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SUBTIDAL AND INTERTIDAL CLASTIC AND CARBONATE SEDIMENTATION IN A MACROTIDAL ENVIRONMENT : AN EXAMPLE FROM THE LOWER PROTEROZOIC OF SOUTH AFRICA

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ABSTRACT

Subtidal and intertidal clastic and carbonate deposits are recognized from the upper part of the 2 200 m.y. old Pretoria Group in the eastern Transvaal, South Africa. These deposits occur within a 400 m sequence which was formed in the following succession of environments, from the base upwards : (1) subtidal sand shoal and channel system; (2) mixed sand and mud intertidal flat with sand-filled tidal channels; (3) shallow subtidal to intertidal sheet sand; (4) sand and carbonate intertidal flat; (5) subtidal biohermal carbonate; and (6) subtidal silt and mud. The lower clastic units form a regressive sequence associated with active detrital influx whereas the upper clastic and carbonate units form a transgressive sequence associated with diminished detrital influx. The absence of barrier complexes and occurrence of thick subtidal sand shoal and intertidal mixed flat sequences indicate a high tide range (macrotidal, greater than 4 m).

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INTRODUCTION

The geologic literature is replete with descriptions of clastic tidal-flat sedimentary units formed in micro- and meso-tidal environments (Klein, 1975). Examples of tidalites formed in the subtidal zone of macrotidal environments, and of mixed carbonate-clastic tidalite formations, are less common. This paper documents a sedimentary succession believed to have formed in both sub- and intertidal, clastic and carbonate-dominated depositional environments, along an un-barred coastline with a large tidal range.

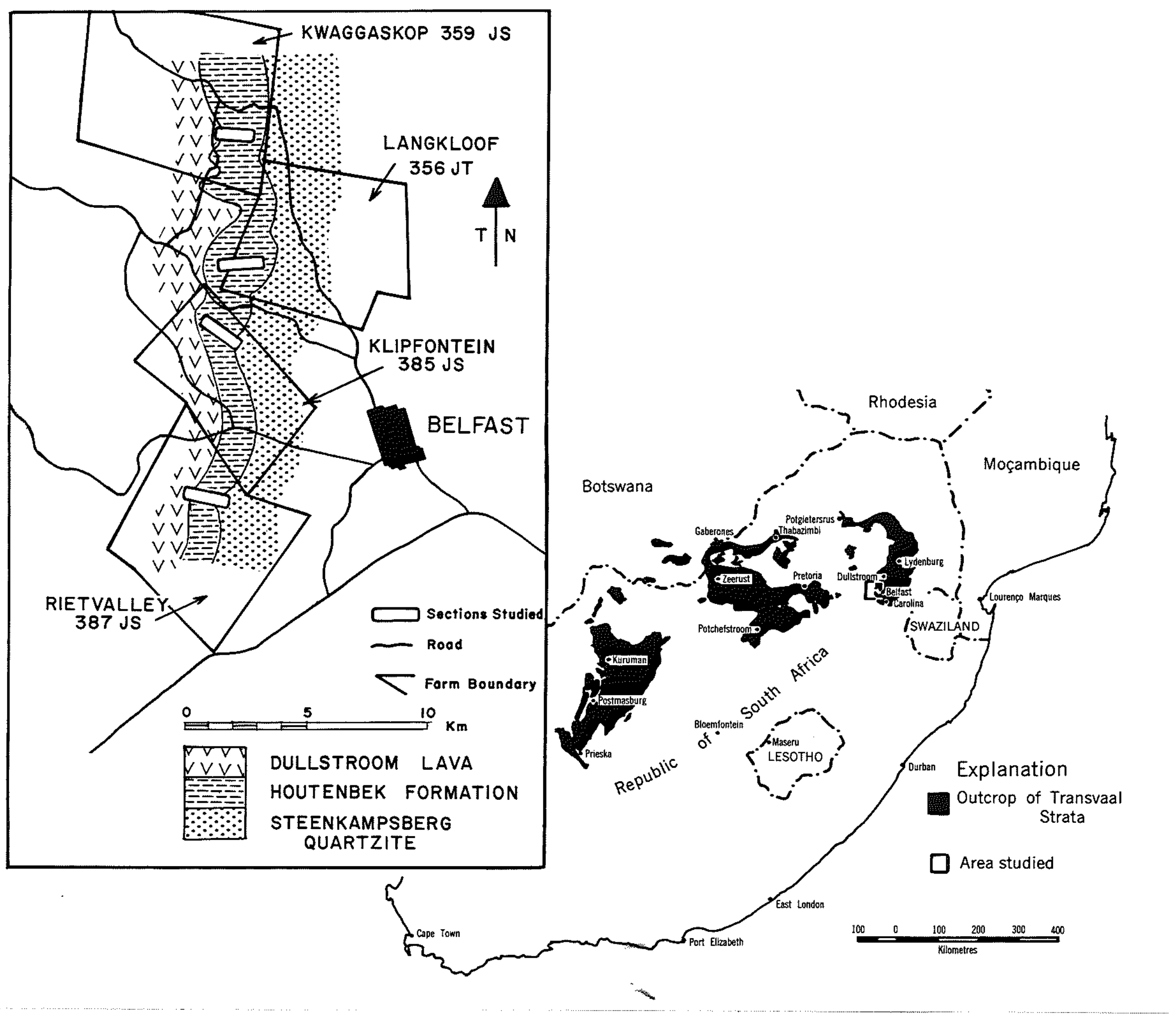


Figure 1 : Map, showing Transvaal Basin and location of detailed study-area (inset).

The sedimentary units of the present study are located at the top of the early Proterozoic Transvaal Supergroup, in the eastern Transvaal (Figure 1). The best exposures are situated west of the town of Belfast, where fieldwork was concentrated on four discrete profiles, over a strike-length of 15 km (Figure 1, inset).

GEOLOGICAL SETTING AND AGE

The Transvaal Basin covers a large tract of the southern African shield (Figure 1), and probably had a depositional area of at least 500 000 km^2 (Button, 1973). In the eastern portion of the basin, the Transvaal Supergroup is approximately 12 km thick. It rests on an Archaean basement, and is overlain and intruded by the mafic phase of the Bushveld Igneous Complex (Figure 2).

The Pretoria Group (upper division of the Transvaal Supergroup) is presently estimated to have an age of about 2 200 to 2 300 m.y. Volcanics within the group have been dated at 2 224 ± 21 m.y.

(D. Crampton, personal communication, 1972). Shales adjacent to the lava have yielded a Rb/Sr whole-rock date of 2 263 ± 85 m.y. (Hamilton, 1975). Hamilton dated the mafic rocks of the Bushveld Complex, which intruded the Pretoria Group, at 2 095 ± 24 m.y.

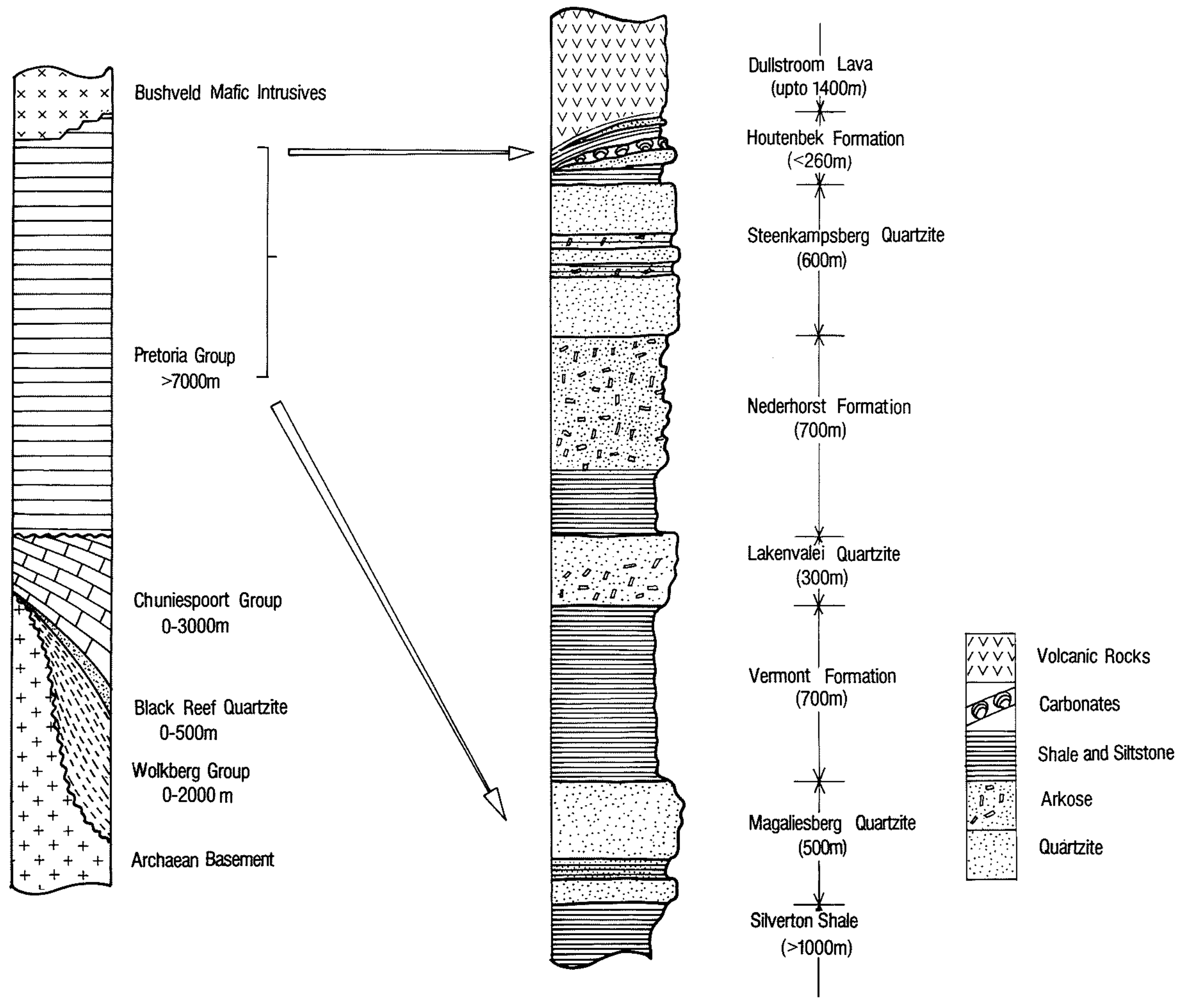


Figure 2 : *Stratigraphic subdivision of the Transvaal Basin in the eastern Transvaal (left-hand column), and of the upper part of the Pretoria Group (right-hand column).*

