Tectonic Influence on the Evolution of the Early Proterozoic Transvaal Sea, Southern Africa

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I declare that this research is my own work and that it was conducted under the supervision of Professor S. Maske and Dr. E. G. Charlesworth. No part of this research has been submitted in the past, or is being submitted, for a degree at another university.

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Abstract

The epeiric Transvaal Sea covered the Kaapvaal Craton of southern Africa during the Early Proterozoic and its remnant strata represent one of the oldest known carbonate depositories. A genetic stratigraphic approach has been used in this research on the evolution and syndepositional tectonics of the Transvaal Sea; research also emphasized the development of basement precursors, which influenced the Transvaal Sea. Eight subfacies were initially recognized and their interrelationships through Transvaal Sea time and space were used to identify ten depositional systems. Paleogeographic reconstructions indicate that the depositional systems developed on morphological variations of a distally-steepened carbonate ramp and that the depositional character of each was simply a function of water depth.

Backstripping of the depositional systems indicates that the Transvaal Sea was compartmentalized; three compartments are preserved on the Kaapvaal Craton. Backstripping also indicates that the depositional center of the Transvaal Sea lay over the western margin of an underlying rift. Rifting had developed a major, north-south-trending structure, and its geographical interrelationships with the east-west-trending Selati Trough created the compartment architecture of the basement.

Interpretation of syndepositional tectonics suggests that six stages of subsidence influenced the Transvaal Sea. Early subsidence consisted of mechanical (rift) subsidence followed by

subaerial tectonic subsidence, which was expanded by subsequent thermal subsidence. Thermal subsidence was relatively short and is explained by a combination of presently accepted models. Three periods of reactivated subsidence followed and produced the major phase of subsidence of the Transvaal Sea. Reactivated subsidence is suggested as the reason for continued to expansion and deepening of the depository with time.

Periods of reactivated subsidence indicate that the Transvaal Sea was a resurgent basin and that compressive in-plane stress influenced reactivated subsidence. Backstripping to the "Old Granite" basement identified the changing regional stress fields which resulted in the rifting event. Intraplate deformation thus identified suggests that a number of Early Proterozoic successor basins developed and that the Transvaal Sea was the end product of a number of distant plate marginal processes. These marginal processes were related to convergence, angle of subduction, and collision between the Kaapvaal and Zimbabwe Cratons at about 2.6 Ga.

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Chapter 1

Introduction

1.1 General Statements

During the Early Proterozoic, a vast sea, in which carbonates, iron-formation, and minor siliciclastics were deposited, spread over the Kaapvaal Craton of southern Africa. Remnants of these strata crop out as the Chuniespoort Group, Transvaal Sequence, of the Transvaal and as the Ghaap Group, Transvaal Sequence, of the northern Cape Province (Fig. 1). This outcrop pattern suggests that this sea, here termed the Transvaal Sea, may have covered most of the craton at one time. The exact age of the sediments is presently unknown, but lavas from below a regional unconformity, which marks the beginnings of deposition, have yielded a 2,7 Ga date, based on ion microprobe analysis of zircon (Armstrong et al., 1986). Lavas from the overlying Pretoria Group, Transvaal Sequence, have a Rb/Sr whole-rock age of 2,2 Ga (Eriksson and Truswell, 1974a). Even within these broad age limits, the Kaapvaal Sea represents one of the oldest known, preserved carbonate depositories. Recent paleomagnetic data suggest that the Kaapvaal Craton was at low latitudes between 2,5 Ga and 2,3 Ga (Klein et al., 1987), and the presence of carbonates support this paleogeographic interpretation because warm marine conditions are needed for their deposition.

Recently, Grotzinger (1986) has pointed out that

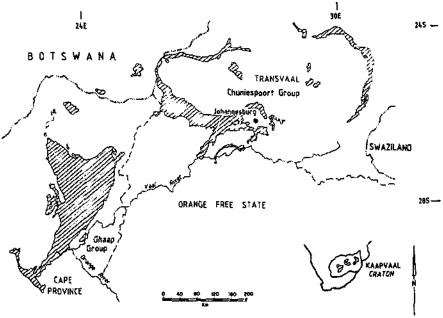

Figure 1. General reference map showing preserved strata of the Chuniespoort Group in the Transvaal and the Ghaap Group in the northern Cape Province.

descriptions of pre-Phanerozoic carbonate platforms are lacking, and little is known concerning the genesis of such platforms or similarities and differences between pre-Phanerozoic and Phanerozoic examples. The purpose of this research is to establish and to interpret basin dynamics, which led to the development of the Transvaal Sea, in an attempt to provide such a description.

1.2 Research Approach

Basin analysis is a multi-disciplinary earth science approach to the history of a basin and requires collection and interpretation of different kinds of data. Data is acquired from stratigraphic, structural, and sedimentological observations of outcrop and borehole core, or by geophysical methods. To make sense of these observations, it becomes necessary to generalize, simplify, and categorize data in an attempt to assess relationships between various types of evidence (Miall, 1984). Analysis of basin dynamics assist this process by necessitating integration and reconciliation of apparently conflicting data from observational and theoretical branches of stratigraphy, tectonics, and geophysics (Gibbs, 1987). What is developed is an overview of the basin via a genetic approach established from a regional framework. This approach focuses on formation of the basin, nature of the sediment fill, and timing of specific events controlled by geodynamic processes (Klein, 1987). Equally important is determination of the size and shape of the basin during various stages of evolution and development.

Although the following statements may be somewhat repetitive, they are felt necessary because synthesis of the observations is rather involved. Questions, which have tractable *solutions*, must be asked so that a rational frame of reference for explanation and model building is developed. This makes the geology more complicated because a constraint to build and to test models within a rational framework rather than to erect ad hoc constructions is imposed (Dewey, 1982). To outline this framework, lithostratigraphy is initially used, which is developed from observable lithologic features, types of sedimentary structures, and *cyclic sequences. Once basic* stratigraphic units are understood, lithostratigraphy can be replaced by a depositional systems approach. This new approach addresses genetic stratigraphy, in which focus is placed on interpretations of interrelationships, based on an understanding of depositional environments and syndepositional tectonics which influence interrelationships (Miall, 1984). It is also a convenient way of establishing a rational framework which is required for interpretation and model building. Use of this approach and identification of unconformity bounded packages allows interpretation of vertical crustal movements. Periods of uplift or subsidence can then be interpreted in terms of regional stress fields, or thermal effects, which may have influenced the crustal movements. Interpretation of regional stress fields leads to development of geodynamic models that account for the timing of various events and the preserved geology and geophysics.

1.3 Previous Work

Only a few researchers have contributed to the understanding of the Transvaal Sea and the stratigraphy of its preserved lithologies (Young, 1933, 1934; Toens, 1966; Eriksson, 1972, 1977; Eriksson and Truswell, 1973, 1974a, 1974b; Eriksson et al., 1976; Truswell and Eriksson, 1972, 1973, 1975; Visser and Grobler, 1972; Button, 1973a, 1976, 1986; Beukes, 1977, 1980a, 1980b, 1983a, 1983b, 1986). These studies were conducted in different parts of the preserved outcrop area (Fig. 1), and local stratigraphic names were developed for particular map areas. Subtle facies changes between the two principal areas of outcrop are responsible for the different stratigraphic names being applied to them (Beukes, 1983a). Furthermore, very little intra-basin stratigraphic correlation has been proposed except for a few general statements and graphics by Button (1973a) and Beukes (1983a, 1986). Most early studies focused on lithostratigraphy for purposes of paleoenvironmental reconstruction. Previous studies do, however, provide insights into the progressive geological thinking about the Transvaal Sea from several points of view.

Young (1933) developed the concept that different stratigraphic structures could be used in the identification of physiographic conditions and he proposed the following three penecontemporaneous depositional phases: shallow, transitional, and deeper. The shallow phase contained small stromatolites, oolites, oncolites, and ripple marks, while the transitional phase was characterized by columnar stromatolites and the deeper

Figure 2. General reference map of the localities in the Transvaal and northern Cape Provinces referred to in the text.

phase by laminated dolomites. Young (1934), by making comparisons with Holocene examples, proposed an analogy between Early Proterozoic Kaapvaal stromatolites and Bermuda algal mats. Based on these observations and interpretations, Young (1933, 1934), and later Toens (1966), suggested that different stromatolite types may have stratigraphic significance.

Detailed studies began to appear in the literature in the early 1970's. Most interpretations and paleoenvironmental reconstructions were based on macroscopically observable features and an application of Walther's Law. Character of the sea was one of many features addressed by these studies. Based on interpretations of tidal environments, Eriksson (1972) proposed that *Shaw's (1964) epeiric* sea model clarified preserved lithostratigraphic relationships in the Potchefstroom area (*Fig.* 2). With expanded work in the Boetsap area, northern Cape, Eriksson and Truswell (1973) considered that depositional patterns alone indicated platform sedimentation in an epeir sea. They supported their conclusion by recognizing a telesc range of environments extending from an intertidal zone through a high-energy agitated regime and out into a shallow subtidal zone (Eriksson and Truswell, 1974a). Based on both interpretations of shallow sea models and comparisons to Shark Bay, Western Australia, these relationships tended to confirm shallow epeiric sea interpretations. From studies in the northern Cape, Beukes (1977, 1980a, 1983a) pointed out that absence of gravity flows in front of shallow carbonate platform features was indicative of shallow foreslope dips and proposed that the subtidal zone ranged from 7 to 20 m. Recently, water depth of the so-called "deep shelf", euxinic basin environment, seaward of the carbonate platform, has been interpreted to have been in the order of 60-80 m (Klein et al., 1987). Button (1986) best summarized the character of the Transvaal Sea when he described it as a spectrum of sedimentary environments developed on a very wide, flat, gently shelving marine platform.

While data was being presented on the character of the epeiric sea, many studies discussed marine, hydraulic energy conditions which may have existed in it. Visser and Grobler (1972) in their study of an area near Schmidtsdrif, northern Cape (Fig. 2), were first to mention the aspect of tidal currents; they suggested that the dominant factor determining depositional environment was depositional energy level. Based on paleoenvironmental interpretations, Truswell and Eriksson (1973) suggested that persistent, but weak, tidal currents existed in the subtidal environment and that coarser carbonate material was indicative of higher depositional energy. However, these authors pointed out that the elongation of subtidal features demanded stronger tidal currents than are generally proposed to have operated in an epeiric sea. An interesting point that Eriksson and Truswell (1974a) made was that particular stromatolite forms may have acted as baffle-like carpets and damped tidal effects. In this same study, they also briefly addressed the question of whether or not stromatolite morphology was environmentally controlled, but left the question unresolved. Nevertheless, Eriksson and Truswell (1974a) did interpret that variable energy conditions reflect changes in water agitation due to storms and that such energy conditions could form and remove small, but effective, barriers to water movement. Beukes (1977) suggested that polymodal paleocurrent directions were due to diversely distributed tidal current directions. In a later study of the northern Cape carbonates, Beukes (1983a) described herringbone cross-laminations and partly washed-out ripples, which he interpreted as indicating fairly high-energy conditions in the intertidal zone.

Following Young's (1934) pioneering work, Truswell and Eriksson (1972) described and classified stromatolite morphologies in the Transvaal outcrop area (Fig. 1). In a study the following year, Truswell and Eriksson (1973) pointed out the paleoenvironmental significance of stromatolites by proposing that Early Proterozoic stromatolites developed in both shallow subtidal and intertidal zones. They also proposed that elongate stromatolite mounds up to 40 m long and 10 m wide, with inheritances up to 13 m, were the largest features of the current-dominated, shallow subtidal regime and that columnar stromatolites were particularly abundant in the shallower subtidal regime. Based on contemporary analogues of Shark Bay, Eriksson and Truswell (1974a) updated their earlier work (Truswell and Eriksson, 1972) by classifying various stromatolitic morphologies into a variety of mat types, i.e. blister, smooth, tufted, and collaform.

Visser and Grobler (1972) were the first workers, after Young (1933), to propose a lithofacies arrangement for the carbonate platform sedimentation. They suggested, based on depositional energy levels, that stromatolites and ripple-laminated carbonate sands developed shoreward of oolitic sand and offshore carbonate silts and shales. They also proposed that as the platform gradually evolved a broad, partially emergent, intertidal lagoon-like feature developed behind offshore bars. This arrangement of lithofacies has been repeated in a number of studies (Truswell and Eriksson, 1975; Eriksson et al., 1976; Button, 1976; Eriksson, 1977; Beukes, 1980b, 1983a). Based on Irwin's (1965) model for an epeiric sea, these studies have suggested that oolitic carbonates, with prevalent reverse grading, ripple marks, and cross-laminations, represent a bar or barrier behind which lay an extensive subtidal to intertidal lagoon. Both Button (1973b) and Beukes (1977) have suggested that shallow intertidal siliciclastic lithofacies developed shoreward of the carbonate platform and that prior to early carbonate-depositing transgressions, braided stream deposits developed. Beukes (1977) has also indicated that mixed siliciclastic-carbonate lithofacies may develop between the shallow carbonate platform and proximal siliciclastic lithofacies. Truswell and Eriksson (1975) interpreted that the intertidal regime dominated the Transvaal area and proposed that this regime was characterized by "larger" stromatolite domes, being succeeded by smaller ones, before being swamped by ripple-marked carbonate sands. In this same study, they also proposed that oolites formed in the seaward agitated zone which separated subtidal stromatolitic zones from intertidal ones. Beukes (1980a, 1983a) suggested that the largest, most mature ooids *developed immediately below* the intertidal zone and suggested that early tidal flats probably faced open ocean. However, Beukes (1980b, 1983a) proposed that, in later stages of platform evolution, oolitic and stromatolitic units represented platform margin, intertidal shoals. Of particular note was the interpretation of Eriksson and Truswell (1974a) that the character of stromatolites ruled out development of a physical barrier in the wave agitated zone, but Eriksson (1977) later disagreed with this earlier interpretation when he proposed a barrier in the wave-agitated zone. As previously mentioned, Truswell and Eriksson (1974) proposed that columnar stromatolites and elongate stromatolitic mounds characterize the subtidal regime. Following up this study, Eriksson (1977) suggested that giant stromatolitic mounds represent a lithofacies that accumulated in the subtidal-below-wave base regime. Beukes (1980b) disagreed with this interpretation in part and interpreted giant mounds as part of a subtidal reef along a *platform margin. However, Beukes seemed* to disagree with himself when he reported, in the same study, that giant subtidal mounds made up extensive parts of the shallow water carbonate platform sequence. Button (1976) envisaged that iron-formation accumulated in the previously mentioned, partially restricted lagoon, or as he termed restricted basin. Beukes (1983a, 1984) argued that sedimentological features did not support Button's interpretation of a high-energy environment for deposition of iron-formation. Based on regional correlation of stratigraphic units, Beukes (1983a, 1984) proposed a deeper water, open shelf environment, situated below-storm-wave base, for deposition of iron-formation. He also proposed that iron-formation was deposited by ferruginous carbonate turbidites (also termed rhythmites), which interfinger with pyritic carbonaceous shale, and that iron-formation was a distal lithofacies of the shallow water carbonate platform. Recently, Button (1986) acknowledged Beukes' interpretations when he suggested that iron-formation was deposited below-wave base on a flat, very extensive shelf.

