theta} = 327^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 11$	$\bar{\theta} = 342^{\circ}$ $r = 0{,}94$ $s = 20^{\circ}$ $n = 8$	$\bar{\theta} = 345^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 6$
$\bar{\theta} = 312^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 39$	$\bar{\theta} = 326^{\circ}$ $r = 0{,}89$ $s = 27^{\circ}$ $n = 13$	$\bar{\theta} = 345^{\circ}$ $r = 0{,}94$ $s = 20^{\circ}$ $n = 15$	$\bar{\theta} = 315^{\circ}$ $r = 0{,}95$ $s = 18^{\circ}$ $n = 10$	$\bar{\theta} = 325^{\circ}$ $r = 0{,}89$ $s = 27^{\circ}$ $n = 14$
$\bar{\theta} = 296^{\circ}$ $r = 0{,}96$ $s = 16^{\circ}$ $n = 13$	$\bar{\theta} = 287^{\circ}$ $r = 0{,}93$ $s = 21^{\circ}$ $n = 29$	$\bar{\theta} = 292^{\circ}$ $r = 0{,}99$ $s = 8^{\circ}$ $n = 4$		
	$\bar{\theta} = 70^{\circ}$ $r = 0{,}97$ $s = 14^{\circ}$ $n = 4$			
$\bar{\theta} = 355^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 18$	$\bar{\theta} = 350^{\circ}$ $r = 0{,}97$ $s = 14^{\circ}$ $n = 13$	$\bar{\theta} = 20^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 4$		
$\bar{\theta} = 200^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 26$				
$\bar{\theta} = 319^{\circ}$ $r = 0{,}95$ $s = 18^{\circ}$ $n = 30$		$\bar{\theta} = 302^{\circ}$ $r = 0{,}98$ $s = 12^{\circ}$ $n = 6$		

Table 7. Palaeocurrent Data for Second-Order Cycles in the Indwe Sandstone Member at Qiba.

explicable within the limits normally expected within such a hydrodynamic system (Miall, 1977a).

3) Qiba Member

Like the Bamboesberg Member, this member contains little cross-stratification, and hence palaeocurrent data are limited. Palaeocurrent distributions from the Cala, Tsomo River bridge and Indwe localities confirm the general north-westerly flow indicated by other members (Fig. 51). The high mean angular deviation seen in the Tsomo River bridge rose diagram may be related to the large area over which the measurements were collected, namely along the Tsomo River between the farms Saunabul and Umnachean.

4) Loskop Member

Measurements of cross-stratification in sandstone units of the Loskop Member reveal the existence of a dominant north-westerly flow direction, together with two subordinate modes indicating flow towards the north-east and south-west respectively (Fig. 52). Single sandstone units commonly show a bimodal distribution, though each mode seems to relate to a different level in the sandstone and to an individual upward-fining cycle.

E) INTERPRETATION

Three significant facts seem to emerge from the analysis of palaeocurrent directions:-

1) The prevailing palaeocurrent direction in the field area during Molteno times was towards the north-west. Subordinate flow directions towards the north-east, south-east and south-west also existed.
2) Mean angular deviation values suggest that the rivers

were of low sinuosity, thus supporting the hypothesis that the river channels were braided in nature.

3) There is no important vertical variation in palaeocurrent direction.

The north-westerly flow direction is not in agreement with the north-easterly direction postulated by Turner (1975a) for the southern part of the Molteno basin. It does, however, agree with the flow direction for the whole of the basin which he proposed. Based on the difference in orientation between palaeocurrent patterns of the southern and northern Molteno, Turner (op. cit.) postulated a two-component flow system governed by source areas in the south and south-east. It would appear that such source areas also controlled deposition in the present field area. The presence of minor flow systems directed towards the south-west and south-east respectively may be indicative of local control within the depositional basin. Where abrupt changes in palaeocurrent direction exist, they always relate to changes from one depositional cycle to another, each cycle being initiated by increased energy conditions. These changes may be due to varying levels of tectonic activity in the source areas to the east, south and west of the depositional basin, changes due to flooding, or to differential alluvial plain subsidence or compaction. Positive relief in the depositional basin may have also been responsible for these variations in current direction.

CHAPTER 9

CYCLIC SEDIMENTATION

A) INTRODUCTION

The concept of cyclic sedimentation has been a subject of controversy for more than a century (Duff et al., 1967). Some authors have considered the subject wide enough to include all aspects of sedimentation, while for others it provided a means of recognizing orderly patterns within sedimentary sequences as a basis for genetic interpretation. Generally, cyclic or rhythmic patterns of sedimentation are regarded as a series of sedimentary facies repeated through a succession (Duff et al., op. cit.). There has, however, been disagreement and contention over the terminology relating to such patterns, and many interpretations and definitions of cyclic and rhythmic sedimentation exist within the literature.

Some authors (Fiege, 1952; Fearnsides, 1970 and others) have restricted the term "rhythm" to alternating sequences of two lithotypes or facies, while Sander (1936) suggested that this term be used only where the rhythmic units were of constant thickness. Less restrictive is the definition of Whitten and Brooks (1972), a rhythm being "... a sequence of sediments which change their character progressively from one extreme to another, a change which is followed directly by a return to the original type.", for example: ABCD ABCD. They regarded a "cycle" as a sedimentary sequence which changes its character progressively from one extreme type to another followed by a return to the initial state, for example: ABCDCBA. Moore (1950) suggested that "rhythm" should refer to sequences that have been formed at equal time intervals, and that "cycle" be used to describe rock sequences that display a regular pattern of sedimentation. The term "cyclothem" was introduced by Wanless and Weller (1932) to define a sequence of beds deposited during a single sedimentary cycle, but its use in some later publications appears to be synonomous with the term "cycle" (for example, Beerbower, 1961; Allen, 1964, 1970a).

Duff et al. (1967) were of the opinion that the terms rhythm, cycle and cyclothem are synonomous and suggested that a sedimentary sequence following the pattern: ABCD ABCD be referred to as an "asymmetric cycle" and the ABCDCBA type be referred to as a "symmetric cycle". It is clear, however, that all three terms (rhythm, cycle and cyclothem) refer to a sedimentary sequence in which the strata are arranged in a recognizable, non-random pattern related to a series of connected events. In this thesis, following a modern trend (Duff et al., 1967; Schwarzacher, 1969, 1975; Turner, 1975a; Miall, 1977a; 1978) the term "cycle" is used for such arrangements.

Cyclicity is an important concept in interpreting and describing the stratigraphic history of sedimentary sequences as it reflects a succession of systematically changing environments and offers the possibility of recognizing some order in the events of geological history (Schwarzacher, 1975). Furthermore, the cause of cyclicity within a sedimentary sequence is an important factor when considering genetic implications. Suggested causes include: tectonic control (Hudson, 1924; Turner, 1975a,b; McLean and Jerzykiewicz, 1978; Steel and Aasheim, 1978), climatic control (Gilbert, 1895; Flint and Gale, 1958; Hollingworth, 1962; Duff et al., 1967), eustatic sea level changes (Fairbridge, 1961; Grabau, 1963; Wells, 1960) and astronomic changes (Blatt et al., 1972; Schwarzacher, 1975). However, in the absence of any reference to the thickness of sedimentary cycles, the concept of cyclicity is of limited use in either stratigraphy or sedimentology, especially with regard to an understanding of underlying controls on cyclicity.

B) SCALE OF SEDIMENTARY CYCLES

A well developed cyclicity developed within strata of the Molteno Formation is present at two scales:

1) First-order cycles (tens of metres thick) which may include one or more stratigraphic members.
2) Second-order cycles (metres thick) which are recognizable within stratigraphic members.