The Pretoria Group (up to 7 000 m thick) is a cyclical alternation of arenaceous and argillaceous formations, punctuated by three volcanic, and two major carbonate episodes. The upper portions of the group are shown in the right-hand column of Figure 2. The depositional facies described in this paper lie at the top of the sedimentary succession, immediately beneath the Dullstroom Lava.

The structural style of the Transvaal Basin is usually one of gentle (5 to 20 degree) dips in towards the Bushveld Igneous Complex. The uppermost few thousand metres of the Pretoria Group have been subjected to contact metamorphism, through the agency of the Bushveld Complex and associated mafic sills. The metamorphism, being of a static type, has not seriously affected the sedimentary and biological structures preserved in the arenaceous, argillaceous and carbonate sediments of the Pretoria Group.

REGIONAL STRATIGRAPHIC RELATIONSHIPS

Regional facies changes in Precambrian basins are usually hard to define because of a lack of reliable chronologic markers. In the case of the upper members of the Pretoria Group a special situation exists. An acid (Rooiberg Felsite) and a mafic (Dullstroom Lava) volcanic unit outcrop in two widely separated parts of the basin, near Rooiberg, 300 km northwest of the study-area, and near Belfast, in the study-area (Figure 1, inset). These volcanic units probably closely approximate chronologic markers. At Rooiberg, thick arkoses (> 600 m), pebbly in places, are separated from the mafic volcanic by a silty arkose and 40 m of pebble-bearing quartz arenite (Boardman, 1946). The arkoses finger out to the south (Figure 3) into a thicker pile of alternating pure quartz arenite and shaly formations, and some carbonates. The unimodal sediment transport patterns and stacked, mutually erosive channels in the arkoses suggest a braided fluvial plain in the northern half of the basin, passing to a marginal marine assemblage in the south. The inferred southerly palaeoslope is confirmed by palaeocurrent determinations in the fluvial arkoses (Rhodes, 1972; A.H. Phillips, personal communication, 1976).

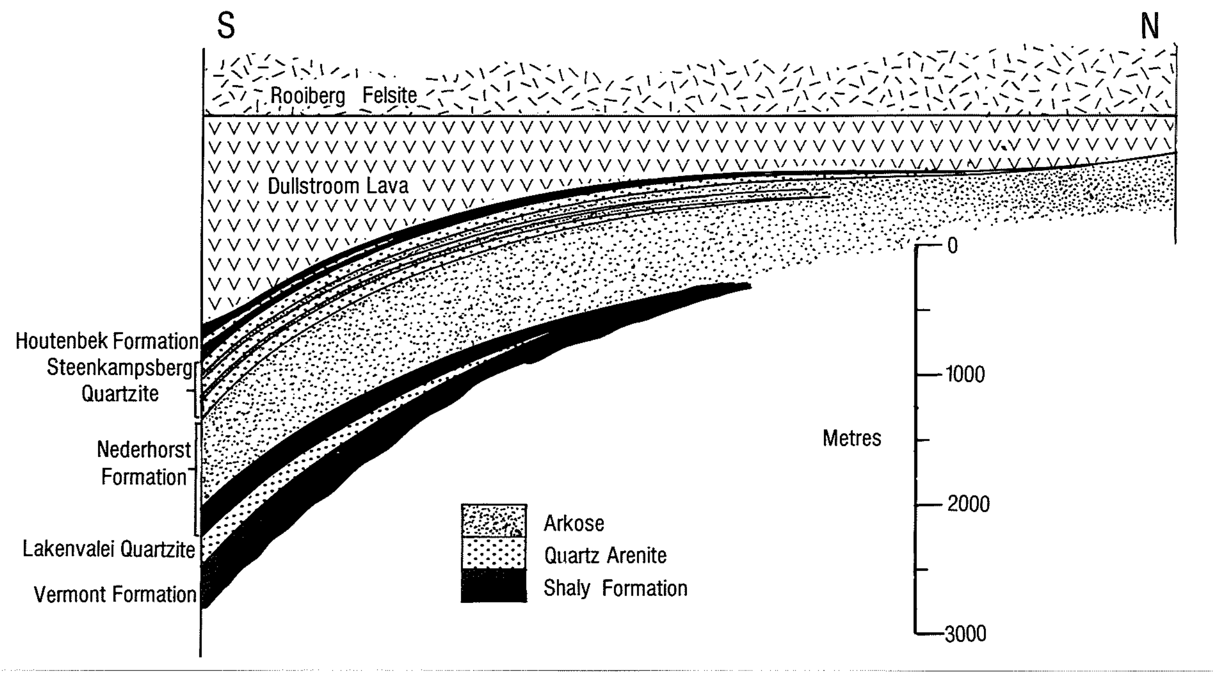


Figure 3 : *Regional stratigraphic relationships of the uppermost formations in the Transvaal Supergroup. A volcanic datum is used to demonstrate interfingering of arkoses (in the north) with quartz arenite and shaly formations (in the south).*

STRATIGRAPHY OF THE STEENKAMPSBERG QUARTZITE AND THE HOUTENBEK FORMATION

The Steenkampsberg Quartzite comprises five stratigraphic units with a combined thickness of about 600 metres. The basal, middle and uppermost members are composed of pure quartz arenites; the intervening members, which outcrop poorly, are dominated by fine-grained arkosic arenites, siltstones and shales (Figure 2, right-hand column).

The Houtenbek Formation follows with an abrupt gradation on the Steenkampsberg. From the base, it comprises an argillaceous unit, a quartz arenite unit, a carbonate unit, a second argillaceous unit which grades upwards to a quartz arenite, which passes in turn to a thin shaly suite. The formation is overlain by the basaltic-to-intermediate volcanics of the Dullstroom Lava. Flows within this formation show no indications of subaqueous extrusion, and are thought to have been poured out essentially on land (Button, 1973).

Detailed observations during this study were restricted to the uppermost member of the Steenkampsberg Quartzite and to the Houtenbek Formation, exclusive of the two uppermost lithologic units (Figure 2, right-hand column). The latter outcrop poorly, and were only studied in a general way.

DEPOSITIONAL FACIES AND ENVIRONMENTS

Six major lithological-sedimentological facies are recognized in the sedimentary succession studied. The attributes of each facies is outlined below, together with an interpretation of its mode of origin.

Non-emergent Quartz Arenite Facies (1)

The principal unifying feature of this facies (referred to as facies 1) is that it does not exhibit features indicative of sub-aerial exposure and desiccation. The medium- and fine-grained supermature quartz arenites which make up the facies are structured by flat-bedding, by southerly-oriented trough cross-bedding, and by north facing, large (up to 3 m) tabular cross-bed sets (Figure 4, Plate 1A, Table I). No definitive cyclical arrangement of these structural types was discerned. Current-rippled surfaces are common, and confirm bipolar and bimodal currents, moving essentially to the north and south.

TABLE I

DEPOSITIONAL STRUCTURES AND INFERRED SEDIMENTARY PROCESSES, NON-EMERGENT QUARTZ ARENITE FACIES (1)