Eriksson (1972) recognized two major cycles of sedimentation in the Potchefstroom area, which he attributed to alternating periods of transgression and regression. He was also the first to introduce the concept of cyclic sedimentation. Visser and Grobler (1972) constructed a model for cyclic tidal flat sedimentation, which was based on interpretations of regularly repeated conditions building up (shallowing upward) and partial destruction (drowning) of the tidal flat environment. Based on unconformity bounded packages in the eastern Transvaal, Button (1973a) proposed three "first order cycles", which he ascribed to transgression due to relative downward flexure (subsidence) of the basin margin. Subsequently, Button (1976) introduced the term "megacycle" for his three "first order cycles". In the northern Cape, Beukes (1977) identified cyclic sedimentation on a smaller scale and proposed that 1 to 6 m thick oolitic cycles represent progradational subtidal-intertidal deposits which were periodically interrupted by rapid transgressions. In a later study, Beukes (1984) also interpreted depositional cycles within distal iron-formation.

It is interesting that only a few studies attempted to address regional stratigraphic relationships or depositional patterns. Visser and Grobler (1972) suggested that early transgressions initially spread over only a small area and that subsequent transgressions covered most of the Kaapvaal Craton. Beukes (1977) proposed a similar pattern of transgression with the development of an initial shallow water siliciclastic platform; and with each transgression, siliciclastic source areas were progessively eliminated and carbonate cycles were deposited. Both Button (1973a, 1973b) and Beukes (1977) have envisaged that early transitions between siliciclastic and carbonate sedimentation filled pre-existing depressions and smoothed basement topography. Beukes (1983a) has also proposed that as deposition continued basement topography and structural highs and lows continued to be smoothed out. Button (1973a) reported that the eastern Transvaal is characterized by a greater portion of clastic sediment, that units of giant stromatolitic mounds are considerably thicker in the western Transvaal, and that prominent unconformities in the eastern Transvaal have no apparent counterpart in the western Transvaal. From these relationships, Button (1973a) proposed that the eastern Transvaal represents a more proximal location of deposition. Two other relationships are of regional interest:

1) Beukes (1980b, 1983a) pointed out that deposition of shallow water carbonates came to an end through a major transgression which spread the distal iron-formation over the craton; and 2) Button (1973a) suggested that basin expansion with time is the most striking feature of deposition.

An amusing aspect of these previous studies is the total disagreement among the various researchers on the situation of the basin margins. This disagreement is based on similar types of current-direction indicators within their various study areas referred to in Figure 2. Visser and Grobler (1972) used asymmetric domes and suggested that the basin margin existed east-northeast of Schmidtsdrif. Based on a northwest-southeast elongation of subtidal mounds, which they related to tidal currents acting at right angles to the paleoshoreline, Truswell and Eriksson (1975) proposed that the basin margin was located to the northwest of Johannesburg. Moreover, Beukes (1980b, 1983a, 1984) identified an east-west elongation direction for subtidal mounds in the northern Cape and suggested that the basin margin lay along the west-southwest edge of the preserved outcrop (Fig. 1).

It is interesting that most of the studies did make a few statements about syndepositional tectonics. Visser and Grobler (1972) pointed out that controls on the depositional environment could be divided into macro- and micro-influences and that the two were superimposed on each other. Macro-influences were controlled by tectonic forces in the crust, while micro-influences were due to current velocity, wave action, and sediment supply. Button (1973a) assumed that, if any differential crustal movements occurred in the vicinity of the depository, movements would be reflected by either introduction of siliciclastics or landward migration of carbonate lithofacies. Truswell and Eriksson (1973) suggested all interbedded shales occur at lithofacies contacts and assumed these shales represented temporary loss of carbonate equilibrium and accumulation due to mild tectonism. Beukes (1977) proposed that cyclic transgressions were the result of periodic, fault-induced subsidence and that cycles provide quantitative information on tectonic activity of the depository. Following Button's (1973a) lead, Eriksson (1977) pointed out that whether transgressive or regressive sedimentation predominates in any part of the depository was largely a function of tectonism. Recently, Button (1986) has suggested that throughout the various depositional cycles the tectonic framework of the Kaapvaal Craton remained essentially constant.

1.4 Research Question

Button (1973a) stated that basin expansion with time was the most striking feature of the Transvaal Sea. Basin subsidence is somewhat time dependent and termination of subsidence, rather than basin expansion, should be expected. Button's (1973a) statement, thus, became one of the major questions requiring explanation by this research. The statement also imposed the constraint that models (interpretations) have to be built and tested within a rational framework (Dewey, 1982), if the basin dynamics of the Transvaal Sea are to be understood.

Chapter 2

Lithofacies and Depositional Systems

2.1 General Statements

Since semantics lead to a great number of arguments among geologists, it is felt that clarification of the depositional systems approach, as used in this research, is necessary, and a number of definitions need to be established. Miall (1984) defined a depositional system as a complete package of environments and sedimentary products, which is bound by unconformities or by facies changes into adjacent, unrelated systems. This definition is rather restrictive because it does not allow for recognition of conformable units that pass laterally into penecontemporaneous unconformities. For this reason, the definition proposed by Mitchum et al. (1977) is preferred, whereby a depositional sequence or system is considered as a stratigraphic unit composed of a relatively conformable succession of genetically related strata, which is bound at its top and base by unconformities or their correlative conformities. In effect, this definition makes the depositional system a chronostratigraphic unit. It also provides a basis for recognition of progressive change, abrupt punctuation, and/or polyphase events within the stratigraphic record.

Basically, the depositional systems approach is an application of Walther's Law and the facies model concept as applied to large depositional tracts up to size of basins (Miall, *1984).* *It could be argued* that this is a lithostratigraphic approach, but in effect the depositional systems approach allows interpretations in terms of broad paleoenvironmental reconstructions without confusion of specific details. It should be emphasized that in this research specific details are not ignored, but are simplified in an attempt to establish the genetic stratigraphy of the Transvaal Sea. This simplification is inherent to the depositional systems approach because it was initially developed by the Texas Bureau of Economic Geology as a means of analyzing and interpreting great thicknesses of sediments in the Gulf Coast region of the United States (Brown and Fisher, 1977; Glaeser, 1979; Casey, 1980; Handford and Dutton, 1980).

2.2 Early Research Assumptions and Data Collection

Goodwin and Anderson (1985, p. 515) stated: "ideas precede detailed observations so that all observations are to a large degree made under the influence of some previously formulated hypothesis." The writer agrees with such an approach to data collection, and the following assumptions were made prior to the establishment of the data base of this study.

1) Strata, in general, would be termed carbonate regardless of whether or not the preserved lithology is dolomite or limestone and any chert associated with these carbonates is considered a diagenetic alteration product.

2) Characteristics of, and structural influences on, the Transvaal Sea could be established from macroscopically observable features, if such features are preserved.

3) Lack of gravity flows in front of shallow carbonate platform features, as pointed out by Beukes (1980a, 1983a), is indicative that the depositional platform was a carbonate ramp or some morphological variation of it as defined by Read (1985).

4) Growth-graded oolites were not transported, but formed in situ, and could be used as a paleodatum marker to separate subtidal from peritidal (intertidal) depositional environments.

5) A precise way of establishing whether or not the sea was expanding during a major depositional cycle is by mapping preserved marginal areas, if they can be identified (Watts et al., 1982).

6) The best record of vertical crustal movements is stored in the preserved strata and good rocks give good data (Beaumont, 1978; Nisbet, 1984).

From an inspection of Figure 1, it is clear that, regardless of these assumptions, the preserved strata covers a rather extensive area in the Transvaal and northern Cape Province. However, the strata are not deformed into a fold-thrust belt like many other Precambrian sedimentary sequences. Although it is highly eroded, the depository is considered to be in a more or less coherent form. Since these strata are part of the Kaapvaal Craton, which represents one of the oldest crustal blocks of the

African plate, paleogeographic reconstructions of a Proterozoic epeiric sea could be developed, if enough data could be collected.

Observations of borehole core provided the initial bulk of stratigraphic information because strata crop out poorly. Field mapping could not provide the fine points needed for paleogeographical reconstructions. Approximately 21,000 m of borehole core was logged in detail. Many boreholes were not continuous sequences and local stratigraphic sections had to be pieced together from a number of boreholes. An unknown amount of borehole core was also simply measured to confirm stratigraphic thicknesses between marker beds or reference surfaces before the stratigraphy of an area was accepted. In general, borehole core measurements were estimated to the nearest 0.1 m; measurements have since been rounded to the nearest 1 m. Detailed logging consisted of two types; and for lack of better titles, these are referred to as true graphic and summary. True graphic logging was performed on log sheets at either a 1:500 or 1:250 scale. Summary logging was neither on log sheets nor to scale and was slightly more interpretative than true graphic. It was used so that more borehole core could be reviewed to identify lateral stratigraphic variations once the unconformity bounded packages had been established. Where lateral changes were identified, true graphic logging was again used for descriptions. Both true graphic and summary logging also evolved from lithostratigraphic description to lithofacies interpretation as the logging progressed. Examples of logging and log sheets are presented in Appendix A.

General holes were logged where borehole core was available in both the eastern and western Transvaal, and in the northern Cape (Appendix A). In the Transvaal, measured geological profiles were continually compared against borehole core, and against each other. Geological profiles were established at Thabazimbi, Potgietersrus, Pilgrims Rest, Sudwala Caves, and in the vicinity of the Johannesburg Dome (Fig. 2). In addition, geological profiles were also established in the northern Cape at Vryburg, Middlerand, and Boetsap. Once a stratigraphic relationship was identified in borehole core, it was checked against surface outcrop so that a larger, three-dimensional picture of the marker bed or reference surface could be developed. In turn, features were identified in surface outcrop, which had not been recognized in the borehole core, e.g. sand-filled channels along particular unconformities. Observations were taken back to the borehole core in particular areas to further clarify regional relationships.

2.3 Carbonate Lithologies

Carbonate petrology has not been presented in any detail in previous literature on the Transvaal Sea. The reason for this may stem from the conclusion of Truswell and Eriksson (1972), that the carbonates were essentially a stromatolitic rock. As a consequence, subsequent studies focused primarily either on the morphology of the stromatolites or on their paleoenvironmental controls. Lack of both carbonate petrology and an understanding of carbonate depositional processes may be the reason why, as late as 1986, Transvaal Sea carbonates have been referred to simply as chemical sediments (Beukes, 1986; Button, 1986). Elsewhere, Klein et al. (1987) have subsequently introduced terms from Folk's (1962) classification. However, terms such as micritic dolomite and intramicsparite do not generate mental pictures of carbonate lithologies as quickly as they bring to mind P. D. Krynine's statement (as reported in Miall, 1984) of the triumph of terminology over common sense.

If carbonates are viewed as <u>in situ</u> clastics, instead of chemical sediments, a new set of parameters can be used to understand them. Many earlier studies discussed the possible influence that marine, hydraulic energy conditions may have had on the depositional environments. Although they did not elaborate on these aspects, Visser and Grobler (1972) suggested that depositional energy level was a principal control on the various depositional environments. The term energy level was first proposed by Plumley et al. (1962), who suggested it as a measure of kinetic energy, produced by either wave or current action, which exists in the water at or a few meters above the depositional interface. Hence, the concept of depositional energy level becomes important because once a carbonate grain, regardless of whether it was formed chemically or biochemically, touches the depositional interface it is subject to all of the physical forces in the sea. The pounding of waves and tides breaks the grain into a number of *size fractions*. These size fractions are simply spread over the sea floor as clastic *fragments* by current action, with finer fractions being transported progressively further away from the highest energy level (Irwin, 1965).

Dunham (1962) termed the physical forces, which winnow the carbonates, "currents of removal" and proposed a carbonate classification based on texture that systematically characterizes carbonate lithologies in terms of depositional energy level. Dunham's (1962) classification is shown in Figure 3 and is based on the fundamental distinction that carbonate sediment deposited in calm water (mudstone) is different from carbonate sediment deposited in agitated water (grainstone). The sediments produced are different because under calm water conditions carbonate mud is able to settle to the depositional interface and remain there; while under agitated water conditions, the *carbonate sediment* is winnowed and coarser carbonate grains accumulate to form grain*stones*. *The relative proportion* of carbonate grains or clasts allows lithologies which contain mud to be subdivided into energy levels. Dunham (1962) also distinguished textures which show signs of binding during deposition (boundstone); he emphasized difference between these lithologies and those originally made up of loose grains.

