ECONOMIC GEOLOGY RESEARCH UNIT

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MARGINAL-MARINE DEPOSITIONAL PROCESSES IN THE ARCHAEAN MOODIES GROUP, BARBERTON MOUNTAIN LAND

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INFORMATION CIRCULAR No. 122

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by

K. A. ERIKSSON
(Senior Lecturer, Department of Geology, University of the Witwatersrand, Johannesburg)

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ABSTRACT

The Moodies Group, which is approximately 3 300 m.y. in age, contains the oldest recognizable sediments of marginal marine origin. These accumulated in estuarine-deltaic, barrier-beach, and back-barrier depositional environments. A paleogeographic model recognizes the interplay of different, shallow-marine processes and the spatial relationships of the depositional environments. Delta-plain sediments consist of tidal-channel and estuarine-tidal-flat deposits. Elongate sand-shoals, oriented perpendicular to the palaeo-shoreline, fronted the delta-plain and indicate that sedimentation occurred under macrotidal conditions in a non-barred estuary. Rapid gravity-flow sedimentation on the delta-front resulted in ubiquitous, soft-sediment deformation and water escape. Longshore reworking of riverborne sediments led to the development of barrier-island and back-barrier deposits lateral to the delta. Chemical and suspension sedimentation predominated in the offshore, and low-energy bedload and storm-surge sedimentation in the nearshore depositional environments. Shoreface sediments display widespread evidence of rip-current activity and were succeeded shorewards by tidal inlet and barrier-spit deposition. Tidal-flat, as well as flood-tidal-delta and washover-fan sediments, accumulated behind the barrier islands. Spit, washover-fan, and abundant rip-current deposits, coupled with the absence of extensive ebb-tidal-delta accumulations, are indicative of a microtidal coastline. The coeval existence of micro- and macro-tidal conditions is attributed to irregularities along the coastline and/or variations in the width of the continental shelf.

While providing no new clues as to the original composition of the Earth's crust, the nature of the Moodies sediments indicates the existence of widespread exposed granitic terranes by 3 300 m.y. In addition, the abundance of marginal-marine, orthoquartzitic sandstones in the Moodies Group suggests a relatively stable crust on which extensive reworking of sediments occurred. The proposed micro- and only-local macrotidal ranges, however, imply a fairly narrow shelf during deposition of the Moodies Group. The conformably-underlying Fig Tree sediments, which are considered to be a deep-water facies-equivalent of the Moodies Group, are further indicative of a narrow shelf. The above criteria have been used to suggest that the Moodies and Fig Tree groups accumulated along an ancient continental margin. Marginal-marine facies are apparently lacking in other Archaean terranes, most notably in Canada; rather alluvial and turbidite sediments occur and were deposited in localized graben-like basins. These two styles of Archaean sedimentation may reflect responses to different stages of continental rifting and spreading.

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INTRODUCTION

The most common Archaean sedimentary facies consists of graded greywacke-shale couplets with occasional associated conglomerates. These are interpreted as deep-water turbidites and are best documented from Canada (Donaldson and Jackson, 1965; Walker and Pettijohn, 1971; Henderson, 1972; Pettijohn, 1972; Turner and Walker, 1973; Hyde, 1975), the U.S.A. (Ojakangas, 1972; Granath, 1975), and Australia (Glikson, 1971; Dunbar and McCall, 1971; Lipple, 1974; Hallberg et al., 1976). A second Archaean sedimentary facies is characterized by evidence of bedload sedimentary processes in the form of clast-supported conglomerates and cross-bedded sandstones. Together with the immaturity of the sediments, these criteria have been used to propose an alluvial origin for this facies which is well-represented in Canada (Turner and Walker, 1973; Hyde, 1975) and Australia (Glikson, 1971; Donaldson and Platt, 1975; Marston and Travis, 1976). Thus, the most-proximal and most-distal clastic depositional environments are abundantly developed in the Archaean, but with no evidence of intermediate- or marginal- (shallow) marine settings.

Both of the above-mentioned facies occur in the Swaziland Supergroup of Southern Africa (Figure 1) - turbidites in the Fig Tree Group (Reimer, 1975) and alluvial sediments in the overlying Moodies Group (Eriksson, 1977; in press). In addition, the Moodies Group contains a diverse assemblage of sediments which are considered to display evidence of marginal-marine depositional processes, such as occur in Holocene deltaic, barrier beach-offshore, and back-barrier environments.

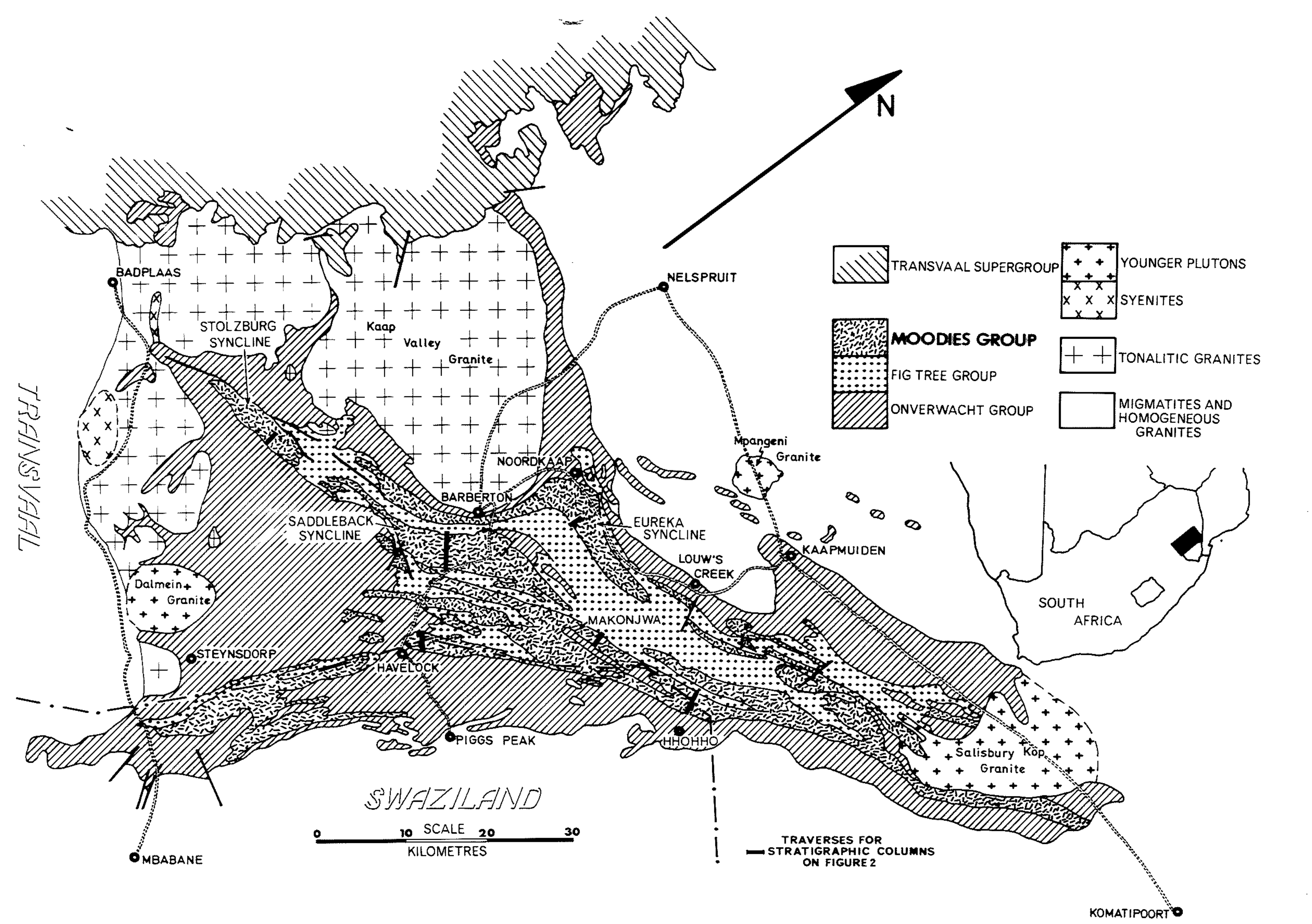

Figure 1 : Geological map of the Barberton Mountain Land, with inset map of South Africa (modified after Anhaeusser et al., 1968).

An appreciation of how Archaean marginal-marine depositional processes and environments compare with those in the Holocene can provide valuable information pertaining to the evolution of the Earth's crust. Mature beach and tidal sediments, for instance, imply a stable crust on which extensive reworking could occur. Furthermore, the occurrence of marginal-marine sediments in the Moodies Group of South Africa and their absence on other continents has important implications with respect to the nature of the Archaean crust in different parts of the world.

GENERAL GEOLOGY AND AGE OF THE MOODIES GROUP

The Swaziland Supergroup in the Barberton Mountain Land is comprised of three stratigraphic units (Figure 1, Anhaeusser, 1973). Basal volcanics and minor sediments constitute the Onverwacht Group which is conformably overlain by Fig Tree Group sediments. The Moodies Group is the upper sub-division and, in the southern and central parts of the mountain land, rests unconformably on Onverwacht volcanics and Fig Tree sediments, respectively. From the Makonjwa Range northwards (Figure 1), a gradational contact exists between the Fig Tree and Moodies groups.

