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Palaeoproterozoic epeiric sea palaeoenvironments: the Silverton Formation (Pretoria Group, Transvaal Supergroup), South Africa

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ABSTRACT

A predominant argillaceous lithofacies association in the Early Proterozoic Silverton Formation (Pretoria Group, Transvaal Supergroup, South Africa) comprises massive mudstones, laminated claystones, laminated siltstones, graded mudstones and graded siltstones. These fine-grained rocks are interpreted as having been laid down as substorm wave-base pelagic deposits within an epeiric embayment. Fine fluvial detritus was able to by-pass a high-energy sand belt and coastline setting (represented by the Magaliesberg Formation, above the Silverton rocks) owing to fluvial flood stages and a high concentration of suspended sediment. High-amplitude storm waves resulted in subordinate graded coarse siltstone and fine sandstone beds being laid down within the transitional zone and offshore mud belt of the shallow epeiric palaeoenvironment. The model proposed for the Silverton Formation is comparable to the classic Shaw–Irwin epeiric sea model, with the exception that a strongly tidal coastline was present. With the initial onset of the Silverton transgression, fluvial sandstones of the underlying Daspoort Formation were reworked in the east of the basin. Approximately coeval lower Silverton braid-deltaic sandstones in the west of the basin were rapidly drowned, to be followed initially by turbidity current sediments, and subsequently by the predominant mudrocks, deposited as transgressive and subsequent highstand systems tracts. Regressive, tidally reworked braid-delta sandstones of the Magaliesberg Formation accompanied retreat of the Silverton epeiric embayment off the Kaapvaal craton, as freeboard of the latter became thermally enhanced.

INTRODUCTION

Epeiric seas were probably common depositional palaeoenvironments during the Palaeoproterozoic (Eriksson *et al.*, 1998). This inference is based on two likely characteristics of early Palaeoproterozoic natural systems: periodically elevated sea-levels globally and aggressive weathering regimes. High rates of mass wasting almost certainly characterized the early Precambrian, owing to elevated temperatures and concomitant humid palaeoclimates, high atmospheric CO_2 content and a lack of vegetation (Corcoran *et al.*, 1998). Topography would thus have been reduced and even peneplained owing to aggresive weathering and rapid erosion; this would have enabled widespread inundation of cratonic regions when marine transgressions occurred, forming large epeiric seas.

Continental freeboard, the maximum elevation of a continent above mean sea-level (Wise, 1972), eustacy and continental crustal growth rates can be considered as interdependent variables (Eriksson, 1999). Increased mid-ocean ridge activity associated with enhanced continental crustal growth would have reduced ocean volumes and raised sea-level globally (Arndt, 1999). Although there is still much debate as to whether accelerated crustal growth occurred prior to *c*.3.6 Ga (Armstrong, 1981; Arndt, 1999), or close to the Archaean–Proterozoic boundary (Eriksson, 1995), a strong school of thought supports the latter (Windley, 1995). Eriksson *et al.* (1999) discuss evidence in support of globally elevated sea-levels affecting African, Indian and Australian (present-day frame of reference)

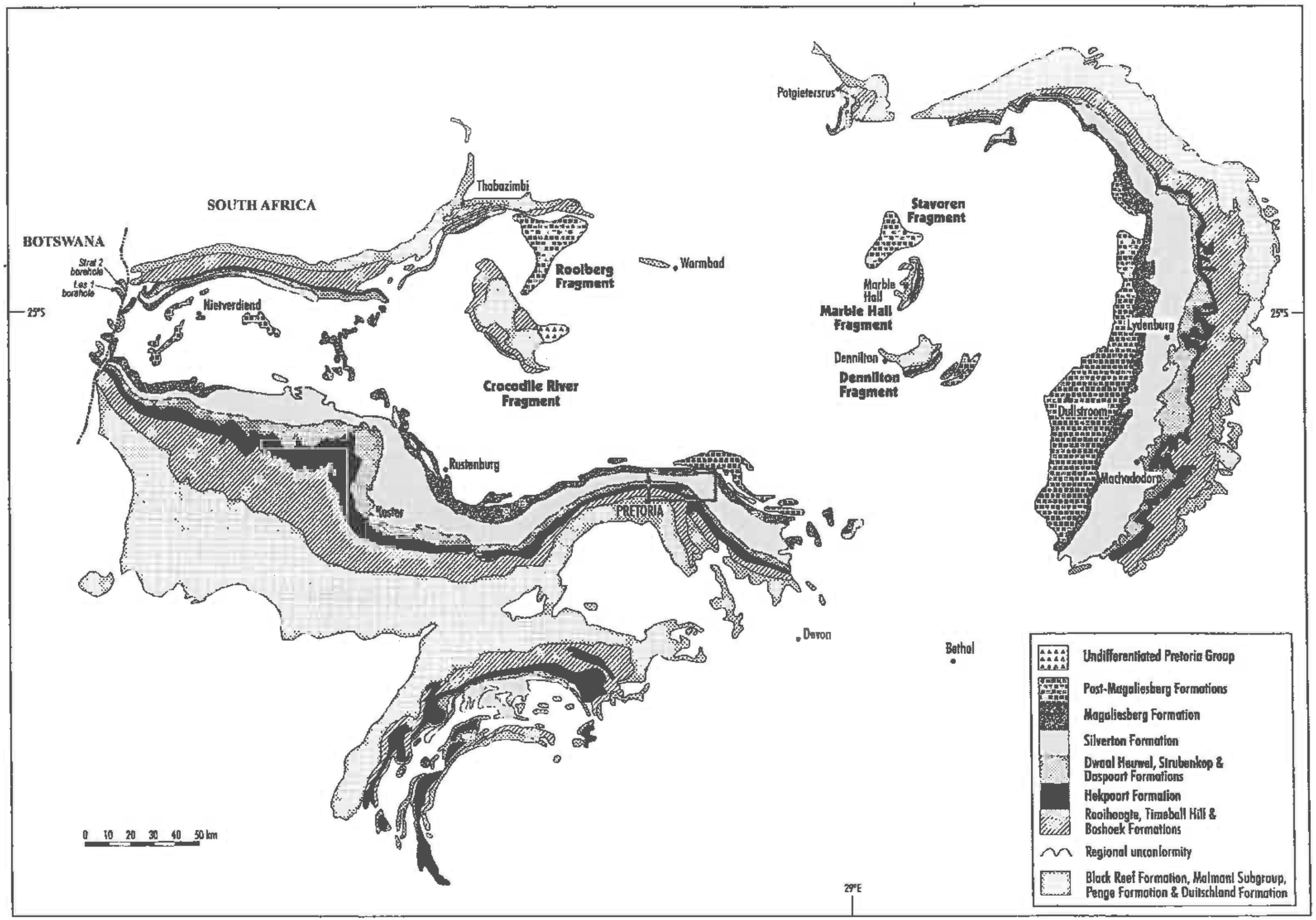

Fig. 1. Geological map of the Pretoria Group, Transvaal Supergroup. Note the Timeball Hill and Silverton formations, both inferred to have been deposited in epeiric marine palaeoenvironments. Note also Daspoort and Magaliesberg formations, which bound the Silverton Formation stratigraphically. Boreholes Les1 and Strat2 in eastern Botswana are summarized in Fig. 7.

cratons in the Late Archaean, during which major epeiric carbonate banded iron-formation (BIF) platforms formed. The same authors postulate a second global transgression at *c.*<2.2 to >2.15 Ga, owing to post-glacial climatic amelioration following the first global refrigeration event at *c.*2.4–2.2 Ga (Hambrey & Harland, 1985; Eyles & Young, 1994).

Within South Africa, the Late Archaean to early Palaeoproterozoic is best represented by deposits of the *c.*2.7–2.1 Ga Transvaal Supergroup (for a review, see Eriksson & Reczko, 1995). Within the upper subdivision of this succession, the Pretoria Group, there are two inferred transgressive epeiric marine deposits, the Timeball Hill and Silverton formations (Catuneanu & Eriksson, 1999) (Fig. 1). The postulated Timeball Hill epeiric sea has been modelled by Eriksson & Reczko (1998), who related a combination of pelagic, low-density turbidite, contourite and tidally reworked braid-delta facies to a relatively deep water basin, which resembled a scale model of a large modern ocean basin. This paper describes the geology of the inferred Silverton Formation epeiric sea and an attempt is made to define some of the more important characteristics of Palaeoproterozoic epeiric sea palaeoenvironments.