First-order sedimentary cycles in the Molteno were first recognized by Rust (1959) who compared them with the classical "cyclothems" of Wanless and Weller (1932). Ryan (1963) and Turner (1970, 1975a,b) elaborated further on this large-scale cyclicity, but made no reference to second-order cycles. Up to twelve first-order cycles have been recognized in the present field area, compared to the maximum of six described by Turner (op. cit.) in the vicinity of Maclear. This discrepency is due to the inclusion of the Loskop Member (which comprises eight first-order cycles) in the Molteno Formation by the present writer.

The thickness and distribution of these sedimentary cycles has been described in the section of this thesis dealing with stratigraphy.

C) TECTONISM, CLIMATE AND SEDIMENTARY CYCLES

The relationship between the Cape Diastrophism and first-order cyclicity in the Molteno Formation has been examined at length by Rust (1959), Turner (1970, 1975a,b) and Lock (1978). There appears to be little doubt that source-area tectonism was the main cause of cyclicity during the deposition of the Molteno, but it is further suggested that climate also played a significant role in influencing the pattern of cyclicity and sedimentation.

Rainfall and vegetation, both functions of climate, influence erosion, sediment discharge and to an important extent the pattern of sedimentation (Blatt. et al., 1972). It is therefore to be expected that changes in climate would be recorded in the sedimentary sequence. Evidence of climatic change during Permian and Triassic times is provided by the fossil record and the differences between the envisaged depositional environments of the Beaufort and the Molteno. It is probable that the onset of Molteno deposition was accompanied by a change to a cool, wet climate able to support a varied vegetation. It is not known whether the change was due to increased relief in the south or was associated with a more general climatic change affecting the whole of Gondwanaland. Turner (1975a) believed that the altitude of the source area could have been in the region of 4 200 m, and by comparison with the Alps, suggested that temperatures were low and precipitation high. Snow and ice would also have been present at such an elevation. Conditions of this kind would scarcely have favoured plant growth, but would have promoted mechanical weathering and runoff, thereby increasing the rate of denudation and sediment yield. A change to drier, warmer climatic conditions would have inhibited the transport of sediment from the source area, irrespective of the amount of weathered material available.

The following points seem to favour tectonism as a major cause of first-order cyclicity:

1) The scale of the cycles is not compatible with energy distributions normally present on an alluvial plain (cf. McLean and Jerzykiewicz, 1978).
2) The asymmetric nature of the cycles (ABCD ABCD) is consistent with tectonic control (Steel, 1976).
3) The cycles persist laterally throughout the field area, and also throughout most of the southern Molteno outcrop area (Turner, 1975a).

In the absence of evidence to suggest the influence of astronomic fluctuations or marine events, only tectonism and climate are considered here as possible causes of cyclicity.

1) Age Relationships Between the Cape Diastrophism and Deposition of the Molteno Formation

The two most significant lines of evidence linking the Cape Diastrophism with deposition during Molteno times are the apparent contemporaneity of these events (Turner, 1975a; Lock, 1978), and the palaeocurrent data which indicates a southerly source for the Molteno sediment.

The age relationship between the Cape Diastrophism and the Molteno Formation has, however, not been irrefutably established owing to the lack of conclusive age evidence. Truswell (1977) thought that the earliest date for the initiation of the Cape Fold Belt was post-Dwyka, the diastrophism having affected strata no younger than the *Daptocephalus* zone of the Lower Beaufort

(Permian). The earliest lithological evidence of the diastrophism is contained in the Lystrosaurus zone (lower Triassic) of the Beaufort Group (Johnson, 1976), which is in close agreement with Anderson and Schwyzer (1977), who set the age of the first phase of folding and uplift at the Permian-Triassic boundary using palaeomagnetic evidence.

Lock (1978) suggested that the Lower Ecca (early Permian) sediments in the Cape Province were largely derived from a southerly source, possibly as a result of an early phase of the Cape orogeny. Then, following a tectonically inactive period, the Katberg Sandstone (Permian-Triassic age) recorded a renewed orogenic pulse in the source area. The tectonic lull, during which the dominantly argillaceous Burgersdorp Formation (Upper Beaufort) was deposited, was followed by the deposition of the Molteno Formation which De Villiers (1944), Rust (1959), Turner (1975a) and Lock (1978) regarded as the climax of the Cape Diastrophism; "... the timing of the orogenic climax can be dated relatively precisely by sedimentological means, and it clearly coincides with the change in conditions reflected by the Beaufort - Molteno boundary within the early Triassic." (Lock, op. cit. p270).

Evidence that the base of the Molteno Formation did not coincide everywhere with an episode of uplift in the source area was presented by Turner (1975a). His thesis is that the disconformable relationship between the Bamboesberg and the Indwe Sandstone Members indicates that the main phase of uplift and diastrophism occurred after deposition of the Molteno strata (Bamboesberg Member) had begun in the south. This caused a transgression by the Indwe Sandstone across the basin so that it overlaps onto successively older rocks of the Beaufort Group in the north.

2) <u>Mechanisms for Source-Area Tectonics</u>

Uplift and tectonism during the Cape Diastrophism is considered to have been of an intermittent nature, as reflected by the large-scale cyclicity of the Molteno Formation. Rust (1959) held the view that the pattern of Molteno sedimentation was due to the oscillatory nature of the diastrophic pulses, each oscillation resulting in a separate cycle of sedimentation. Turner (1975a, p290) stated that if Rust's interpretation was correct, then "... the source area diastrophism must have culminated in one gigantic pulse followed by successively weaker pulses as the level of tectonic energy declined towards the close of Molteno times."

Newton (1973) proposed a gravity-folding model to account for the origin of the Cape Fold Belt. By means of this mechanism unconsolidated, water-saturated sediments supposedly slid down a palaeoslope to generate folding. This model has not been universely accepted. De Swardt (1974) disagreed with Newton, as he believed that the strata were by that time lithified and had undergone incipient green-schist facies metamorphism prior to folding. De Swardt <u>et al</u>. (1974) suggested that the Cape orogeny is best explained by assuming a collision of crustal plates, and Rhodes (1974) proposed a plate tectonic model in which the Cape Fold Mountains represented a foreland fold thrust-belt which originated following a collision between the African continental plate and another continental plate to the south. The latter may have included parts of South America, the Falkland Islands and Antarctica.

Anderson and Schwyzer (1977) considered that a clockwise-anticlockwise wobble of eastern Gondwanaland during Triassic times resulted in the repetitive onset and release of compressional stress against the southern tip of Africa. Urien <u>et al</u>. (1967) proposed a model by means of which the present day African and

South American continents rotated or pivoted about a point near the extreme south-western tip of Africa and separated initially in the north along the African west coast. By this mechanism the southern part of South America was forced northward against the African continent during Triassic or early Jurassic times producing compressive deformation of the Cape and southern Karoo which resulted in the Cape Diastrophism.

The most recent model is that proposed by Lock (1980), based on the idea of flat-plate subduction. He postulated that the subduction zone of southern Africa was located on the Andean margin of western South America about 2000 km south of the present South African coastline. The lack of metamorphism and igneous activity generally associated with the orogenesis is attributed to the subduction of oceanic crust along the Andean margin of the supercontinent which became coupled with the overthrust continental crust late in the Palaeozoic Era. Continued plate convergence (subduction) was taken up by tectonic deformation and crustal shortening in the Andean and Cape Fold Belts. The Cape Fold Belt is thought to have been the zone where the two plates decoupled, and a return to orthodox subduction is envisaged during Karnian (upper Triassic) times.

Irrespective of which plate-tectonic model is accepted, the Cape Diatrophism is attributed to the convergence of crustal plates. The alternating onset and release of compressional stress within the orogenic zone resulted in varying rates of tectonism and uplift, which was ultimately reflected in the cyclic depositional pattern of the Molteno.

3) First-Order Cycles

The interaction between an orogenic belt and its foreland basin is complex, and attempts to relate observed cyclicity in the Molteno to tectonic control of sedimentation must necessarily oversimplify the situation. Major factors controlling deposition in the sedimentary basin would have been tectonism and uplift in the source area and these would have resulted in the steepening of river-profile gradients. Such processes would have led to disequilibrium and an increase in energy level of the fluvial system, enabling it to transport coarser material. Through erosion and aggradation the system would then have tended progressively towards a state of equilibrium in which, ideally, there would be no further degradation or aggradation.