Sediments of the Moodies Group can be dated, relative to upper Onverwacht felsic volcanics, with an age of 3 360 ± 100 m.y. (van Niekerk and Burger, 1969), at less than 3 400 m.y. and, relative to the intrusive Lochiel granite, which is dated at 3 070 ± 60 m.y. (Allsopp et al., 1962), at greater than 3 000 m.y. The Moodies Group is thus older than any of the sedimentary basins on the Kaapvaal Craton, the oldest of which is the Pongola Supergroup which rests on a Lochiel-type granite.

The Moodies Group attains its greatest thickness in the Eureka Syncline (Figure 1), where it is subdivided into five stratigraphic units, termed MD1 through MD5 (Figure 2). A prominent amygdaloidal lava zone at the base of unit MD4 allows correlation between the Eureka, Saddleback, and Stolzburg synclines; in the latter two synclines, unit MD5 is absent. South of the Saddleback Syncline, no correlatable stratigraphic units can be recognized, apart from a basal conglomerate (Figure 2).

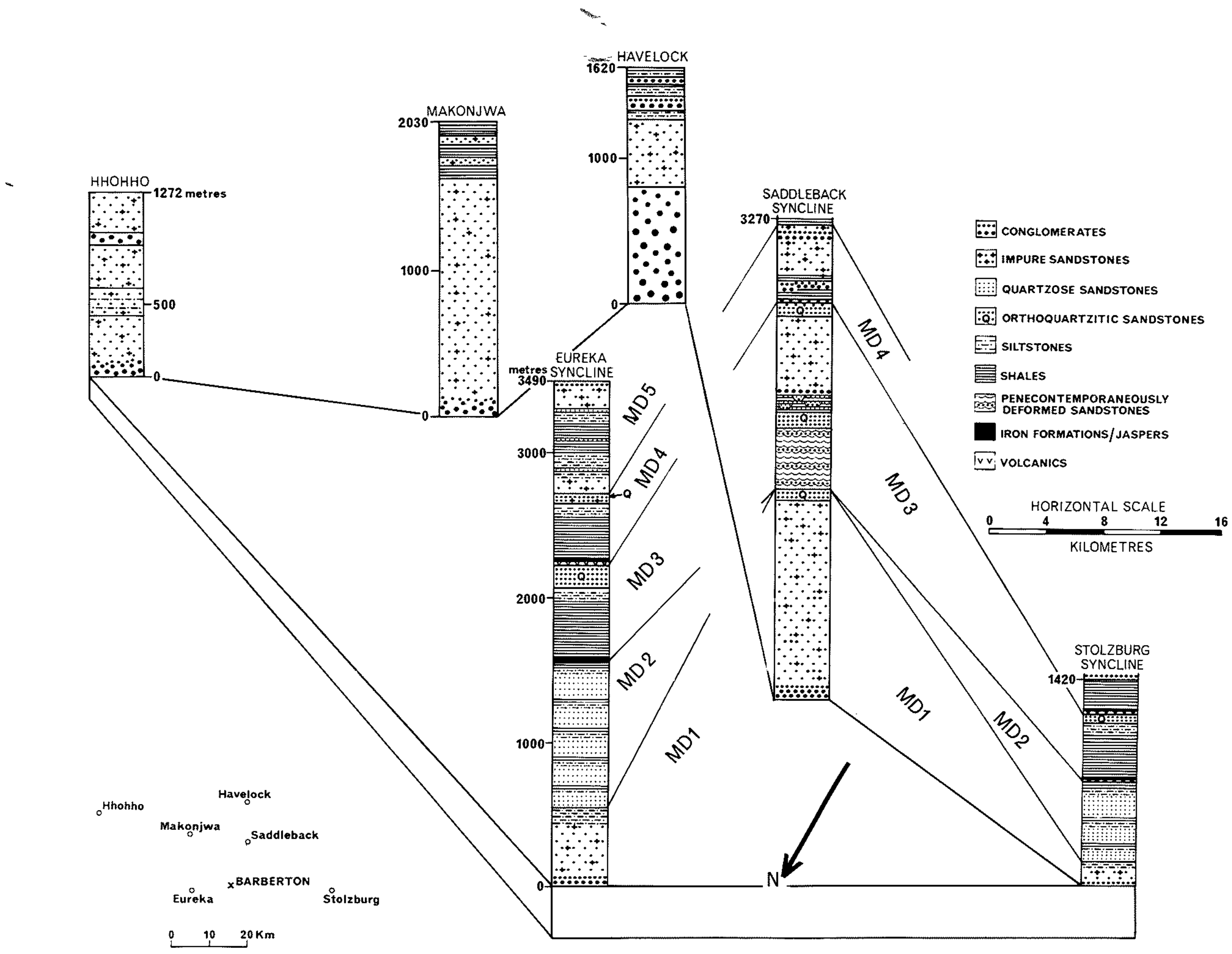

Figure 2 : Representative stratigraphic columns of the Moodies Group. Inset shows ground positions of column localities relative to Barberton.

In the southern parts of the Barberton Mountain Land, notably along the Swaziland border and northwards to the Saddleback Syncline (Figure 1), fluvial sediments predominante. Palaeocurrent determinations on these and sediments of similar origin further north (Eriksson, in press) indicate that the source-area lay to the south of the outcrop belt. Fluvial sediments decrease in abundance down the palaeoslope and contain intercalated orthoquartzitic sandstones and associated sediments in the Saddleback Syncline and thick argillaceous and clean arenaceous sequences in the Eureka and Stolzburg synclines (Figure 2). In this account, the non-fluvial Moodies sediments have been characterized in terms of their lithologies, sedimentary structure-types, palaeocurrent patterns, and vertical sequences. These parameters have then been used to interpret specific marginal-marine depositional environments with respect to Holocene depositional processes and models. Finally, the significance of the marginal-marine sediments has been analyzed, specifically with respect to the nature of the Archaean crust in South Africa.

DELTAIC DEPOSITIONAL ENVIRONMENT

A progradational deltaic assemblage of sediments is developed in unit MD3 in the Saddleback Syncline (Figure 2). Recognizable sub-environments are delta-plain, tidal-sand-shoal, and delta-front (Figure 3). The maturity of the sand-shoal sediments and the frequency of bimodal-bipolar palaeocurrent patterns (Figure 3) indicate that the delta was strongly influenced by tidal processes.

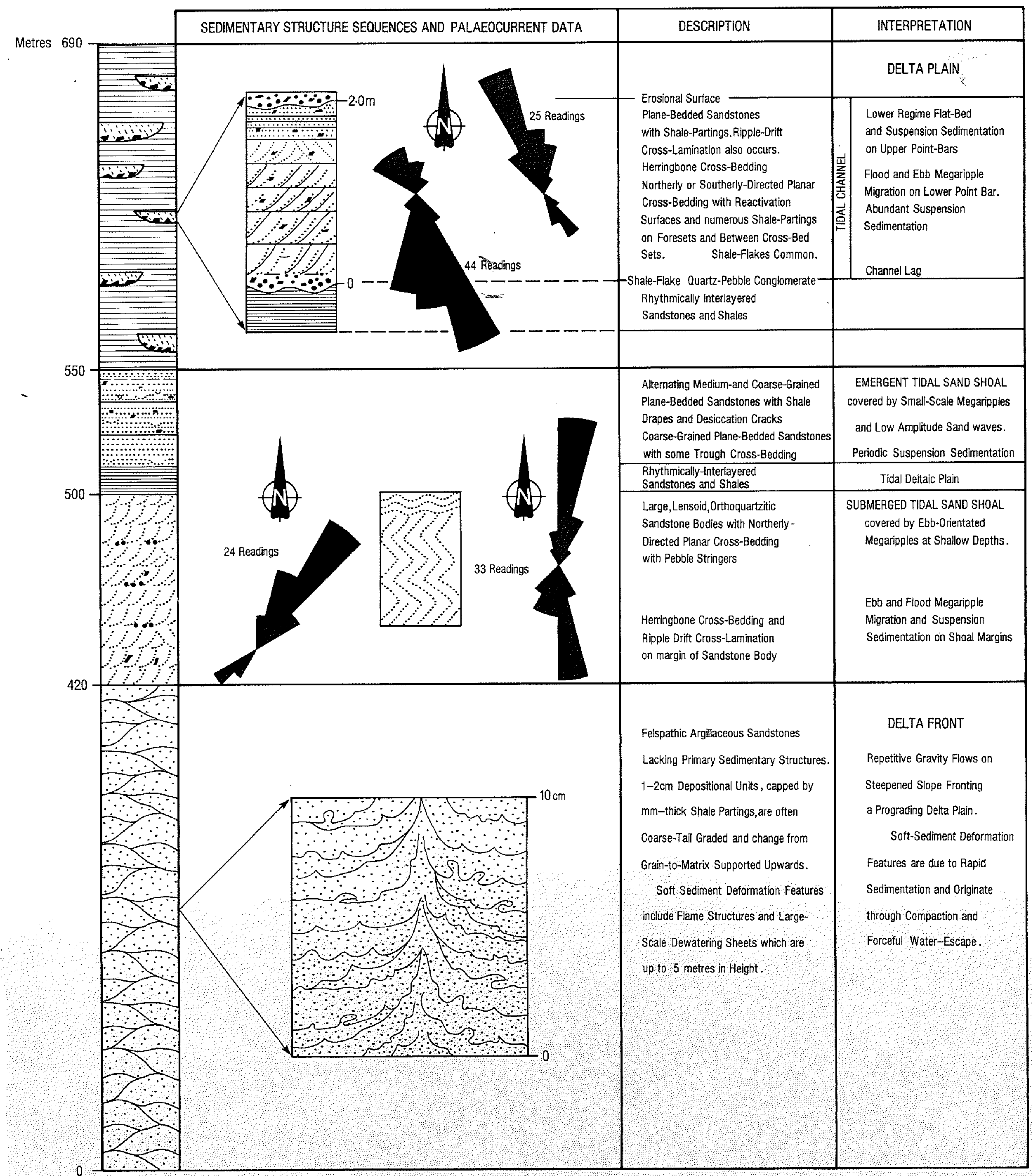

Figure 3 : Detailed descriptive-interpretive stratigraphic column for prograding deltaic depositional environments. Lower half of unit MD3, Saddleback Syncline.