Dunham's classification was originally proposed for microscopic work, but it was found that his lithological textures could be easily recognized macroscopically with aid a 7X hand lens. To maintain consistency with the classification scheme,

DEPOSITIONAL TEXTURE				
Original components not bound together during deposition				Original components were bound together during deposition as shown by intergrown skeletal matter, lamination contrary to gravity or sediment-floored cavities that are roofed over by organic matter
Contains mud (particles of clay and fine silt size)			*Lacks mud* and is grain supported	
Mud supported		Grain supported		
Less than 10 per cent grains	More than 10 per cent grains			
Mudstone	Wackestone	Packstone	Grainstone	Boundstone

Figure 3. Dunham's classification of carbonate lithologies based on depositional energy level. (After Dunham, 1962)

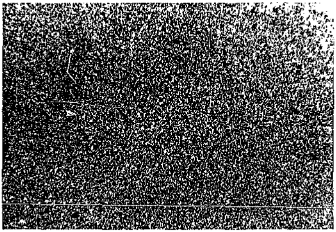

Figure 4A. Photomicrograph of carbonate mudstone showing less than 10 per cent grains. (Magnification 10X)

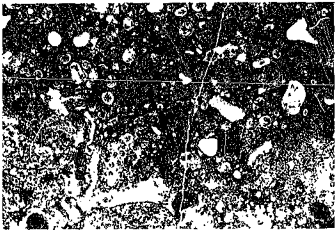

Figure 4B. Photomicrograph of carbonate wackestone showing greater than 10 per cent mud-supported grains. (Magnification 10X)

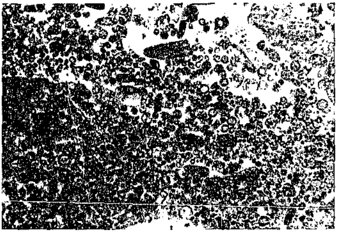

Figure 4C. Photomicrograph of carbonate packstone showing grain support and minor mud. (Magnification 10X)

Figure 4D. Photomicrograph of oolitic grainstone showing grain support. (Magnification 10X)

Figure 4E. Photomicrograph of boundstone texture. (Magnification 10X) field observations were compared with thin sections. Photomicrographs of Transvaal Sea carbonate rock textures are shown in Figures 4A, B, C, D, and E. It soon became apparent, however, that the classification scheme could be considered in terms of three end members: mudstone, grainstone, and boundstone. Such a simplification allowed rapid interpretation of depositional energy levels during examination of thousands of meters of borehole core. Probably the greatest advantage of the modified classification scheme was that it also facilitated subdivision of boundstone lithologies into depositional energy levels based simply on associated unbound lithologies, i.e. mudstone or grainstone, and an application of Walther's Law. These relationships are discussed in the following section.

2.4 Boundstones and Associated Lithologies

During the past 15 years, studies of "algal stromatolites" have firmly established that they can be used to delimit broad subdivisions of terrains and to provide paleoenvironmental information. In this research, the term boundstone is used to describe "stromatolitic" textures which were bound together during deposition. Aitken (1967) proposed the term "cryptalgal" for similar textures which result from sediment-binding activities of "blue-green algae". Recent paleobiological studies have revealed that the true sediment-binding engineers of such boundstone textures, or simply mats, are bacteria and cyanobacteria (formerly called "blue-green algae") (Monty, 1984). Since these findings were published, there has been a subtle retreat from reference to algae in regard to these boundstones.

Boundstone fabrics have a number of subtypes. When they are associated with their unbound lithologies, boundstones are true energy level indicators of paleoenvironment. Logan et al. (1974) suggested that, on tidal flats with gentle gradients, a broad zonation of mats (boundstones) can develop; they described distinctive fabrics associated with particular mats from the peritidal habitat of the Hamelin Pool, Shark Bay, Australia. It is pertinent that Proterozoic mats had no predators and that colonization was able to take place from the peritidal to the *basinal marine* settings (Monty, 1984). The only exception to total colonization was within the highly agitated, subtidal-*above-wave base zone because mats* could *not* develop on an unstable substrate (James, 1979).

With the realization that virtually *total colonization* could occur, boundstone fabrics were carefully examined in the field so that features could be identified in core when a *three*-dimensional picture was not available. Recently, Pratt and James (1982) clarified boundstone fabric descriptions. Based on their suggestions, a boundstone having a stromatolitic fabric refers to one that is internally laminated (Fig. 5A), while thrombolitic fabric refers to one that lacks any distinct laminations (Fig. 5B). Logan et al. (1974) used mats and fabrics somewhat interchangeably; and because of this, several of their mat types are used here solely as fabric terms. Of the seven mat-fabrics

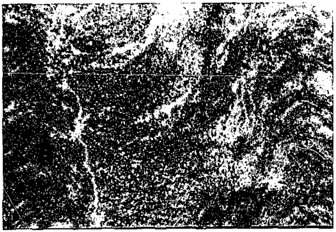

Figure 5A. Photomicrograph of stromatolitic boundstone fabric showing internal laminations. Packstone fills in between boundstone columns. (Magnification 10X)

Figure 5B. Photomicrograph of thrombolitic boundstone fabric with vague internal laminations. Packstone fills in between boundstone columns. (Magnification 10X)

Figure 6. Small peritidal, stromatolitic boundstone dome showing smooth fabric in Lyttelton-Eccles depositional system near Pilgrims Rest.

Figure 7. Cross sectional view of tufted boundstone mat developed by elongate subtidal mounds in Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

Figure 8. Small, peritidal, thrombolitic boundstone dome developed by pustular mat in the Lyttelton-Eccles depositional system north of Thabazimbi. (Coin is 3 cm in diameter)

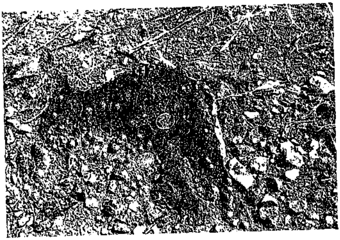

Figure 9. Stromatolitic boundstone showing blister mat texture of supratidal smooth mat in the Lower Lyttelton grandcycle north of Potchefstroom. (Coin is 3 cm in diameter)

Logan et al. (1974) described, only three have been identified with regular consistency and these have been used as sub-types of either stromatolitic or thrombolitic fabrics. Two of the three are stromatolitic sub-types and are either a smooth fabric with a regular lamination (Fig. 6) or a tufted fabric with a scalloped lamination (Fig. 7). The third is a thrombolitic sub-type that has a pustular fabric with a matted and unlaminated appearance (Fig. 8). An additional planar stromatolitic sub-type was subsequently added to this scheme. This sub-type displays a smooth fabric with a blister-like morphological expression (Fig. 9).

Inability of mats to colonize the wave-agitated zone provides a practical paleodatum marker for the separation of peritidal and subtidal boundstone depositional environments. This paleodatum marker also indicates the energy level progression for the associated unbound lithologies in both a landward or basinward direction (Fig. 10). Starting from the high-energy zone, this progression of unbound lithologies in either direction is grainstone, packstone, wackestone, and mudstone. Combining the boundstone fabric criteria with the unbound lithology progression (Fig. 11), landward boundstone associations away from the high-energy grainstones are: smooth stromatolitic boundstone with ripple-laminated grainstone, followed by pustular thrombolitic boundstones with packstone-wackestone, and finally planar stromatolitic boundstones associated with mudstones. In a basinward direction, the associated sequence is reversed. Smooth stromatolitic

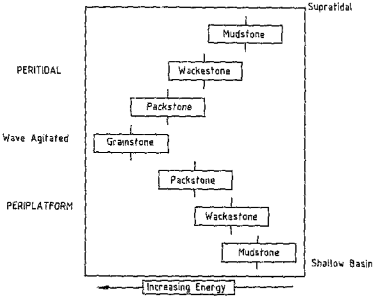

Figure 10. Relationships of unbound lithologies in a landward and a basinward direction.

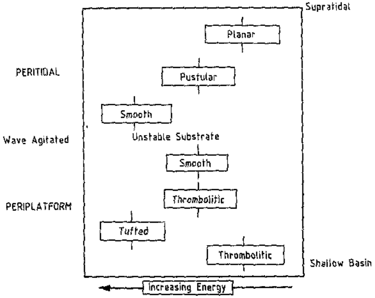

Figure 11. Relationships of mat types to depositional energy level from supratidal to shallow basin.

boundstones associated with packstone-wackestones are replaced by thrombolitic boundstones associated with wackestone-mudstone, followed by tufted stromatolitic boundstones associated with ripple-laminated grainstones, and finally thrombolitic boundstones associated with mudstone-carbonaceous shale. Association of ripple-laminated grainstones with subtidal, tufted stromatolitic boundstones is an indication that currents at the depositional interface, in either "shallow" or "deep" water, can produce textures similar to those produced by wave turbulence at the same energy level (Plumley et al., 1962). These macroscopic relationships and application of Walther's Law form part of the basis for the identification of a facies assemblage.

2.5 Carbonate Ramp Identification

One of the early assumptions in this research was that depositional patterns were influenced by a carbonate ramp or a morphological variation thereof. This assumption was based on interpretations by Beukes (1977) that gravity flow deposits are not present seaward of shallow platform carbonates and that early tidal flats faced an open ocean. Such an assumption is critical to the identification of a facies arrangement based on depositional energy level. The reason is that carbonate platforms can be divided into either ramps or shelves as shown in Figure 12. Primary difference between these two types of platforms is the presence or absence of a distinct break-in-depositional slope. A break-in-depositional slope determines whether or not gravity flow deposits accumulate seaward of the

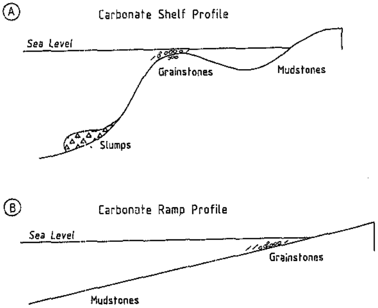

Figure 12. Cartoons showing the difference between the profiles of carbonate shelves and ramps. (No scale)

shallow platform (Fig. 12A) This may seem somewhat arbitrary, but a break-in-depositional slope is generally a shoaled barrier of some kind. Presence or absence of such a barrier determines whether or not landward facies are subject to open ocean depositional energy levels and, therefore, essentially controls the arrangement of shallow lithofacies.

On ramps, landward facies are subject to open ocean conditions; arrangement of shallow facies developed on a ramp are opposite to those developed on a shelf (Ahr, 1973). On a ramp, high-energy grainstones and packstones are deposited landward of mudstones (Fig. 12B); while on a shelf (Fig. 12A), mudstones are deposited landward of shelf-margin grainstones and boundstones due to the presence of the barrier (Ahr, 1973). If platform character can be predicted at an early stage of the analysis, facies arrangement, which characterizes that type of platform, is somewhat pre-determined.

A review of some of the previous work is considered necessary so that distinction between platform types, as applied to the Transvaal Sea, can be understood. Platform models, which are proposed and applied here, are on a broad basis because they were originally established for depositional patterns that characterize Atlantic-type passive margins, rather than epeiric seas. This lack of distinction has erroneously led previous workers to locate basin margins only on local paleoenvironmental data without considering the regional overview. Such models have produced only two-dimensional reconstructions of the Transvaal Sea, which accommodate lateral and vertical lithofacies changes similar to passive margin models. However, in the study of an epeiric sea, the third dimension, which includes the size and shape of the sea's depository during its evolution, must also be considered. Several previous workers have in fact misinterpreted Irw ' (1965) epeiric sea model. This misinterpretation is embodied in Truswell and Eriksson's (1975, p. 295) statement that "oolitic rocks are considered to be an approximation to the bar or barrier of Irwin's (1965) limestone shelf model." Although Irwin . p. 452) mentioned a physical barrier, he did not imply that such a barrier had necessarily to exist; he was discussing how the presence of such a barrier would affect depositional energy and sedimentation zones. These misconceptions have led to interpretations that a lagoon developed as the Transvaal Sea evolved (Truswell and Eriksson, 1975; Beukes, 1980a, 1983a) and have given rise to the impression that the Transvaal Sea was nothing more than an oversize puddle!

In order to clarify the neglected third-dimension of the Transvaal Sea, it was important to establish depositional patterns that develop on a ramp-like platform. Wilson (1975) expanded Ahr's (1973) concept of a ramp into three-dimensions by explaining that sedimentation on a ramp built huge carbonate "bodies" away from positive areas down gentle regional paleoslopes without a pronounced break-in-slope, and that facies patterns were apt to be wide, irregular belts with the highest energy zone close to shore. This explanation is believed to be adequate for explaining depositional patterns in Proterozoic epeiric seas, if depositional paleoslopes can be established.

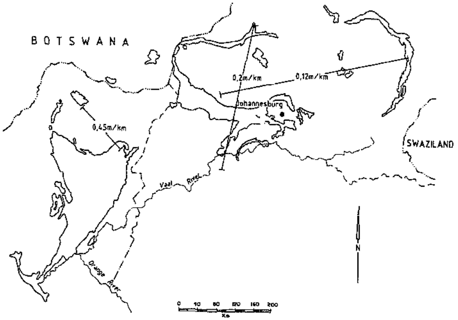

Figure 13. General map showing the location of the lines used to calculate depositional slope of the Transvaal Sea.

With mats capable of total colonization, except over unstable substrate, application of Walther's Law is not readily applicable in this situation because boundstone fabrics developed in the shallow subtidal could be indistinguishable from boundstone fabrics developed in landward peritidal zones.

Irwin (1965) explained that the determination of depositional slopes is straightforward; calculations are based on paleodatum surfaces which were time equivalent. Two closely spaced unconformities in the Transvaal and another two unconformities in the northern Cape were used for the basis of calculations. Since the sedimentary packages in the Transvaal thinned from south to north and from west to east and in the northern Cape from southeast to northwest, paleoslopes were calculated along the three lines shown in Figure 13. The preserved outcrop pattern in the Transvaal allow paleoslope calculations to cover a 340 km south to north distance and a 450 km west to east one. In the northern Cape, the paleoslope calculation covers only a projected linear distance of 125 km. In the Transvaal, a paleoslope of 0.2 m/km to the south exists along the south to north line, while the paleoslope along the west to east line is slightly flatter at 0.12 m/km to the west. In the northern Cape, the southeast to northwest paleoslope is strikingly different to those in the Transvaal; it is twice as steep at 0.45 m/km to the southeast. Several more calculations were made to check for any variations in the paleoslopes over preserved outcrop area. These shorter calculations were made over areas where lithofacies changes are known to occur and were

Table 1. Facies classification of the Transvaal Sea.