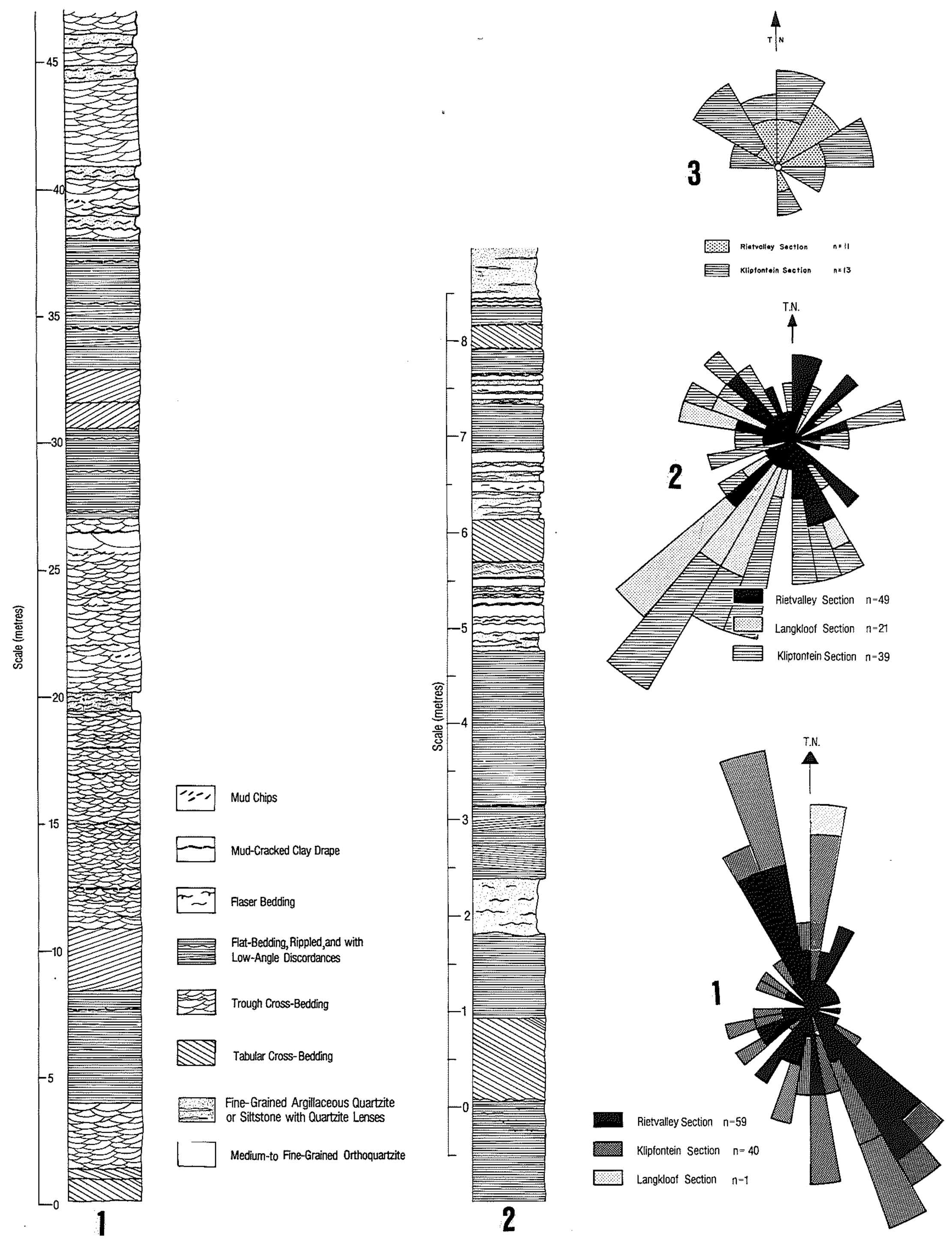
Structure	Inferred Process
1. North-facing tabular cross-beds in sets up to 3 m thick	Landward migration of slip-off faces of sand waves or of elongate, asymmetric sand shoals
2. Southerly-oriented trough cross-beds	Megaripple migration in ebb-dominated domains of the subtidal shelf
3. Flat-bedded sands, some with very low-angle discordances	(i) Settling of suspension clouds on sand shoals (ii) Backs of elongate sand shoals (iii) Toe sets, landward of slip-off faces of sand waves or asymmetric sand shoals (iv) Current ripple generated
4. Current ripples, bipolar and bimodal orientation on shore - off shore	Ripple migration in response to ebb and flood currents
5. Symmetrical ripples	Wave generated, or modified current-ripples
6. Films of mud	Suspension settling during slack water

The non-desiccated nature of clay drapes in this facies is taken as an indication of deposition in a non-emergent (i.e. sub-tidal) environment. The bipolar-bimodal distribution of currents, as evidenced by cross-beds and by current-ripples, is probably most satisfactorily accounted for by the daily current reversals typical of tidal environments. Regional relationships suggest an east-west depositional strike and a southerly palaeoslope, so that southerly-oriented cross-beds are interpreted as ebb-generated, and vice-versa. In general terms, a subtidal, tide-dominated shelf appears to be the most satisfactory depositional environment for this facies.

Perhaps one of the most apt sedimentary models is that of the channels and sand tongues and shoals of the Nordergründe and Outer Jade in the North Sea (Reineck and Singh, 1973). Channels, and intervening tongues of sand are oriented perpendicular to the shoreline. Water depths (up to 20 m) and velocities (average maxima up to 140 cm/sec) are greatest in the channels. On the intervening tongues, water depths are less (bottom frequently above the wave base), and maximum velocities are lower (30-50 cm/sec). Bipolar currents operate in both environments. Largest bed-forms (sandwaves up to 5 m high, and megaripples) are developed mainly in the channels. The sands of the shoals and tongues are rippled, megarippled and laminated. The latter structure results from suspension cloud settling, generated by shoaling waves or strong tidal currents (Reineck and Singh, 1973).

In terms of this analogy the large tabular cross-beds would represent the products of sand wave migration in channels, the trough cross-bedded arenite could have formed in channels or on shoals, while the rippled and flat-bedded sands were deposited mainly on sand shoals.

The non-emergent quartz arenite facies has been studied in the lower 100 m of the upper member of the Steenkampsberg Quartzite. In Figure 4, column 1, it is represented by the basal 12 m of the section.



<u>Figure 4</u> : *Composite diagram, Steenkampsberg Quartzite. Column 1 shows uppermost 45 metres of formation, Rietvalley section. Column 2 shows upward transition to Houtenbek Formation. Rose diagram 1 shows sediment transport from current ripples, 2 shows orientation of cross-bed foresets, 3 shows orientation of tabular cross-bed sets thicker than 0,6 m.*

<u>Emergent Quartz Arenite Facies (2)</u>

This facies is conveniently discussed under the headings of two subfacies, termed the flat-bedded subfacies and the cross-bedded subfacies. Both show evidence of exposure of sediments to sub-aerial desiccation processes. Their characteristics, and the inferred processes and environments of deposition, are outlined below.

<u>Flat-bedded Subfacies (2a)</u>

The flat-bedded subfacies (Figure 6, base of column) is found in medium- and fine-grained, pure quartz arenites. Flat beds are subtly colour-banded due to minor composition-changes (Plate IB). Rippled surfaces are very common, and are sometimes covered by mud-cracked clay-drapes. There is good evidence for late-stage runoff effects, including local wash-out structures on rippled surfaces, and superimposed ripple sets (Plate IC). Other evidence for modification of ripples during falling water-stage include flat-topped and double-crested ripples (Table II). Cross-bed sets are very rare; where present they have trough geometry and are oriented to the south.

TABLE II

DEPOSITIONAL STRUCTURES AND INFERRED SEDIMENTARY PROCESSES, FLAT-BEDDED SUBFACIES (2a) OF THE EMERGENT QUARTZ ARENITE FACIES

Structure	Inferred Process
1. Flat-bedding	(i) Settling from suspension clouds on sand shoals (ii) Current-ripple generated
2. Ebb-oriented trough cross-beds (very rare)	Megaripple migration in ebb-dominated domain
3. Straight-crested current ripples, bipolar and bimodal orientation (Figure 6, rose diagram 1)	Ripple migration during ebb and flood periods
4. Symmetrical ripples	Wave-generated, or modified current ripples
5. Flat-topped ripples	Modification of ripples during falling water stage
6. Double-crested ripples	Reworking of ripple during falling water stage
7. Superimposed ripples (Plate IC)	Late-stage runoff down troughs between master ripples
8. Mud-cracked clay-drapes on rippled surfaces	Waning tidal current, ripples become fixed, followed by suspension settling, followed by desiccation
9. Isolated clay-chips	Reworking of desiccation mud polygons by tidal currents

Currents operating during deposition of the flat-bedded subfacies were bipolar and bimodal. A current rose, based on measurement of 56 current ripples, is shown in Figure 6, bottom right. It illustrates currents moving in a general northerly and southerly sense.

The evidence presented above suggests that the flat-bedded subfacies was deposited in the lowermost part of the intertidal zone, and, in part, in the shallowest, wave-influenced part of the subtidal. The balanced current rose suggests ebb and flood currents of almost equal intensity.

A possible contemporary depositional analogue of the flat-bedded facies might, once again, be the sand shoals and tongues of the North Sea (Reineck and Singh, 1973). In the shallowest subtidal domain, the shoals are dominated by lamination and ripple cross-bedding (85 per cent), which is comparable to the facies under discussion. A second possible environment might be like the lower tidal terraces of South Carolina, U.S.A., which are dominated by flat and ripple bedding (D.K. Hobday, personal communication, 1976).

Stratigraphically, the flat-bedded subfacies dominates the quartz arenites of the Houtenbek Formation. In both the upper and lower quartzites, the flat-bedded subfacies is overlain by the cross-bedded subfacies (see following section) in an overall prograding sequence. This factor suggests that the former was deposited lower down the shoreline profile than the latter.

Cross-bedded Subfacies (2b)

This depositional facies is characterized by 10-30 cm thick trough and tabular cross-bed sets, oriented towards the south, or as herringbone cross-bedding, towards the north and south (Figure 6, middle current rose). Other indications of reversal of currents include such features as rare reactivation surfaces and flaser-bedded units (Table III). Flat bedding makes up no more than 50 per cent of this assemblage. Linguoid ripples are rare, but linear current ripples are abundant and show bimodal, bipolar orientation, parallel to cross-bed vector maxima. Features associated with late-stage runoff, and with desiccation, are abundantly developed (Table III). They include superimposed, washed-out and flat-top ripples (Plate ID), and mud-cracked clay-drapes on rippled surfaces (Plate IE).