(a) Delta-Plain

Delta-plain deposits are composed of upward-fining channel-fill sequences enclosed within rhythmically-interlayered sandstones and shales (Figure 3). The channel-fill sediments display many characteristics in common with fluvial point-bar deposits, most notably the immaturity of the sandstones and the vertical sequences of sedimentary structures (see Figure 3, Allen, 1970; Visher, 1972). A number of criteria, however, serve to distinguish these sequences as tidal-channel deposits. While individual outcrops may reveal essentially unimodal palaeocurrent patterns, the thin herringbone cross-bedded units frequently give a weak bipolarity (Figure 3). Furthermore, spatially-separated outcrops reveal dominant southerly or northerly palaeocurrent modes, respectively reflecting flood- or ebb-currents in different tidal channels. Shale-drapes are ubiquitously developed on foresets, between cosets and within plane-bedded sandstones (Figure 3) and are considered by Oomkens (1974) to adequately distinguish between upward-fining fluvial and tidal channel-fill sequences. Reactivation surfaces (Figure 3; Plate 1a) have been taken as diagnostic evidence for tidal-influenced depositional environments (Klein, 1970). The recognition of similar structures in Holocene fluvial sediments (Collinson, 1970) partially negates this contention but, in association with other evidence, lends support to the tidal-channel interpretation for these sediments.

Within the tidal-channel sequences, different sub-environments can be recognized when compared to similar deposits from estuaries along the Netherlands coast. The basal conglomerates (Figure 3) represent channel-lag deposits, with the extra-formational quartz clasts implying a connection to a fluvial supply of sediment. Overlying cross-bedded sandstones are thought to indicate a transition from upper- to lower-flow-regime conditions from the channel-floor to the lower point-bar. Current flow was unidirectional at greater, and bidirectional at shallower, depths. The plane-bedded upper unit probably formed on upper point-bars, with the thin shale-laminae and absence of primary current lineations distinguishing these deposits as a response to lower- as opposed to upper-flow-regime conditions. Associated ripple-drift cross-lamination (Plate 1b) may represent levee or upper point-bar deposition.

The rhythmically-interlayered sandstones and shales which enclose the tidal-channel sequences frequently display evidence of desiccation and are interpreted as overbank deposits which accumulated on estuarine tidal-flats through alternating bedload and suspension sedimentation. Shale-flakes in the tidal-channel deposits were probably derived from these sediments during lateral channel-migration and cutbank erosion.

(b) Tidal Sand-Shoal

Large, lensoid orthoquartzitic sandstone bodies (Figure 3), which have a north-south orientation, are interpreted as tidal sand-shoal deposits and are analogous to similar elongate sand bodies at the mouth of the Elbe River in the German Bight (Reineck and Singh, 1973, p. 318). This estuary is exposed to the open ocean and, largely due to the macrotidal ranges, is influenced by strong tidal currents. On the surface of the Elbe shoals, megaripples occur below, and smaller-scale bedforms and clays above, low-water level (Dörjes et al., 1970). Dominant northerly-directed planar cross-beds, and associated pebble-stringers, within the sandstone body (Figure 3) are considered to be a response to strong ebb-currents flowing across the surface of a submerged sand-shoal. The occurrence of bimodal-bipolar herringbone cross-bedding (Plate 1c) around the margin of the shoal indicates both a flood- and ebb-influence and illustrates the time-velocity asymmetry of tidal currents (Klein, 1970). Associated ripple-drift cross-lamination provides further evidence for the existence of strong currents which were capable of transporting appreciable quantities of medium- and coarse-grained sand in suspension (Gustavson et al., 1975). The predominance of low-amplitude sedimentary structures and the eventual appearance of desiccated shale-drapes in the upper 40 m of the sandstone body (Figure 3) indicate a shallowing and eventual emergence of the sand-shoal. Interlayered, plane-bedded, coarse- and medium-grained sandstones are diagnostic of a lower-flow regime (Jopling, 1964) and probably formed through the migration of very low-amplitude sand-waves (Smith, 1971).

(c) Delta-Front

The interpretation of the third, and lowermost, deltaic facies as a delta-front deposit (Figure 3) is based largely on its association with previously-interpreted delta-plain and tidal sand-shoal sequences. The lack of preserved primary sedimentary structures and the immature, often loosely-packed nature of the delta-front sediments indicate rapid deposition in the absence of bed-load processes. The frequently-encountered coarse-tail grading of depositional units is suggestive of gravity-flow processes (Middleton and Hampton, 1973). One possible gravity-flow mechanism is

<u>Plate 1(a):</u> *Planar cross-bed set overlying a basal shale-flake conglomerate. Note reactivation-surface within cross-bed set, as well as grading within foreset-laminae. Tidal-channel-fill deposits, Unit MD3, Saddleback Syncline. (scale is 11 cm in length).*

<u>Plate 1(b):</u> *Type-A ripple-drift cross-lamination within upper point-bar facies of tidal-channel-fill. Unit MD3, Saddleback Syncline. (scale 1 and 5 cm divisions).*

<u>Plate 1(c):</u> *Herringbone cross-bedding on margin of submerged tidal sand-shoal. Unit MD3, Saddleback Syncline.*

liquefaction, which occurs when an unconsolidated, grain-supported sediment is transformed into a transitory, fluid-supported suspension, as a result of a rapid, but temporary, increase in the pore-fluid pressure (Lowe, 1975). Sedimentary particles are transported in this state, in response to gravity, as long as the pore-pressure exceeds the hydrostatic pressure. Re-sedimentation (upon loss of pore-pressure) results in the downward settling of solids through the fluid (Lowe, 1976). This often develops basal, grain-supported, coarse fractions similar to the coarse tails present within individual depositional units of this facies. Deposition of the finer-grained debris from a suspended state in diluted turbidity-currents (Lowe, 1976) could account for the upper, loosely-packed portions of graded units and the capping shale-laminae.

Penecontemporaneous deformation-structures in liquefied flow-deposits form as a result of water migration either during or after deposition of overlying units (Lowe, 1976). The vertical persistence of water-escape pipes or sheets points to the simultaneous dewatering of depositional sequences upwards of 3 m in thickness. The ragged contacts between individual depositional units, and specifically the small-scale flame-structures (Figure 3), probably formed through loading and/or passive, as opposed to forceful, water-escape. Evidence for the accumulation of saturated water below the thin shale-laminae is provided by the common silica concretions within the upwarped irregularities. The lack of dish-and-pillar structures (Lowe and Lo Piccolo, 1974) suggests that rapid sedimentation resulted in an excessive load, which limited the forceful escape of water to large cross-cutting pipes and sheets which may follow penecontemporaneous joints.

In summary, it is considered that repetitive, liquefied, gravity-flow surges on a steepened slope, fronting the prograding delta-plain, could adequately account for the primary and secondary characteristics of the delta-front sediments.

(d) Discussion

This deltaic assemblage of sediments displays few, if any, characteristics in common with classical deltas, such as the Mississippi (see Coleman, 1976). Often, however, deltas which experience high, tidal ranges display primarily tidal-flat depositional features, such as are represented in the delta-plain and, to a certain extent, in the sand-shoal sediments. Tidal processes at river-mouths produce intensive meandering above the zone of tidal influence, cause tidal channels to be sand-filled, and result in the accumulation of large, linear, sandy tidal ridges seaward of the river-mouth (Coleman and Wright, 1975). The Ord River delta in northern Australia illustrates the above processes. Semi-diurnal tides have a mean range of 3,80 m and an average spring range of 5,15 m, but an upstream amplification of the tidal wave causes mean and spring tidal ranges of 4,75 and 6,60 m., respectively, within the delta itself. Tidal currents are orientated dominantly in an offshore-onshore direction, and, as is also the case for the macrotidal Fly Delta (Galloway, 1975), produce sand-shoals, covered by megaripples, oriented perpendicular to the shoreline (Wright et al., 1975).