EPEIRIC SEAS: GENERAL CONCEPTS

Epeiric seaways inundate large proportions of cratonic terranes, and closely resemble open ocean shelves (Brenner, 1980), with analogous sedimentation processes and products (Brenner & Davies, 1974; Spearing, 1976; Brenner, 1978, 1979; Klein & Ryder, 1978; Bouma *et al.*, 1982). Smaller equivalents, epeiric embayments, lack true shelf-breaks and ocean-type currents (Eriksson *et al.*, 1998). A lack of adequate modern examples (Friedman *et al.*, 1992) makes interpretation of Precambrian epeiric sea deposits problematic. Another problem with modern comparisons is one of scale, especially when contrasted with examples such as the Late Cretaceous seaway in North America, which at one time extended from the Gulf of Mexico to the Arctic Ocean (Swift & Rice, 1984). Estimating scale for Precambrian epeiric transgressions is difficult owing to incomplete preservation of basins. For the Archaean Witwatersrand epeiric basin, preserved outcrops give a minimum estimate of 600 by 400 km (Eriksson *et al.*, 1998), whereas that for the Palaeoproterozoic Timeball Hill Formation is 500 by 300 km (Eriksson & Reczko, 1998).

The Shaw (1964) and Irwin (1965) conceptual epeiric sea model, still widely accepted, is based on the Palaeozoic successions of North America, and encompasses three belts, X, Y and Z, which are summarized in Fig. 2. Certain qualifications need to be applied to this relatively simple conceptual model (Schopf, 1980), including water depths, which were probably shallower and equivalent to modern continental shelves (e.g. Eriksson & Reczko, 1998), rather than the maximum 200 m proposed in the model. Phanerozoic seaway successions include both widespread carbonates, indicating water depths up to about 30 m, and

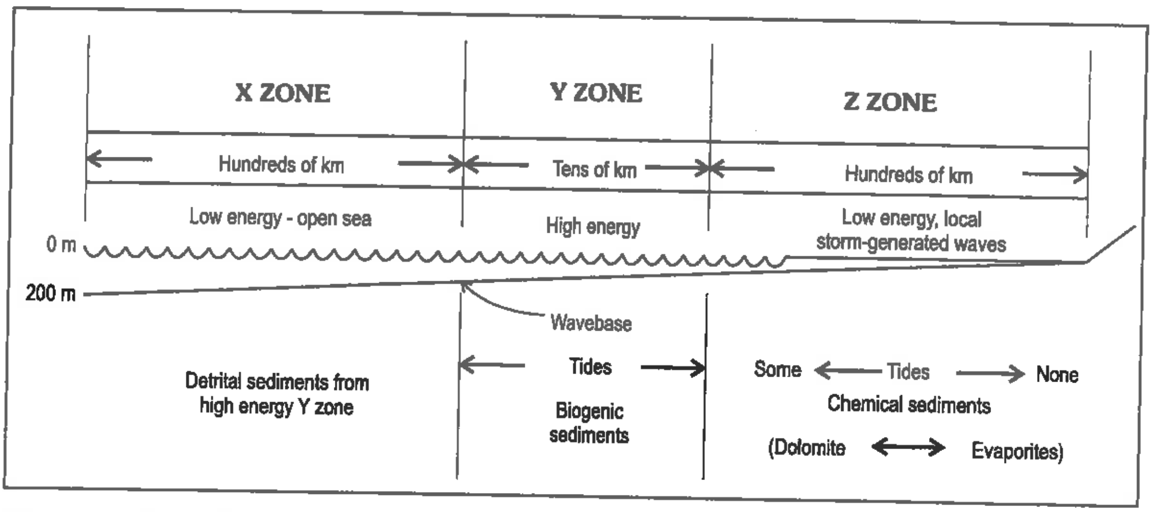

Fig. 2. Classic Shaw (1964) and Irwin (1965) epeiric sea model. Note wide and low-energy X (most seaward) and Z (most landward) zones, with narrow and high-energy Y zone in between.

phosphate nodules in black shales, suggesting the possibility of depths greater than 100 m (Friedman *et al.*, 1992, p. 391). As modern fairweather wave base is *c.*10 m and storm wave base seldom exceeds 200 m (Swift & Thorne, 1991; Johnson & Baldwin, 1996), most epeiric seas were probably subject to a measure of wave action. Thus, although long-period swells would have been dissipated at epeiric sea margins (distal X zone in Fig. 2) (Friedman *et al.*, 1992), storm waves may have been a significant influence on epeiric sea sedimentation further landwards. Tidal action was probably also more significant, as evidenced by extensive preserved peritidal flat deposits in Phanerozoic epeiric successions (e.g. Swett *et al.*, 1971; Pratt & James, 1986). Tidal height may even have increased as open ocean tides approached the shallow platform of an epeiric sea (Pratt & James, 1986).

GENERAL GEOLOGY OF THE TRANSVAAL SUPERGROUP

The 2.7–2.1 Ga Transvaal Supergroup includes lowermost 'protobasinal' units, preserved in discrete, rift-related basins, and consisting of subaerial to basinal continental sedimentary facies and acid to basic volcanic rocks (Eriksson & Reczko, 1995). These were related to the widespread rifting and *c.*2.7 Ga volcanism of the Ventersdorp Supergroup on the Kaapvaal craton (Eriksson & Reczko, 1995). Subsequent thermal subsidence formed an intracratonic sag basin, in which the thin sheet sandstones of the Black Reef Formation were laid down, by braided fluvial channels and succeeding shallow marine and braid-delta systems (Catuneanu & Eriksson, 1999). Continued slow thermal subsidence led to the accumulation of almost 2 km of carbonate rocks and up to 700 m of succeeding BIF of the Chuniespoort Group (Eriksson & Altermann, 1998), under general highstand conditions (Catuneanu & Eriksson, 1999). This carbonate-BIF epeiric sea is estimated to have covered 600 000 km^2 (Beukes, 1987) and to have been 40–80 m deep (Eriksson & Altermann, 1998), and was probably a seaway rather than an embayment.

A sequence stratigraphic interpretation of the Pretoria Group (Fig. 3) suggests that thermal (?) uplift and erosion of the Chuniespoort chemical sedimentary rocks was followed by two cycles of syn-rift and post-rift sedimentation, separated by crustal doming. The lower Pretoria Group cycle comprises alluvial and lacustrine syn-rift deposits of the Rooihoogte Formation and post-rift clastic epeiric sea sediments of the Timeball Hill Formation (Fig. 3). The Timeball Hill Formation is described in detail by Eriksson & Reczko (1998), who propose that thermohaline contour currents reworked pelagic and turbidite deposits within this epeiric basin; thin stromatolitic carbonate beds interlayered with these facies suggest photic water depths up to about 100 m (Eriksson & Reczko, 1998). A relatively deep-water epeiric sea model is thus proposed for the Timeball Hill Formation (Fig. 4). Eriksson *et al.* (1999) note that the Timeball Hill epeiric transgression occurred within the period of the first global glaciation, at *c.*2.4–2.2 Ga, and that it thus probably reflects local tectonic subsidence rather than a major cratonic inundation event; an embayment model thus seems pertinent.

The upper Pretoria Group cycle followed crustal doming, probably thermal in origin, subsequent to which syn-rift alluvial to lacustrine deposits (Boshoek, Dwaalheuwel and Strubenkop formations) and the subaerial Hekpoort lavas were laid down (Fig. 3). Daspoort sedimentation began with alluvial gravel and fluvial sand lobes of syn-rift affinity, which became drowned in the east of the basin by a transgressive marine palaeoenvironment (Eriksson *et al.*, 1993). The thick Silverton shales which followed reflect the transgressive systems tract of an epeiric sea, which forms the subject of this paper; the regressive shoreline sands of the Magaliesberg Formation were laid down during the highstand systems tract which characterized upper Silverton deposition (Fig. 3). Post-Magaliesberg units formed under remnant marine coastline and continental sedimentation systems as base-level fall occurred owing to thermal uplift related to the *c.*2050 Ma Bushveld Complex intrusion (Catuneanu & Eriksson, 1999).