Bloom (1967) indicated that even relatively small loads are compensated isostatically over a geologically short period, and subsidence due to sediment loading may therefore be expected to be directly proportion to the rate of infilling. McLean and Jerzykiewicz (1978) recognized three general states which are possible as subsidence due to sediment infilling takes place. All involve aggradation, but the rates are necessarily variable:

1) subsidence greater than infilling;
2) subsidence equal to infilling; and
3) subsidence less than infilling.

The minimum distance of the present field area from the orogenic belt during Permian-Triassic times has been estimated by Turner (1975a) to be 180 km. This is considered to be beyond the influence of loading due to thrusting in the orogenic zone, and subsidence would therefore be dependent only on sediment infilling which would, in the short term, result in the third of the above states being attained. According to McLean and Jerzykiewicz (op. cit.) the river system would continue aggrading until it had established an equilibrium profile, adding only enough new detritus to maintain this. Excess sediment would bypass the proximal area to be deposited more distally and, with approaching equilibrium conditions in the source area, the energy level would progressively decrease. The distance between the approximate source area of the Indwe Sandstone Member and its extreme northern limit, about 450 km, confirms that extensive aggradation and distal alluviation did, in fact, take place.

The Bamboesberg Member differs from first-order cycles higher in the formation in that it does not constitute an upward-fining cycle. Turner (1975a) suggested that its deposition was initiated by epeirogenic movements involving only gentle elevation prior to the main phase of tectonic activity and that the gradual infilling of the basin resulted in a decrease in the gradient and competency of the streams. He observed that the upward-fining nature of the Bamboesberg to the west of the present field area may well be ascribed to this phenomenon, but no such pattern is evident at Indwe or Cala where some outcrops show the upper part of the member to be slightly coarser than the underlying strata. On the other hand, sedimentary evidence suggests that the Indwe Sandstone was initiated by a major, prolonged phase of uplift punctuated by a brief pause during which the Little Bamboo Mountain Shale was probably deposited. Renewed tectonic activity, probably of a lesser scale than that indicated by the Kolo Pebble Bed, is reflected by the locally persistent Emnxe Pebble Bed. Continued erosion in the source area and along the river profile led to a decrease in competency of the river system as reflected by the finer deposits of the upper part of the Indwe Sandstone Member and the Mayaputi Member.

The Qiba Member reflects tectonism of lesser intensity than that experienced during deposition of the Indwe Sandstone. Coarse-grained components of first-order cycles within the Loskop Member imply renewed tectonic activity, and it would appear that the tectonic pulses were of a short, but intense nature. They were followed by relatively long tectonically stable periods during which the argillaceous components were deposited.

Deposition of the Elliot Formation recorded the end of the Cape Diastrophism, but sporadic occurrences of pebbles and cobbles (Botha, 1968) in that formation probably reflects late, spasmodic pulses of tectonic activity.

Sandstone components of first-order cycles in the Molteno Formation have rapidly gradational or abrupt tops suggesting a rapid decrease in energy conditions. Visser and Dukas (1979) and Nami and Leeder (1978) described an upward gradation from low sinuousity, braided-river deposits into meandering-river deposits with decreasing gradient and energy conditions. No such gradation was found to exist in the present field area, but borehole core from the Molteno at Ficksburg (about 300 km to the north of the field area) revealed cycles suggestive of meandering rivers (thin basal sandstone and thick upper argillaceous component). It therefore appears that the absence of the meandering-river phase in first-order cycles may be due to proximity of the field area to the source region where tectonically induced uplift may have increased the river-profile gradient for some distance basinward. Such steep gradients may have precluded the formation of the meandering-river phase, and even during periods of diminished river discharge and sediment supply, drainage would probably have been directed along previously incised, braided or low-sinuosity channels.

If, as Rust (1959) suggested, alluvial fans were present along the margins of the source region, the change in gradient from a mountainous interior to a relatively flat alluvial plain would have been abrupt. A high river discharge would have been necessary for the transport of sediment away from the source area under the braided-river conditions envisaged for sandstone units of the Molteno Formation. Normal river discharge would have resulted in the deposition or dumping of much of the coarser material relatively close to the source region, and only finer sediment would have reached more distal parts of the depositional basin where a large inland flood-plain or swamp-like environment is suggested to have existed.

An abrupt decrease in sediment supply and river discharge would not have allowed the river profile to achieve a grade condition in the proximal region, and the steep gradient would have persisted. During this period rivers would have drained onto distal flood-plains which would, with increasing time and infilling, have overlapped onto progressively more proximal, inactive braided-stream deposits. It is by such a process that the apparently abrupt transition from braided-stream to dominantly argillaceous flood-plain conditions is thought to have occurred.

4) Second-Order Cycles

Cycles within sandstone components of first-order cycles represent the infilling of a channel or local channel system under progressively decreasing energy levels followed by channel abandonment as a result of avulsion. Cycles in the argillaceous dominated sequences indicate a sheet-flood event followed by long periods of deposition by low energy currents.

Second-order cycles therefore reflect fluctuations in river activity on the alluvial plain. Although tectonism played a a major role in the control of first-order cyclicity, the deposition of each second-order cycle was ultimately controlled by climate. Owing to the fact that subsidence was a function of sediment infilling, it was probably not a major modifying factor.

CHAPTER 10

DEPOSITIONAL HISTORY

During the Upper Beaufort the climate was warm and arid. Streams were of lower energy and flowed more intermittently than during early Molteno times, carrying fine sand, silt and mud from a tectonically stable source area of low relief (Rust, 1959; Turner, 1975a). The commencement of Molteno sedimentation is indicated by the Bamboesberg Member which is thought to have been the product of an epeirogenic phase of slight uplift and erosion in a southerly source area (Turner, op. cit.). This was accompanied by a change to a wet, cool climate with precipitation that was perhaps seasonal. It seems that during deposition of the Bamboesberg coarse detritus was not generally available, but the competence of currents was in excess of that required for the movement of the fine- to medium-grained sediment load, as indicated by the presence of quartzite pebbles and cobbles. Flood events were violent and short-lived. Conditions were locally favourable for peat-swamp formation, as reflected by the presence of the Indwe and Guba Coal Seams.

Indwe Sandstone deposition was initiated by rapid uplift in the source area resulting in an increase in the gradient and competency of streams. Large amounts of coarse detritus were released, including rock clasts of pebble, cobble and boulder size. In contrast to the Bamboesberg, the Indwe Sandstone was deposited by streams with relatively well defined channels. The formation of the Kolo Pebble Bed was, however, probably due to sediment being released over a wide, flat surface on emerging from a mountainous terrain and forming a thin sheet-like deposit (Turner, 1975a). Flooding was still of an intermittent nature, but channels probably carried water for longer periods than during deposition of the Bamboesberg Member. The laterally persistent nature of the Indwe Sandstone was probably due to the formation of a sheet- or blanket-deposit (Campbell, 1976) by coalescing braided-stream channels or channel systems. The large area over which the Indwe Sandstone is today present (approximately 80,000 km^2) suggests that source-area tectonism and Molteno sedimentation reached a climax during this period. Decrease in sediment supply and river size caused the formation of extensive flood plains in distal parts of the basin. These in time transgressed southward over the more proximal braided stream deposits. Local peat swamps established at the close of Mayaputi times ultimately formed the coals of the Cala Pass Seam.

Renewed source-area tectonism is reflected by the Qiba Member, which was deposited from shallow, high energy ephemeral streams. A brief pause in sedimentation, during which the Ulin Seam was deposited,was followed by a further influx of high energy, sediment-laden flood waters. A more distal environment than that of the Indwe Sandstone is implied by the finer-grained nature of the Qiba Member, but its higher plagioclase content suggests an immature sediment. This change in composition might, however, be attributed to variations in source-area mineralogy.