BARRIER-BEACH DEPOSITIONAL ENVIRONMENT

Thick, upward-coarsening, progradational depositional sequences, of the type developed in unit MD3 in the Eureka and Stolzburg synclines (Figures 2 and 4) are compatible with the prograding, barrier-island-shallow-shelf models of Bernard et al. (1962), Reineck and Singh (1971), and Howard and Reineck (1972). The maturity of the arenaceous sediments within this sequence, coupled with the complex palaeocurrent patterns (Figure 5), are suggestive of marine processes and further support a barrier-beach model.

(a) Offshore Shelf

The abundant banded iron-formations and shales which developed in the lower (deeper) part of the offshore-shelf environment (Figure 4) indicate that quiet-water chemical and suspension sedimentation were the dominant depositional processes. Banded iron-formations were precipitated in environments furthest removed from terrigenous input and are the deepest-water or most-distal shelf sediments. Finely-alternating, ferruginous and siliceous layers in banded iron-formations most readily form as a response to cyclinally-fluctuating Eh and pH conditions (Walter, 1972). Photo-synthetic organisms are the agents most likely to have effected such short-term changes, be they diurnal or seasonal, and it is possible that primitive blue-green algae inhabited photic shelves during the Archaean (Muir and Grant, 1976; Knoll and Barghoorn, 1977). Although reflecting different depositional processes, the laterally-persistent, shelf, shell beds of the Mississippi Delta (Coleman and Gagliano, 1965) and the Pennsylvania marine-platform carbonates of the Eastern Interior Basin (Pryor and Sable, 1974), both of which represent intervals of non-detrital deposition, are possible analogues of the chemical sediments of this facies. The overlying shales with jasper lenses and layers indicate an offshore environment, intermittently receiving fine-grained detritus which settled from suspension and alternated with short periods of siliceous, chemical sedimentation at relatively low pH's and high Eh's. At shallower water-depths, a continuous supply of fine-grained detritus prevented the formation of chemical precipitates. Dominant suspension-sedimentation and periodic migration of 'starved' ripples developed shales with siltstone lenses (Figure 4). Low-energy bedload processes became increasingly significant, with progressive shallowing of the offshore shelf, resulting in interlayered, laterally-persistent, ripply-cross-laminated and horizontally-laminated siltstones and shales.

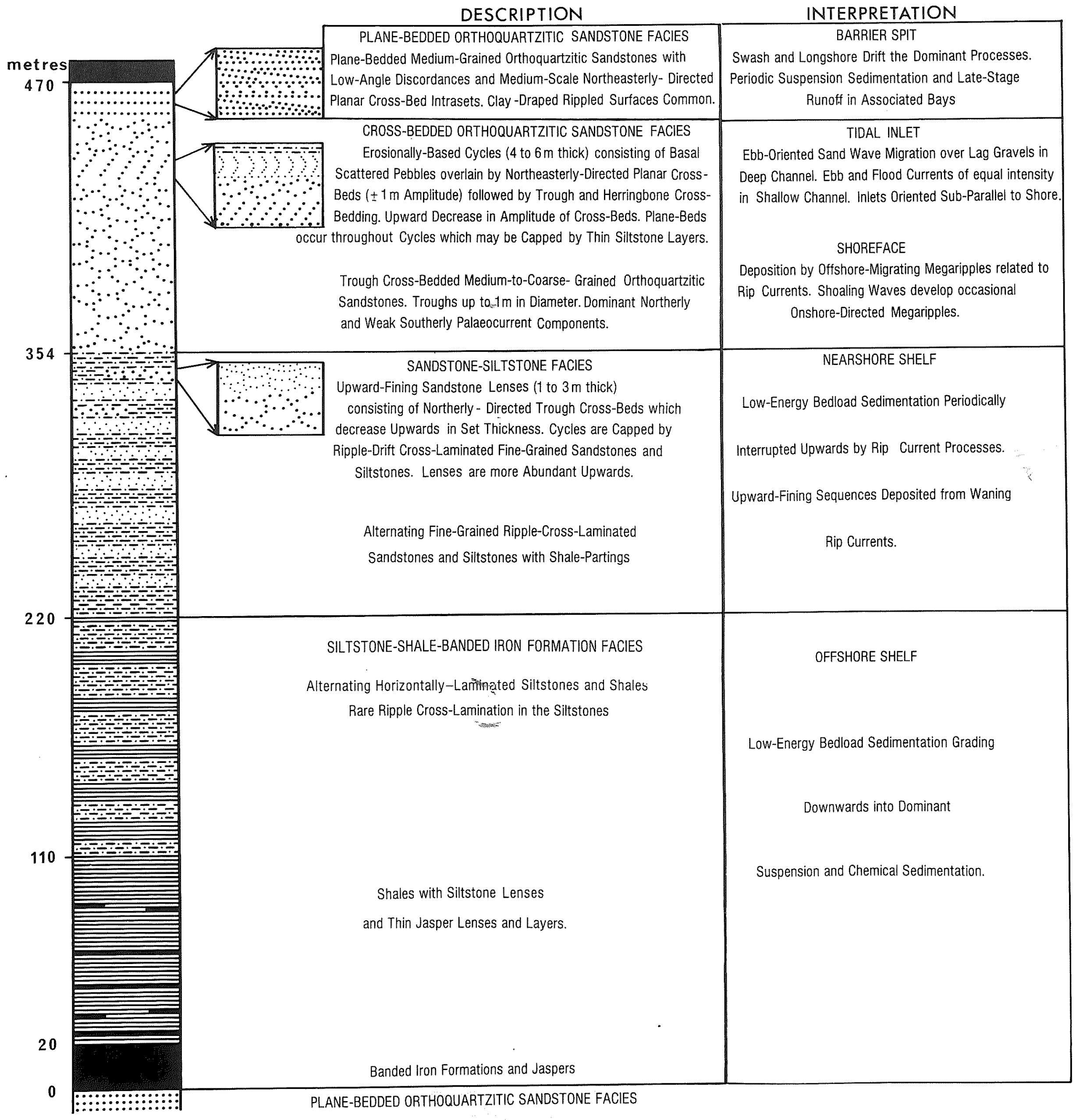

Figure 4 : *Detailed descriptive-interpretive stratigraphic column for prograding barrier-beach depositional environments. Unit MD3, Eureka Syncline.*

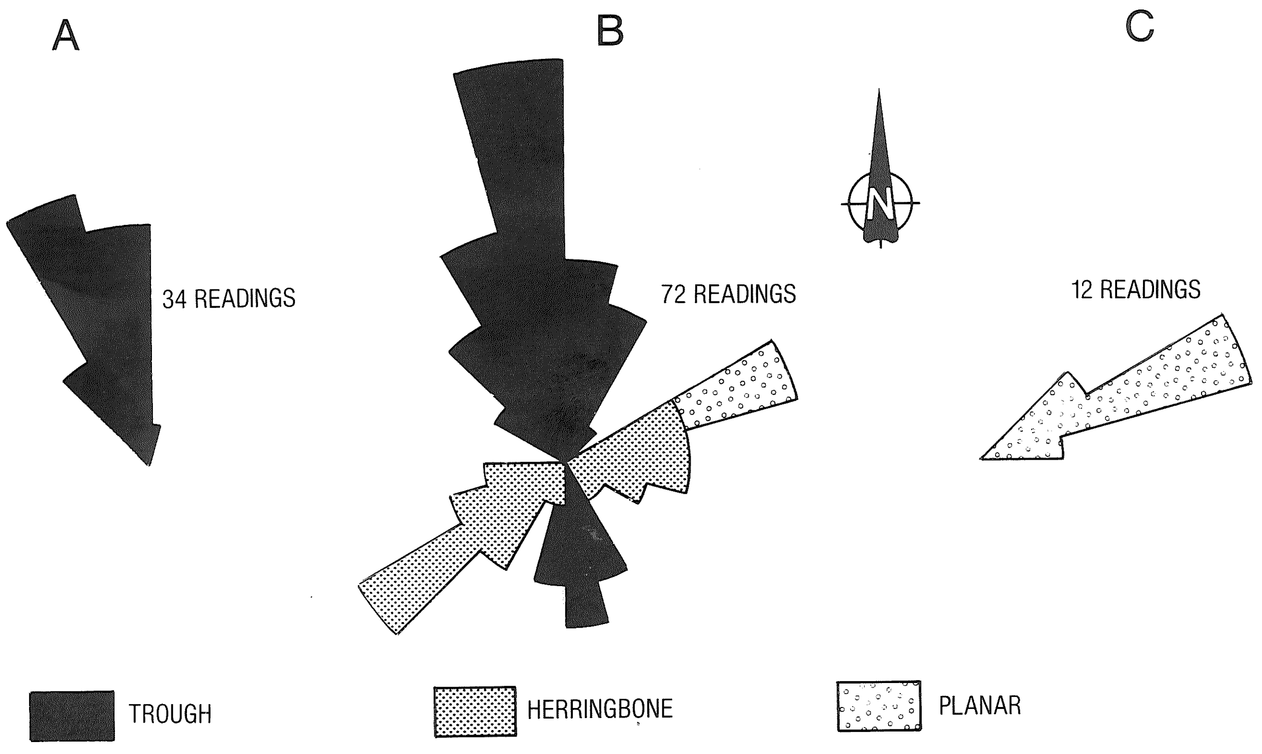

Figure 5 : *Crossbed-vector rose-diagrams for nearshore-shelf-sandstone lenses (A); trough-crossbedded-offshore sandstones (B); planar and herringbone-crossbedded-tidal-inlet sandstones (B) and barrier-spit-planar-crossbedded sandstones (C).*