Depositional Position	Basin (Deep Water →)			Ramp (← Shallow Water)					Flat			
Facies	Basinal			Periplatform					Peritidal		Shallow Siliciclastic	
Subfacies	Deep Basinal	Shallow Basinal		Submerged Shelf		Shoaled Flat			Emergent Peritidal	Shallow Peritidal	Tidal Flat	Fluvial
Detail Position	Deepest part of Basin	Shoaled Basin	Toe of Ramp to Shoaled Basin	Lower to Upper Middle Ramp	Upper Middle to Shoaled Ramp	Lower Shoaled Ramp	Lower to Upper Shoaled Ramp	Upper Shoaled Ramp	Emergent Ramp	Ramp Margin	Shoaled to Emergent Ramp	Ramp Margin
Lithofacies	Banded Iron-Formation	Shale Mudstone *	Thrombolitic Shale *	Tufted Thrombolitic Mound	Columnar Stromatolitic	Planar Laminated *	Ripple Laminated	Oolitic	Domal Boundstone	Evaporitic Mudstone *	Siliciclastic	
Contact with Shallower Lithofacies	Gradational	Arbitrary	Abrupt	Gradational	Abrupt	Gradational	Gradational	Erosional	Abrupt to Gradational	Unknown	Abrupt	Unknown
Dominant Grains	Brown-Intraclasts Chert Clasts	Gray & Brown-Intraclasts [Minor Oolites]	Gray & Brown-Intraclasts Oolites Boundstone-Lithoclasts	Brown-Intraclasts	Wackestone-Lithoclasts Oolites	Gray & Brown-Lithoclasts [Minor Oolites & bound lithoclasts]	Brown-Intraclasts	Oolites Brown-Intraclasts	Oolites Brown-Lithoclasts [Minor Qtz Arenite]	Gray-Intraclasts [Minor Qtz Arenite]	Sorted Qtz Arenite [Local Chert & Volcanic Pebbles]	Sorted Qtz Arenite [Local Qtz Gravel-Cobbles Chert Clasts]
Associated Unbound Lithologies	Mudstone Wackestone (Turbidites)	Mudstone [Minor Wackestone]	Mudstone [Minor Wackestone]	(Channel Fill) Sorted Grainstone Packstone	Oolitic Wackestone [Minor Packstone]	Packstone Wackestone	Grainstone Packstone	Grainstone	Grainstone to Wackestone	Mudstone		
Boundstone Character			Biohermal Thin-Biostromal	Biostromal	Biostromal	Random Mound			Individual to Laterally linked Domes	Thin Planar Biostrome		
Bedding	Thin Rhythmic	Thin Rhythmic Alternating Shale and Mudstone	Thin Bedded Alternating Mudstone-Boundstone & Shale	Medium to Massive	Medium	Thin to Medium	Thin to Medium Cross-laminated	Thin to Medium Reverse graded	Medium Cross-laminated	Thin to Medium	Medium Cross-laminated	Thick
Tidal Range	Subtidal Below Storm Wave Base	Subtidal Below Wave Base and Below Active Current Flow		Subtidal Below Wave Base in Active Current Flow		Subtidal Above Wave Base			Low- to High-Intertidal	High-Intertidal to Supratidal	Subtidal Above Wave Base to High-intertidal	Supratidal and Above
Energy Level	Low to Turbidite	Low to Turbidite	Low to Medium	Medium to High	Medium	Medium	Medium to High	High	High to Medium	Low	High to Medium	
Weathering Color	Alternating Red-Brown to White	Light Gray Brown Mudstone Dark Gray Shale	Brown Mudstone Boundstone Dark Gray Shale	Dark Brown	Dark to Light Brown	Light Brown to Light Gray	Light Gray to Buff White	Light Gray to Buff White	Light Gray to Light Brown	Light Gray	Light Yellow to Orange	Light Yellow

calculated to verify paleoslope control on lithofacies distributions. The northern half of the south to north Transvaal line shows paleoslopes in the order of 0.15 m/km to the south, while a steeper paleoslope of 0.36 m/km to the south occurs on the southern end of the line. The northern Cape line was also shortened and the shorter line shows an even steeper 1.2 m/km slope to the southeast.

Although depositional slopes varied somewhat between the Transvaal and the northern Cape, all calculations show relatively gentle slopes well within the one to a few meters per kilometer range proposed by Read (1985) for homoclinal ramps. It is also interesting that the calculated Transvaal depositional slopes are consistent with Irwin's (1965) approximation that epeiric sea bottoms had paleoslopes of less than 0.19 m/km. These calculations tentatively verify that the Transvaal Sea was an epeiric sea and that a ramp-type platform model, or some morphological variation thereof, could be applied to the development of a facies arrangement.

2.6 Facies Assemblage and Arrangement

Four facies, eight subfacies, and eleven lithofacies have been identified. These are listed with other related features in Table 1. The eleven lithofacies were established from the inferred depositional energy level; stars in four pigeonholes of Table 1 denote lithofacies that have not been previously

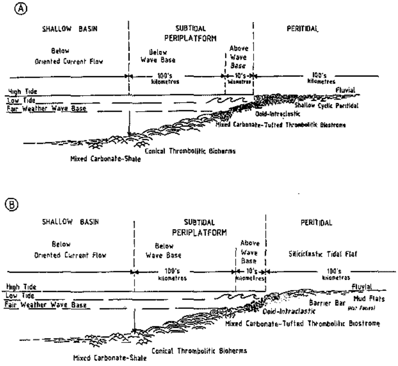

Figure 14. Cartoons of simple carbonate ramps developed in the Transvaal Sea.

Figure 15. Fluvial *facies channel* which erodes into regional unconformity developed on the top of the Lower Monte Christo depositional system, west of Thabazimbi. Re-worked chert clasts can be seen in channel fill.

discussed in the literature. Interrelationships influencing a particular facies can be somewhat involved and Table 1 represents a summary of a combination of numerous macroscop: -microscopic observations and interpretations. Table 1 is simplified and its data are explained with the use of two sketches of a two-dimensional ramp (Figs. 14A, B). However, it must be understood that these sketches are no more than cartoons of three-dimensional depositional patterns.

From shallowest to deepest, the four facies are namely, shallow siliciclastic, peritidal, periplatform, and basinal (Table 1; Figs. 14A, B). [illegible] llow siliciclastic facies may seem somewhat out of pla [illegible] cussing a carbonate depository, but it has been [illegible] ized previously as an integral part of the Transvaal Sea (Button, 1973a; Beukes, 1977) and cannot be ignored because of its lithological composition. This facies is subdivided into tidal flat and fluvial subfacies; subdivision is based on both energy level and sediment character. Fluvial subfacies varies in character through time from deeply-cut, conglomerate-filled gorges or troughs to meandering, quartzarenite-filled channels. Both of these fluvial characteristics have been recognized only in the Transvaal where they mark transitions or erosional unconformities. The conglomerate-filled troughs developed on the surface underlying the initial siliciclastic-carbonate transition; in some places, troughs carry economically exploitable gold concentrations. Quartzarenite-filled channels erode several higher unconformities. In several places, e.g. Thabazimbi and Potgietersrus,

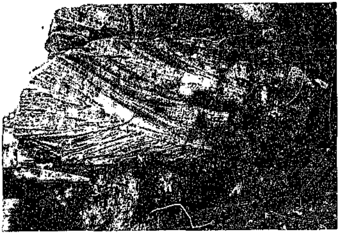

Figure 16. Trough cross-laminated quartzarenite of the tidal flat subfacies in the Upper Oak Tree depositional system along road cut near Sudwala Caves.

Figure 17. Desiccation cracks developed in the tidal flat subfacies of the Lower Lyttelton grandcycle north of Pilgrims Rest

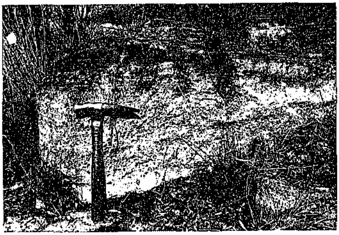

Figure 18. Small outcrop of the Vryburg depositional system showing a variety of matrix-supported clasts that characterize it south of Vryburg.

they rework chert clasts remaining on the erosional surface (Fig. 15). Channels are seldom over 3 m deep, but they may be greater than 150 m in width. Although individual channels could not be traced due to preserved outcrop pattern, channels on a particular unconformity were identified for over 225 km in a north-south direction from Thabazimbi to near Potchefstroom in (Fig. 2). Macroscopically, quartzarenite channel-fill consists of well sorted, rounded to well-rounded quartz grains that have a fairly uniform texture. Thin sections show the quartzarenite to be highly recrystallized due to an allotriomorphic overgrowth of secondary quartz.

Tidal flat subfacies is developed periodically throughout the carbonate succession and marks depositional transitions. This subfacies is generally composed of blanket-like, fining-up cycles which are typically trough cross-laminated (Fig. 16). Desiccation cracks, associated with interbedded argillaceous layers, substantiate its tidal flat character (Fig. 17). Locally, giant sand waves, herringbone cross-stratifications, or a variety of ripple laminations may be developed. The abrupt appearance of this subfacies in the carbonate succession indicates its landward position of the carbonate depository. Quartzarenite, which dominates this subfacies, is characterized by texturally mature, rounded to well-rounded quartz grains and is quite similar to fluvial subfacies quartzarenite. The subfacies is slightly different where it is developed below the

Figure 19. Pseudomorphs of salt hoppers developed in the evaporitic mudstone lithofacies in the Lyttelton-Eccles *depositional system south of Reivilo.* (Coin is 3 cm in diameter)

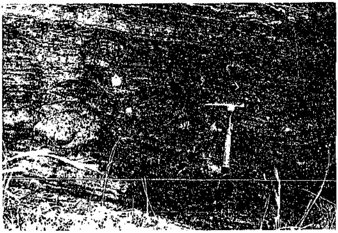

Figure 20. Small outcrop of peritidal stromatolitic boundstone in the Lower Lyttelton grandcycle north of Thabazimbi.

Figure 21. Small outcrop of desiccated, pustular thrombolitic domes in the Lower Lyttelton grandcycle north of Potchefstroom.

initial siliciclastic-carbonate transition and contains clasts of vein quartz, chert, and/or volcanic pebbles, as well as re-worked quartzarenite lithoclasts (Fig. 18).

The peritidal facies lies seaward of shallow siliciclastic facies; contacts between them appear to be somewhat abrupt. However, contacts are considered somewhat gradational, since minor amount of quartzarenite continues to be present both in emergent and in shallow peritidal subfacies (Table 1, Fig. 14A). Evaporitic mudstone lithofacies of the shallow peritidal subfacies is not always developed; but when it is, the lithofacies is characterized by a uniformly textured mudstone with randomly scattered salt hoppers (Fig. 19) or by thin biostromal beds of planar stromatolitic boundstone (Fig. 9). The shallow peritidal subfacies seems to develop locally at the expense of tidal flat subfacies and may represent areas of restricted circulation or periods of low siliciclastic influx. Emergent subfacies has been well described in the literature because of its similarity to Shark Bay (See Logan et al., 1974). It is characterized by individual and laterally linked boundstone domes, which may be 60 to 70 cm in diameter and which have between 30 to 50 cm of synoptic relief (Fig. 20). Smooth fabric domes are closely associated with oolitic grainstone and lie seaward of pustular fabric domes of similar dimensions. Locally, desiccated pustular fabric domes grade vertically into thin planar stromatolitic biostromes (Fig. 21). Between the boundstone domes, ripple-laminated grainstones, edgewise conglomerate, and oolites may accumulate.

The periplatform facies represents an extensive transition between the peritidal and basinal facies (Fig. 14). Due to its transitional nature through the highest energy levels developed on the ramp, the facies is the most complex of the three carbonate facies identified. Based on energy level, the facies can be subdivided into shoaled flat and submerged shelf subfacies (Table 1). These two subfacies have a rather abrupt contact that is indicated by the change from stromatolitic boundstones of the submerged shelf subfacies into planar laminated packstone-wackestones of the shoaled flat subfacies. The entire shoaled flat subfacies was continuously subjected to slightly agitated bottom conditions even though small, asymmetric, mound-like clusters of stromatolitic boundstone develop in planar-laminated lithofacies (Fig. 22). Oolitic lithofacies formed near mean low tide where wave energy is greatest (Reineck and Singh, 1975) and appears also to have an abrupt contact with the emergent peritidal subfacies (Table 1). Microscopic examination of this abrupt contact reveals it to be, in fact, erosional (Fig. 23).

Recognition of an abrupt erosional contact separating these two adjacent lithofacies, together with growth-grading of the ooids makes the oolitic lithofacies an ideal paleodatum marker. Growth-grading results from growth characteristics of ooids and has been referred to as reverse-grading (Fig. 24). Since carbonates are considered here as <u>in situ</u> clastics, the following brief explanation of ooid growth is provided. Once seed ooids form, regardless of whether they are of chemical or biological origin, they come to rest on the depositional interface and are

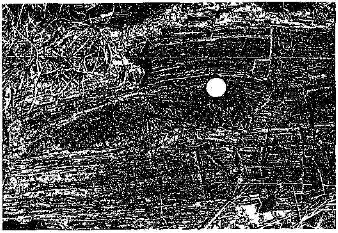

Figure 22. Asymmetrical boundstone mound developed in the planar laminated packstone *lithofacies in the Duitschland depositional* system north of Potgietersrus. (Coin is 3 cm in diameter)

Figure 23. Photomicrograph of the erosional contact between the shoal flat and emergent peritidal subfacies in the Lower Lyttelton grandcycle. (Magnification 30X)

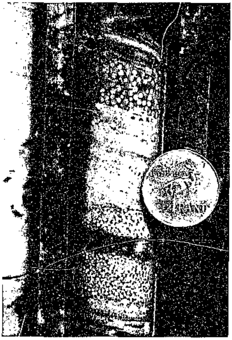

Figure 24. Growth-graded oolitic grainstone in core from near Reivilo. (Coin is 3 cm in diameter)

partially buried. As tidal energy levels increase, some of these seed ooids are exhumed and are rapidly coated by another layer of carbonate (Weyl, 1967). Since a decreasing proportion of ooids are continually exhumed following each growth cycle, growth-grading results because only the exhumed proportion receives any additional precipitate. Current transport seems to sort ooids; growth-grading indicates that little or no transport has occurred and that growth-graded ooids formed where the texture is identified. The presence of this texture is an ideal paleodatum marker for two other reasons. First, peritidal and periplatform boundstone fabrics are difficult to distinguish when their associated unbound lithologies cannot be identified. Secondly, ripple-laminated grainstones may also form in the submerged shelf subfacies, as well as in the wave-agitated, shoaled flat subfacies. Transvaal Sea ooids may reach 2 mm in diameter before new, 0.3 mm, seed ooids form and the growth cycle is repeated.