GEOLOGY OF THE SILVERTON FORMATION

Lithology, thickness and stratigraphy

This formation is characterized by various mudstones, with locally significant volcanic rocks, and minor carbonates, cherts and sandstones. Both contacts of the formation are sharp, but gradational in the sense that sandstone lenses are present in the predominantly argillaceous Silverton lithologies close to the contacts (Button, 1973; Schreiber, 1990; van der Neut, 1990). Total thickness of the Silverton Formation varies from *c.*2000 m in the east of the preserved basin to several hundred metres in the west; erosional removal

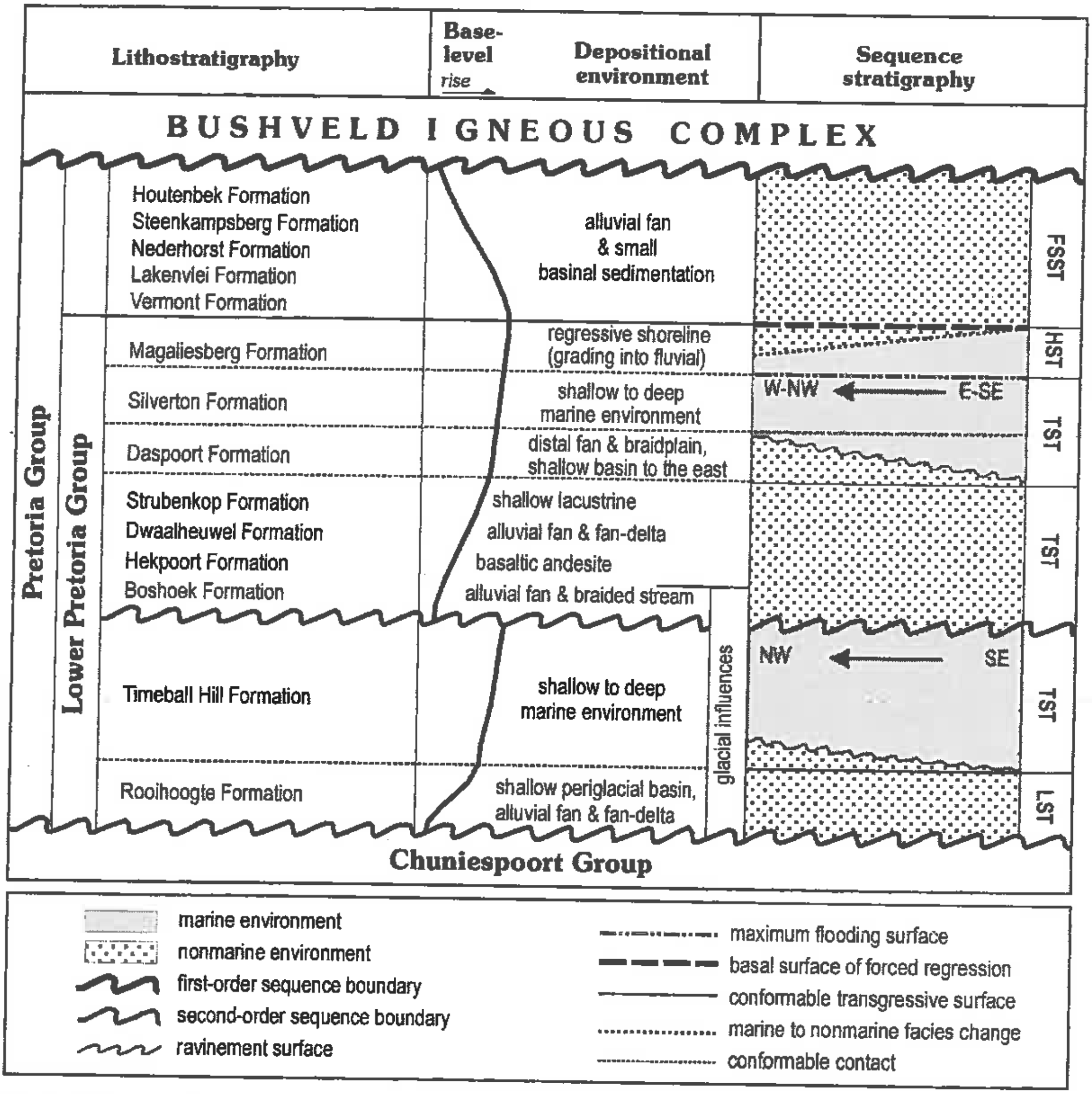

Fig. 3. Sequence stratigraphic interpretation for the Pretoria Group. Note two cycles of synrift and post-rift sedimentation (Rooihoogte–Timeball Hill and Boshoek–Houtenbek cycles) separated by a second-order sequence boundary reflecting crustal doming. Note also the two major marine transgressions, during Timeball Hill and Silverton epeiric sedimentation. Modified after Catuneanu & Eriksson (1999).

characterizes much of the southern and central preserved occurrences (Fig. 5).

Button (1973) discriminated between lower Boven Shale, medial Machadodorp Volcanic and upper Lydenburg Shale members in the eastern part of the basin. Their differentiation becomes problematic further westwards, due to poor outcrop quality and lack of boreholes (Fig. 5), but geochemical characteristics (Reczko, 1994) enable separation of the two shale members in this region (Fig. 6). Locally, in the far west, thin dolosiltites eroded from Chuniespoort lithologies cap the Silverton mudstones (Eriksson &

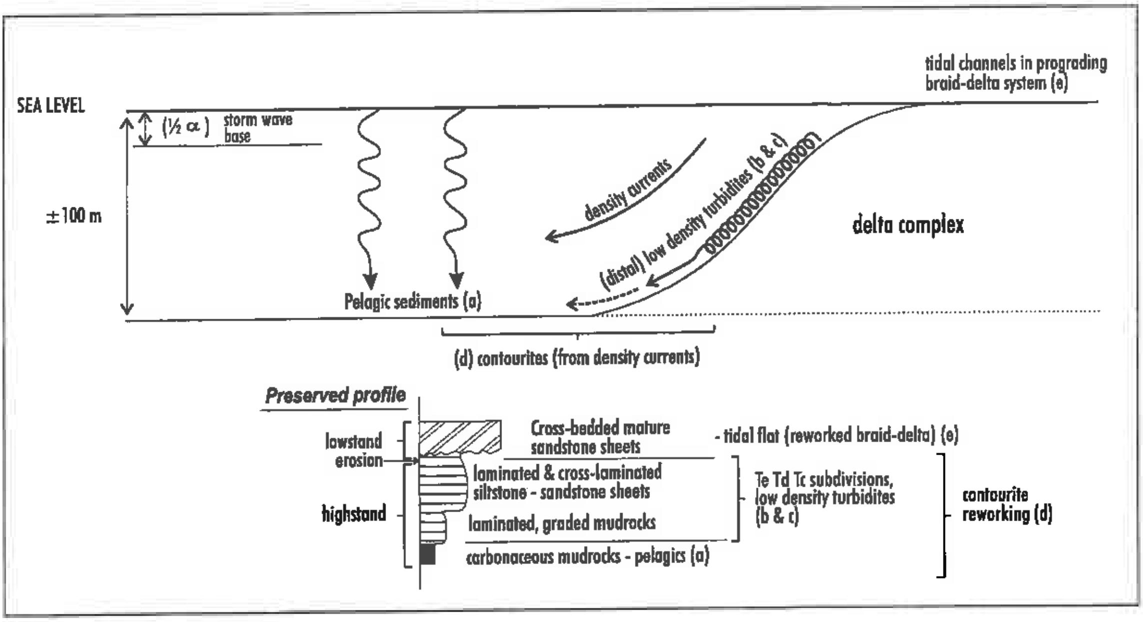

Fig. 4. Relatively deep water epeiric model postulated for the Timeball Hill Formation (modified after Eriksson & Reczko, 1998).