(b) Nearshore Shelf and Shoreface

Alternating, fine-grained, ripple-cross-laminated sandstones and siltstones, with thin shale-partings, which occur through much of the nearshore shelf (Figure 4), are analogous with those reported from the same environment off Sapelo Island (Howard and Reineck, 1972) and are indicative of dominant, low-energy bedload- and infrequent suspension-sedimentation. The common, upward-fining, orthoquartzitic sandstone lenses higher up in the nearshore-shelf facies (Figure 4), however, imply periodic higher-, but waning-, energy currents on the nearshore shelf. As indicated by the cross-bed rose-diagram for these lenses (Figure 5A), these currents had a predominant northerly or offshore orientation and were probably generated by rip-currents, which operate perpendicular to modern coasts. As a result of longshore processes and onshore mass-transport by incident waves, water accumulates inside breaker zones (Huntley and Bowen, 1975; Komar, 1975). The seaward escape of this water sets up offshore currents capable of erosion and transportation of sand through the upper shoreface (Davis and Fox, 1972; Vos, 1976). Broadening of the rip-current into a rip-head results in waning-flow (Huntley and Bowen, op cit.) which generates conditions suitable for the offshore migration of megaripples and the formation of trough cross-beds. A further decrease in velocity results in current-ripple migration and suspension-sedimentation of fine-grained particles. Ripple-cross-laminated and ripple-drift-cross-laminated fine-grained sandstones and siltstones are developed and represent decreasing bedload-to-suspended-load deposition. Upward-fining cycles similar to those present in this facies, and recording single depositional events, are generated in this way.

In progradational barrier-island sequences, shelf deposits most commonly coarsen gradationally upwards into shoreface sands. The sharp basal contact (Figure 4) and the dominant offshore palaeocurrent component for the trough-cross-bedded or orthoquartzitic sandstones (Figure 5B; Plate 2a) are not typical of normal shoreface sediments. A possible analogue exists in the Miocene of California, where Clifton (1973) has attributed shoreface sediments with a sharp basal contact to channelized rip-currents which reworked sediment within the zone of wave-build-up and surf. Resurgent rip-currents operating in the lower shoreface are invoked as the causal process, with an upward-decrease in trough-cross-bed thickness within 1-3 m-thick depositional units, as the only manifestation of waning rip-current velocities. The weak onshore palaeocurrent component (Figure 5B) can be related to the shoreward motion of shoaling waves (Clifton, et al. 1971; Greenwood and Davidson-Arnot, 1975) between individual rip-current pulses.

(c) Tidal Inlet

Stacked, upward-fining cycles, which overlie the shoreface sandstones (Figure 4), closely resemble tidal-inlet deposits from Long Island (Kumar and Sanders, 1974). Tidal inlets are narrow channels between barrier-islands, dominated by tidal currents, the formation of which has been attributed by Pierce (1970) to tidal surges associated with storms, that cause water to flow over, and possibly incise into, barrier-islands. Depending on the magnitude of longshore currents, tidal inlets vary in orientation, ranging from perpendicular to acute angles to the shoreline (Kumar and Sanders, op cit; Hubbard and Barwis, 1976). The modal migration-direction of ebb-oriented bedforms in South Carolina inlets is more commonly subparallel, rather than perpendicular to the shoreline (Hubbard and Barwis, op cit.). Tidal inlets migrate parallel to longshore currents, with resultant spit development on the up-current end of the inlet. Hydrodynamic conditions vary in different parts of inlets and develop characteristic sequences of sedimentary structures. Basal conglomerates in the cycles of this facies are interpreted as channel-floor deposits. Overlying planar cross-beds are generated by migration of northeasterly, ebb-oriented sandwaves (see Figures 4 and 5B) in deep-channel portions of tidal inlets. The interlayered plane-bedded sandstones are thought to have developed during upper-flow regime conditions, probably as a response to periodic water-level changes. Whereas deeper parts of tidal inlets are generally characterised by unidirectional flow, shallow-water realms contain bidirectional currents related to ebb-and-flood tides (Van Beeck and Koster, 1972). The herringbone cross-bedding at the top of the cycles (see Figures 4 and 5B) can be related to such processes, while the common shale-drapes on cross-bed foresets provide further evidence of a strong tidal influence during the deposition of these sediments (Oomkens, 1974). Palaeocurrent patterns for these cycles (Figure 5B) are compatible with tidal inlets oriented in a northeast-southwest direction, which is subparallel to the palaeoshoreline. This, by implication indicates a strong, easterly, longshore drift component. The vertical superimposition of tidal inlet cycles is due to successive longshore migration and reopening of inlets at their original sites (Kumar and Sanders, op. cit.). Extensive scouring during longshore migration results in incomplete preservation of underlying inlet sequences.

(d) Barrier-Spit

The sediments at the top of the upward-coarsening barrier-beach sequence (Figure 4) superficially resemble foreshore deposits, with the plane-bedded sandstones (Plate 2b) developed by swash processes and the planar cross-bed intrasets representing ridge-and-runnel accumulations (Hayes and Boothroyd, 1969; Wunderlich, 1972). Abundant, clay-draped, ripple-marks (Figure 4) are, however, atypical of foreshores, while the planar cross-beds have a longshore attitude (Figure 5C), which contrasts with the normal landward-dip of ridge-and-runnel cross-stratification. A depositional environment influenced by swash and longshore currents, and incorporating protected settings suitable for suspension sedimentation, is indicated. Barrier-spits contain sub-environments in which each of the lithologies present could have accumulated. Subaqueous spit-platforms consist of long, planar

Plate 2(a): Trough-crossbedded, orthoquartzitic, shore-face sandstones developed by offshore-directed rip-currents. Unit MD3, Eureka Syncline. (scale is 14 cm in length).

Plate 2(b): Plane-bedding with low-angle discordances in spit-beach-face deposits. Unit MD3, Eureka Syncline.

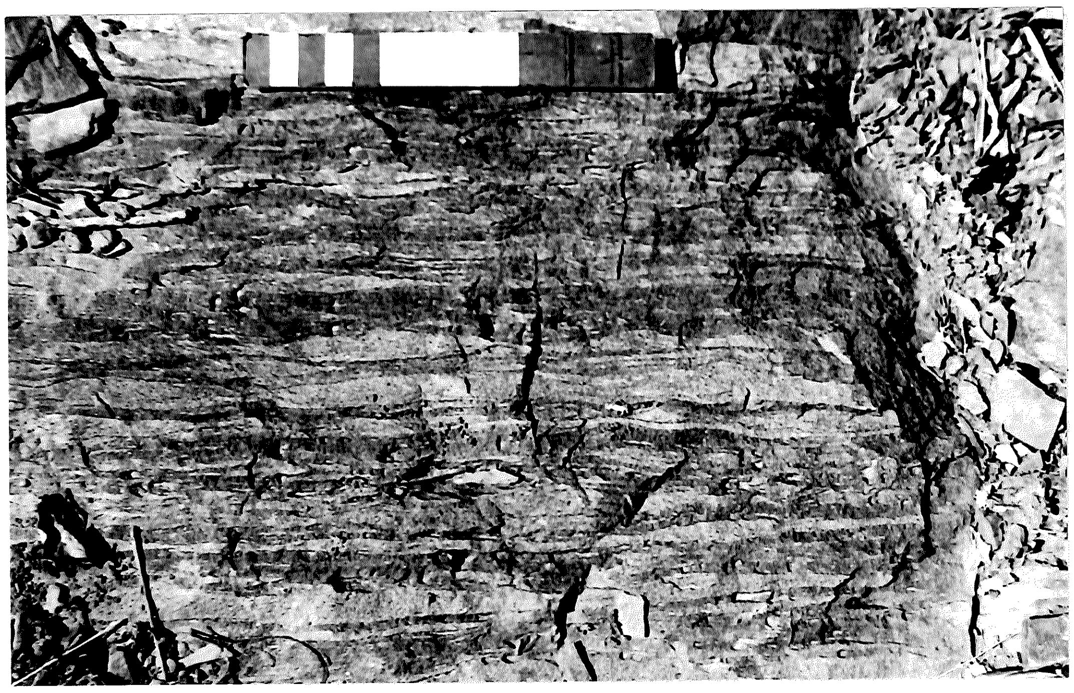

Plate 2(c): Mid-tidal-flat lenticular bedding. Unit MD2, Eureka Siding. (scale in 1 and 5 cm divisions).

cross-beds generated by beach-drifting in response to longshore currents (Meistrel, 1972; Kumar and Sanders, 1974). Spit beach-faces are subjected to upper flow-regime swash-processes and are structured by plane-bedded sandstones with low-angle discordances. Bays commonly occur behind the spit beachface and are conducive to current-ripple migration, modification of rippled surfaces during falling water-level, and periodic suspension-sedimentation. The sequences of lithologies and sedimentary structures developed in this barrier-spit complex (Figure 4) can be accounted for through seaward-progradation of these three sub-environments.