The contact between oolitic and ripple-laminated lithofacies of the shoaled flat subfacies is gradational. In most cases, it is assigned where ooids can be macroscopically identified. In the field, the ripple-laminated lithofacies is quickly identified by climbing ripple-laminations and a uniform texture (Fig. 25). Microscopically, the lithofacies is made up of well-sorted brown intraclasts which are approximately 0.2 mm in diameter; there is a noticeable absence of interspersed ooids in this cross-laminated grainstone (Fig. 26). However, sorted ooids have been identified both in interstratified layers and resting in ripple

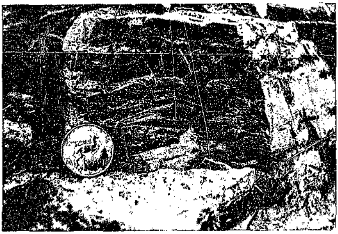

Figure 25. Climbing ripple-laminations characteristic of ripple-laminated lithofacies along road cut near Sudwala Caves. *(Coin is 3 cm in diameter)*

Figure 26. Photomicrograph of ripple-laminated grainstone. (Magnification 10X)

Figure 27. Small lens of transported oolites lying in trough of ripple-laminated grainstone in the ripple-laminated lithofacies in core from near Potchefstroom. (Coin is 3 cm in diameter)

cusps (Fig. 27). The contact between ripple-laminated and planar-laminated lithofacies is also gradational. In the field, the two lithofacies are simply grouped together as laminated grainstone. However, planar-laminated lithofacies is distinctive because of its laminations and because of the local development of boundstone mounds (Fig. 22). Microscopically, this lithofacies it is a wackestone-packstone in character (Fig. 28), which indicates decreasing energy levels in deeper portions of the shoaled flat subfacies. Near its contact with the ripple-laminated lithofacies, packstones, which contain oolites, replace slightly wavy-laminated grainstones and there is frequently an appearance of both sub-rounded grains, which do not appear to be well-sorted, and gray intraclasts. Near the contact with the deeper submerged shelf subfacies, the lithofacies contains thin, alternating stratifications of packstone, which carry seed-size oolites, and wackestone, which contains a mixture of oolites, gray intraclasts, and boundstones lithoclasts. Packstone stratifications are also slightly wavy in character while wackestones are planar. Appearance of wackestone implies that mud was able to remain in the lower limits of this depositional environment and that grains and clasts were being transported in both landward and seaward directions.

Submerged shelf subfacies of the periplatform facies has been extensively studied and a subtidal-below-wave base depositional environment for its two lithofacies is well established (Truswell and Eriksson, 1972, 1973). However, several aspects of the subfacies were re-examined in terms of

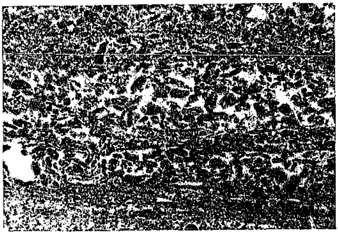

Figure 28. Photomicrograph of wackestone-packstone depositional texture in the planar laminated *lithofacies. (Magnification 10X)*

Figure 29. Columnar stromatolitic boundstone biostrome developed in the Lyttelton "ccles depositional system near Boetsap.

Figure 30. Chevron-shaped, columnar stromatolitic boundstone biostrome developed in the Lyttelton-Eccles depositional system northwest of Reivilo.

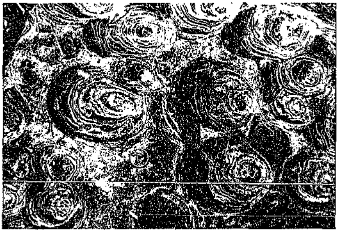

Figure 31. Asymmetrical, columnar stromatolitic boundstones lean into easterly directed paleocurrent in the Boomplaas depositional system east of Middlerand. (Coin is 3 cm in diameter)

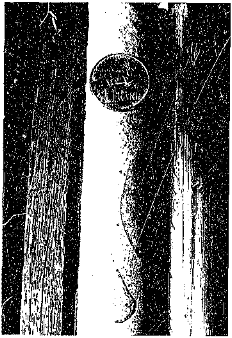

Figure 32. Wackestone filling in around columnar stromatolitic boundstone in core from near Reivilo. (Coin is 3 cm in diameter)

depositional energy level so that previous interpretations could be verified. Both lithofacies of the submerged shelf subfacies develop extensive biostromes (Table 1; Fig. 14); biostromal character may be the reason that this subfacies has been previously interpreted as reef-like in character. Columnar stromatolitic lithofacies is generally made up of individual, club-shaped columns that have approximately 50 cm synoptic relief (Fig. 29); chevron-shaped columns with only few a centimeters of synoptic relief and a meter of inheritance have also been identified (Fig. 30). Locally, columns are asymmetric and can be used as paleocurrent indicators because asymmetry develops where columns lean seaward into the current flow (Fig. 31). Macroscopically, infill between columns appears to be a gray intraclastic wackestone (Fig. 32); microscopic examination of these mud-supported clasts reveals them to be lithoclasts of planar-laminated lithofacies (Figs. 28; 33). These eroded lithoclasts, which may be up to 3,0 mm in size, are angular to subrounded and are considered evidence of short transport distances between the two adjacent lithofacies (Table 1).

The contact between columnar stromatolitic and tufted thrombolitic mound lithofacies is transitional and is characterized by the development of narrow thrombolitic columns, above tufted fabric mats, that transform rapidly upwards into equal sized columnar stromatolitic columns (Fig. 34). The general elongate shape of tufted mounds is maintained during this transition, but both types of transitional columns trap packstone sediment between them (Figs. 5A, B). These features indicate the

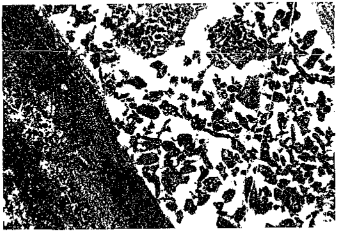

Figure 33. Photomicrograph of wackestone that fills in between columnar stromatolitic boundstone. Intraclasts in mudstone matrix are of planar laminated lithofacies. (Magnification 10X)

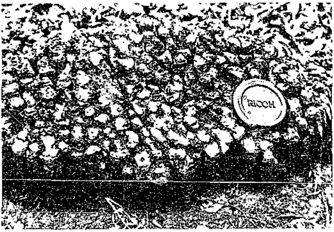

Figure 34. Thrombolitic columns developed on the upper surface of an elongate subtidal mound in the Upper Monte Christo depositional system west of Thabazimbi.

Figure 35. Three dimensional view of elongate subtidal mounds developed in the tufted thrombolitic mound lithofacies. Subtidal mounds colonize vi:tually all available space and develop an extensive biostrome. Elongation direction is east-west in the Lyttelton-Eccles depositional system near Boetsap. Small arrow points to rock hammer used for scale.

Figure 36. Cross sectional view showing inheritance of elongate subtidal mound developed in the tufted thrombolitic mound lithofacies in the Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

transitional character of the contact because the mound shape is characteristic of the deeper submerged shelf, while the sediment-trapping process described above is characteristic of shallower portions of the submerged shelf. Large, elongate, tufted fabric mounds attempt to colonize all available space within the depositional environment below the transition (Figs. 14; 35). Elongation of mounds is indicative of a strong current flow and develops parallel to the direction of current, which is generally normal to the shoreline in these depositional environments (Gebelein, 1969). An individual mound is made up of tufted stromatolitic boundstone layers and can be up to 55 m in length, 12 m in width, and 15 m in inheritance (Figs. 35; 36). The term inheritance is used instead of height because synoptic relief on an individual growth layer is only 30 to 50 cm (Fig. 37). This lithofacies might be described as low-amplitude, high inheritance biostrome made up of elongate mounds which were shaped by an active, oriented current flow. Channels, filled with ripple-laminated grainstone, strike parallel to the elongation direction of mounds and these channels can be 2 to 4 m wide and 3 m thick (Fig. 38). In most cases, mounds develop over underlying channels and this mega-encapsulation of channels by tufted fabric mounds may be the reason that the associated grainstone lithology has not been recognized previously. It is interesting that only one or two channels can be identified in an outcrop of tufted mounds. Channel-fill (Fig. 39) has the general characteristics of the ripple-laminated lithofacies. In borehole core, the two are difficult to distinguish. Use of the oolitic

Figure 37. Small cusp which indicates low amplitude of synoptic relief of elongate subtidal mounds developed in the Lyttelton-Eccles depositional system near Boetsap.

Figure 38. Ripple-laminated grainstone channels developed in Lyttelton-Eccles depositional system along road cut near Sudwala Caves. Encapsulated channel can be seen in the upper right.

Figure 39. Close up of ripple-laminated grainstone which fills channels between elongate subtidal mounds in the Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

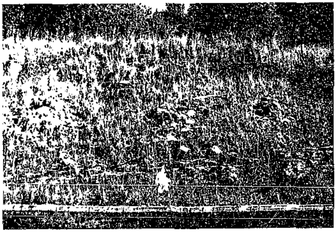

Figure 40. Small outcrop of conical thrombolitic boundstone bioherms developed in the Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

Figure 39. Close up of ripple-laminated grainstone which fills channels between elongate subtidal mounds in the Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

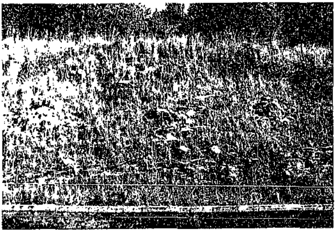

Figure 40. Small outcrop of conical thrombolitic boundstone bioherms developed in the Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

paleodatum marker becomes critical because channel-fill does not grade into lenses of growth-graded oolites as does ripple-laminated lithofacies.

It is difficult to distinguish where ramp depositional environments end and basinal ones begin when dealing with depositional slopes of only a few tenths of a meter per kilometer. However, the distinction between the two depositional environments may be based on energy level. This distinction is not arbitrary because lithofacies, which are controlled by an active current flow, can be recognized from ones in which transport velocities decrease and fines begin to settle out of suspension. *In the field, the contact is placed where mudstones* and carbonaceous shales become associated with thrombolitic boundstones; those lithologies have been used to identify one of the shallow basinal lithofacies. Once recognized, the contact between the two depositional environments seems to be quite abrupt and is located where bioherms of shale-draped, conical thrombolitic mounds transform into tufted mound biostromes (Figs. 14A, B; 40). This transformation is also characterized by a change in boundstone fabric and by a rapid lateral-linking of boundstone organosedimentary structures, which lead to the development of the tufted mound biostrome. Within thrombolitic shale lithofacies, boundstones have two distinct characters. Boundstones are either the previously mentioned "shallow" conical thrombolitic bioherms or "deeper" thrombolitic biostromes. Individual conical thrombolitic mounds are 20 to 50 cm in diameter and have a synoptic relief of 25 to 50 cm (Fig. 41).

Figure 41. Close up of conical thrombolitic boundstone bioherm developed in the Lyttelton-Eccles depositional system along road cut near Sudwala Caves.

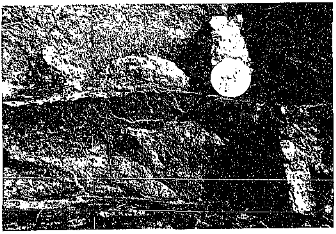

Figure 42. Stubby, thrombolitic columns developed in the thrombolitic shale lithofacies along road cut near Sudwala Caves. (Coin is 3 cm in diameter)

Figure 43. Bifurcating thrombolitic columns developed in the thrombolitic shale lithofacies in the Lower Monte Christo depositional system north of Potgietersrus. (Coin is 3 cm in diameter)

Figure 44. Small outcrop of shale mudstone lithofacies developed in the Lower Monte Christo depositional system north of Potgietersrus.

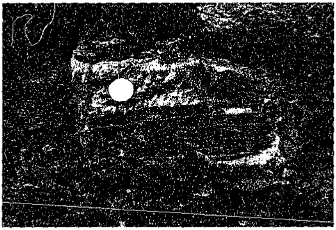

Figure 45. Small lens of color-banded rhythmite developed in the Upper Oak Tree depositional system north of Potchefstroom. (Coin is 3 cm in diameter)

conical bioherms vary in width and have a low 1 m inheritance (Fig. 40). In deeper water, bioherms gave way to thin, 2 to 5 cm thick, biostromal layers interbedded with variable thicknesses of carbonaceous shale (Fig. 42). These biostromal layers are generally made up of stubby, thrombolitic columns that trap carbonaceous shale between them. Locally, thrombolitic columns bifurcate to form a discontinuous cluster-like biostrome which can have an inheritance of 12 to 100 cm (Fig. 43). Carbonaceous shale fills in around these cluster-like boundstones and forms drapes over them. Lenses of interstratified wackestone are also present in this lithofacies and a mixed variety of well-rounded grains and intraclasts occur in the mudstone-matrix.

The contact between thrombolitic shale lithofacies and shale mudstone lithofacies is arbitrary. It is assigned where thromobolitic boundstones can no longer be identified as discreet interbedded layers. The shale mudstone lithofacies is made up of two distinct lithologies. One is a predominantly convolute-laminated shale interstratified with layers of graded mudstone-wackestone (Fig. 44), while the other is a succession of 1 to 5 cm thick rhythmites which grade from light gray mudstone to dark gray argillaceous mudstone (Fig. 45). Slump folds, which may occur down to the microscopic scale, and truncation surfaces are also common in the lithofacies. Thin-bedded rhythmites, which are less than 5 cm thick and which have a single row of ripples, may occur. The entire lithofacies is considered to be

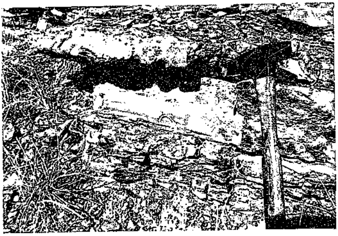

Figure 46. Small outcrop of color-banded rhythmites developed in the banded iron-formation lithofacies of the Frisco-Penge depositional system west of Reivilo.