The Loskop Member reflects periods of intermittent tectonic activity which resulted in the deposition of coarse-grained, braided-river sheet-sandstones. The relatively thick argillaceous components were deposited during periods of little tectonic or fluvial activity in an environment similar to that envisaged during Mayaputi times. There is no evidence that the amplitude of tectonic activity diminished appreciably, for even the highest sandstone unit of this member is coarse-grained and pebbly. Evidence of an increasingly warm, arid environment is provided by the appearance of red argillites. The climate still, however, permitted the local formation of peat swamps, as indicated the Umnachean and Offa Seams, but these were of a short-lived duration.

The red colouration of siltstones and mudstones in the Elliot Formation (Botha, 1968) reflects a warm, arid environment (Allen, 1970b; McBride, 1974). Tectonic activity had almost completely ceased, but thin, local concentrations of pebbly sandstone in the Elliot Formation (Botha, 1968) are thought to have resulted from late stage, intermittent tectonic activity.

REFERENCES

Allen, J.R.L. (1963). The classification of cross-stratified units with notes on their origin: Sedimentology, 2, 93-114.

——————— (1964). Studies in fluviatile sedimentation: six cyclothems from the Lower Old Red Sandstone, Anglo-Welsh Basin. Sedimentology, 3, 163-198.

——————— (1965a). A review of the origin and the characteristics of recent alluvial sediments. Sedimentology, 5, 89-191.

——————— (1965b). Fining upwards cycles in alluvial successions. Lpool. Manchr. geol. J., 4, 229-246.

——————— (1965c). The sedimentation and palaeogeography of the Old Red Sandstone of Anglesey, North Wales. Proc. Yorks. geol. Soc., 35, 139-185.

——————— (1970a). Studies in fluviatile sedimentation: a comparison of fining-upwards cyclothems, with special reference to coarse-member composition and interpretation. J. sedim. Petrol., 40, 298-328.

——————— (1970b). Physical Processes of Sedimentation. Allen and Unwin, London, 248pp.

——————— (1974). Sedimentology of the Old Red Sandstone (Siluro-Devonian) in the Clee Hills area, Shropshire, England. Sedim. Geol., 12, 73-167.

Allen, J.R.L. and Banks, N.L. (1972). An interpretation and analysis of recumbent-folded deformed cross bedding. Sedimentology, 19, 257-283.

Anderson, T.W. and Goodman, L.A. (1957). Statistical inference about Markov Chains. Ann. math. Statist., 28, 89-110.

Anderson, J.M. and Schwyzer, R.U. (1977). The biostratigraphy of the Permian and Triassic. Part 4 - Palaeomagnetic evidence for large-scale intra-Gondwana plate movements during the Carboniferous to Jurassic. Trans. geol. Soc. S.Afr., 80, 211-234.

Banks, N.L. and Collinson, J.D. (1974). Discussion of "Some sedimentological aspects of planar cross-stratification in a sandy braided river." J. sedim. Petrol., 44, 265-267.

Barret, P.J. (1970). Palaeocurrent analysis of the mainly fluviatile Permian and Triassic Beacon rocks, Beardmore Glacier area, Antarctica. J. sedim. Petrol., 40, 395-411.

Beerbower, J.R. (1961). Origin of cyclothems of the Dunkard Group (Upper Pennsylvanian - Lower Permian) in Pennsylvania, West Virginia, and Ohio. Bull. geol. Soc. Am., 72, 1029-1050.

________________ (1964). Cyclothems and cyclic depositional mechanisms in alluvial plain sedimentation, 31-42. In Merriam, D.F., Ed., Symposium on Cyclic Sedimentation. St. Geol. Surv. Kansas, Bull. 169.

Blatt, H. and Christie, J.M. (1963). Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. J. sedim. Petrol., 33, 559-579.

Blatt, H., Middleton, G.V. and Murray, R. (1972). Origin of Sedimentary Rocks. Prentice-Hall, New Jersey, 634pp.

Bloom, A.L. (1967). Pleistocene shoreline: a new test of isostacy. Geol. Soc. Am. Bull., 78, 1477-1494.

Boothroyd, J.C. and Ashley, G.M. (1975). Process, bar morphology and sedimentary structures on braided outwash fans, north-eastern Gulf of Alaska, 193-222. In Jopling, A.V. and McDonald, B.C., Eds., Glaciofluvial and Glaciolacustrine Sedimentation. S.E.P.M., Spec. Publ., 23.

Botha, B.J.V. (1968). The stratigraphy of the Red Beds Stage, Karoo System, at Elliot, C.P. Trans. geol. Soc. S.Afr., 71, 101-117.

Bull, W.B. (1972). The recognition of alluvial fan deposits in the stratigraphic record, 63-83. In Rigby, J.K. and Hamblin, Hamblin, W.K., Eds., Recognition of Ancient Sedimentary Environments. S.E.P.M., Spec. Publ., 16.

Butler, B.E. (1961). Ground surfaces and the history of the Riverine Plain. Aust. J. Sci., 24, 39-40.

Campbell, C.V. (1976). Reservoir geometry of a fluvial sheet sandstone. Bull. Am. Ass. Petrol. Geol., 60, 1009-1019.

Cant, D.J. and Walker, R.G. (1976). Development of a braided-fluvial facies model for the Devonian Battery Point Sandstone, Quebec. Can. J. Earth. Sci., 13, 102-119.

Cant, D.J. and Walker, R.G. (1978). Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada. Sedimentology, 25, 625-648.

Coleman, J.M. (1969). Brahmaputra River: channel processes and sedimentation. Sedim. Geol., 3, 129-239.

Collinson, J.D. (1970). Bed forms of the Tana River, Norway. Geogr. Ann., 52A, 31-55.

——————— (1978). Vertical sequence and sand body shape in alluvial sequences, 577-586. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Crook, K.A.W. (1965). The classification of cross stratified units, comment on a paper by J.R.L. Allen. Sedimentology, 5, 249-252.

Dapples, E.S. (1942). The effect of macro-organisms upon near-shore sediments. J. sedim. Petrol., 12, 118-126.

Davis, J.C. (1973). Statistics and Data Analysis in Geology. John Wiley and Sons, Inc., New York, 550pp.

De Swardt, A.M.J. (1974). Note on orogenic style in the Cape Fold-Belt. Authors reply to discussion. Trans. geol. Soc. S.Afr., 77, 385-388.

De Swardt, A.M.J. and Rowsell, D.M. (1974). Note on the relationship between diagenesis and deformation in the Cape Fold Belt. Trans. geol. Soc. S.Afr., 77, 239-245.

De Villiers, J. (1944). A review of the Cape Orogeny. Ann. Univ. Stellenbosch, 22, 183-208.

Duff, P.McL.D., Hallam, A. and Walton, E.K. (1967). Cyclic Sedimentation. Developments in Sedimentology, 10. Elsevier, Amsterdam, 271pp.

Dunn, E.J. (1873). Report on the Stormberg coalfield. Parliamentary report G31, Cape Town.

——————— (1878). Geological report of the Stormberg coalfield. Parliamentary report, G4, Cape Town.

Du Toit, A.L. (1905). The geological survey of Glen Grey, and parts of Queenstown and Wodehouse, including the Indwe area. Ann. Reps. geol. Commn. C.G.H.

Du Toit, A.L. (1954). The Geology of South Africa. Oliver and Boyd, 576pp.

Fairbridge, R.W. (1961). Eustatic changes of sea level, 99-185. In Ahrens, L.H., Ed., Physics and Chemistry of the Earth, Pergamon, Oxford.

Fearnside, W.G. (1950). Rhythm in sedimentation: introduction. Int. Geol. Congress, 18th, London, 1948, Rept., 4, 4pp.

Fiege, K. (1952). Sedimentationszyklen und Epirogenese. Z. Deut. Geol. Ges., 103, 17-22.