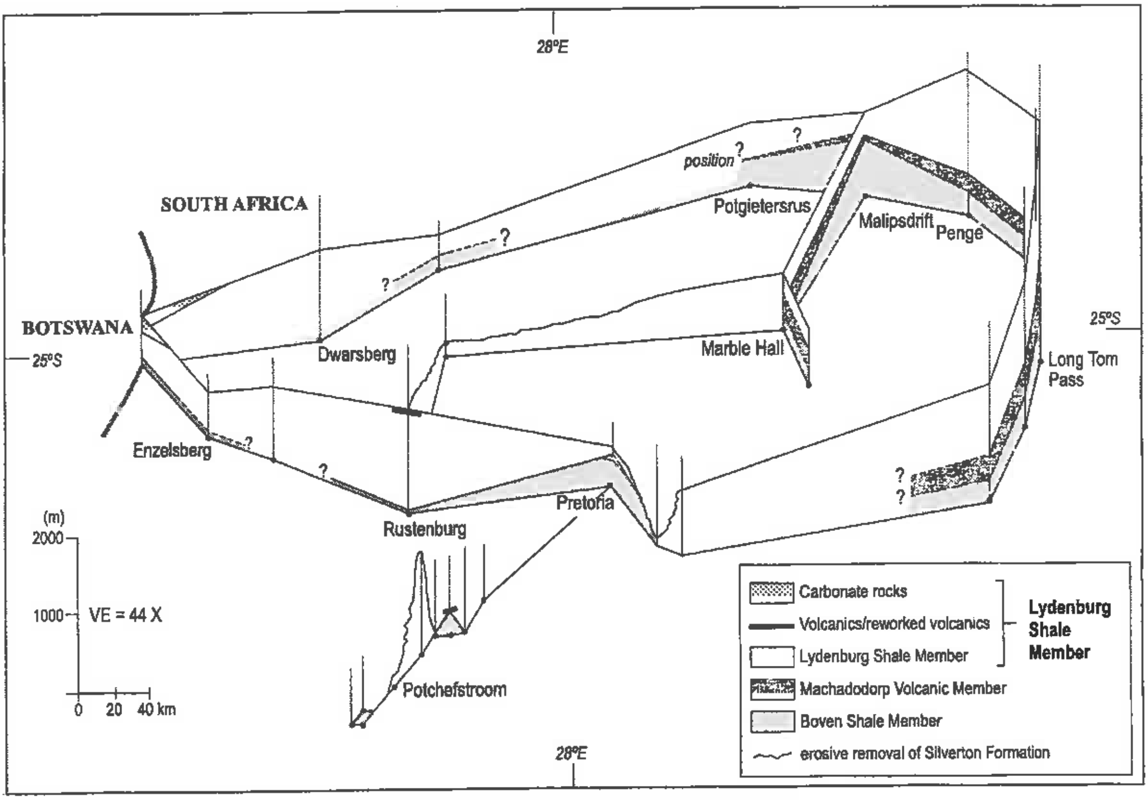

Fig. 5. Fence diagram illustrating preserved thicknesses of the Silverton Formation across the Pretoria Group basin. Note also threefold subdivision into Boven Shale, Machadodorp Volcanic and Lydenburg Shale members, and how this stratigraphy becomes impossible to apply to the western and southern parts of the preserved basin.

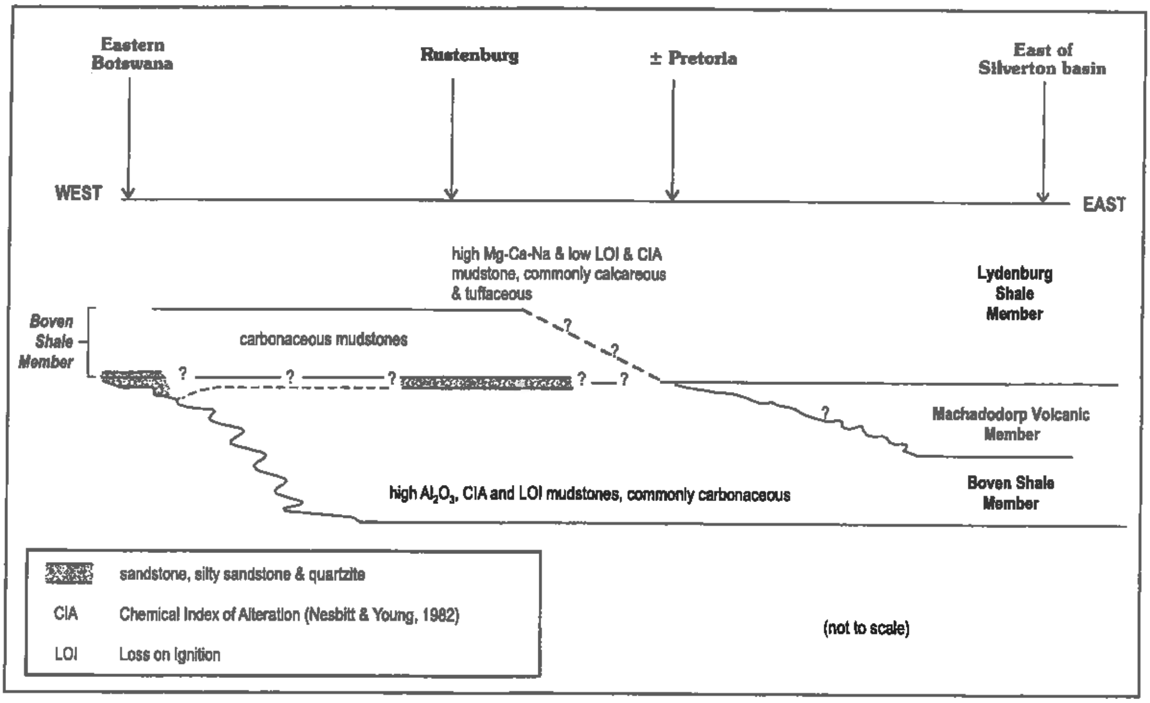

Fig. 6. Schematic (not to scale) east–west profile through the Silverton basin, illustrating a possible geochemically based stratigraphic subdivision applicable throughout the preserved basin (data from Reczko, 1994). Note basal arenaceous lithologies in the far west, recorded in boreholes Les1 and Strat2 (see also Fig. 7) of the basin.

Reczko, 1995). The Machadodorp volcanic rocks, up to 500 m in the east, comprise basal pyroclastic lithologies overlain by low potash tholeiitic basalts (Button, 1973; Reczko, 1994). Water-lain tuffs, locally pillowed basalts and minor cherts and carbonate rocks support subaqueous eruption (Button, 1973).

Lithofacies

Lithofacies in the Silverton Formation can best be examined in the far west of the preserved basin. Here, despite the formation being thinner than in the east, two borehole (see Fig. 1 for location) cores are available for study at the Geological Survey of Botswana. Borehole Les1 starts in the lower Magaliesberg Formation and encompasses the upper part of the Silverton succession, whereas borehole Strat2 represents the lower part of the Silverton Formation. Detailed logging of the two cores (Eberhardt, 1997) suggests that the the basal part of Les1 and the upper part of Strat2 are stratigraphically approximately contiguous (Fig. 7).

Arenaceous lithofacies association

Description

The lower 65 m of the Silverton Formation in borehole Strat2 encompasses an association of sandy and argillaceous lithofacies displaying rapid vertical variations (Fig. 8). The lower 36 m of this lithofacies association is characterized by inverse grading; within this interval, mudstone beds, 2–5 cm thick and each comprising laminated graphitic claystones passing up into cross-laminated, wavy laminated and normally graded quartz siltstones occur. These mudstone beds thicken (7–20 cm thick) and coarsen upwards to inversely graded fine sandstones (Fig. 8). The inversely graded beds have sharp to gradational lower contacts.

The lower, inversely graded interval is succeeded gradationally by 11.5 m of medium-grained cross-bedded, haematitic quartz sandstone beds, 30–40 cm thick, and containing internal normally graded quartz siltstone–claystone beds of 10–20 cm thickness. Upwards within the thickness of 11.5 m, the normally

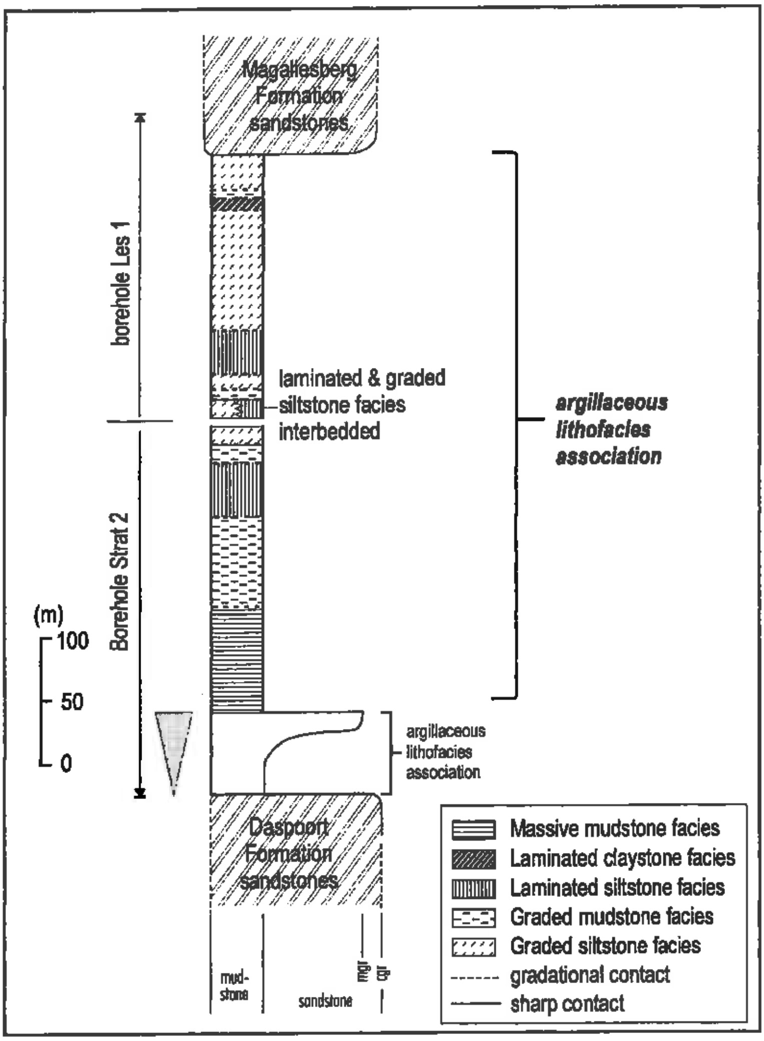

Fig. 7. Facies succession recorded in the two boreholes in eastern Botswana, considered to be stratigraphically approximately contiguous (Eberhardt, 1997). Note basal, relatively thin arenaceous lithofacies association, and overlying, predominant argillaceous lithofacies association. Modified after Eberhardt (1997).

graded internal beds thin, whereas the enclosing sandstones become fine-grained, more ferruginous and laminated; in the same direction, calcareous cement and micaceous matrix grains also increase within the sandstones, and isolated medium to coarse sand grains occur as well (Fig. 8).