TABLE III

DEPOSITIONAL STRUCTURES AND INFERRED SEDIMENTARY PROCESSES, CROSS-BEDDED SUBFACIES OF THE EMERGENT QUARTZ ARENITE FACIES (2b)

Structure	Inferred Process
1. Southerly-oriented trough cross-beds (Figure 4, rose diagram 2)	Megaripple migration in ebb-dominated domain of lower tidal flat
2. Northerly-oriented tabular cross-bed sets (Figure 4, rose diagram 3)	Sand-wave migration in flood-dominated region of lower tidal flat
3. Herringbone cross-bedding, Figure 6, rose diagram 2 (rarely well-developed)	Megaripple or sand-wave migration in response to ebb and flood currents
4. Reactivation surfaces (rare)	Cycles of bedform migration followed by erosion in ebb- or flood-dominated domains
5. Flat beds, some with very low-angle discordances	(i) Suspension cloud settling (ii) Backs and toes of sand-waves (iii) Some pseudo-flat bedding due to ripple migration
6. Flaser bedding	Cycles of ripple-migration followed by suspension settling
7. Linear (some linguoid) current ripples, bipolar-bimodal orientation (Figure 4, rose diagram 1)	Ripple migration in response to ebb and flood currents
8. Symmetrical ripples	Wave-generated, or modified current ripples
9. Flat-top (Plate ID), superimposed and washed-out ripples	Falling water and emergence runoff effects
10. Very small (1 cm wavelengths) ripples	Possibly wind-generated in very shallow water
11. Mud-cracked clay-drapes (often on rippled surfaces) (Plate IE)	Suspension sedimentation during slack water, followed by desiccation
12. Mud-clasts in quartz arenite	Reworking of desiccation polygons
13. Overturned foresets, some convolute bedding	Liquifaction of sand, by various mechanisms
14. Ball-and-pillow structure (in transition to facies 3)	Rapid sedimentation and dewatering

The attributes of the cross-bedded subfacies point towards deposition on the lower intertidal sand flat. Such an environment would explain the dominance of sand over mud, the bipolar-bimodal orientation of sediment transport vectors, the structures associated with late-stage runoff and with desiccation. This interpretation is in good agreement with the North Sea environment described by Reineck and Singh (1973). That part of the sand shoals deposited principally above the low-water mark is dominated by "mega-ripple cross-bedding", and is also structured by ripple cross-bedding and flat-bedding.

The cross-bedded subfacies is well-represented in the study-area. It dominates the top 50 m of the Steenkampsberg Quartzite (Figure 4, columns 1 and 2), and is also found at the top of the two Houtenbek quartzites (see Figure 6, 16-23 m marks). The relation of the cross-bedded subfacies to the previously described facies agrees well with the North Sea sand shoal model. The change from facies 1 to 2b (Figure 4) corresponds to a progradational sequence of lower intertidal flat over subtidal shelf, while that from 2a to 2b represents a progradation of lower tidal flat over the transitional environment of lower tidal flat and the shallow subtidal.

The Mixed Quartz Arenite, Arkose and Argillite Facies (3)

This facies, as its name implies, is typified by the vertical alternation of bedload traction and suspension deposition sediments. Two distinct subfacies (3a and 3b) can be recognized, and are described below.

Arkosic Subfacies (3a)

This assemblage is typified by fining-up, erosional-based sedimentary successions in fine-grained arkosic arenite (Table IV, Figure 5, right-hand column). The cycles overlie an erosional surface (up to 50 cm of relief locally), on which may be concentrated a lag of mud clasts. The arenite is structured by plane (or gently inclined) bedding, followed by trough cross-bedding, followed by ripple cross-lamination and, finally, a film of flat-bedding in a silty arkose.

The plane-bedded units at the base of the cycles are arranged in accretionary sets with an inclination of 3 to 4 degrees to the master stratification. The plane-bedded surfaces are characteristically current lineated. Another feature of the cycles is the fact the uppermost portions, most frequently the ripple cross-laminated arenites, are usually convoluted (Figure 5).

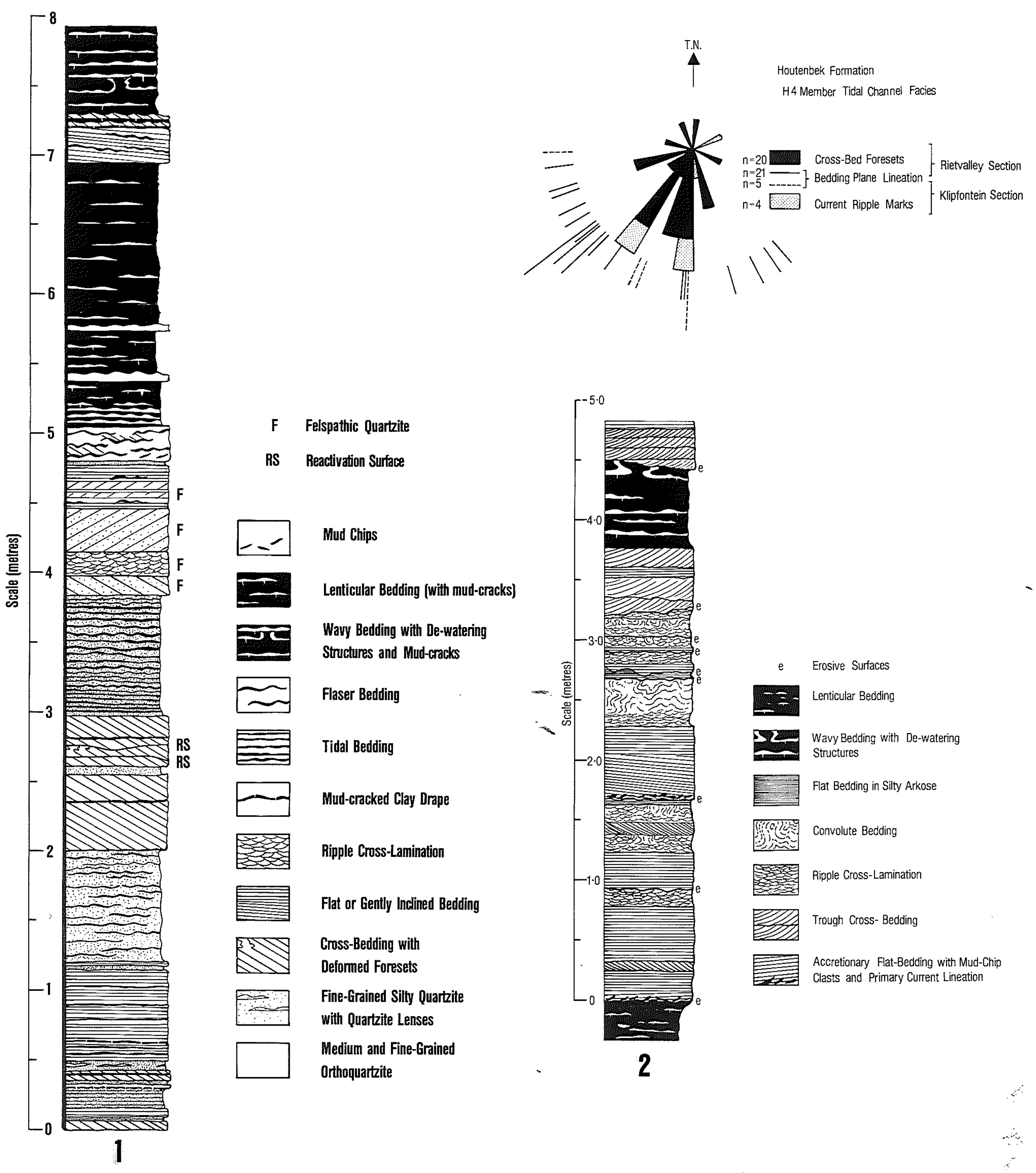


Figure 5 : Composite diagram, mixed quartz arenite, arkose and argillite facies (3) of the Houtenbek Formation. Column 1 shows transition from facies 2 to facies 3, Steenkamps-berg-Houtenbek contact, Rietvalley traverse. Column 2 shows a composite cycle in the arkosic subfacies, basal member of Houtenbek Formation, Rietvalley section. Rose diagram shows orientation of directional structures in arkosic subfacies.

Most cycles of this type are frequently composite in nature, being composed of a number of smaller cycles separated by erosional surfaces. For example, the 4,5 metre-thick succession in Figure 5 (right-hand column) has eight distinct erosive surfaces within it.

TABLE IV

DEPOSITIONAL STRUCTURES AND INFERRED SEDIMENTARY PROCESSES, ARKOSIC SUBFACIES (3a)

Structure	Inferred Process
1. Sharp erosional base, up to 50 cm relief	Erosion on cut-bank of meander-bend
2. Mud-clasts on basal surface	Channel lag deposit
3. Accretionary plane-beds with 3-4 degree inclination	Upper-regime plane bedding on point-bar face near channel thalweg
4. Primary current and parting step lineation	Grain orientation on upper flow regime flat bed
5. Southerly-oriented trough cross-bed sets	Megaripple migration in ebb-dominated tidal channel
6. Reactivation surfaces (rare, poorly developed)	Cycles of megaripple migration, followed by erosion
7. Ripple cross-lamination, rib-and-furrow structure, linguoid ripple-marks	Ripple migration in response to ebb current, lower regime flow on emergent point-bar face
8. Flat-bedding in silty arenite	Lower regime flat bedding on emergent point-bar face
9. Mud-cracked clay drapes	Suspension sedimentation during slack water, followed by desiccation
10. Convolute lamination	Liquefaction of sand (various mechanisms possible)
11. Multiple erosive surfaces	Spring tidal currents, storm surge currents, or riverine floods

Erosional-based, fining-up successions are characteristically produced by accretion on point-bars in a meandering channel (Allen, 1965). The cycles in the arkosic subfacies are interpreted as the results of this process operating in a system of meandering tidal creeks on a mud-flat. The distinction between meandering channels in a tidal and an alluvial setting could not be made on the basis of the point-bar succession alone. It rests on the nature of the associated finer-grained facies, which is described in the subsequent section.