(e) Discussion

The morphology of Holocene coastlines is determined to a large extent by tidal ranges (Hayes, 1975). Mesotidal coasts are characterised by short and stubby barrier-islands and are dominated by tidal deltas. Barrier-islands along microtidal coasts, by contrast, are markedly elongated and, because of the dominant wave-effects, contain features such as spits and washover-fans. Tidal currents are only important at inlet mouths. The abundant spit-deposits inferred in the upper facies of this assemblage, coupled with the absence of ebb-tidal-delta accumulations, are suggestive of a microtidal coastline similar to that fronting Laguna Madre in Texas (Dickinson, et al., 1972). Furthermore, rip-currents only occur where high-wave conditions exist, while deposits formed by these currents are most-commonly preserved along microtidal coastlines free from the modifying effects of tidal processes (Vos and Hobday, 1977). Tidal currents appear to have been confined to tidal inlets during the development of this facies assemblage.

BACK-BARRIER DEPOSITIONAL ENVIRONMENT

Abundant evidence exists in unit MD2 in the Eureka and Stolzburg synclines for a depositional environment influenced by tidal processes. The ubiquitous bidirectional palaeocurrent patterns (Figure 6) are indicative of bedload transport, with bipolar reversals of flow-direction. Two other criteria, notably interbedded sandstones and shales, which point to alternating bedload- and suspension-sedimentation, and desiccated shale-drapes, reflecting periodic exposure, indicate the existence, among others, of a tidal-flat environment.

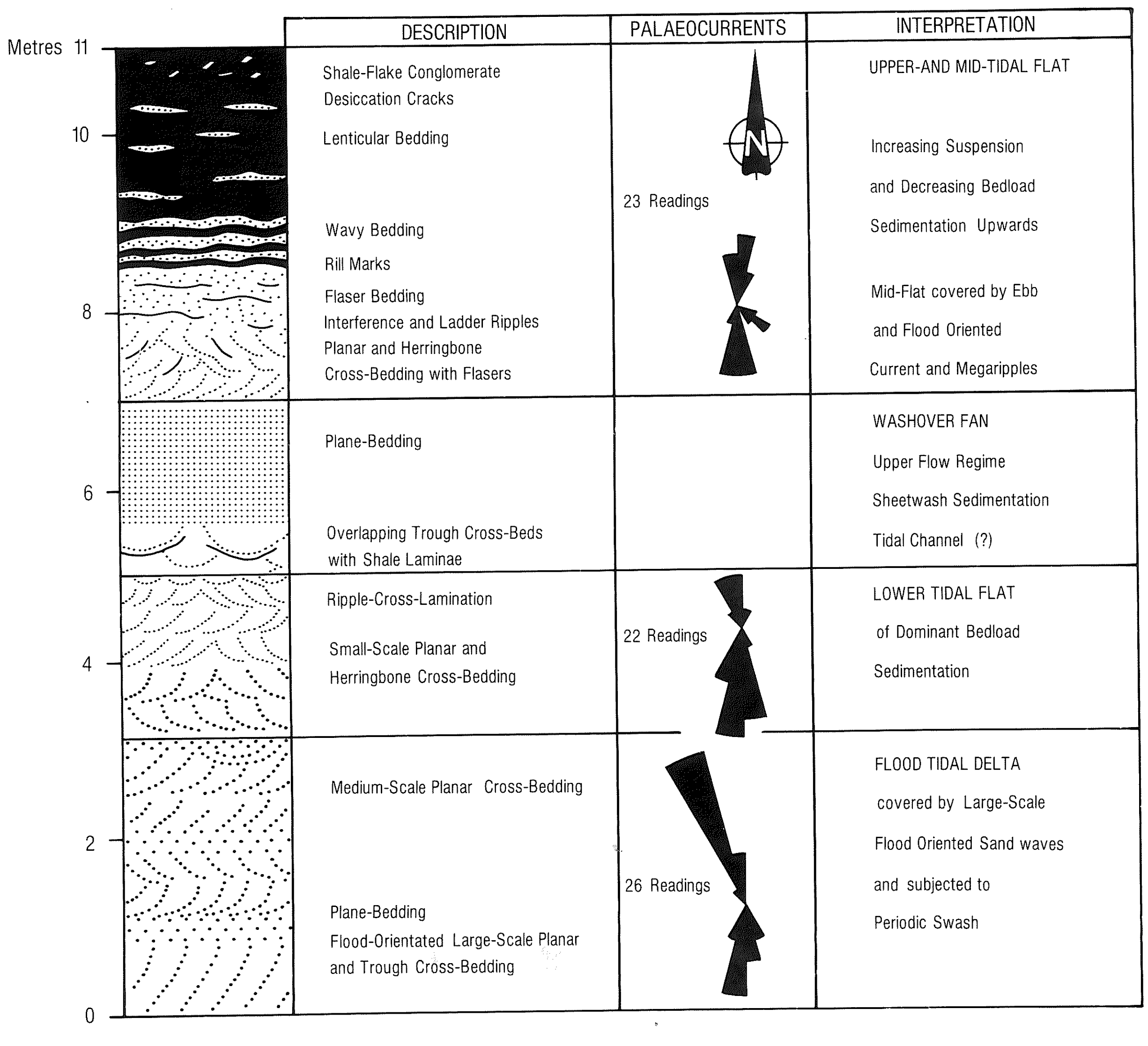

Figure 6 : Detailed, idealized, descriptive-interpretive stratigraphic column for back-barrier depositional environments. Unit MD2, Eureka and Stolzburg synclines.

(a) Tidal-Flat

On extensive tidal flats, such as along the north German and Netherlands coasts, fine-grained sediments accumulate near high-water line and coarser sandy sediments around low-water level (Reineck, 1967; van Straaten and Kuenen, 1957). On mid-tidal flats, interbedded sands and muds are developed. Representatives of each of these sub-environments can be recognised in the Moodies Group (Figure 6). Lenticular- (Plate 2c), wavy-, and flaser-bedded sandstones and shales accumulated on upper- and mid-tidal flats as a response to alternating bedload and suspension sedimentation processes. Interference- and ladder-ripples, as well as rill-marks, illustrate the diagnostic tidal process of ebb-phase runoff accompanying rapid lowering of water-level prior to exposure (Klein, 1971).

Small-scale, planar- and herringbone-cross-bedded sandstones probably accumulated on lower tidal flats (Figure 6), under current velocities precluding suspension-sedimentation. Lower-flow-regime conditions are, however, indicated by the amplitude of cross-bed sets, with flood-and-ebb currents apparently of equal importance in the migration of current-ripples (Figure 6). The thin, ripple-cross-laminated units which often rest on cross-bedded sandstones are analogous to the B-C sequences of Klein (1970), who related interval B to tidal bedload-transport and the rippled unit C to late-stage emergence-runoff.

(b) Tidal Delta and Washover-Fan

In contrast to current-ripples, sand-waves and megaripples are not common on tidal-flat surfaces, where current velocities are too low for their propagation. High-amplitude bedforms, which could have produced the large- and medium-scale planar and trough cross-beds intercalated within the tidal-flat sediments (Figure 6), have been observed on Holocene tidal deltas (Hayes et al., 1967; Boothroyd and Hubbard, 1975). Slip-faces of sand-waves on flood-tidal-delta ramps are oriented landwards during both flood- and ebb-tides (Boothroyd and Hubbard, op. cit.) and would have generated large-scale, flood-oriented, cross-beds analogous to those illustrated on Figure 6. Associated plane-bedding probably formed as a result of high-tide wave-swash on the flood-ramp. In those portions of flood-tidal deltas not shielded from ebb-flow, megaripples display a high bimodality (Boothroyd and Hubbard, op. cit.) which may be reflected in the lower bimodal-bipolar rose-diagram pattern of Figure 6.

The plane-bedded sandstones intercalated within tidal-flat sediments (Figure 6), and which reach 8 m in thickness, are interpreted as washover-fan deposits. These are related to storm-flooding over barrier-islands (Hayes, 1967), which results in upper-flow-regime sheetwash and the generation of plane-bedded sandstones, usually with a gentle, onshore dip (Andrews and van der Linger, 1969). The toes of wash-over fans are commonly structured by landward-dipping, planar cross-beds (Schwartz, 1975), but the strike-section of available outcrops precludes their exposure in this facies. The underlying, multiple-channeled sandstones with shale-drape laminae (Figure 6) are more difficult to assign to a specific environment, but probably originated in back-barrier, tidal channels, or represent the infilling of scour-channels developed during the early stages of washover (Pierce, 1970).

(c) Discussion

The thickness of upward-fining tidal sequences has been used to estimate palaeotidal ranges (Klein, 1972). Based on this reasoning, a macrotidal situation is indicated by the composite, 6 m-thick, tidal-flat, depositional cycle (Figure 6). Barrier-beach sequences which immediately overlie the stacked, back-barrier deposits of unit MD2 in the Eureka and Stolzburg synclines (Figure 2) do not, however, develop under macrotidal conditions (Hayes, 1975) and have already been used to imply a microtidal setting. The presence of washover-fan deposits and the lack of back-barrier, tidal-channel and associated point-bar accumulations in this facies assemblage further support a microtidal environment (Hayes, op. cit.). In addition, the limited occurrence of large-scale cross-beds and associated sedimentary structures is compatible with small, flood-tidal deltas which also characterise microtidal coasts. The exaggerated tidal-cycle thickness illustrated in Figure 6 can thus be interpreted as resulting from stacking of facies.