Following 2 m of massive fine-grained sandstone, a 1.5 m thick succession of fine-grained normally graded oolitic ironstone beds, 8–35 cm thick and with basal pebbles of quartz and chert occurs (detailed section shown in Fig. 8). These basal pebbles resemble traction carpets and one of the graded ironstone beds has basal cobbles of ironstone, claystone and pyrite (Fig. 8). These pyrite cobbles themselves comprise goethitic/haematitic iron oolites embedded in pyrite; the rims of the oolites are not altered and the pyrite was thus most likely syngenetic (Reczko *et al.*, 1995). The oolites in the ironstones are up to 3 cm in diameter and polished sections reveal a polycyclic development of the oolitic grains. Normally graded medium- to coarse-grained sandstone–mudstone beds characterize the next 1.2 m above the 1.5 m thick oolitic ironstone interval (Fig. 8). The upper 13 m of the sandy facies association is made up of normally graded, mature, medium-coarse sandstone beds which alternate with massive calcareous sandstone beds (Fig. 8). The entire vertical succession of the sandy lithofacies association thus coarsens upwards and contacts

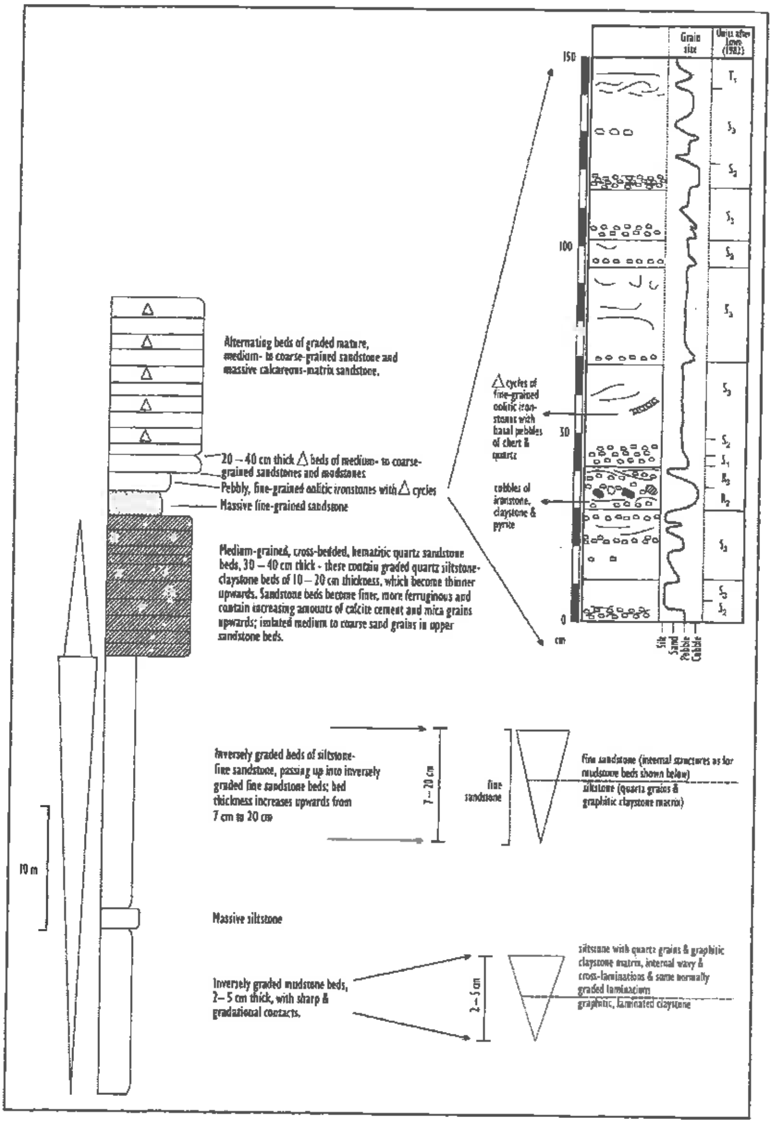

Fig. 8. Detailed sedimentary profile of the lower 65 m of borehole Strat2, illustrating the characteristics of the arenaceous lithofacies association of the Silverton Formation. Note common inversely graded beds in the lower 36 m interval, and, in contrast, the predominant normal grading above this. Detailed profile at top right shows 1.5 m interval of oolitic ironstone beds (inferred turbidite intervals, T, S and R, after Lowe, 1982).

between the facies tend to be gradational rather than sharp (Figs 7 and 8).

Interpretation

The lower predominant facies, inversely graded mudstones passing up into inversely graded fine sandstones, is problematic to interpret. Inverse grading is an uncommon sedimentary structure, and is often related to grain flows (e.g. Collinson & Thompson, 1982), where high dispersive pressure between the larger clasts may be responsible for smaller particles being displaced upwards, such as in density-modified grain flows (Lowe, 1982). However, in the Silverton facies discussed here, a debris flow origin is excluded owing to the laminated nature of the claystones and the cross-lamination and wavy lamination in the siltstones/sandstones together making up the inversely graded beds (Fig. 8); quite clearly, suspension sedimentation and low-energy traction current processes must have been operative.

Common inverse grading is typical of aeolian deposition (e.g. Hunter, 1977), and examples of this structure may also be found at the base of some coarse-grained turbidite beds (e.g. Stow *et al.*, 1996). It is well known that deltaic deposits often form upward-coarsening successions, from fine prodeltaic mudrocks, through silty and fine-sandy distal mouthbars, up into coarser sandstones of the proximal mouth bar and distributary channels, and that such successions may be repeated due to progradation of the deltaic system seawards (e.g. Reading & Collinson, 1996). Owing to the characteristic braided nature of Palaeoproterozoic fluvial systems (e.g. Eriksson *et al.*, 1998), a large number of channels of various sizes would have flowed into seas such as the Silverton epeiric basin, as is apparent for the coeval Magaliesberg braid-delta systems (Eriksson *et al.*, 1995). It is thus possible that the lower 36 m of the arenaceous lithofacies association identified in the Silverton borehole represents stacking of thin upward-coarsening cycles of distal braid-deltaic mudrocks and fine sandstones, formed as the Silverton epeiric sea transgressed across the Kaapvaal craton and slowly drowned the Daspoort braided rivers (Eriksson *et al.*, 1993) systems. The increasing sediment calibre and greater inversely graded bed thickness observed with increasing stratigraphic height in this lower part of the Silverton Formation presumably reflect a relative increase in energy of numerous small prograding braid-delta complexes debouching into the shallow advancing epeiric sea.

The medium- to coarse-grained sandstones that make up most of the upper portion of the lower 65 m of the Silverton Formation (Fig. 7) are typically either graded themselves or contain thinner graded siltstone–claystone beds (Fig. 8). These sandstones are compatible with the deposits of high-density, coarse-grained turbidity currents; successive pulses of surging turbidity flows could have produced the discrete graded beds observed in the lower Silverton Formation (Lowe, 1982). The cross-bedded sandstones in the arenaceous lithofacies association (Fig. 8) probably reflect lower flow regime sandy ripple and megaripple bedform migration, equivalent to the B interval of Bouma's (1962) medium-grained turbidites. Massive sands, as found interbedded with the above Silverton graded arenitic beds, are commonly found associated with turbidite deposits (Stow *et al.*, 1996).