Flint, R.F. and Gale, W.A. (1958). Stratigraphy and radiocarbon dates at Searles Lake, California. Am. J.Sc., 256, 689-741.

Folk, R.L. and Ward, W.C. (1957). Brazos river bar - a study in the significance of grain size parameters. J. sedim. Petrol., 27, 3-26.

Fox, C.S. (1931). Coal in India. Part 1 - The natural history of Indian coal. Mem. geol. Surv. India., 57, 283pp.

Friedman, G.M. (1958). Determination of sieve size distribution from thin-section data for sedimentary petrological studies. J. Geol., 66, 394-416.

Friend, P.F. (1978). Distinctive features of some ancient river systems, 531-542. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Gabelman, J.W. (1971). Sedimentology and uranium prospecting. Sedim. Geol., 6, 145-186.

Galloway, W. (1889). Report on the coal deposits in the Indwe basin and Stormberg range of mountains. Parliamentary report, G50, Cape Town.

Gilbert, G.K. (1895). Sedimentary measurement of Cretaceous time. J. Geol., 3, 121-127.

Gill, W.D. and Kuenen, P.H. (1958). Sand volcanoes and slumps in the Carboniferous of County Clare, Ireland. Q. J. geol. Soc. Lond., 113, 441-460.

Gould, H.R. (1972). Environmental indicators - a key to the stratigraphic record, 1-3. In Rigby, J.K. and Hamblin, W.K., Ed., Recognition of Ancient Sedimentary Environments. S.E.P.M., Spec. Publ., 16.

Grabau, A.W. (1936). Oscillation or pulsation? Int. Geol. Congress, 16th, Washington, 1933, Rept., 1, 539-552.

Green, A.H. (1883). Report on the coals of the Cape Colony. Parliamentary report, Cape Town.

Greenwood, J.A. and Durand, D. (1955). The distribution of length and components of the sum of n random unit vectors. Ann. Math. Statist., 26, 233-246.

Harbaugh, J.W. and Bonham-Carter, G. (1970). Computor Simulation in Geology, Wiley, New York, 575pp.

Harms, J.C. and Fahnestock, R.K. (1965). Stratification, bed forms and flow phenomena (with an illustration from the Rio Grande), 566-580. In Middleton, G.V. Ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation. S.E.P.M., Spec. Publ., 12.

Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G. (1975). Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. S.E.P.M. Short Coarse No. 2.

Haughton, S.H. (1969). Geological History of Southern Africa. Geol. Soc. S.Afr., 529pp.

Hein, F.J. (1974). Gravel transport and stratification origins, Kicking Horse River, British Columbia. M.Sc. thesis (unpubl.), McMaster University, 135pp.

High, L.R. and Picard, M.D. (1974). Reliability of cross-stratification types as palaeocurrent indicators in fluvial rocks. J. sedim. Petrol., 44, 158-168.

Hoffmann, H. and Hoehne, K. (1960a). Petrographische Eigenschaften und rheologisches Verhalten von permischen Steinkohlen, insbesondere der Gondwanaformation. 11. Die Gondwanakolen von Ostaustralien und Vorderindien. Brennst.-Chemie, 41, 70-79.

———————— (1960b). Petrographische Eigenschaften und rheologisches Verhalten von permischen Steinkohlen, inbesondere der Gondwanaformation. 11. Die Gondwanakohlen von Südafrika. Brennst.-Chemie, 41, 142-150.

Hollingworth, S.E. (1962). The climatic factor in the geological record. Q. J. geol. Soc. Lond., 118. 1-21.

Hudson, R.G.S. (1924). On the rhythmic succession of the Yoredale Series in Wensleydale. Proc. York. geol. Soc., 20, 125-135.

Johnson, M.R. (1976). Stratigraphy and sedimentology of the Cape and Karoo Sequences in the Eastern Cape Province. Ph.D. thesis (unpubl.), Rhodes Univ. Grahamstown. 336pp.

Jopling, A.V. (1965a). Laboratory study of the distribution of grain sizes in cross-bedded deposits, 53-63. In Middleton, G.V., Ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation. S.E.P.M., Spec. Publ., 12.

________ (1965b). Hydraulic factors controlling the slope of laminae in laboratory deltas. J. sedim. Petrol., 35, 777-791.

Kelling, G. (1969). The environmental significance of cross stratification parameters in an Upper Carboniferous fluvial basin. J. sedim. Petrol., 39, 857-875.

Kerr, P.F. (1959). Optical Mineralogy. McGraw-Hill, New York, 442pp.

Krynine, P.D. (1936). Genetic significance of arkose deposits (abstract). Proc. geol. Soc. Am., for 1935, 87.

Kübler, M. (1977). The sedimentology and uranium mineralization of the Beaufort Group in the Beaufort West - Fraserburg - Merweville area, Cape Province. M.Sc. thesis (unpubl.), Univ. Witwatersrand, Johannesburg, 106pp.

Leeder, M.R. (1973). Fluviatile fining-upward cycles and the magnitude of palaeochannels. Geol. Mag., 110, 265-276.

Lock, B.E. (1978). The Cape Fold Belt of South Africa; tectonic control of sedimentation. Geol. Ass. (London) Proc., 89, 263-281.

________ (1980). Flat-plate subduction and the Cape Fold Belt of South Africa. Geology, 8, 35-39.

Mathes, G.H. (1947). Macroturbulence in natural stream flow. Am. Geoph, Un., Trans., 28, 255-262.

McBride, E.F. (1974). Significance of colour in red, green, purple, olive, brown and gray beds of Difunta Group, north-eastern Mexico. J. sedim. Petrol., 44, 760-773.

McKee, E.D. (1966). Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). Sedimentology, 7, 1-69.

McKee, E.D., Crosby, E.J. and Berryhill, H.L. (1967). Flood deposits, Bijou Creek, Colorado, June 1965. J. sedim. Petrol., 37, 829-851.

McLean, J.R. and Jerzykiewicz, T. (1978). Cyclicity, tectonics and coal: somes aspect of fluvial sedimentology in the Brazue-Paskapoo Formations, Coal Valley area, Alberta, Canada, 441-468. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Miall, A.D. (1973). Markov chain analysis applied to an ancient alluvial plain succession. Sedimentology, 20, 347-364.

——— (1976). Palaeocurrent and palaeohydrologic analysis of some vertical profiles through a Cretaceous braided stream deposit, Banks Island, Arctic Canada. Sedimentology, 23, 459-484.

——— (1977a). A review of the braided river depositional environment. Earth-sc. Rev., 13.

——— (1977b). Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Calgary, 92pp.

——— (1978). Lithofacies types and vertical profile models in braided river deposits: a summary, 597-604. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Moore, D.G. and Scruton, P.C. (1957). Minor internal structures of some recent unconsolidated sediments. Bull. Am. Ass. Petrol. Geol., 41, 2723-2751.

Nami, M and Leeder, M.R. (1978). Changing channel morphology and magnitude in the Scalby Formation (M. Jurassic) of Yorkshire, England, 431-440. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Neumann-Mahlkau, P. (1976). Recent sand volcanoes in the sand of a dyke under construction. Sedimentology, 23, 421-425.

Ore, H.T. (1964). Some criteria for the recognition of braided stream deposits. Wyo. Univ. Contr. Geol., 3, 1-14.

Pettijohn, F.J. (1957). Sedimentary Rocks. Harper and Row, New York, 718pp.

Pettijohn, F.J., Potter, P.E. and Siever, R. (1972). Sand and Sandstone. Springer-Verslag, 618pp.

Picard, M.D. and High, L.R. (1973a). Sedimentary Structures of Ephemeral Streams. Developments in Sedimentology, 17. Elsevier, Amsterdam, 215pp.

__________ (1973b). Criteria for recognizing lacustrine rocks, 108-145. In Rigby, J.K. and Hamblin, W.K., Eds., Recognition of Ancient Sedimentary Environments. S.E.P.M., Spec. Publ., 16, 340pp.