Accretionary plane beds (with primary current lineations) are thought to represent the toes of point-bar faces, formed under the upper flow-regime condition. The sets resemble the "longitudinal cross-bedding" formed by channel migration on the North Sea tidal flats of Germany (Reineck, 1975). Cross-beds represent a megarippled domain higher up the point bar, while ripple cross-lamination and flat-bedding represent weak flow on the emergent surface of the bar, which merges with the mud flat.

The multiple erosive surfaces within the cycles could represent riverine floods, storm surges or abnormally large tides. The thickness of the composite cycles is taken as a measure of channel depth, which could be a rough indication of tidal range. Cycles are frequently thicker than 4 metres, an indication of a macrotidal coastline (Hayes, 1975).

Directional structures (cross-beds, current ripples and current lineations) show dominant southerly and southwesterly orientation (Figure 5, rose diagram). The palaeogeography inferred thus far suggests that this is in the ebb direction. Certain present day tidal creeks (for example those of the Ord River, Wright et al., 1975) show ebb-dominated time-velocity asymmetry, an attribute which is enhanced by fluvial flow into the system.

Quartz Arenite-Argillite Subfacies (3b)

This subfacies (Table V) is intimately related to the arkosic subfacies, usually forming the topmost phase of a series of fining-upward cycles (Figure 5). It comprises an alternation of mudstone and quartz arenite, in units which range in thickness from a millimetre to a few tens of centimetres. There is abundant evidence of the alternation of bedload traction sedimentation and suspension settling (Table V and Plate IF). Sedimentation and dewatering occurred continuously, and resulted in numerous ball-and-pillow, or pseudonodule structures with eroded tops (Plate 2A). Desiccation frequently preceded deposition of arenite units, since arenite-filled mud-cracks are very common at the top of argillaceous layers (Plate IF). A cyclical sequence of arenite transportation and deposition, followed by suspension settling of a muddy fraction followed by exposure and desiccation, can be inferred.

TABLE V

DEPOSITIONAL STRUCTURES AND INFERRED SEDIMENTARY PROCESSES, QUARTZ ARENITE-ARGILLITE SUBFACIES (3b)

Structure	Inferred Process
1. Wavy bedding (arenites have flat base, rippled top, and are internally cross-stratified (Plate IF).	Alternating traction transport (as ripples) and suspension sedimentation
2. Flaser bedding	As above
3. Lenticular bedding	As above
4. Tidal bedding	Alternation of bedload traction and suspension sedimentation
5. Reactivation surfaces (rare, poorly-developed)	Cycles of bedform migration followed by erosion
6. Cross-beds (tabular and trough)	Megaripple or sand-wave migration
7. Flat bedding	Very weak tidal currents?
8. Current ripple-marks (straight-crested and linguoid)	Bedform migration in response to tidal currents
9. Mud-cracks, frequently sand-filled and contorted (Plate IF)	Desiccation, with cracks filled by traction load of following tidal cycle
10. Ball-and-pillow structures (Plate 2A)	Rapid sedimentation, dewatering and compaction

The attributes of this subfacies (particularly the alternation of bedload traction and suspension sedimentation, and the ubiquitous evidence of desiccation) are indicative of deposition on the middle tidal flat. This interpretation is strengthened by the relationship of this subfacies to the underlying Steenkampsberg Quartzite (Figure 5, left-hand column). There is an upward gradation from inferred lower tidal sand flat (facies 2b) to inferred middle tidal mixed flat (facies 3b). Such a sequence is progradational, and is typical of situations with active clastic input.

Carbonate and Clastic Facies (4)

This facies comprises limestone (about 75 per cent) and siliclastic sediments (25 per cent). The latter include quartz arenites, fine-grained quartzose siltstones and some mudstone (now hornfels). Metamorphic reaction between the carbonate and siliclastic components has resulted in a suite of secondary minerals, including epidote, tremolite, wollastonite and grossularite. Only in rare instances do the secondary minerals seriously obscure primary depositional structures. The attributes of the facies are summarized in Table VI.

The quartz arenites occur in beds up to about 1 m thick. They are structured by tabular cross-bedding, by plane-bedding and some ripple cross-lamination. The arenites are calcareous, carrying up to about 10 per cent $CaCO_3$, as cement. Thin mud drapes are occasionally developed, and are mud-cracked.

TABLE VI

DEPOSITIONAL STRUCTURES AND INFERRED SEDIMENTARY PROCESSES, CARBONATE-CLASTIC FACIES

Structure	Inferred Process
1. Tabular cross-bedding (5-20 cm sets in carbonate and quartz arenites, bimodal-bipolar orientation. Figure 6, column and rose diagram 2)	Bedform migration in response to tidal currents
2. Current ripple-marks	Ripple migration in response to tidal currents
3. Flat-bedding in quartz arenite layers	? Upper flow regime currents
4. Quartz-arenite layers (5-30 cm) wedge out laterally against small (up to 50 cm high) algal heads	Storm-current-transported quartz sand introduced onto carbonate flat and deposited in shallow tidal channels
5. Mud-cracked clay-drapes (rare)	Slack-water suspension sedimentation, followed by desiccation
6. Layers of intraclastic carbonate breccia (Plate 2B)	Desiccation and cracking of algal mat, clasts reworked by tidal currents
7. Algal lamination (Plate 2B)	Sheet-like algal mats on upper tidal flat
8. Variety of stromatolites (linked domes, ornate domes, linked-domical columns)	Stromatolite growth on middle tidal flat

The carbonates are abundantly stromatolitic, the most common form being small (< 20 cm) linked domical forms and crinkly algal lamination (Plate 2B). Solitary algal heads (referred to as small bioherms in Figure 6) are developed and are up to 50 cm high. In many instances, quartz-arenite layers wedge out against such heads, suggesting that the quartz sand may have been transported in channel-like depressions bounded by algal mounds. Other structures commonly found include layers of carbonate intraclastic breccia and thin (< 20 cm) tabular cross-bed sets in what must originally have been carbonate sands (Plate 2B).

Evidence for an intertidal origin for the carbonates includes the occasional mud-cracked clay-drape, the abundantly developed crinkly algal lamination and linked domes, and the layers of intraclastic breccia. The latter probably represent the products of a calcareous algal mat, fragmented by desiccation and reworked by currents.

Severe problems arise in an attempted comparison of the Houtenbek carbonate-clastic tidal flat to contemporary settings. Descriptions of modern-day mixed carbonate-clastic tidal flats are rare. Two examples are the Mont Saint-Michel Bay (Larsonneur, 1975) and the Langebaan Lagoon, South Africa (Flemming, 1977). In neither of these examples are stromatolites significantly developed. While numerous stromatolitic carbonate tidal flats have been described from modern-day settings (Roberts et al., 1977; Evans et al., 1973; Hagan and Logan, 1975; Woods and Brown, 1975), these differ from the example under discussion in two important aspects. Firstly, all deal with protected or barred environments. No barrier facies has been found associated with the Houtenbek stromatolites. Secondly, biological controls would have been significantly different in the Proterozoic. In the absence of species which graze on algal colonies, stromatolites would have thrived in most shallow-water environments with little or no clastic input, and would not have been restricted to highly saline settings, as is the case today.

Consequently, the distribution of biological and mechanical features on the Houtenbek carbonate-clastic tidal flat cannot be stated with any confidence. The quartz arenites were probably deposited in channels in the lower flat. Channels may have been controlled by biohermal banks. Cross-bedded carbonates indicate the presence of regions of megarippled carbonate sand. Small domical stromatolites, algal lamination and patches of intraclastic breccia were probably developed higher up the tidal flat, which was covered by water for relatively short periods of time.

Biohermal Facies (5)

This facies attains a maximum thickness of just over 10 m (Figure 6). It comprises limestone biohermal heads, up to 10 m high and 10 m wide (Plate 2C). The bioherms are elongated and show a very