Similar surging, high-density turbidity current deposition is inferred for the 1.5 m thick interval of oolitic ironstone beds (detailed profile in Fig. 8; note also T, S and R turbidite intervals after Lowe (1982)). This interpretation is supported by the inferred traction carpet layers, cross-lamination and graded bedding in this interval (Reczko *et al.*, 1995). Syngenetic freezing of goethitic/haematitic ooids in rapidly precipitating pyrite to form the pyrite cobbles observed at the base of one of the ironstone beds (Fig. 8) was most probably related to localized exhalative processes, occurring at fault intersections along the western margin of the Silverton basin (Reczko, 1994). The goethitic/haematitic oolites probably formed along the transgressive margin of the inferred epicontinental Silverton sea and thus could have marked transgressive surfaces in the preserved rock record. However, sulphide cobbles and ferruginous oolites are assumed to have been redeposited in deeper water by high-density turbidity currents as the Silverton epeiric sea advanced westwards and rapidly drowned (Catuneanu & Eriksson, 1999; Fig. 3) the braid-deltaic inversely graded deposits discussed above. Highly mature reworked arenites with bipolar palaeocurrent trends occur in the upper Daspoort Formation in the east of the Pretoria Group basin (Eriksson *et al.*, 1993); they support an interpretation that preceding Daspoort fluvial sandstones were drowned as the Silverton epeiric sea transgressed on to the Kaapvaal craton, with an active coastline advancing rapidly westwards to include the present-day western preserved margin of the basin where boreholes Les1 and Strat 2 were drilled.

Argillaceous lithofacies association

Description

These facies make up the rest of the Silverton succession recorded in the two boreholes and comprise massive mudstones, laminated claystones, laminated siltstones, graded mudstones and graded siltstones (Fig. 7). Thick (86 m), apparently massive mudstones (Fig. 9) immediately follow the arenaceous facies association discussed above; the contact zone in the core is brecciated and thus of uncertain affinity. These mudstones comprise carbonaceous and pyritic quartz siltstone and claystone, with minor interbeds, 5–10 cm thick, of laminated quartz siltstone. The pyrite occurs primarily as intergranular cement. The laminated claystone facies has laminae of 1–5 mm thickness and forms a 9 m thick unit near the top of the Silverton succession (Fig. 7). The laminated siltstone facies is characteristic of the medial part of the succession where two intervals of *c.*45 m thickness occur (Fig. 7); these siltstones and minor fine-grained sandstone laminae comprise clasts of quartz as well as calcareous grains set within a graphitic matrix.

The graded siltstone facies occurs in the upper half of the Silverton succession where intervals of 20–91 m thickness are found (Fig. 7). These beds of siltstone

Fig. 9. Massive mudstone facies from an outcrop in the east of the Silverton basin, analogous to that described from the boreholes to the west. Note spheroidal weathering, a common feature of field occurrences of this facies.

Fig. 10. Graded siltstone facies, illustrated from an outcrop in the Pretoria region, and analogous to that described from the western boreholes. Note predominant thin graded beds, a few centimetres in thickness (pen for scale), with tops of individual beds marked by more voluminous dark coloured graphitic matrix material. Also note thicker bed of fine-grained sandstone, about 20 cm thick, in the middle of the photograph.

and subordinate fine-grained sandstone are mostly a few centimetres to 10 cm thick, uncommonly up to 20 cm (Fig. 10), and comprise mainly calcareous clasts and lesser quartz grains within a micaceous to graphitic matrix, as well as minor calcite and haematite cement. Many of the beds are sharply based, some with obvious scoured bases, and internal structures in the beds include soft sediment deformation and compaction features, cross-lamination and lenticular lamination.

The graded mudstone facies, spread throughout the Silverton succession in the boreholes, with intervals from 8 to 71 m in thickness (Fig. 7), comprises calcareous and quartz siltstones (matrix graphitic with pyritic cement) which pass up into graphitic mudstones. These graded beds and laminae vary from a few millimetres to 20 cm in thickness (Fig. 11), contain similar internal structures to the graded siltstone facies and are separated locally by 1–5 cm thick graphitic mudstones.

Fig. 11. Field outcrop (Pretoria region) of graded mudstone facies, similar to that described from western boreholes. Individual graded beds and laminae separated by thin, dark coloured graphitic mudstones; note variable thickness of graded beds, between a few millimetres and several centimetres (pencil for scale).

Interpretation

In view of the Silverton Formation being bounded by underlying largely braided fluvial sandstones of the Daspoort Formation (Eriksson *et al.*, 1993) and by overlying Magaliesberg sandstones ascribed to regressive tidally reworked braid-delta complexes (Eriksson *et al.*, 1995), large quanitities of fine fluvial detritus would have been supplied to the Silverton basin. Enhanced weathering regimes, typical of the early Precambrian due to atmospheric composition (Corcoran *et al.*, 1998), and rapid erosion in the absence of land vegetation, would have promoted large amounts of fine fluvial detritus, transported in enormous braided systems (Eriksson *et al.*, 1998). Swift *et al.* (1991) recognize supply-dominated shelves, analogous to the Silverton epeiric sea, and accommodation-dominated shelf settings. For supply-dominated shelves, terrestrial sediment supply via rivers and deltas exceeds the combination of accommodation space creation and sediment dispersal (Johnson & Baldwin, 1996); a high concentration of suspended load is needed for muddy sediment to be laid down on the shelf, with >150 mg l^{-1} probably being required (Friedman *et al.*, 1992, p. 391). However, in the Palaeoproterozoic, with an inferred absence of filter-feeding invertebrates to remove significant quantities of mud from the water column, lower concentrations of suspended load may have sufficed for mud to escape into deeper water (B.M. Simonson, personal communication, 2000). On modern supply-dominated shelf settings, fine fluviodeltaic detritus will by-pass the high-energy coastal sand belt and be deposited on the medial to outer shelf regions, as, for example, found in the modern shelf off the Amazon River (e.g. Kuehl *et al.*, 1986); the offshore transport is dominated by river flood events, aided by rip currents, ebb-tidal currents and downwelling storm currents (Johnson & Baldwin, 1996). Thick successions (tens to hundreds of metres) of essentially homogeneous fine sediments will accumulate on supply-dominated shelves as a result, similar to the facies succession observed in the two Silverton boreholes (Fig. 7).

A transition zone on the shelf environment, between coastal sands and offshore muds, at an average depth of 8–10 m, is characterized by clayey silt and silty clay (Reineck & Singh, 1975), analogous to the predominant facies in the Silverton argillaceous association. Thin interbedded silts or fine sands in these predominant muds, characterized by graded bedding or appearing as graded rhythmites, and ascribed to storm suspension processes (e.g. Hayes, 1967; Reineck & Singh, 1975), strongly resemble the graded mudstone and graded siltstone facies of the Silverton Formation. Outer shelf deposits, both Precambrian and Phanerozoic, are typically dominated by massive or laminated mudstones, comparable to the massive mudstone, laminated claystone and laminated siltstone facies of the Silverton succession (Fig. 7), with subordinate graded siltstone to fine sandstone storm beds (e.g. Schieber, 1989; Chakraborty & Bose, 1992; Tirsgaard & Sønderholm, 1997; Eriksson *et al.*, 1998). Whether the massive mudstone facies of the Silverton Formation is really primarily massive or only apparently so, due to secondary processes such as diagenesis (bioturbation being excluded due to the age of these rocks), is uncertain; outcrops of this facies tend to be spheroidally weathered (Fig. 9), which, although not proving a primary massive nature, is compatible with it.

Applying conventional wisdom, the common presence of graphitic matrix material and pyrite cement in the Silverton mudrocks also supports below wave base suspension sedimentation within a generally anoxic and low-energy palaeoenvironment. However, modern shallow water examples of graphitic–pyritic mudrocks are known (e.g. Devonian Chattanooga Shale, North America; J. Schieber, personal communication, 2000), and in the Precambrian, with significantly less oxygen in the atmosphere, carbonaceous mudrocks may have been likely to accumulate in shallow water. The graded storm beds in muddy shelf settings may also exhibit cross-lamination and are often sharply based or even erosional (Tirsgaard & Sønderholm, 1997); similar features occur within the argillaceous facies association of the Silverton Formation, and may be ascribed to unidirectional bottom currents related to storm events (e.g. Walker & Plint, 1992). The apparent absence of wave-formed structures in the Silverton mudrock facies supports deposition having taken place beneath storm wave base.