Figure 47. Outcrop of mudstone-matrix breccia developed in the Upper Monte Christo depositional system west of Thabazimbi.

turbiditic; the repeated nature of graded rhythmites resembles only the upper *divisions of the* typical Bouma sequence (Beukes, 1983a).

The contact between *shallow and deep* basinal subfacies is gradational as interbedded, ferruginous mudstone and shale grade into banded iron-formation. Banded *iron-formation is a distal* equivalent of shale mudstone lithofacies. Beukes (1977, 1980a, 1980b, 1983a, 1984) has studied extensively the banded iron-formation lithofacies and his observations were accepted after color-banded rhythmites were identified in the field (Fig. 46). Beukes (1984) had interpreted banded iron-formation was deposited by ferruginous carbonate turbidites; color-banded rhythmites verifies this occurred.

Two other lithofacies, that are developed somewhat randomly among the facies, were identified. The first is a rhythmite which has all of the characteristics of those found in the shale mudstone lithofacies. However, this rhythmite is interbedded between shallowing upward units of columnar stromatolitic and tufted thrombolitic mound lithofacies in the submerged shelf subfacies. The second is a poorly sorted, mudstone-matrix breccia (Fig. 47) which is interbedded with either submerged flat or submerged shelf subfacies lithologies, as well as over some *regional* unconformities. Interpretation of the depositional environments of both of these lithofacies will be discussed later.

Figure 48. Chert increases to unconformity at top of the Upper Monte Christo depositional system along the road cut near Sudwala Caves. Shallow angular unconformity cuts from left to right.

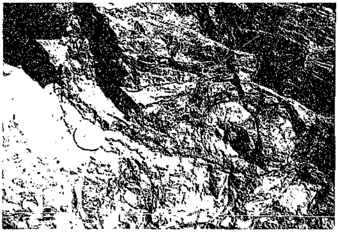

Figure 49. Paleosol marks regional unconformity developed on the upper surface of the Lower Monte Christo depositional system along the road cut near Sudwala Caves. (Coin is 3 cm in diameter)

2.7 Synthems and Regional Correlations

While establishing the various lithofacies, the nature of contacts between the stratigraphic units was examined so that synthems could be identified. A synthem is a body of rock bounded by unconformities and can be considered the largest scale of depositional cyclicity (Miall, 1984). In order to identify synthems, reference criteria had to be recognized both above and below unconformity surfaces. Ten synthems were identified and correlated between the Transvaal and the northern Cape with the use of these reference criteria.

Below or on an unconformity, two features are found to be consistent: a marked increase in chert to the surface (Fig. 48) or a paleosol (Fig. 49). The presence of shallow siliciclastic facies above an unconformity is the most pronounced reference criteria. As previously mentioned, quartzarenite-filled channels of the fluvial subfacies, containing reworked chert clasts, erode into the unconformity surfaces (Fig. 15). The use of tidal flat subfacies as a marker criteria is slightly more restricted because numerous occurrences of 15 to 20 cm thick lenses are indicative of regressions along the depository margins. However, beds of tidal flat subfacies, which are 4 to 5 m thick, do overlie unconformities, as well as erode into them.

Five additional marker criteria develop above unconformities and several of them are quite subtle. Four of the criteria are *interpreted as being produced by rapid transgression and are:* black carbonaceous shale; chert-in-shale breccia; paraconformable contacts; and hybrid erosional breccia. The fifth is simply a

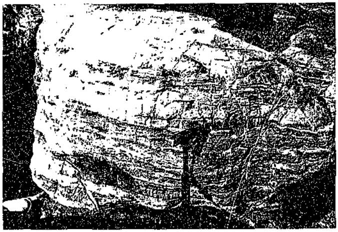

Figure 50. Shallow angular unconformity outlined in yellow. Unconformity separates the first and second grandcycles of the Lyttelton-Eccles depositional system north of Thabazimbi.

Figure 51. Hybrid erosional breccia of subangular to angular clasts. Hybrid breccia separates second and third grandcycles in the Lyttelton-Eccles depositional system north of Johannesburg.

1 to 3 *m thick* chert breccia which overlies a zone of increased chertification in the underlying carbonate unit. The character of *the four transgressive* criteria is directly related to whether or not the surface on which they are developed was subaerially exposed. *Two reference criteria, which* develop over subaerial surfaces, are characterized by either chert-in-shale breccias or 1 to 3 m thick black carbonaceous *shale units. Such* lithologies are developed during a period of non-depositional or lag time, as poorly oxygenated bottom waters spread outward *depositing black* carbonaceous shales prior to carbonate sedimentation (Brett and Baird, 1985). They represent a period of sediment starvation. Chert-in-shale breccia results from the reworking of chert clasts scattered on the eroded subaerial surface (Fig. 48). There is no real difference between it and marker shale beds except for the presence of chert clasts. The third drowning criteria is important in those areas where unconformities pass into conformable sequences or where rapid transgression drowns a shallower subfacies before subaerial exposure could occur. The contact between the overlying deeper subfacies and the shallower drowned one is sharp and paraconformable in character (Fig. 50). Such contacts indicate that non-depositional lag time was relatively short and that no extended period of sediment starvation occurred, as the subfacies transgressed in broad belts. The fourth drowning criteria is somewhat of a hybrid intermediate between the other three. It consists of sub-angular

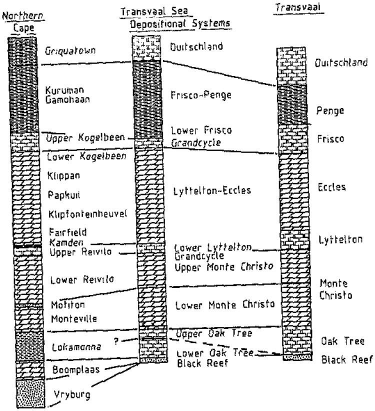

Figure 52. Correlation chart showing the relationships of stratigraphic subdivisions in the northern Cape and the Transvaal to the interpreted depositional systems of the Transvaal Sea.

to angular chert and carbonate lithofragments in a carbonate matrix (Fig. 51). This lithology may have been developed by drowning just after subaerial exposure and erosion began.

The regional correlation of the various synthems is based on a mixture of data, e.g. lithological character, unconformities, and paraconformable transgressive-regressive contacts. Button (1973a, 1976) divided the stratigraphy of the Transvaal Sea in the eastern Transvaal into three stages and subdivided these stages into seven units, which he called "megacycles". These subdivisions were based on lithological character and unconformities marked by chert-in-shale breccias. Beukes (1980a) used paraconformable contacts and shallow siliciclastic facies, as well as chert-in-shale breccias to delineate 13 formations in the northern Cape. Beukes (1986) has since graphically correlated his northern Cape stratigraphy with that of the Transvaal. By doing this, he has proposed eight quasi-synthems based on the nomenclature of the South African Committee for Stratigraphy (SACS) (1980). Although some of the formations in the Transvaal are based on unconformity bounded packages, there is a reluctance in introducing SACS nomenclature because these formations are really no more than Button's (1973a) chert-rich and chert-poor field units. One of the early assumptions of this research was that chert is a diagenetic alteration product, and the use of a secondary feature, such as chert alone, to define synthems is not considered a true diagnostic feature. The radical variations in chert content within particular formations, also, does not allow regional correlation on the basis of the SACS classification and formations; this leads to misidentification of formations in the field. Nevertheless, since SACS formation names are accepted and in print, they are retained as chronostratigraphic divisions that are used to delineate the history of the synthems within the developing Transvaal Sea.

The correlation of the ten synthems between the northern Cape and the Transvaal, based on unconformities described below, is presented in Figure 52. The Vryburg-Black Reef (simplified to Vryburg) synthem is the oldest and overlies a regional unconformity which separates it from the underlying Ventersdorp Supergroup and older stratigraphic units. The contact between the Vryburg synthem and the overlying Boomplaas-Black Reef (Boomplaas) synthem is interpreted as transitional and is placed on a paraconformity. This paraconformity is distinct in borehole core from near Reivilo (Appendix A) and is marked by approximately 10 m of black carbonaceous shale. The shale zone separates lithologies of the underlying shallow, tidal flat subfacies from those of the overlying, shallow basinal subfacies which introduce carbonate sedimentation within the Transvaal Sea.

The contact between the Boomplaas synthem and the overlying Lokamonna-Lower Oak Tree-Black Reef (Lower Oak Tree) synthem is abrupt and is marked by a 2 m thick black carbonaceous shale unit which has the appearance of a chert-in-shale breccia. In borehole core from near Reivilo, this contact does not appear to have been subaerially exposed, but seems to represent a transgressional scour (Appendix A). No reference criteria could be identified either above or below the contact, other than the

Figure 53. Thin, 15 cm ash bed marker in core from near Potchefstroom. (Coin is 3 cm in diameter)

Figure 54. Breccia on unconformity over Ancestral Rand Anticline between the Upper Oak Tree and the Lower Monte Christo depositional systems in core from near Potchefstroom. Disaggregation of oolitic lithoclast can be seen in center of photograph. (Coin is 3 cm in diameter)

presence of black carbonaceous shale. Rounded lithoclasts within the breccia-like zone indicate that a certain degree of re-working occurred during transgression.

The Upper Oak Tree synthem, which overlies the Lower Oak Tree synthem, seems to be developed only in the Transvaal. Although it could not be traced into the northern Cape, the Upper Oak Tree synthem is the first synthem that is traceable throughout the preserved outcrop area in the Transvaal. This synthem has a lower paraconformable contact marked by mudstone-matrix breccias in the northern Transvaal and by rhythmites in the western Transvaal. At Sudwala Caves, a 5 m thick layer of black carbonaceous shale overlies the fluvial lithofacies and marks the lower contact. Lenses of tufted thrombolitic mound lithofacies are locally present in this shale layer (appendix A). In the west-central Transvaal, a light green-grey, 15 cm thick, ash bed can be found 3 to 10 m above the lower paraconformable contact (Fig. 53). This ash bed can be traced in borehole core from east of Springs, to north of Koster, and to south of Bothaville (Fig. 2; Appendix A). It was recognized in the field north of Potgietersrus and near Sabie. The upper contact of the synthem is both unique, as well as problematic over the Transvaal. In the western Transvaal, the contact is a unique 0.5 to 1.5 m thick, chert-in-shale breccia that is characterized by disaggregation and re-working of oolitic lithoclasts (Fig. 54). It is problematic because disaggregated fragments are only present above the contact along an east-west line from west of Potchefstroom to Pilgrims Rest (Fig. 2).

Elsewhere in the western Transvaal, the contact is assigned to the upper of two shale beds which lie stratigraphically 40 m apart and which are approximately 280 m above the Black Reef Quartzite contact (Fig. 52). At other correlation localities in the eastern Transvaal, the contact is marked by a black carbonaceous shale unit that can be up to 3 m thick.

The Monteville-Lower Monte Christo (Lower Monte Christo) synthem may incorporate the Upper Oak Tree synthem in the northern Cape. The lower contact of this synthem is generally assigned where boundstones replace interlaminated shales and mudstones. However, locally in the northern Cape, this contact is revealed in borehole core from near Reivilo as a truncation surface marked by overlying rhythmites (Appendix A). One might logically assign the Upper Oak Tree contact here; but where the rhythmites are developed, thev are nearly continuous to the upper contact of the Lower Monte Christo synthem (Appendix A). In the northern Cape, the upper contact of the Lower Monte Christo synthem is a paleosol which is overlain by a chertified breccia. In the Transvaal, the upper contact is marked by both a paleosol (Fig. 49) and an increase in chert.

The contact between the overlying Middle Monte Christo-Motiton (Motiton) and the Lower Monte Cristo synthems marks a change in the character of synthems. This change is characterized by the appearance of interthems within subsequent synthems. Interthems were traced through two bore holes some 120 km apart in the western Transvaal (Appendix A) and have been identified in geological profile areas. Depending on where a contact is

Figure 55. Chert-in-shale breccia developed by transgression over the unconformity on the top surface of the Upper Monte Christo depositional system along the road cut near Sudwala Caves. Surface upon which the Lower Lyttelton grandcycle was deposited is flat and is an indication sea floor was created.

placed, interthems are between 100 and 150 m thick, with an average of about 120 m. Bounding contacts of various interthems are marked by either mudstone-matrix breccias or "paraconformable" transgressive surfaces (Appendix A).

The Motiton synthem is a siliciclastic unit that marks the contact with the Lower Monte Christo synthem. The synthem is not over 5 m thick in either the northern Cape or the Transvaal. Although it has the characteristics of an unconformity criteria, the Motiton unit is given synthemal status or rank because it has the exact aerial extent and facies distribution as does the older Vryburg synthem, except in the eastern Transvaal. In the eastern Transvaal, the Motiton synthem is not developed and the contact between the Lower Monte Christo and the Upper Monte Christo-Lower Reivilo (Upper Monte Christo) synthems is marked by a paleosol that is overlain by a chert-in-shale breccia (Fig. 49).

The Upper Monte Christo synthem is the first of the subsequent carbonate synthems and is made up of two interthems. The contact between the Upper Monte Christo synthem and the Lower Lyttelton-Upper Reivilo (Lower Lyttelton) interthem of the Lyttelton-Eccles synthem is complex and is marked by a number of unconformity criteria. The contact is a paraconformity in the northern Cape. In the northwestern Transvaal, the contact is marked by a paleosol that is eroded into by fluvial subfacies channels; and in the eastern Transvaal, it overlies a paleosol above a zone of increased chert (Fig. 48). In other localities in the Transvaal, three other reference criteria can be present above this synthemal contact; they may or may not erode the contact. Around the Johannesburg dome, and in parts of the western Transvaal, the contact is marked by mudstone-matrix breccias which erode into it. In the northeastern Transvaal, a thin 4 m thick unit of siliciclastic tidal flat subfacies, locally known as the Blyde River Quartzite, erodes into a chert-in-shale breccia that overlies the contact over much of the eastern Transvaal (Fig. 55). Where the chert-in-shale breccia is highly eroded, this siliciclastic unit may lie directly on the underlying chert-rich zone. Chert-in-shale breccia is locally developed in the northwestern Transvaal, but a thin, black carbonaceous shale unit overlies fluvial subfacies channels which rework the remnant chert fragments on the contact.