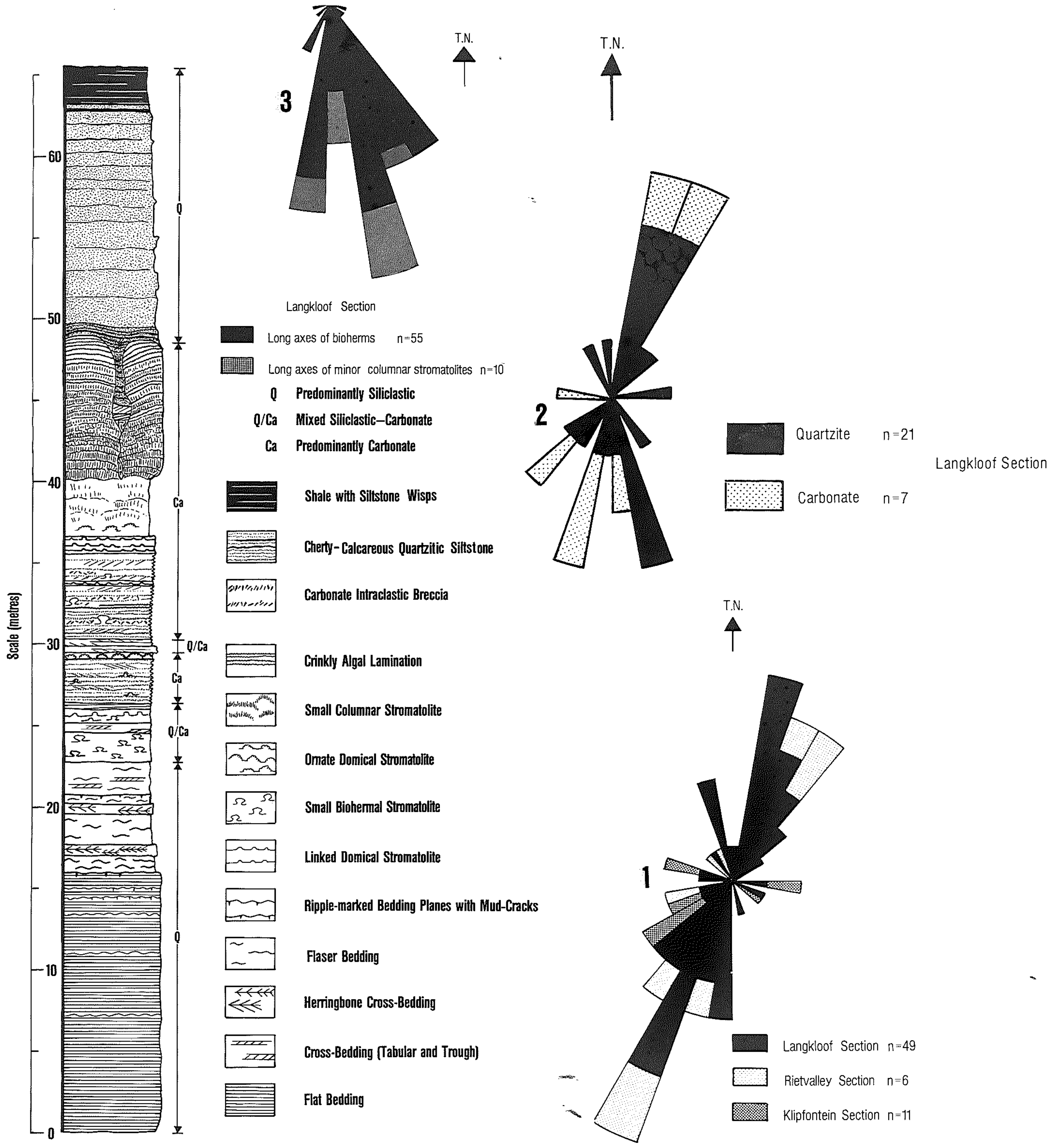


Figure 6 : *Composite diagram, upper members of Houtenbek Formation. Column shows flat and cross-bedded subfacies of the emergent quartz arenite facies (0-23 m), carbonate and clastic facies (23-40 m), biohermal facies (40-50 m) and fine-clastic facies (50 m - top). Rose diagram 1 shows sediment transport directions from current ripples in quartz arenite, 2 shows orientation of cross-beds in quartz arenite and carbonates, 3 shows elongation direction of subtidal bioherms and of minor columnar stromatolites.*

marked preferred north-south orientation (Figure 6, rose diagram 3). The long axis dimension of the bioherms cannot be measured, but is quite possibly as much as 100 m.

Internally, the bioherms are structured by a vertical alternation of algal structures, including algal lamination and finger-sized, linked and unlinked columnar forms (Plate 2D). The uppermost metre of the bioherm is dominated by algal lamination. Large-scale stratification is usually convex-up (Plate 2C), and is sometimes vertical, or even overturned, near the bioherm margin (Plate 2E).

Individual bioherms are separated by linear channels, filled with cross-bedded quartz-arenite, cherty siliceous siltstone, and some mudstone (now hornfels) and carbonate intraclastic breccia. Stratification within channels is often concave-up (Plate 2C), and is, in places, deformed by gravity-induced slump rolls, directed into the channel-axis.

Bioherms can be seen to have grown by both vertical and lateral accretion. Some inter-biohermal channels are up to 10 m wide, while other channels were ultimately closed by lateral growth of the colony.

A subtidal origin for the bioherms is suggested by their size, their high degree of vertical inheritance and the absence of erosive surfaces on bioherm crests. Similar structures have been described from the subtidal zone off the coast of Bermuda (Gebelein, 1969).

Fine-Clastic Facies (6)

Two lithological units make up the facies, a lower calcareous, cherty quartzitic siltstone, and an upper shaly unit. The former is laminated on a centimetre scale, and weathers into a ribbed pattern due to alternating resistant and less-resistant layers. The original lithology was probably a siliceous marl. This grades to the overlying muddy unit by an increase in the shaly fraction (Figure 6). The shaly fraction is very delicately laminated, and includes lenticular wisps of quartzose silt (Plate 2F). No signs of desiccation are evident in either the shaly or the siliceous silty sediments; both are thought to have been deposited below low-water level.

The fine-clastic facies, up to 40 m thick, rests directly on the biohermal facies. The inter-biohermal channels are partly filled with this fine-grained material. It is thought that the deposition of the fine-clastic material became dominant only at the deepwater limit of biohermal growth, since sedimentation rates were probably much greater for the algal structures. The subtidal stromatolites described by Gebelein (1969) grow vertically at rates of up to 1 mm/day. The shelf mud of the North Sea is accumulating at a rate of 20-50 cm/100 years (Reineck and Singh, 1973). Sedimentation rates in the carbonate are some 70 times faster than those in the fine-clastic facies.

DEPOSITIONAL HISTORY

The depositional model proposed is one of a non-barred, macro-tidal, tide-dominated coastline. The coastline is inferred to have been interacting with a braided fluvial plain, which fed in arkosic sediment from the north. The depositional history closely reflects the activity of the fluvial system. An active fluvial input resulted in seaward progradation of depositional environments. An inactive fluvial system (due to abandonment of a local fluvial distributary complex or to a regional decrease in tectonism) resulted in marine transgression and drowned coastlines, where carbonate sedimentation was the rule.

The evidence for a macro-tidal environment in the sediments studied is :

(i) the lack of any vestige of a preserved barrier island complex;

(ii) the large amplitude of bedforms (up to 3 m); and

(iii) the thickness of tidal creek cycles (often over 4 m).

The coastal morphology for the deposition of the sediments under discussion was inferred from contemporary macrotidal environments, principally the macrotidal domain of the North Sea, off Germany, and the north coast of Australia (Reineck and Singh, 1973; Hayes, 1975; Wright et al., 1975). Such coastlines are characterized by wide-mouth estuaries with elongate sand-bars. The estuaries communicate with semi-circular tidal basins, some of which receive a substantial fluvial input. The subtidal domain of the North Sea is characterized by sand tongue and channel systems, which are the offshore continuations of intertidal mud flats and tidal channels, respectively.

The depositional history of the succession under discussion is summarized in the stratigraphic column of Figure 7 and in the block diagrams of Figure 8. An initial progradational cycle (Figures 7 and 8.1) shows an active braided fluvial system feeding from the north. Broad, semi-circular tidal basins (subfacies 3b) are inferred to have been drained by meandering tidal creeks (subfacies 3a), which fed into wide-mouthed estuaries (facies 2). Estuarine sand-bars (facies 2b) are thought to have been elongated normal to the coastline, and to have had both ebb- and flood-dominated domains. The subtidal shelf (facies 1) probably comprised a system of channels and sand tongues (or shoals). If this model is correct, the tongues were characterized by ebb-dominated megaripple fields and by plane-bedded regions, while the channels were ornamented by sandwaves which moved in response to flood currents.

An alternative interpretation is modelled after the relations of the Klang-Langat delta in Malaysia (Coleman et al., 1970). The latter is probably a particularly apt example, involving a deltaic system on a meso-to-macrotidal coastline. The delta is characterized by asymmetric, shoreline-parallel and shoreward-accreting sand ridges. Migration of these sand ridges, some of which may have been exposed at lowest tides, could have been responsible for the large cross-bed sets of the Steenkampsberg (Plate IA).