The argillaceous facies association of the Silverton Formation, as identified in the two boreholes Les1 and Strat2, thus supports outer shelf mud-type low-energy deposition of abundant fluvial fines with intermittent graded storm beds and laminae also being preserved. This below wave base facies association suggests that rapid drowning of the Silverton epeiric coastline (arenaceous facies association, above) occurred and that the argillaceous facies association reflects the transition from a transgressive systems tract to a highstand condition (Fig. 3). The tidally reworked braid-delta sandstones of the Magaliesberg Formation represent the coeval fluvial feeder systems supplying abundant fine sediment to the adjacent Silverton epeiric basin. Coarse Magaliesberg fluvial sands were trapped in the high-energy coastal belt by strong tidal currents and storm wave activity.

Basinal trends

Although there are no further borehole cores available for study from elsewhere in the preserved Silverton Formation, limited outcrop data, described by Button (1973), Schreiber (1990) and van der Neut (1990), exist for the central and eastern parts of the basin. Although argillaceous lithofacies, analogous to those described here, account for most outcrops examined, there are subtle differences across the basin. Within the south-central portion, around Pretoria (Fig. 1), van der Neut (1990) notes that channel-fills of laminated to cross-laminated mudrocks, ripple marks and interbedded sandstone lenses and thin beds occur within massive, laminated and graded mudrock facies. These combined features suggest the action of directed, eroding bottom currents, and deposition depths closer to storm wave base than the facies from the Botswana boreholes examined here (Fig. 7). The bottom currents may reflect downwelling storm processes, ebb-tidal

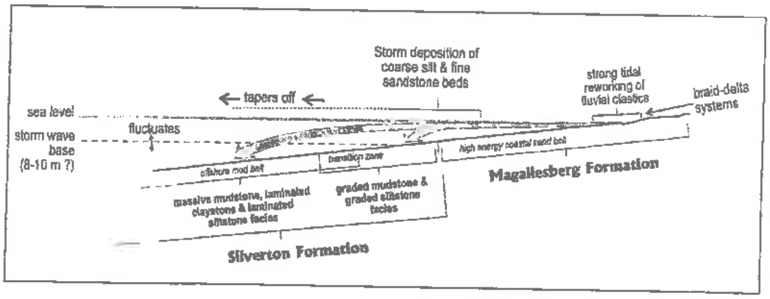

Fig. 12. Sedimentary model postulated for the Silverton Formation epeiric sea. See text for discussion.

currents, rip currents or, possibly, thermohaline geostrophic current action (e.g. Eriksson & Reczko, 1998).

In contrast, outcrops from the east of the preserved basin exhibit carbonate rocks and cherts associated with predominant graded, laminated and massive mudrock facies, and also more common high-graphite mudrocks (Button, 1973; Schreiber, 1990). These attributes, together with the greatly enhanced thickness of the Silverton Formation in the east (Figs 5 & 6), point to an outer shelf-like depositional realm further removed from fluvial feeder systems than those in the west of the basin. As Daspoort sedimentation, which preceded Silverton deposition, is characterized by eastern shallow marine sandstones, coeval with western fluvial deposits (Eriksson *et al.*, 1993), a westerly fluvial source for the Silverton is also assumed. Magaliesberg regressive coastal sandstones, interpreted as a lateral facies equivalent of deeper water Silverton sediments, show a similar western provenance (Eriksson *et al.*, 1995). With less clastic input and, most likely, slower sedimentation rates further from the fluvial feeder systems situated in the west, chemical sedimentation (carbonates and chert) became more prominent towards the east. Greater subsidence presumably accommodated more pelagic material and subordinate graded storm beds. The calcareous siltstones and fine sandstones, which are common in the facies identified in the western boreholes, are fully clastic rock types derived from Chuniespoort Group dolomitic source areas, and should not be confused with the chemically/biochemically precipitated carbonate muds and marls in the east. The latter also exhibit vague stromatolitic structures (Button, 1973), thereby suggesting relatively shallow depths, above the photic limit, albeit predominantly below storm wave base.

Depositional model

A shallow epeiric sea model is proposed for the Silverton Formation (Fig. 12). Approximately coeval sheet sandstones of the Magaliesberg Formation were laid down by widespread braid-delta systems which debouched into the Silverton basin from an extensive western hinterland. Strong tidal reworking occurred in the braid-delta channels (Eriksson *et al.*, 1995), thus forming a higher energy sand belt above storm wave base at the margins of the Silverton basin. Aggressive Precambrian weathering, allied to a lack of terrestrial vegetation, provided high concentrations of fine fluvial sediment, which by-passed the high-energy coastal sand belt through a combination of river flood events, rip, ebb-tidal and downwelling storm (wave) currents, and laid down a thick succession of argillaceous sediments, essentially below wave base (Fig. 12). Graded mudstone and graded siltstone facies of the Silverton Formation were deposited from suspension in a transition zone between the coastal sand belt and an offshore mud belt. The latter accumulated massive mudstone, laminated claystone and laminated siltstone facies as outer shelf-like deposits in the Silverton basin (Fig. 12). Subordinate, thin-graded storm beds/laminae of fine sandstone and coarse siltstone occur within the argillaceous Silverton facies, attesting to intermittent storm wave deposition, probably reflect a fluctuating depth to storm wave base in the transition zone. Storm wave base probably fluctuated owing to the varying combination of wave lengths and wave periods (Friedman *et al.*, 1992).

The model proposed (Fig. 12) is based largely on the borehole cores examined from the far western portion of the preserved Silverton basin. Outcrops in the south-central part of this depository suggest deposition closer to storm wave base, whereas those from the east of the basin point to deeper water outer shelf-like conditions, further removed from the fluvial feeder systems. Greater subsidence in the east led to a much thicker accumulation of pelagic beds there than in the west (Fig. 5).

Silverton deposition was preceded by largely fluvial sedimentation of the Daspoort Formation. More mature Daspoort sandstones with bimodal and polymodal palaeocurrent trends in the east of the preserved basin support transgressive marine reworking of fluvial detritus as Silverton epeiric transgression began. In the west of the basin, in the boreholes examined, initial Silverton sandy deposits (Fig. 8) point to coastline deposition, largely by numerous small braid-deltaic systems which formed inversely graded beds. Subsequent rapid drowning of this prograding braid-delta coastline led to the formation of coarse, sandy, high-density turbidite deposits, including resedimented ferruginous oolites and pyritic cobbles. The oolites probably developed along a trangressive surface and were redeposited in deeper water by turbidity currents as the epeiric basin deepened. Subsequent deposition of predominant mudrocks, below wave base, formed the later transgressive and highstand facies tracts of the Silverton Formation (Fig. 3). Coeval tidally reworked braid-delta Magaliesberg sandstones reflect a regressive shoreline which supplied fluvial fines for offshore suspension sedimentation, and which gradually advanced eastwards as the Silverton epeiric sea retreated off the Kaapvaal craton.

DISCUSSION

The small scale of the preserved Silverton basin, approximately 500 by 300 km (Fig. 1), compares poorly with the vast epeiric seas of the Phanerozoic, such as the Late Cretaceous seaway of North America, which measured approximately 5000 by 1400 km at maximum transgression (Reading, 1978). The Silverton sea was thus probably an epeiric embayment rather than a seaway.

Water depths in the Silverton embayment are likely to have been shallower than those inferred for the Cretaceous seaway (Fig. 12). Although it is difficult to estimate accurate water depths in such settings, common black, pyritic mudrocks in the west of the Silverton basin (boreholes examined here) are compatible with sub-wave base deposition and point to anoxic deeper waters; however, as pointed out above, there are Phanerozoic examples of pyritic black shales which formed in depths significantly less than 100 m, and even shallower depths would probably have been possible in the Precambrian with less oxygen in the atmosphere. Locally stromatolitic carbonates and cherts in the east of the basin (Button, 1973) suggest photic water depths between approximately 100 and 30 m (Eriksson & Reczko, 1998). Unlike the Timeball Hill Formation, where evidence for common turbidite deposits and contour currents supports depths close to 100 m (Eriksson & Reczko, 1998) (Fig. 4), most of the Silverton Formation (possibly excluding the lower inferred turbidite deposits) was probably laid down nearer the upper depth limit envisaged above.

At such shallow depths, normal waves would have become dampened within about 100 km from the open ocean (Eriksson & Reczko, 1998) and the Silverton epeiric embayment would have been subject to less frequent storm wave action. Storm wave base fluctuates according to combined changes in wave length and wave period (Friedman *et al.*, 1992), with waves having the greatest lengths and amplitudes deepening effective storm wave base (Reading & Collinson, 1996). The middle shelf or transition zone (Swift & Thorne, 1991) and outer shelf zones are affected by storm waves at depths of approximately >10 m and >20 m, respectively (Johnson & Baldwin, 1996). The relative scarcity of thin-graded coarse siltstone and fine sandstone beds in the predominant Silverton mudrock facies suggests either that large storm waves were uncommon in the epeiric palaeoenvironment, or that water depths were in excess of the 10–20 m proposed above. Much of the Silverton basin was thus probably analogous to a middle to outer shelf setting, and characterized by predominant pelagic settling of fluvial fine material, with limited storm wave deposition of coarse silt and fine sandstone beds (Fig. 12). As such relatively shallow depths (<30 m?) appear to have applied over the central and eastern parts of the preserved basin too, the Silverton epeiric basin floor must have been characterized by a very shallow gradient.