SPATIAL RELATIONSHIPS OF THE DEPOSITIONAL ENVIRONMENTS

(a) The Palaeographic Model

Any palaeographic model which relates depositional environments in space must be constructed relative to a time-plane. Such a datum exists in the Eureka, Saddleback, and Stolzburg synclines as the laterally-persistent lava at the base of unit MD4 (Figure 2). Off-shore, banded iron-formations and shales in the Eureka and Stolzburg synclines, and siltstones and shales in the Saddleback Syncline, which were deposited on a distal, alluvial plane (Eriksson, in press), rest on this time-plane (see Figure 2) and provide three reference-points for the construction of a paleographic map. The preparation of such a map relies heavily on the interpretation of vertically-stacked, sedimentary facies in terms of their lateral distribution at any instant in time. Thus, more-proximal, barrier-island-shallow-shelf, as well as deltaic, sediments must have existed on the time-plane (palaeoslope) as facies-equivalents of the distal-alluvial-plain siltstones and shales in the Saddleback Syncline and of offshore, banded iron-formations and shales in the Eureka and Stolzburg synclines. The inferred spatial relationships of the different depositional environments in the Moodies Group, including a diverse proximal-through-distal, fluvial assemblage, are illustrated in Figure 7.

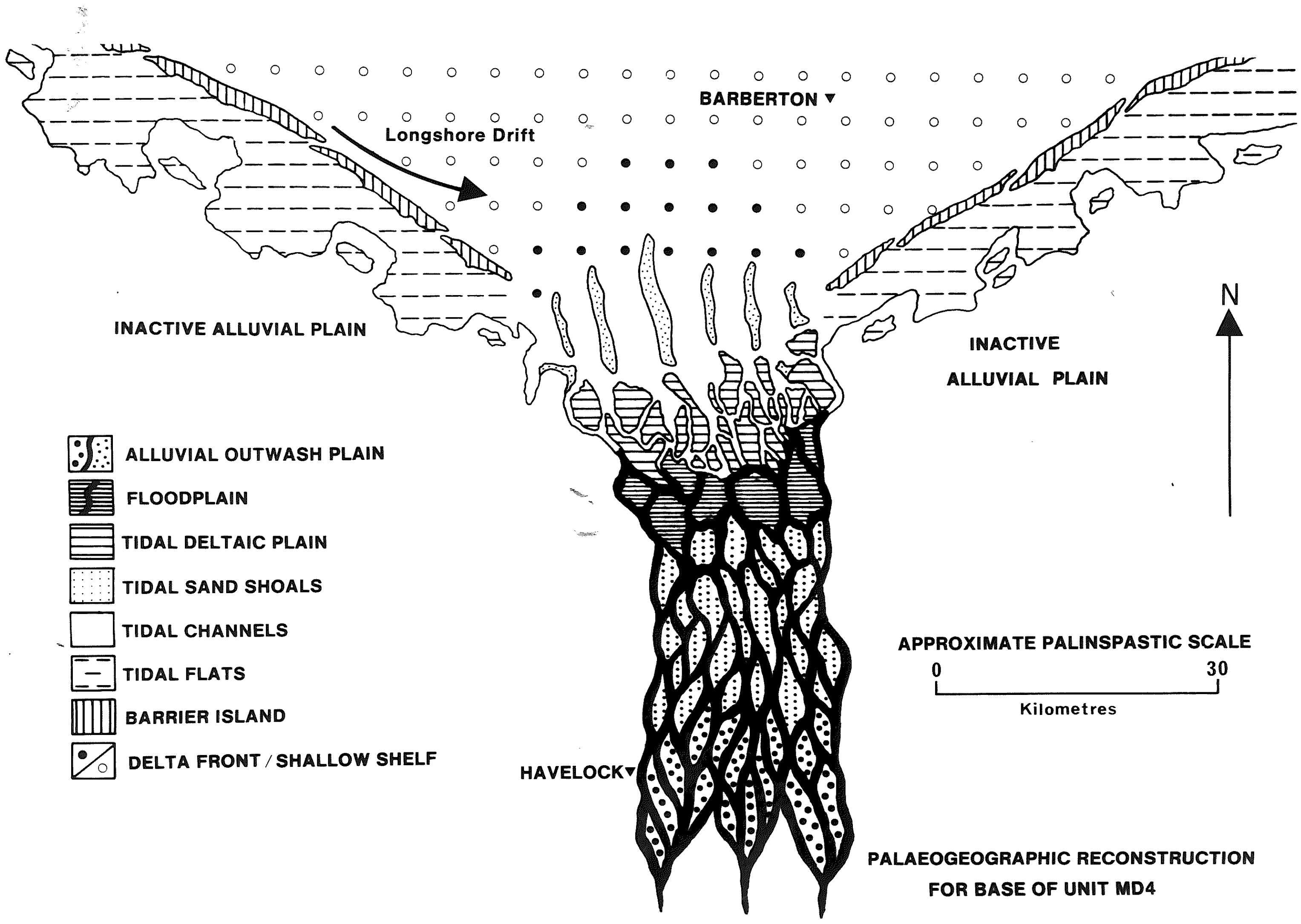

Figure 7 : Inferred palaeogeographic map for base of unit MD4, Moodies Group, Barberton Mountain Land. Note that a volcanic horizon in the Eureka, Saddleback, and Stolzburg synclines was used as a time-datum. Palinspastic procedures are reviewed by Eriksson (1977).

The model recognizes the interaction of the three, major, marginal-marine, depositional environments previously proposed and consists of constructive-deltaic and distributive-barrier-beach and back-barrier elements. A deltaic plain was influenced by high, tidal energies which resulted in the development of tidal-channel and more-distal, sand-shoal deposits under macrotidal conditions. Further seawards, rapid-gravity-flow sedimentation occurred in the delta-front depositional environment. Easterly-directed longshore currents redistributed sediments from deltaic to adjacent interdeltaic settings. Elongate barrier-islands developed under the prevailing microtidal conditions, with the shoreline profile a response to interacting, onshore, shoaling waves, longshore currents, offshore rip-currents, and swash-backwash processes. Easterly-directed longshore currents resulted in the development of laterally-persistent, stacked, upward-fining, tidal-inlet cycles. Ebb-and-flood currents within tidal inlets had a modifying effect on the shoreface. Low-energy, bedload- and suspension- (with associated chemical) sedimentation characterised the nearshore and offshore shelves, respectively. Back-barrier depositional environments were influenced largely by tidal processes, which reworked, by weak, fluvial processes, sediment introduced both from seaward, through tidal inlets, and from landward. Bedload-sedimentation predominated on flood-tidal deltas and bedload- and suspension-sedimentation prevailed on tidal flats. Rare washover-fan deposits were developed during storms.

The suggestion by Kumar and Sanders (1976) that ancient shore-face sediments are storm phenomena is supported by this investigation. Rip-currents, probably generated during storm periods, were the dominant depositional agent in the shoreface. Washover-fan sequences in the Moodies Group provide further evidence of storms (Hayes, 1967), while the formation of tidal inlets has also been related to barrier overwash (Pierce, 1970).

(b) Factors Influencing Tidal Range

The palaeogeographic model (Figure 7) suggests the contemporaneous existence of macro- and microtidal conditions along the coastline during the deposition of the Moodies Group. Variations in tidal range along Holocene coastlines (Davies, 1964) can be shown to result from one, or a combination, of the following factors :

(i) Continental-shelf width has a significant effect on tidal range; coastlines fronted by narrow shelves have low tidal ranges and those fronted by wide shelves characteristically have amplified tidal ranges. This relationship has been especially well-illustrated along the east coast of the U.S.A. (Redfield, 1958) and also exists off the northwest coast of Australia and the southeast coast of South America.

(ii) Embayments in the coastline may also modify the tidal range. An import parameter determining the effect of embayments is the ratio $R = L/\lambda$, where L is the distance between the reflecting barrier within the embayment and the mouth of the embayment, and λ is the wavelength of the Kelvin or tidal wave rotating about an amphidromic point. When this ratio is small, tidal ranges within the embayments tend to be the same as those outside. However, if L is larger, and of the order of one-fourth of the tidal wavelength, the embayment resonates with the outside tides, and tidal ranges are up to four times higher, and currents are considerably stronger (Mofjeld, 1976). Holocene embayments such as the Elbe estuary off the coast of Germany, the Gulf of California, the Bay of Belgal, the Gulf of Siam, and certain bays in Australia are characterised by exaggerated tidal ranges, without any apparent shelf-width influence. The Bay of Fundy, with tidal ranges up to five times those in the adjacent Atlantic Ocean, illustrates this resonant effect particularly well. Coasts off British Columbia and northeast Brazil also have amplified tidal ranges, apparently due to the mildly-arcuate, concave-seaward nature of the coastlines, as the continental shelves at these localities are exceptionally narrow.