Powers, M.C. (1953). A new roundness scale for sedimentary particles. J. sedim. Petrol., 23, 117-119.

Reineck, H.E. and Singh, I.B. (1973). Depositional Sedimentary Environments. Springer-Verslag, New York, 439pp.

Reynolds, A.J. (1980). Garnet in the Molteno Formation. Terra, 2, 46-51.

Rhodes, R.C. (1974). A gravity-folding model for the Cape Fold-Belt, Discussion. Trans, geol. Soc. S.Afr., 77, 207-209.

Rust, B.R. (1972). Structure and process in a braided river. Sedimentology, 18, 221-246.

__________ (1978). Depositional models for braided alluvium, 605-625. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Rust, I.C. (1959). On the sedimentation of the Molteno sandstones in the vicinity of Molteno, Cape Province. Ann. Univ. Stellenbosch, 37, 167-223.

Ryan, P.J. (1963). Petrology, origin and deposition of the Molteno Stage in the Indwe area of the north-east Cape Province. M.Sc thesis (unpubl.), Univ. Witwatersrand.

Sander, B. (1936). Beiträge zur Kenntnis der Anlagerungsgefüge. Mineral. Petrog. Mitt., 48, 27-139.

Sanderson, D.J. (1973). Some inference problems in palaeocurrent studies. J. sedim. Petrol., 43, 1096-1100.

Schwarzacher, W. (1969). The use of Markov chains in the study of sedimentary cycles. J. Int. Ass Math. Geol., 1, 17-39.

Schwarzacher, W. (1975). Sedimentation Models and Quantitative Stratigraphy. Developments in Sedimentology, 19. Elsevier, Amsterdam, 382pp.

Siever, R., Beck, K.C. and Berner, R.A. (1965). Composition of interstitial waters of modern sediments. J. Geol., 73, 39-73.

Simons, D.B., Richardson, E.V. and Nordin, C.F. (1965). Sedimentary structures generated by flow in alluvial channels, 34-52. In Middleton, G.V., Ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation. S.E.P.M., Spec. Publ., 12.

Smith, N.D. (1970). The braided stream depositional environment: comparison of the Platte River with some Silurian clastic rocks, North Central Appalachians. Bull. geol. Soc. Am., 81, 2993-3014.

________ (1971). Transverse bars and braiding in the Lower Platte River, Nebraska. Bull. geol. Soc. Am., 82, 3407-3420.

________ (1972). Some sedimentological aspects of planar cross-stratification in a sandy braided river. J. sedim. Petrol., 42, 624-634.

South African Committee for Stratigraphy, The. (1977). South African Code of Stratigraphic Terminology and Nomenclature, Revised Edition, 1977. Department of Mines, Geological Survey, 22pp.

Stach, E. (1975). Coal Petrology. Gebrüder Borntraeger, Berlin, 428pp.

Steel, R.J. (1976). Devonian basins of western Norway - sedimentary response to tectonism and to varying tectonic context. Tectonophysics, 36, 207-224.

Steel, R.J. and Aasheim, S.M. (1978). Alluvial sand deposition in a rapidly subsiding basin (Devonian, Norway), 385-412. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Till, R. (1974). Statistical Methods for the Earth Scientist. Macmillan, London, 154pp.

Toens, P.D. (1975). Advances in Prospecting for Uranium. I.M.M. Symposium and Geological Society Summer School - Salisbury, 26pp.

Truswell, J.F. (1977). The Geological Evolution of South Africa. Purnell, Cape Town, 218pp.

Turner, B.R. (1969). The stratigraphy and sedimentary history of the Molteno Stage in part of the north-east Cape Province. M.Sc. Thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

——— (1970). Facies Analysis of the Molteno Sedimentary Cycle, 313-319. In Haughton, S.H., Ed., Proc. 2nd I.U.G.S., Symposium on Gondwana Stratigraphy and Palaeontology, Cape Town and Johannesburg, C.S.I.R., Pretoria.

——— (1971). The geology and coal resources of the north-eastern Cape Province. Bull. geol. Surv. S.Afr., 52, 74pp.

——— (1975a). The stratigraphy and sedimentary history of the Molteno Formation in the main Karoo basin of South Africa and Lesotho. Ph.D. thesis (unpubl.), Univ. Witwatersrand, Johannesburg, 314pp.

——— (1975b). Statistical appraisal of Molteno (Triassic) sedimentary cycles from the upper part of the Karoo (Gondwana) System in South Africa. J. sedim. Petrol., 45, 95-104.

——— (1978). Sedimentary patterns of uranium mineralisation in the Beaufort Group of the southern Karoo (Gondwana) basin, South Africa, 831-848. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

Urien, C.M., Martins, L.R. and Zambrano, J.J. (1976). The geology and tectonic framework of southern Brazil, Uruguay and northern Argentina continental margin: Their behaviour during the southern Atlantic opening. Anais. da Academia Brasileira de Ciencias, 48, 365-376.

Visher, G.S. (1972). Physical characteristics of fluvial deposits, 84-97. In Rigby, J.K. and Hamblin, W.K., Ed., Recognition of Ancient Sedimentary Environments. S.E.P.M. Spec. Publ., 16.

Visser, J.N.J. and Dukas, B.A. (1979). Upward-fining fluviatile megacycles in the Beaufort Group, north of Graaff-Reinet, Cape Province. Trans. geol. Soc. S.Afr., 82, 149-154.

Walker, R.G. (1975). From sedimentary structures to facies models: example from fluvial environments, 63-80. In Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. S.E.P.M. Short Course No. 2, Dallas.

Wanless, H.R. and Weller, J.M. (1932). Correlation and extent of Pennsylvanian cyclothems. Bull, geol. Soc. Am., 43, 1003-1016.

Weller, J.M. (1964). Development of the concept and interpretation of cyclic sedimentation. Kansas geol. Surv. Bull., 169, 607-621.

Wells, A.J. (1960). Cyclical sedimentation: a review. Geol. Mag., 97, 389-403.

Weyl, P.K. (1959). Pressure solution and the force of crystallization - a phenomenological theory. J. geophys. Res., 64, 2001-2025.

Williams, G.E. (1966). Planar cross-stratification formed by the lateral migration of shallow streams. J. sedim. Petrol., 36, 742-746.