Comparing the inferred Silverton model with that of Shaw (1964) and Irwin (1965) (Fig. 2), a very extensive X zone probably characterized the Silverton, with the Z zone not being preserved in the present basin. The high-energy Y zone in this classical model compares favourably with the tidal braid-delta setting inferred for the Magaliesberg Formation sandstones, thought to be the coeval high-energy sand belt and coastline of the Silverton Formation (Fig. 12). Strong tidal currents reworked the Magaliesberg braid-delta sandstones (Eriksson *et al.*, 1995). The preserved stacking pattern, of regressive Magaliesberg shoreline sandstones overlying offshore, transgressive to highstand-type epeiric mudrocks of the Silverton Formation (Fig. 3), resulted from retreat of the epeiric embayment off the Kaapvaal craton. This retreat may well reflect thermal elevation of the central Kaapvaal craton towards the end of Transvaal Supergroup sedimentation, as the Bushveld magma plume (intrusion at *c*.2.05 Ga; Eriksson & Reczko, 1995) became active (Catuneanu & Eriksson, 1999).

The model proposed for the Silverton epeiric embayment (Fig. 12) thus strongly resembles a modern clastic, supply-dominated shelf (Swift *et al.*, 1991), but with one significant difference, namely a scarcity of fair weather wave activity. However, with the broad shelf palaeoenvironment envisaged for the Silverton deposition, tidal range would have been enhanced and preservation of fair weather wave deposits would be unlikely (e.g. Hayes, 1979). In the absence of significant fair weather wave activity, strong tidal currents characterized the high-energy sand belt and coastline, and would have reworked the storm wave beach deposits that formed intermittently. In a modern shelf setting, tides would generally predominate in the coastal zone where barrier islands absorbed fair weather wave energy, leaving tidal lagoonal settings behind them. A general lack of preserved barrier island deposits is noted in many Precambrian shallow marine palaeoenvironments (Eriksson *et al.*, 1998). As tidally influenced epeiric seas appear to have been much more common in the Precambrian (Eriksson *et al.*, 1998; Eriksson & Reczko, 1998), probably reflecting the influence of continental crustal growth (and therefore freeboard) on eustacy (e.g. Eriksson, 1999), this provides a possible explanation for the perceived paucity of Precambrian barrier island deposits.

The Silverton epeiric embayment model (Fig. 12) may thus be added to the classic Shaw–Irwin epeiric sea model, as reflecting a common Precambrian permutation thereof. The Silverton model was probably more common in this regard than that proposed for the Timeball Hill Formation (Fig. 4) of the Transvaal Supergroup. The latter epeiric sea has a preserved size compatible with an embayment, but facies indicate water depth up to *c*.100 m and hence support an alternative seaway interpretation. However, in view of the Timeball Hill epeiric sea being coeval with the first global glaciation known (Eyles & Young, 1994), eustatic sea levels would logically have been reduced and large-scale flooding of the Kaapvaal craton unlikely. This suggests that that main control on the Timeball Hill transgression (Fig. 3) was structural rather than eustatic. The Timeball Hill epeiric palaeoenvironment (Fig. 4), with evidence for deeper water, and a combination of turbidite, pelagic, contourite and deltaic sedimentation (Eriksson & Reczko, 1998) within a shallow marine setting, is thus probably not a widely applicable epeiric sea model. The Silverton model (Fig. 12) discussed here appears to have a much wider relevance for the early Precambrian, when the interplay between continental freeboard, continental crustal growth rates and eustacy is thought to have been important (Eriksson, 1999).

CONCLUSIONS

The Silverton Formation comprises a predominant argillaceous facies association of massive mudstones, laminated claystones, laminated siltstones, graded mudstones and graded siltstones, and a subordinate arenaceous lithofacies association. The latter is ascribed to braid-deltaic and turbidity current deposition under transgressive conditions. The argillaceous facies are interpreted as sub-storm wave base pelagic deposits, laid down in an epeiric embayment under transgressive and highstand conditions. The muddy detritus laid down in the transitional and offshore mud belt zones of this shallow epicontinental sea was derived from fine fluvial sediment which was able to by-pass a high-energy coastal sand belt, represented by the Magaliesberg Formation which overlies the Silverton rocks. Storm wave action locally produced graded coarse siltstone and fine sandstone beds.

The model suggested for the Silverton Formation epeiric embayment (Fig. 12) compares reasonably with the Shaw–Irwin classic model applied to Phanerozoic epeiric seaways, but with some significant differences. In the Silverton model, the inshore low-energy Z zone (Fig. 2) was either absent or not preserved, and a strongly tidal coastline (Y zone) appears to have been present much of the time. The Silverton epeiric model may also be favourably compared to a modern clastic, supply-dominated shelf, but with the difference that fair weather wave action was limited. As a result, strong tidal action reworked fair weather wave deposits and the development of wave-built barrier islands would have been uncommon. The depositional environment proposed for the Silverton Formation was probably quite widespread in the early Precambrian, when extensive inundation of continental margins, thereby forming epeiric embayments, occurred owing to enhanced continental crustal growth rates.

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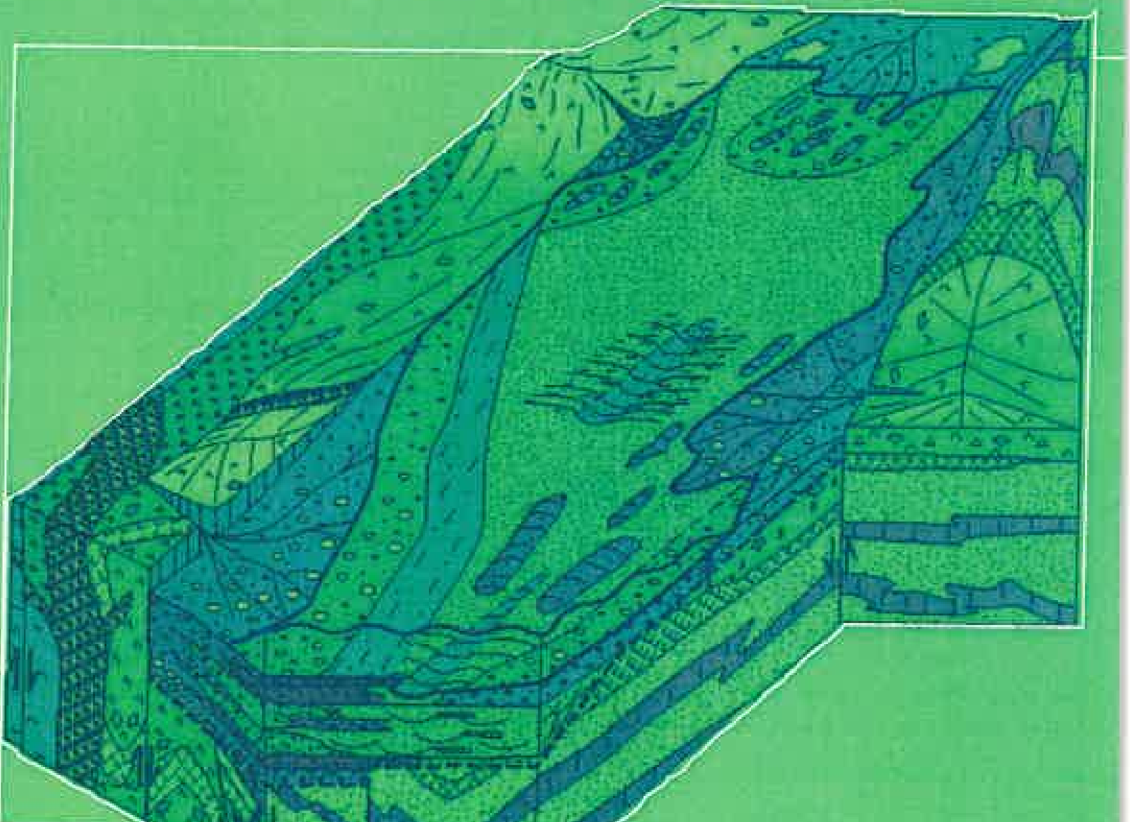

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