The bounding surfaces of the Lyttelton-Eccles synthem are unconformable contacts in the Transvaal, which pass into conformable ones in the northern Cape. In the northern Cape, this synthem is made up of the upper half of the Reivilo Formation and of the Fairfield, Klipfonteinheuvel, Papkuil, and Klippan Formations, as well as the lower half of the Kogelbeen Formation (Fig. 52). The Lower Lyttelton interthem is the only named interthem of the six, which make up the Lyttelton-Eccles synthem. The upper contact of the Lower Lyttelton interthem is pronounced in the northern Cape and is marked by a paraconformity that is overlain by a thin unit of banded iron-formation lithofacies. This iron-formation unit is traceable throughout the northern Cape and is locally known as the Kamdem Member (Beukes, 1980a). In the Transvaal, the upper contact is a paraconformity which occurs between units of emergent peritidal, or tidal flat, and submerged shelf subfacies. The contact represents an abrupt drowning event and was consistently recognized in borehole core in the western Transvaal. On the farm Leeuwbosch 129KQ, north of Thabazimbi (Fig. 2), the contact is marked by a 1.5° angular unconformity (Fig. 50). This relationship was verified at the Sudwala Caves locality in the eastern Transvaal, where the contacts marking both the Lower Monte Christo-Upper Monte Chisto synthem and the Upper Monte Christo synthem-Lower Lyttelton interthem are 1.5° to 2° angular unconformities. Unfortunately, this could not be confirmed at other localities in the Transvaal, due to lack of suitable exposures. Based on these observations, which were made at localities 350 km apart, it could be assumed that all synthem and interthem contacts above and including the Lower Motiton contact are angular unconformities. However, these contacts will be referred to as "paraconformities" because of the very shallow nature of the angular unconformities. Other interthem contacts within the Lyttelton-Eccles synthem are marked either by hybrid erosional breccias (Fig. 51) or by paraconformities, which follow a rapidly shallowing-upward sequence.

The Frisco-Penge synthem is named after the two Transvaal formations. In the northern Cape, the Frisco-Penge synthem is made up of the upper Kogelbeen, the Gamahaan, and the Kuruman Formations. The contact between the Lyttelton-Eccles synthem and the Lower Frisco-upper Kogelbeen (Lower Frisco) interthem of the Frisco-Penge synthem is also variable over the preserved outcrop area. The lower contact of the interthem in the northern Cape is

Figure 56. "Shoe-sole" breccia developed on the top contact of the Lower Frisco grandcycle north of Potgietersrus. (Coin is 3 cm *in diameter)*

Figure 57. Folding, which is overlain by mafic lava flow, near the top of the first grandcycle in the Duitschland depositional system north of Potgietersrus. Hammer marks crest of anticline.

assigned to a paraconformable contact above a rapidly shallowing upward sequence, while the upper contact is marked a chertified carbonate-matrix breccia. In the Transvaal, the lower contact is marked by a silicified breccia, by a chert-in-shale breccia, or by a black carbonaceous shale zone, while the upper one is underlies a silicified breccia, which has been informally called the "shoe-sole breccia" (Fig. 56). This breccia contact was first identified by C. du Plessis (pers. commun., 1985) in the Thabazimbi area and is so named because the breccia fragments are reminiscent of the bottom of a tennis shoe. One aspect of the Lower Frisco interthem is that it has a variable thickness over the Transvaal. In the western Transvaal it is 40 to 60 m thick, while in the eastern Transvaal it is only 20 m thick. Since the interthem is over 100 m thick in the northern Cape, the preserved strata in the Transvaal is considered to be minimum thicknesses because of the erosional character of the upper contact. The Upper Frisco interthem overlies the previously described contacts and is the last carbonate unit preserved over much of the Transvaal because of erosion that preceeded the deposition of the Pretoria Group, Transvaal Sequence. The number of banded iron-formation interthems were not determined because of a lack of borehole core and the frustratingly repetitive nature of the banded iron-formation lithofacies. However, based on the average thickness of an interthem, three banded iron-formation interthems are believed to make up the remainder of the Frisco-Penge synthem.

The upper contact of the Frisco-Penge synthem with the Duitschland-Griquatown (Duitschland) synthem is transitional both in the northern Cape and in the Transvaal (Fig. 52). Color-banded rhythmites mark the contact and herald the reappearance of carbonate sedimentation in the Transvaal, while banded iron-formation continued to be deposited above the contact in the northern Cape. The Duitschland synthem is preserved only in a limited area of the northeastern Transvaal and the west-southwestern northern Cape. Four interthems have been identified in field exposures near Potgietersrus (Fig. 2). The contact between the first and second interthem is marked by folded paleosol, which is overlain by a mafic lava flow (Fig. 57). This lava, which thickens in synclines while thinning over anticlines along the contact, is dark green and contains potassic feldspar phenocrysts. The upper contact of this, maximum 3.0 m thick, lava is flat and could be considered the lower contact of the second interthem. The second and third interthems are separated by a paleosol, overlain by siliciclastic tidal flat lithofacies. The contact between the third and the fourth interthems is marked again by a paleosol, which is overlain by a lava. This lava is a light green-buff white, felsic volcanic with quartz phenocrysts and may be up to 1.5 m thick. The upper contact of the lava is fairly flat and is locally marked by thin lenses of mudstone-matrix breccia (Fig. 58). The fourth interthem is abruptly terminated by the regional pre-Pretoria Group unconformity. This unconformity is marked by a thick chert-clast breccia which is similar to those developed where the unconformity decapitates

Figure 58. Small, mudstone-matrix breccia on the upper lava flow which marks the top contact of the third grandcycle in the Duitschland depositional system north or Potgietersrus.

other synthems over the region.

2.8 Depositional Systems

If the ten previously proposed synthems are regarded as packages of genetically related strata, which are bound by unconformities, they are by definition depositional systems (Fig. 52). These ten depositional systems are in many respects depositional supercycles and are comparable to second order cycles proposed by Vail et al. (1977). Although the depositional systems are made up of genetically related strata, they tend to be dominated by a particular subfacies, and this dominance is here termed depositional character. From this genetic stratigraphic point of view, interthems (third order cycles) represent shallowing upward cycles within a depositional system and are here termed grandcycles. Grandcycles represent cycles within cycles and are considered to be a stratigraphic event. A grandcycle has the overall depositional character of the depositional system. Grandcycles are themselves made up of shallowing-upward cycles or Punctuated Aggradational Cycles (PACs) (Goodwin and Anderson, 1985) (Appendix A). PACs are for all practical aspects cycles within cycles within cycles.

PACs were identified on the scale at which logging was conducted (0.1 m). However, the scale of the analysis was not taken below the scale of the grandcycle (approximately 120 m) because of the limited preserved outcrop and because of an adherence to the development of a regional overview without the confusion of specifics. Nevertheless, observations of Transvaal

Sea PACs, combined with four generalizations on PACs proposed by Goodwin and Anderson (1985), provide a number of insights into the characteristics of the grandcycles. The four generalizations by Goodwin and Anderson (1985) are:

1) PACs occur in sedimentary assemblages which respond directly to sea-level fluctuation.

2) The fundamental pattern is a shallowing-upward sequence of facies above a sharply defined surface of abrupt drowning.

3) PACs seem to result from a unidirectional succession of relative deepening events.

4) Each punctuation event produces an abrupt contact between depositional events.

Observations of PACs within the preserved strata of the Transvaal Sea indicate:

1) PACs range from 0.1 m to 20 m in thickness, with an average between 2 m and 5 m.

2) PACs are shallowing upward sequences consisting of two to five lithofacies, with three lithofacies being common.

3) The initial PAC of a grandcycle is generally the thickest and consists of the largest number of lithofacies.

4) The first lithofacies deposited in the initial PAC is the deepest lithofacies of the previous grandcycle or depositional system.

5) PACs thin and the number of lithofacies within them decrease as the grandcycle shallows upward.

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4) The first lithofacies deposited in the initial PAC is the deepest lithofacies of the previous grandcycle or depositional system.

5) PACs thin and the number of lithofacies within them decrease as the grandcycle shallows upward.

With this combination of features in mind, a number of observations were made concerning grandcycles. These observations are based on borehole core which represents practically complete exposure. Any major lithological changes, which could be identified within them, reflected directly on the depositional character of their particular depositional system. Grandcycle observations are as follows:

1) Grandcycles are not present in depositional systems below the Upper Monte Christo depositional system.

2) One to six grandcycles make up a depositional system and all grandcycles are shallowing-upward sequences.

3) Grandcycles may consist of as many as 16 PACs.

4) Each grandcycle except one (the initial Duitschland grandcycle) begins with abrupt drowning event.

5) Grandcycles range in thickness from 100 to 150 m, with 120 m being average. An exception to this is the Lower Frisco grandcycle, which is from 20 to 60 m thick.

6) The first grandcycle of each depositional system is followed by a rapidly deepening grandcycle and an abrupt change in depositional character.

7) The depositional character of the first grandcycle of each carbonate depositional system is similar to the overall depositional character of the previous depositional system, with the exception of the Duitschland depositional system.

8) The depositional character of the second grandcycle determines the depositional character of the depositional system.

9) The second grandcycle consists of the thickest units of the subfacies, which characterizes the depositional system.
10) The second grandcycle also consists of primarily the deepest lithofacies developed in the depositional character subfacies.
11) If the depositional system consists of more than one grandcycle, the number of and thickness of shallower lithofacies increases in subsequent grandcycles as the overall depositional system shallowed upward.

The lower portions of the carbonate stratigraphy in western Transvaal boreholes reveal several differences between the depositional systems above and below the regional unconformity which separates the Lower Monte Christo depositional system from the overlying three (Fig. 52). Depositional systems below the regional unconformity represent a somewhat continuous north-northeast succession of relative deepening events across the Kaapvaal Craton. These depositional systems were due to initial deepening, which was followed by rapid shallowing into the depositional character of the depositional system, and are dominantly transgressive, which resulted in overall expansion of the depository. Depositional systems above the regional unconformity represent a see-saw pattern of transgression-regression, which resulted in both expansion and overall deepening of the Transvaal Sea.

2.9 North-South Reconstructions

It was assumed that the Transvaal Sea was a very wide, flat, gently-shelving marine platform and that north-south, two-dimensional reconstructions would indicate how the depositional character of the depositional systems was modified by these depositional patterns. North-south reconstructions were also justified on the observation that unconformities in the Transvaal could be correlated with paraconformable contacts above regressive sedimentary prisms in the northern Cape. Such correlations indicate that during several depositional systems the Transvaal Sea had left the Transvaal and retreated into the area of the northern Cape. Correlations between the Transvaal and the northern Cape also indicate that a particular occurrence of fluvial subfacies (Black Reef Quartzite) was time transgressive (Fig. 52). Time transgressive relationships of this particular occurrence of the subfacies and its stratigraphic thicknesses developed in the Selati Trough will be discussed.

Boreholes in the western Transvaal continued to provide most of the data. The reason for this was that the depositional character of the majority of carbonate depositional systems in the northern Cape is submerged shelf subfacies (N. J. Beukes, pers. commun., 1986). Borehole core from near Reivilo (Appendix A) confirmed that tufted thrombolitic lithofacies predominates. Western Transvaal boreholes were also used because field relationships indicate that eastern Transvaal sections

Figure 59. Lens of re-worked siliclastic intraclasts deposited in a transgressive shale sequence in core from near Bothaville. (Coin is 3 cm in diameter)

represent only 44 to 54 percent of their respective western Transvaal correlatives, if thicknesses in the Selati Trough are not considered.

Since the Vryburg and the Boomplaas depositional systems are not represented in a type-section borehole in the Potchefstroom area (Fig. 2; Appendix A), the region to the south of Klerksdorp was examined for evidence of their eastward continuance and any lateral lithofacies modifications, which might have occurred. Boreholes near Bothaville in the Orange Free State (Appendix A) yielded the most information and indicated that:

1) neither the Vryburg nor the Boomplaas depositional systems are present along the southeastern limit of preserved strata of the Transvaal Sea;

2) lenses of re-worked siliciclastic intraclasts (Fig. 59) are present in the lower, transgressive, carbonaceous shale units above the equivalent fluvial subfacies (Black Reef Quartzite) of the two depositional systems (Fig. 52); and

3) the depositional characters of the Lower and Upper Monte Christo depositional systems are submerged shelf subfacies instead of shoaled flat subfacies as over the Transvaal.

As a result of these observations, the previously described grouping of certain depositional systems to geographical regions seemed quite reasonable.

In order to complete the north-south reconstructions, field traverses were also conducted some 125 km west of the Thabazimbi due to the lack of borehole core. These traverses were to verify relationships found in type-section boreholes to the south near Koster and Potchefstroom (Fig. 2; Appendix A). Traverses indicated that all of the Transvaal depositional systems are present, that depositional character of the depositional systems is the same as previously observed in boreholes to the south, and that fluvial troughs and channels mark unconformity contacts as they do in the Thabazimbi area. Other observations were made during these traverses. Numerous siliciclastic lenses in the Lower Oak Tree, Upper Oak Tree, and Lower Monte Christo depositional systems are comparable to those in the Potgietersrus area and lenses of reworked siliciclastic lithoclasts are present in the lowest transgressive, carbonaceous shale units. Of these variou[illegible]stic units, the first overlies the lowest transg[illegible]ale unit above the Black Reef Quartzite (Fig. 52). [illegible]s siliciclastic unit is tidal flat subfacies and is characterized by trough cross-laminations, herringbone cross-stratifications, and desiccation cracks. One other difference is that mudstone-matrix breccias are developed intermittently throughout each of the depositional systems. The breccias mark both shallowing and deepening events and are made up of lithoclasts of the particular depositional system in which they occur. In one locality, mudstone-matrix breccias are interbedded with color-banded rhythmites in a series of fining upward cycles. The profiles shown are based primarily on borehole data. The reason for this is that fault repetition of chert-rich units in the northwest Transvaal confused stratigraphic measurements. The following brief discussion is of these

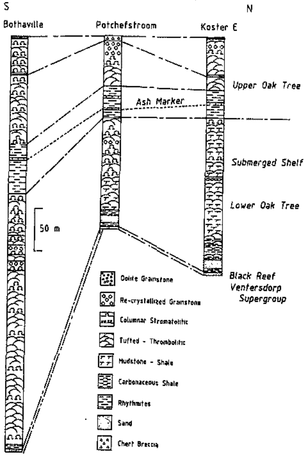


Figure 60. Combined north-south stratigraphic section of the Lower and Upper Oak Tree depositional systems based on borehole core observations from south of Bothaville to near Koster.