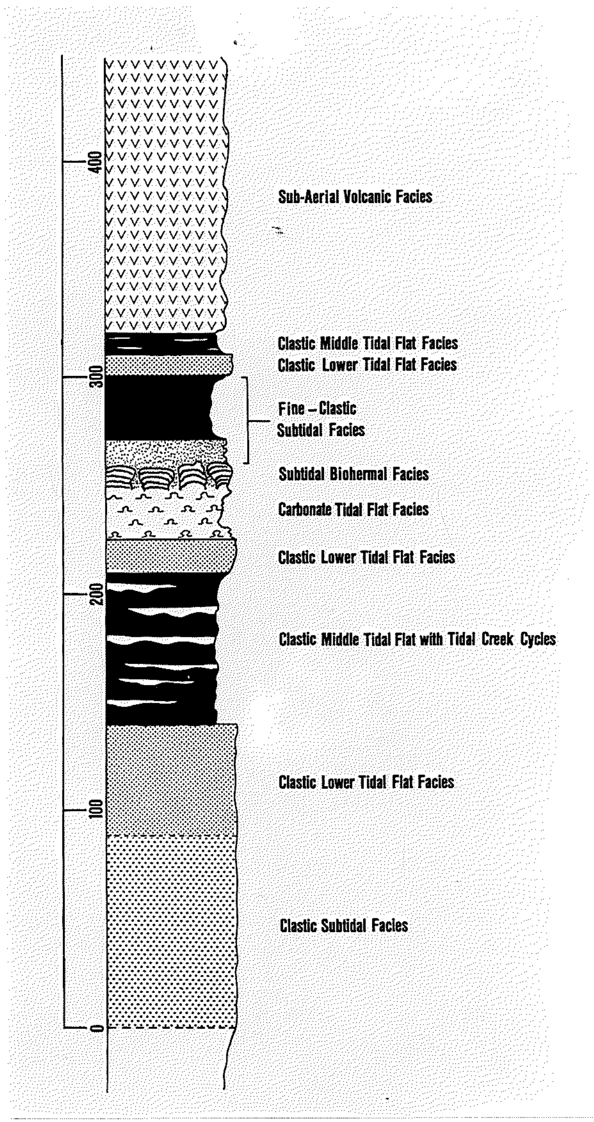


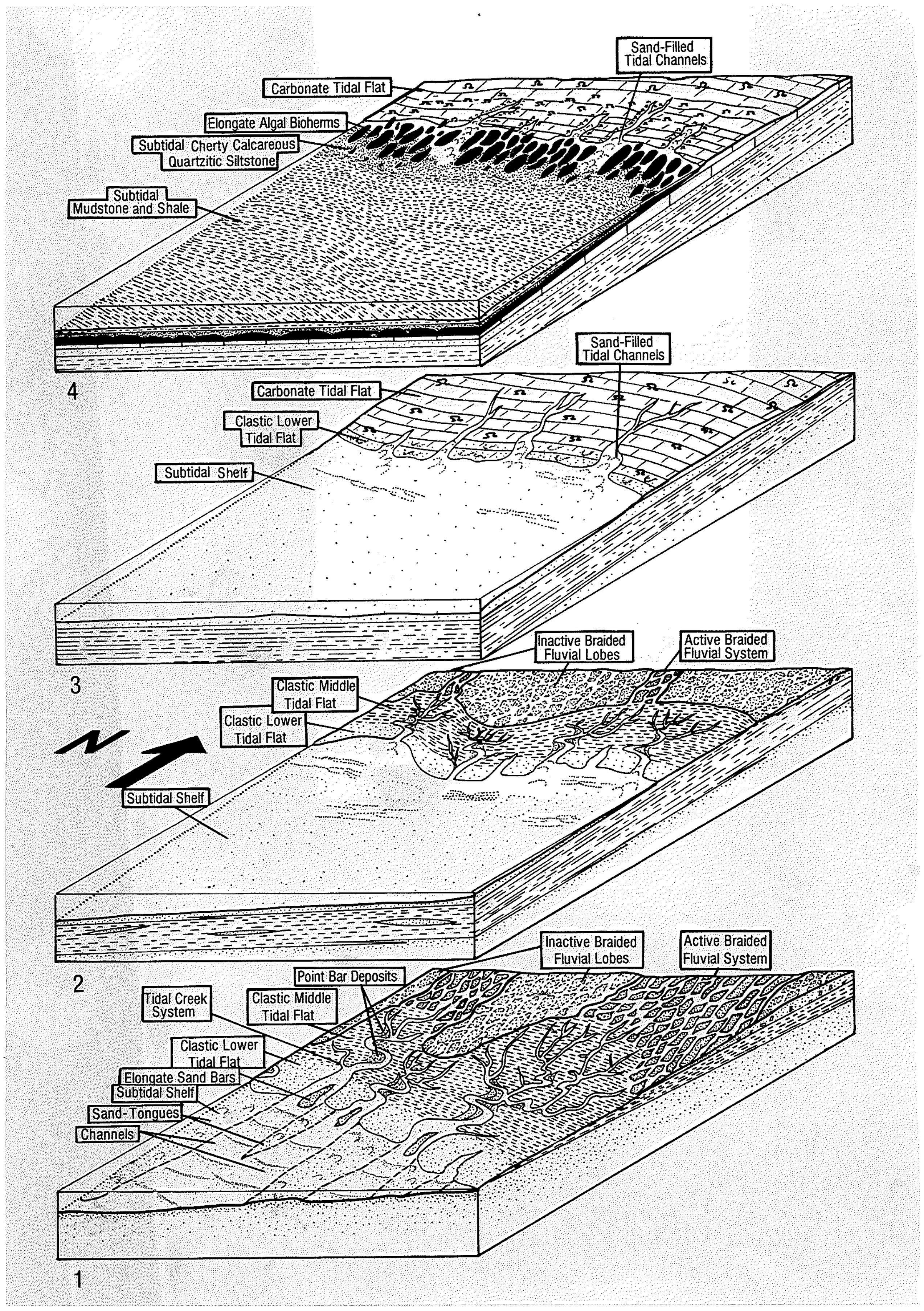
Figure 7 : Vertical succession of inferred depositional environments.

Reduced clastic input to the system resulted in the transgressive event pictured in Figure 8.2, and was followed by a subordinate progradational sequence, shown in Figure 8.3. Here, subsidence must have been at critical slow rate, such that carbonate sedimentation on a middle tidal flat (facies 4) could build out over a lower intertidal sand flat. The lower tidal environment is inferred, from the stratigraphic record, to have ranged from megaripple ornamented (high up the flat) to ripple ornamented and plane-bedded (further down the flat). Cross-bedded arenites in broad, thin lenses between algal heads could have been transported up into the carbonate flat by storm tidal surges, and are restricted to tidal channels.

Cessation of clastic input, combined with continued subsidence, resulted in drowning of the carbonate intertidal flat and the growth of subtidal, elongate algal bioherms (Figure 8.4). At depths beyond the photic zone, algal colonies could not survive, and deposition of mud from suspension occurred to produce the fine-clastic facies. Continued gradual subsidence resulted in a transgression of the shelf muds across the biohermal colonies.

A final depositional event, shown in Figure 7 (two upper sedimentary members) involved a presumed gradual increase with time in the volume of sediment supplied to the shoreline. The shelf mud was covered by a shelf and lower tidal flat sand, which was covered, in turn, by sediments formed on a middle tidal flat.

A number of points of broader application are raised by the relationships described above. Firstly, the use of major progradational cycles as indicators of tidal range is questioned. A tidal range of the order of 50 m would be indicated in the Steenkampsberg-basal Houtenbek prograding cycle. Secondly, modern environments appear to be inadequate to explain all the facies encountered. In particular, the mixed carbonate-clastic facies has no satisfactory modern counterpart. Restriction of algal colonies to sheltered supersaline situations is a characteristic of Phanerozoic environments. Proterozoic stromatolites would have formed in widely differing settings, being restricted only by extremes of water depths, rate of sediment supply and temperature. Depositional models applicable to carbonate systems in the Proterozoic will have to be developed by a synthesis from a large number of individual successions.



<u>*Figure 8*</u> : *Block diagrams, showing the envisaged depositional environments during deposition of some of the uppermost formations of the Pretoria Group.*

ECONOMIC IMPLICATIONS

Limestone

The biohermal facies of the Houtenbek Formation comprises principally low-magnesian limestone. The only impurity of any significance is SiO_2, found mainly in the inter-biohermal channels. The biohermal unit is 10 metres thick on Langkloof 356 JT, and could thus supply some 28 000 000 tonnes per square kilometre. On this farm, and on neighbouring Zuikerboskop 361 JS, an area of about 1,2 km^2 of the limestone is overlain by a cover of hornfels and diabase sills on a dip-slope. An estimated 34 million tonnes of limestone could be won beneath overburden which ranges from 0 to about 50 m in thickness.

The grade of limestone could be appreciably increased by selective mining of the biohermal complex. Fortunately this could be easily undertaken, since the silica-rich inter-biohermal fills trend essentially north-south. Thus north-south quarry faces, retreating westward, would encounter alternating bands of limestone and siliceous material, in a ratio estimated at roughly 10:1.

The limestone unit can be followed on strike for roughly 17 km. It is thus possible that other favourable quarry sites could be found.

Lead-Zinc

Considering the world-wide association of lead and zinc deposits with carbonate rocks, the Houtenbek Formation could possibly warrant some attention. In this connection, a weathered and laminated ferruginous calc-silicate rock from the west-central part of Langkloof 356 JT assayed 610 ppm Zn and 190 ppm Pb (atomic absorbtion method), and over 5 000 ppm Ba (emission spectrographic determination).

Silica

The quartz arenites of the Houtenbek and Steenkampsberg are exceptionally pure, and could yield high-grade SiO_2 in virtually limitless quantities. The outcrops with their 10-20 degree dips and extensive dip-slopes are ideally suited to quarrying.

The high purity of the quartzites is a consequence of deposition in the shallow subtidal and lower intertidal environments. In addition to repeated movement of sand grains with ebb and flood currents, some tidal sand-bars are characterized by "race track" type circulation of sand grains. Both processes ensure removal of all but the most stable mineral components.

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KEY TO PLATE 1

A. Large cross-bed sets in Steenkampsberg Quartzite, resting on and overlain by flat-bedded arenite, non-emergent quartz arenite facies (1), Rietvalley traverse.

B. Flat-bedded quartz arenite with mud-cracked clay drapes on rippled surfaces, upper Houtenbek Quartzite, Kwaggasfontein section.