_______________ (1971). Flood deposits of the sand bed ephemeral streams of central Australia. Sedimentology, 17, 1-40.

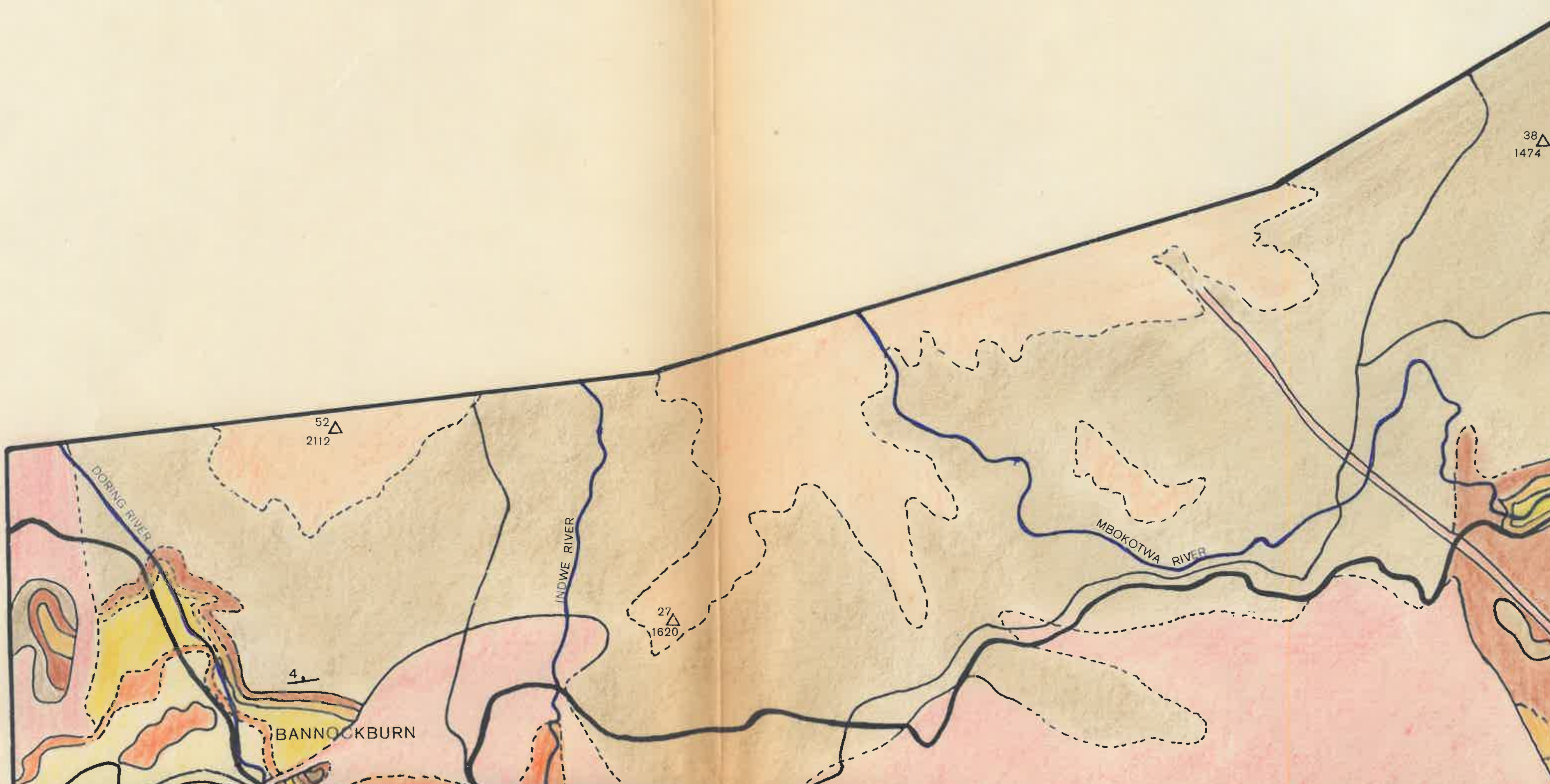
Williams, P.F. and Rust, B.R. (1969). The sedimentology of a braided river. J. sedim. Petrol., 39, 649-679.

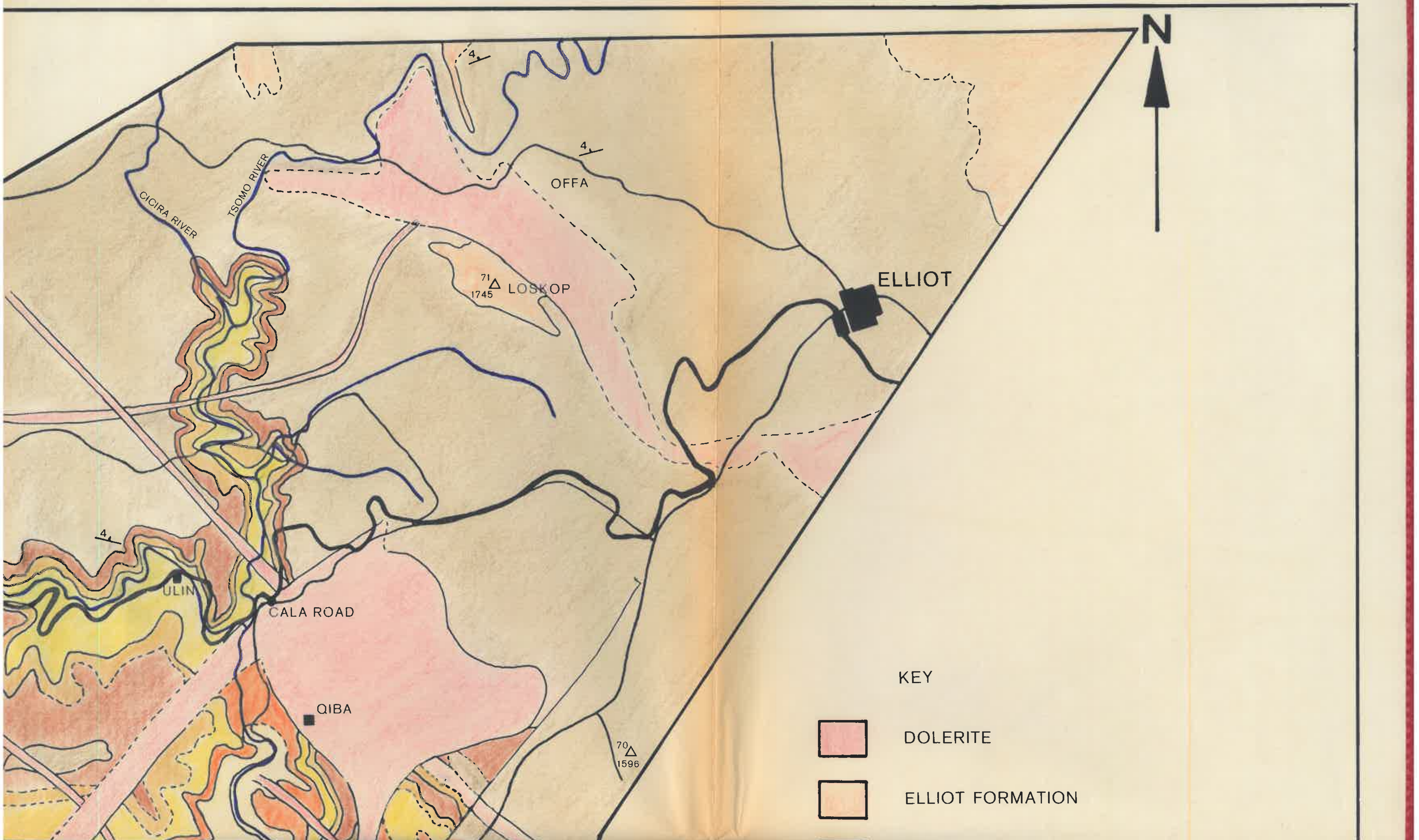
Winston, D. (1978). Fluvial systems of the Precamcrian Belt Supergroup, Montana and Idaho, U.S.A., 343-359. In Miall, A.D., Ed., Fluvial Sedimentology. Memoir 5. Canadian Society of Petroleum Geologists, 859pp.