(iii) Where large quantities of water are introduced into open-ended constrictions, amplified tidal ranges also result. This effect is illustrated in the North Sea, where the east coast of Britain is influenced by macrotidal ranges. Off the coast of east Africa, the presence of Madagascar has the effect of generating macrotidal conditions in the Mocambique Channel, while much of the African coast is mesotidal in character.

An embayment model, based on the contemporary German-Danish coastline, and possibly enhanced by a locally wider shelf, will account for the coexisting macro- and microtidal conditions inferred in the Moodies palaeographic reconstruction (Figure 7). The macrotidal Elbe estuary contains proximal tidal flats incised by tidal channels and distal sand-shoals oriented in an onshore-offshore direction (Reineck and Singh, 1973, p. 318). Barrier-islands and back-barrier tidal flats become progressively more prolific to the west and north of the Elbe embayment, as tidal ranges decrease and wave-processes become increasingly important (Hayes, 1975). The amplification effect of an embayed coastline is also illustrated on the Norfolk and Lincoln coast of England, which serves as a second comparative Holocene model. Except at neap-tide, the Wash experiences tidal ranges greater than 5 m (Evans, 1975), while mesotidal conditions exist off northeast Norfolk and result in the development of barrier-islands, washover-fans, and spits (M.R. Leeder, personal communication, 1977).

PALAEO-ENVIRONMENTAL RELATIONSHIPS BETWEEN THE MOODIES AND FIG TREE GROUPS

There can be no doubt that the Fig Tree sediments, as preserved in the Barberton Mountain Land to-day (Figure 1), are older than the Moodies. What is less clear, however, is whether these two sequences belong to a single depositional cycle, or to pre- and post-orogenic flysch- and molasse-type cycles, respectively, as first suggested by Anhaeusser et al. (1968).

Greywackes are the predominant lithology in the Fig Tree Group and constitute greater than 80 per cent of the lower half of this unit. Shale, chert, and banded iron-formation become more abundant upwards, along with a sympathetic decrease in grain-size of the greywackes. Local, small-pebble, and resedimented greywacke conglomerates occur throughout the group and lens out along strike. In vertical sequence, the sediments of the Fig Tree Group are ubiquitously graded, in units from a few inches to several feet in thickness (van Vuuren, 1964). Complete Bouma (1962) cycles are rarely observed; instead, a coarse, graded, basal unit is overlain by plane-bedded, fine-grained sandstones and siltstones, followed by an argillaceous layer. The most complete cycles are capped by cherts or banded iron-formations (Reimer, 1975). Frequently, however, the grading is only apparent through the presence of thin argillaceous layers on top of the greywacke units (van Vuuren, op. cit.). Sole-markings, flute-casts, load-casts, and flame-structures are frequently developed at the base of graded units, where in contact with shale (Anhaeusser, 1976). Small-scale slump-structures are often present within the greywackes. In the absence of cross-bedding, palaeocurrent determinations have been based on the orientation of long axes of flute-casts and sole-markings. These have revealed that dispersal currents operated in a general northwesterly-to-northeasterly direction (Reimer, op. cit.).

Sediments of the Fig Tree Group are analogous to re-sedimented deep-water deposits described from a number of Archaean greenstone terranes (see introduction). The greywackes and conglomerates were formed by turbidity-current re-sedimentation from shallow- into deep-water, and the shales, cherts, and banded iron-formations developed as a result of background, deep-water suspension-sedimentation and chemical-depositional processes. Turbidite sediments owe their origin to subaqueous, deep-water, gravity-flow processes, and turbidity currents most commonly developed in submarine canyons (Klein, 1975). Sufficiently-detailed studies to distinguish between regional slope, turbidity feeder-channel, and proximal and distal, submarine fan-facies have not yet been undertaken on the Fig Tree Group, but it is reasonably safe to conclude that this sequence accumulated in neritic and/or bathyal environments. The lower Fig Tree greywackes, shales, and cherts may represent the most distal sediments, passing upwards into regional slope, predominantly argillaceous and chemical deposits, with the greywacke grits at the top of the succession providing evidence of shallow-water reworking immediately prior to the deposition of the Moodies Group (van Vuuren, 1964). A similar turbidite-to-shallow-water transition is described from the Namurian Mann Tor Sandstone and Shale Grit turbidite of northern England (Walker, 1969).

Contrary to the often indirect evidence proposed by Visser (1956) for an unconformity between the Moodies and Fig Tree groups, this contact is mostly transitional. This is best seen along the northern and southern limbs of the Eureka Syncline, while detailed mapping in the Saddleback and Makonjwa areas (Bell, 1967, Figure 1) has revealed a similar relationship. Available field evidence thus suggests that the Moodies and Fig Tree groups were formed during a single, major, depositional cycle, and it is suggested that the latter simply represents a deep-water facies of the continental and shallow-marine Moodies Group. Active progradation towards the north was responsible for the observed stratigraphic relationships between the two groups. Additional support for this proposal comes from a common source-area to the south for these two sedimentary sequences (Reimer, 1975). Furthermore, the Fig Tree greywackes are lithologically very similar to the little-reworked fluvial sediments in the Moodies Group.

DISCUSSION

The preceding palaeo-environmental analysis of Archaean sediments in the Barberton Mountain Land can be used to suggest that the Moodies and Fig Tree sediments accumulated along an ancient continental margin, deepening to the north. Implicit in this proposal is a relatively narrow, continental shelf along which physical depositional processes, analogous to those along Holocene coastlines, operated.

Voluminous sediment-supply to Holocene coastlines results in the outward construction of a progradational embankment composed of Moodies-type continental and marginal marine sequences (Dickinson, 1974). An example of such a situation is the Niger Delta of West Africa, the outer embankment-edge of which contains depositional phases of the types developed in the Fig Tree Group. These comprise a basal phase of sandy turbidites near the toe of the embankment, a middle phase of largely-argillaceous sediments deposited on the advancing frontal slope of the embankment, and an upper phase of largely-arenaceous, shallow-marine strata deposited along the outer edge of the top of the embankment (Burke, 1972). Continued progradation of a Niger-type coastline would generate a vertical stratigraphic relationship analogous to that represented by the Fig Tree and overlying Moodies groups in the Barberton Mountain Land.

The few detailed sedimentological analyses of Archaean sequences elsewhere in the world, which are lithologically similar to the Moodies and Fig Tree groups of the Barberton Mountain Land, have suggested that turbidite and alluvial deposits predominate (see introduction for specific references). With the exception of Donaldson's and Platt's (1975) study in the Yilgarn Block of Western Australia, no marginal-marine sediments of the Moodies-type have been recognised. This may be largely a function of inadequate palaeo-environmental analyses, although Turner and Walker (1973) have provided convincing evidence that turbidite and alluvial-fan sediments alone occur in the Sioux Lookout greenstone belt in Canada. Available information on other sequences thus suggests that a second style of sedimentation existed during the Archaean, which involved high-energy alluvial and turbidite sediments being fed into localized, elongate, trough-like depositories from proximal source-areas.

These two contrasting styles of sedimentation may provide new evidence pertaining to the nature of the Archaean crust, especially if a single tectonic model can be developed to account for both styles. A well-established model for greenstone evolution involves rifting of an older sialic crust and the accumulation of volcanics and sediments in grabens (see for example Hunter, 1974; Archibald et al., in press). While this model may well account for the lower volcanic sequences in greenstone belts and for the rift-valley-type sedimentation that occurred in the Canadian Archaean, the sedimentary facies patterns recognized for the Moodies and Fig Tree groups cannot be reconciled with an elongate, fault-bounded depository. Continued rifting, followed by spreading and separation of adjacent sialic blocks would, however, produce a large ocean basin (Hoffman et al., 1974), with a stable continental margin (McCrossan and Porter, 1973), similar to that envisaged as the depositional setting for the Archaean Moodies and Fig Tree sediments in the Barberton Mountain Land.

CONCLUSIONS

(i) This palaeo-environmental analysis has revealed that physical-depositional processes during the Archaean were remarkably similar to those operating today.

(ii) The recognizable similarities between Archaean and Holocene depositional processes have led to the conclusion that the Moodies and Fig Tree groups accumulated along an ancient continental margin.

(iii) The widespread evidence of microtidal sedimentation during the deposition of the Moodies Group suggests the existence of a narrow continental shelf. Embayments along the coastline and/or widening of the continental shelf generated localized macrotidal conditions, under which sand-shoals developed perpendicular to the shoreline, at the expense of beaches.

(iv) The abundant development of tidal sediments in the Moodies Group indicates that the Earth-Moon system was in existence at least 3 000 m.y. ago.

(v) This study has revealed the existence of widespread marginal-marine deposits and contrasts with most other palaeo-environmental investigations on sediments of this age, which have suggested that alluvial and turbidite sedimentation may have characterised the Archaean.

(vi) The suggestion is made that Archaean sedimentation may have been induced by rifted-continental-margin tectonics. If this is the case, the two contrasting sedimentary styles may reflect :

(a) an early response to rifting, as typified by the Archaean sediments of Canada; and,

(b) a response to more-stable continental-margin conditions after rifting and opening of the sea, as represented by the Moodies and Fig Tree groups.

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