C. Casts of superimposed ripples, lower Houtenbek Quartzite, Langkloof section (flat-bedded subfacies).

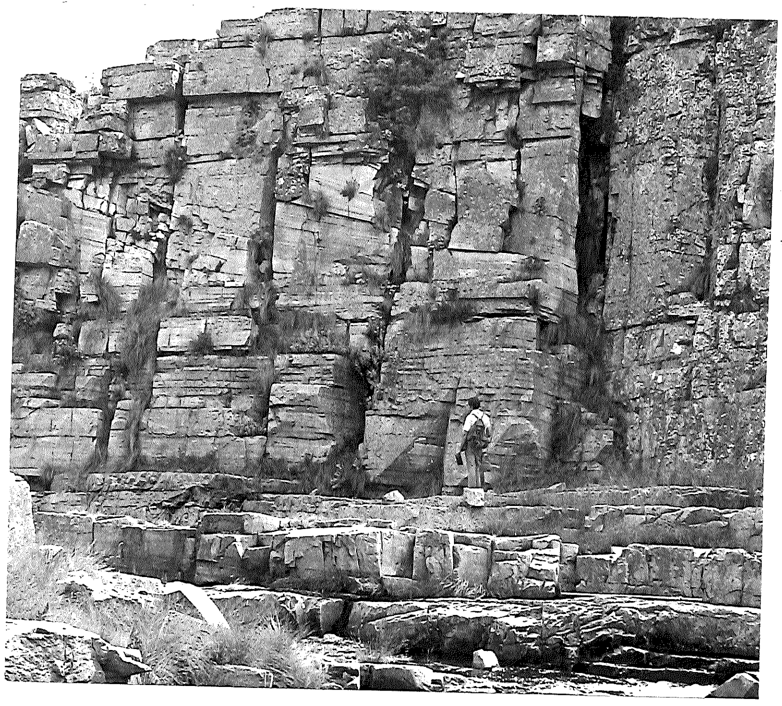
D. Flat-topped ripples, Steenkampsberg Quartzite, Rietvalley section (cross-bedded subfacies).

E. Ripple marked surface covered by mud-cracked clay-drape, emergent quartz-arenite facies of the Steenkampsberg Quartzite, Klipfontein section.

F. Alternating bedload traction (arenite) and suspension settling (argillite) sedimentation, facies 3b, basal member of Houtenbek Formation, Rietvalley section (note internal cross-stratification in arenite layers, and sand-filled desiccation cracks beneath same).

<u>PLATE 1</u>

A



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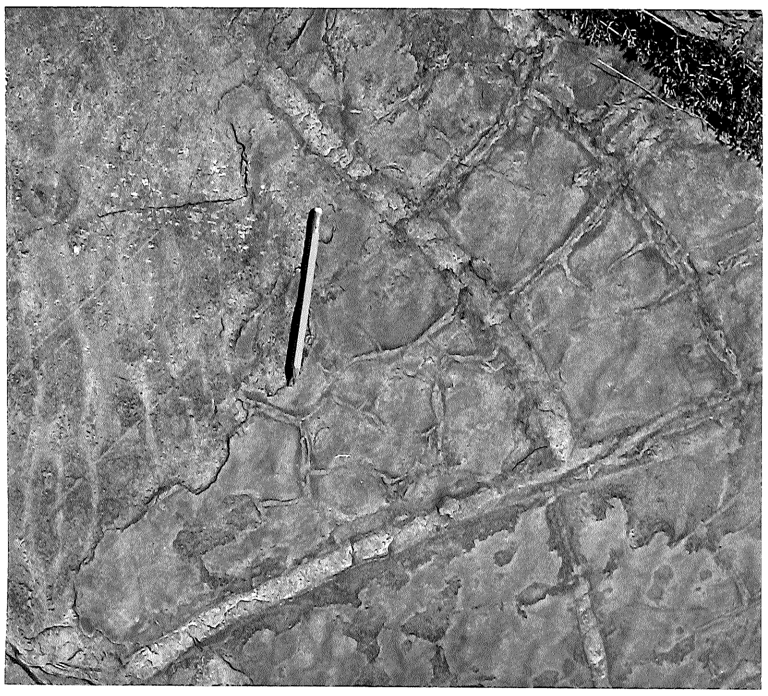

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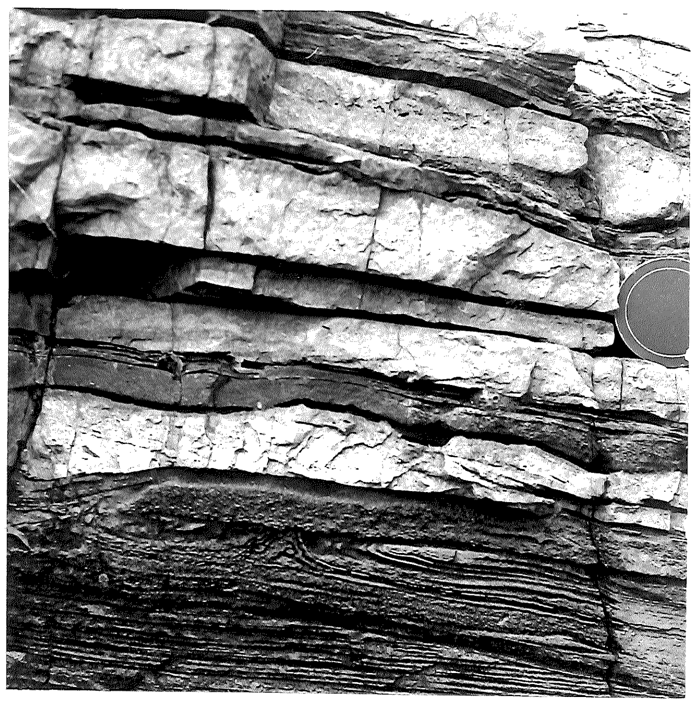


KEY TO PLATE 2

A. Ball-and-pillow structure, facies 3b, basal member of Houtenbek Formation, Rietvalley section.

B. Limestone of carbonate and clastic facies, showing crinkly algal lamination, cross-bedding and layers of intraclastic breccia, Klipfontein section.

C. Exposure of uppermost 2 metres of bioherms, showing convex-up internal structure, and overlying and interbiohermal siliclastic material, Langkloof section.

D. Minor structure within bioherms consists of an alternation of algal lamination with linked and unlinked small columnar stromatolites, Langkloof section.

E. Small bioherm, showing oversteepened margins, Klipfontein section.

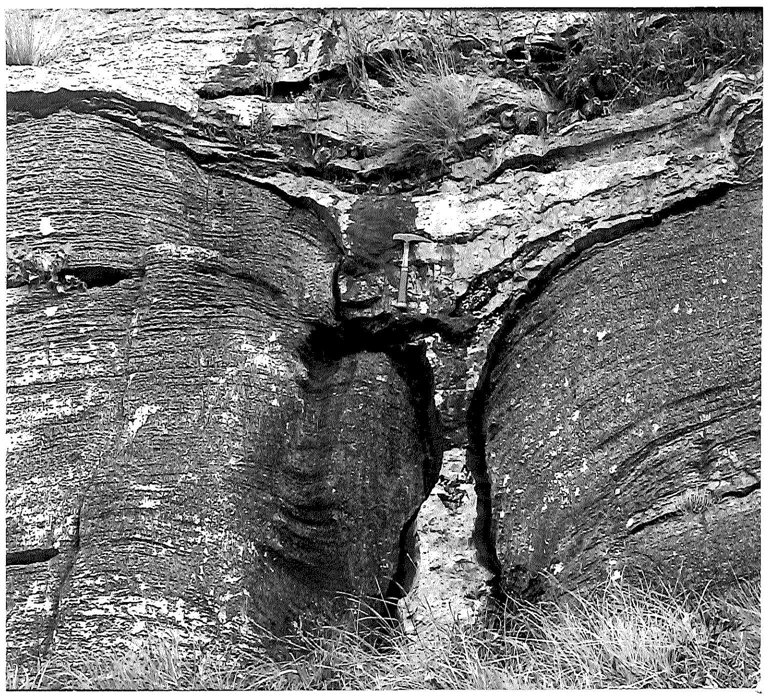
F. Delicate lamination and silty wisps in mud (now hornfels), fine-clastic facies, Langkloof section.

<u>PLATE 2</u>

A

B

C



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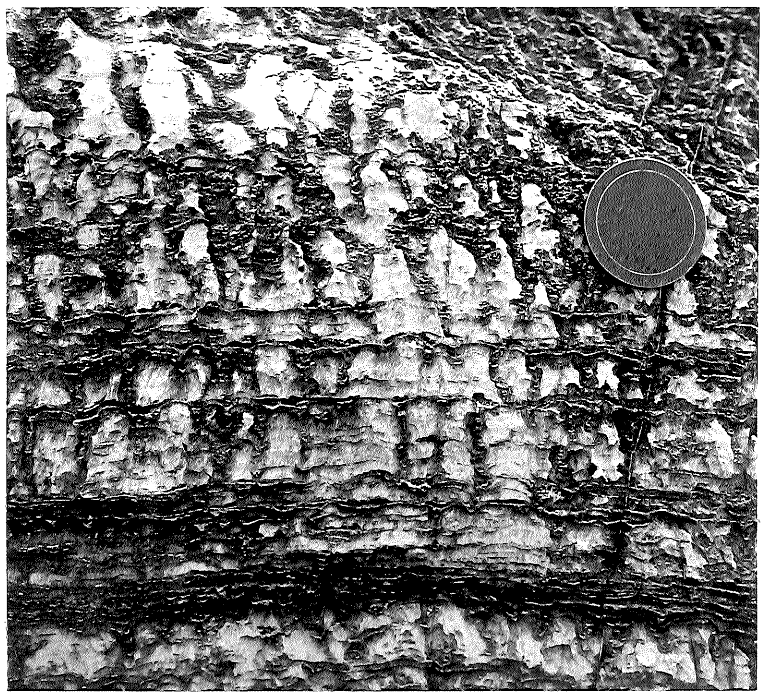

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