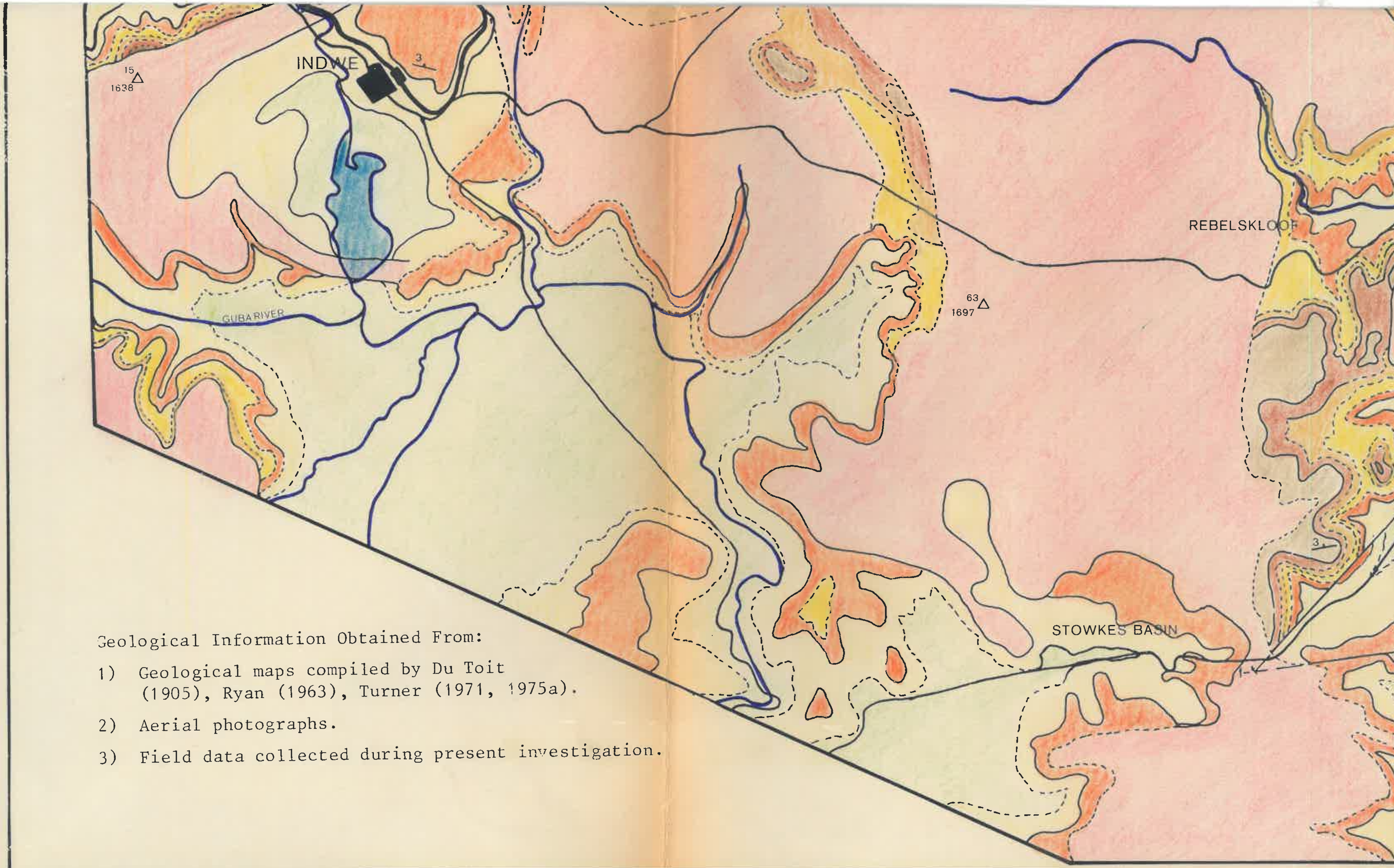
Wyley, A. (1856). Report on coal in the Stormberg and adjoining districts. Parliamentary report G6, Cape Town.

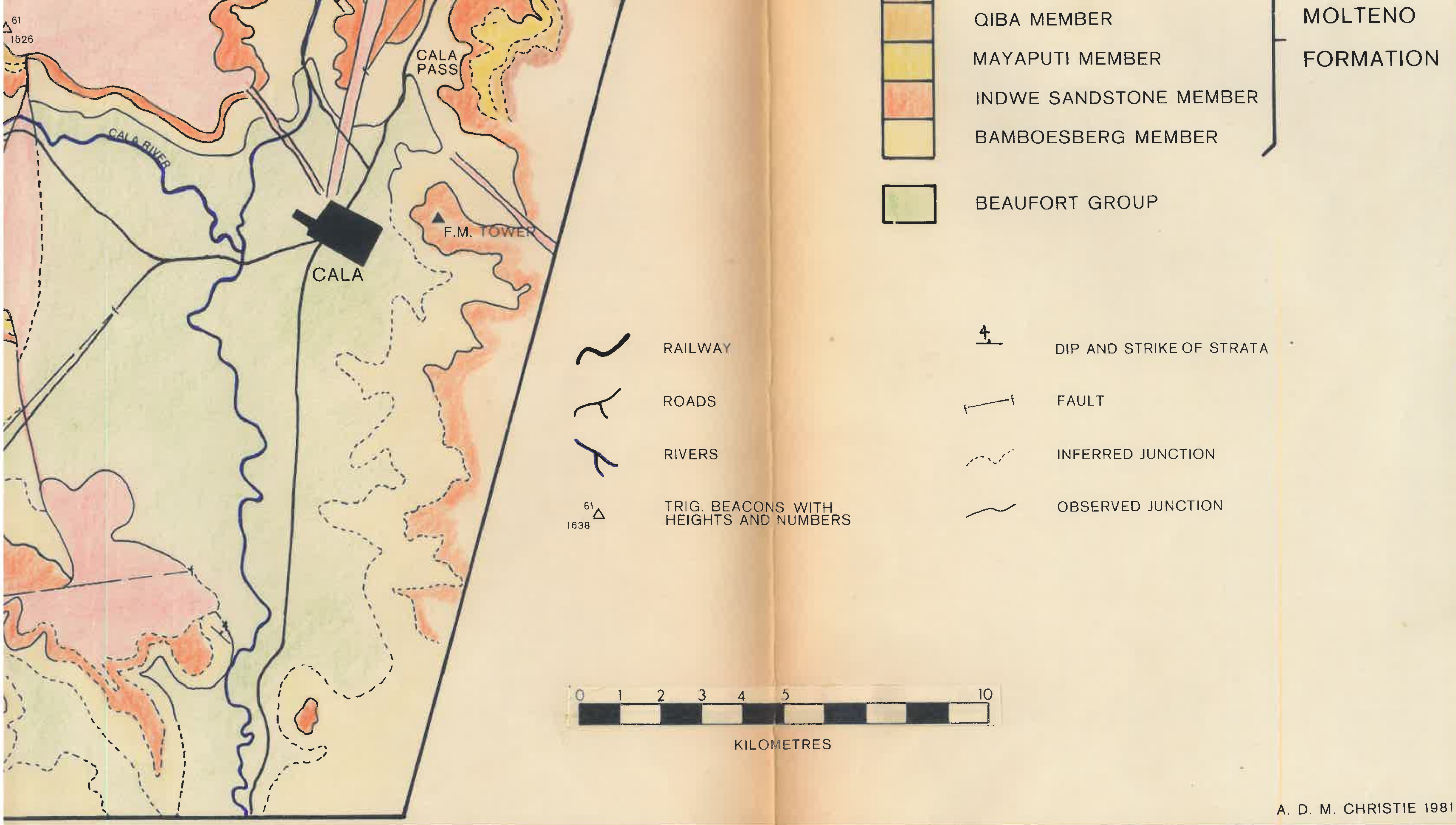
Zingg, T. (1935). Beiträge zur Schotternanlyse. Schweiz. min. pet. Mitt., 15, 39-140.

GEOLOGICAL MAP OF THE ELLIOT, INDWE AND CALA AREAS.




N
CICIRA RIVER
TSOMO RIVER
OFFA
71
1745
LOSKOP
ELLIOT
ULIN
CALA ROAD
QIBA
70
1596
KEY
DOLERITE
ELLIOT FORMATION


INDWE
15
1638
3
GUBA RIVER
63
1697
REBELSKLOOF
STOWKES BASIN
3
Geological Information Obtained From:
1) Geological maps compiled by Du Toit (1905), Ryan (1963), Turner (1971, 1975a).
2) Aerial photographs.
3) Field data collected during present investigation.


61
1526
CALA PASS
CALA RIVER
CALA
F.M. TOWER
QIBA MEMBER
MAYAPUTI MEMBER
INDWE SANDSTONE MEMBER
BAMBOESBERG MEMBER
MOLTENO FORMATION
BEAUFORT GROUP
RAILWAY
ROADS
RIVERS
61
1638
TRIG. BEACONS WITH HEIGHTS AND NUMBERS
4
DIP AND STRIKE OF STRATA
FAULT
INFERRED JUNCTION
OBSERVED JUNCTION
0 1 2 3 4 5 10
KILOMETRES
A. D. M. CHRISTIE 1981.