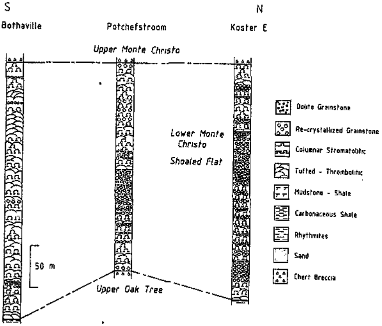


Figure 61. North-south stratigraphic section of the Lower Monte Christo depositional system based on borehole core observations from south of Bothaville to near Koster.

profiles and of related field observations.

By concentrating on only marine subfacies developed within each of the depositional systems, it became apparent that only eight of the ten depositional systems were deposited in the Transvaal (Fig. 52). It is on these two missing depositional systems and repeated retreat of the Transvaal Sea into the northern Cape that the observational interpretation of a north-northeastward succession of relative transgressive events is based. The Vryburg depositional system is one of the missing depositional systems in the Transvaal. Its depositional character is considered to be tidal flat subfacies, even though the depositional character of the synthem in the Transvaal is fluvial subfacies (Black Reef Quartzite) (Figs. 14A; 52). The other missing Transvaal depositional system is the Boomplaas depositional system and its depositional character is shoaled flat subfacies (Table 1). However, depositional patterns of the Boomplaas depositional system may have been very similar to those of a simple ramp (Fig. 14A, 14B). The fluvial subfacies (Black Reef Quartzite) continued to accumulate in the Transvaal as the Boomplaas depositional system carbonates encroached from the south-southwest.

Following a second deepening event, the Lower Oak Tree depositional system spread carbonate sedimentation into the Transvaal for the first time (Fig. 60) and its depositional character is submerged shelf subfacies. This event drowned the fluvial subfacies (Black Reef Quartzite) in the western Transvaal. Deepening occurred for the third time during the

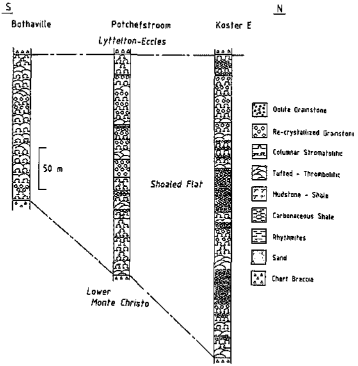


Figure 62. North-south stratigraphic section of the Upper Monte Christo depositional system based on borehole core observations from south of Bothaville to near Koster.

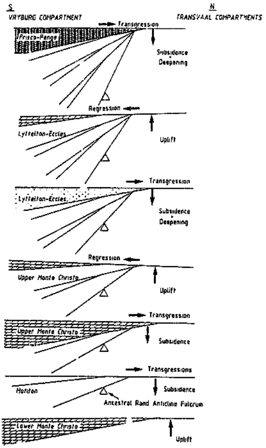


Figure 63. Cartoon of see-saw pattern of transgressions and regressions associated with depository deepening which was developed above the Lower Monte Christo depositional system. The Ancestral Rand Anticline acted as a structural fulcrum, which did not move, for this see-saw pattern.

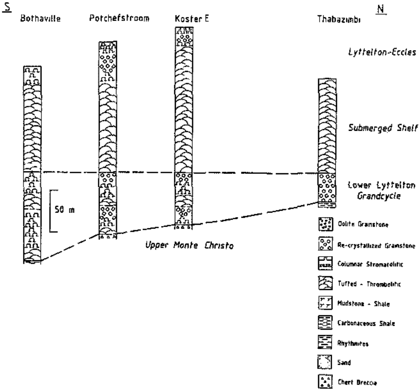


Figure 64. Condensed south to north stratigraphic section of the Lyttelton-Eccles depositional system based on borehole core observations from south of Bothaville to north of Thabazimbi.

Upper Oak Tree depositional system as the depository continued to expand, but the depositional character of the Lower Oak Tree depositional system did not change with shallowing (Fig. 60). Above the Upper Oak Tree unconformity, the Lower Monte Christo depositional system spread over the Transvaal (Fig. 61) and has a depositional character of shoaled flat subfacies. If the locally developed Upper Oak Tree unconformity is ignored, depositional patterns in the Upper Oak Tree and the Lower Monte Christo depositional systems have an overall shallowing-upward pattern of a single depositional system (Figs. 60; 61).

Carbonate sedimentation was disrupted at the end of the Lower Monte Christo depositional system and a regional unconformity was produced. When sedimentation resumed, marine facies were again restricted to the northern Cape. The Motiton depositional system was dominated by siliciclastic sedimentation and its depositional character is siliciclastic tidal flat subfacies. Siliciclastic subfacies were similar to that of the initial Vryburg depositional system, with fluvial subfacies accumulating in the Transvaal. Rapid deepening, associated with north-northeastward transgressions, reintroduced carbonate sedimentation into the depository during the Upper Monte Christo depositional system (Fig. 62). The depositional character of this depositional system is shoaled flat subfacies. Facies patterns in the Upper Monte Christo depositional system are similar to facies distributions of the Lower Monte Christo depositional system [illegible] Upper Monte Christo depositional system was relatively short [illegible]ved and produced only two grandcycles.

The re-drowning of the Transvaal was followed by a see-saw pattern of transgression-regression in subsequent depositional systems (Fig. 63). This see-saw pattern resulted in a progressive change in sedimentary patterns as the depository deepened and expanded to the north-northeast with each depositional system, except the Duitschland depositional system. Following the Upper Monte Christo depositional system, marine facies retreated again into the northern Cape as a sub-regional unconformity was produced in the Transvaal. After this hiatus in deposition, re-drowning took place as the Lyttelton-Eccles depositional system spread carbonate sedimentation north--northeastward again. The Lower Lyttelton grandcycle (Fig. 64) marks this event and has the shoaled flat subfacies depositional character of the Upper Monte Christo depositional system. This initial grandcycle was subsequently drowned by a rapid north-northeastward transgression at the beginning of the second Lyttelton-Eccles grandcycle (Fig. 64). This second grandcycle has a submerged shelf subfacies depositional character, which is also characteristic of the following four Lyttelton-Eccles grandcycles.

The end of the Lyttelton-Eccles depositional system is marked by a second retreat of marine facies into the northern Cape and by a second sub-regional unconformity in the Transvaal. Following this second hiatus, re-drowning took place and the Lower Frisco grandcycle of the Frisco-Penge depositional system spread carbonate sedimentation again to the north-northeast into the Transvaal. Rapid regression occurred soon after deposition of this grandcycle began. A third sub-regional unconformity was produced by this retreat, which left an average 40 m of the lower Frisco grandcycle in the Transvaal. A further re-drowning event led to the deposition of the Upper Frisco grandcycle. The depositional character of both the Lower and Upper Frisco grandcycles is submerged shelf subfacies which characterizes the Lyttelton-Eccles depositional system. Basin deepening and expansion continued as the third Frisco-Penge grandcycle spread distal banded iron-formation over the carbonates. Banded iron-formation defines the deep basinal depositional character of this depositional system.

Although the Duitschland depositional system is not preserved in the western Transvaal, shallowing at the end of the Frisco-Penge depositional system resulted in a re-introduction of carbonate sedimentation from the northeast. This second major change in sedimentary patterns indicates that a new set of parameters was starting to influence sedimentation within the Transvaal Sea. Depositional patterns within the Duitschland depositional system are also different from the other depositional systems and its depositional character is characterized as one of dynamic change. This character is indicated by the see-saw pattern of transgression-regression within the depositional system and by the reappearance of volcanic flows.

2.10 East-West Reconstructions

To complete the regional paleogeographic reconstructions, east-west dimensions of each of the depositional systems also had to be considered. Two east-west profile lines illustrate the areal extent of the various Transvaal depositional systems. The first profile extends from Potchefstroom to Sudwala Caves (Fig. 65) and the second extends from Koster to Pilgrims Rest (Figs. 66; 67; 68). The profiles have suitable borehole coverage at both ends, as well as in the central section in the vicinity of Springs. These profiles also avoid complicating effects of the Selati Trough.

Eastward along the Potchefstroom to Sudwala Caves profile, boreholes in the Springs area disclose that:

1) lenses of re-worked siliciclastic intraclasts are present in the lower, transgressive, carbonaceous shale units;
2) transition to carbonate sedimentation was marked by mudstone-matrix breccia flows into fluvial subfacies troughs (Black Reef Quartzite); and
3) only the Upper Oak Tree depositional system was deposited above fluvial subfacies strata (Black Reef Quartzite).

Observation 3 was based on the identification of the ash bed marker (Fig. 52), which lies only 3 m above the upper contact of fluvial subfacies troughs (Appendix A). To the west, the ash marker lies some 200 m above the fluvial subfacies in a unit of color-banded rhythmites.

Towards the eastern end of the profile (Fig. 65), a borehole at Ngodwana (Appendix A), near the Sudwala Caves locality, shows

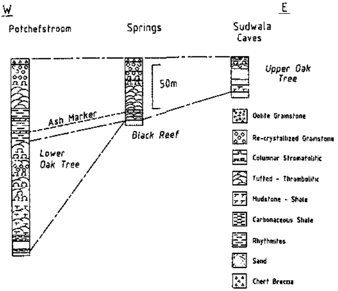


Figure 65. Condensed west to east stratigraphic section of the Lower and the Upper Oak Tree depositional systems based on borehole core observations from west of Potchefstroom to near Sudwala Caves.

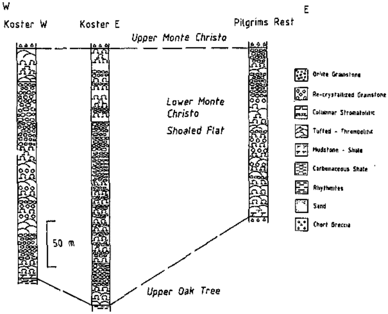


Figure 66. East-west stratigraphic section of the Lower Monte Christo depositional system based on borehole core observations from west of Koster to Pilgrims Rest.

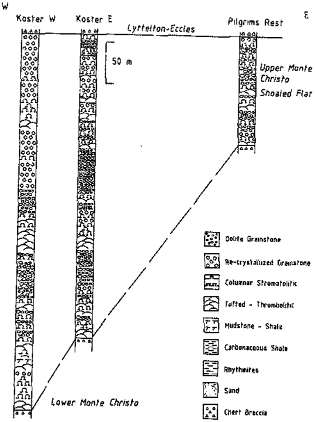


Figure 67. Condensed west to east stratigraphic section of the Upper Monte Christo depositional system based on borehole core observations from west of Koster to Pilgrims Rest.

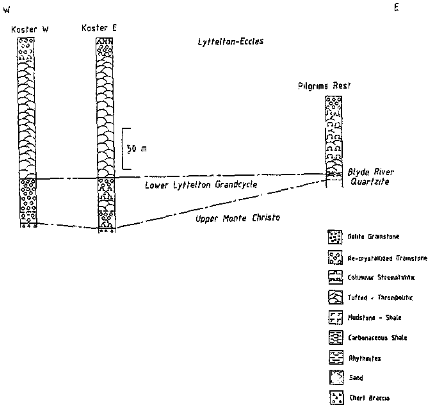


Figure 68. Condensed west to east stratigraphic section of the Lyttelton-Eccles depositional system based on borehole core observations from west of Koster to Pilgrims Rest.

that:

1) only the Upper Oak Tree depositional system was deposited above fluvial subfacies strata (Black Reef Quartzite);

2) the Upper Oak Tree depositional system has a tidal flat subfacies depositional character rather than one of submerged shelf subfacies;

3) the Lower Monte Christo depositional system consists of six 7 to 14 m thick PACs; and

4) the depositional characters of the Lower Monte Christo, the Upper Monte Christo, and what was preserved of the Lyttelton-Eccles depositional systems were the same as they were in the western Transvaal, regardless if the sections were condensed.

The same relationships are present in the Sudwala Caves Road section, in boreholes in the Pilgrims Rest (Figs. 66; 67; 68), and in surface exposures in the Potgietersrus area. However, in the Pilgrims rest area, tidal flat subfacies (Blyde River Quartzite) overlies the Upper Monte Christo depositional system unconformity and characterizes the Lower Lyttelton grandcycle (Fig. 68).

2.11 Depositional Patterns Within The Selati Trough

Button (1973a) recognized the presence of tidal flat subfacies below the carbonates in the eastern Transvaal, which he referred to as the "Transition Zone". Geological profiles in the eastern Transvaal confirm that such a tidal flat environment was present (Fig. 68) with the only notable exceptions being in the

Selati Trough (Fig. 2). Significantly, the sedimentary patterns in the Selati Trough differ from the rest of the eastern Transvaal in that:

1) shallow siliciclastic facies deposited below the carbonates may be up to 500 m thick in comparison to only a few meters elsewhere (Button, 1973b);

2) both the Lower and Upper Oak Tree depositional systems are present, whereas only the Upper Oak Tree depositional system is developed elsewhere;

3) there are no exaggerated thickness variations in the depositional systems in the eastern Transvaal above the Upper Monte Christo depositional system; and

4) tidal flat subfacies (Blyde River Quartzite) lies over the unconformity, which marks the Upper Monte Christo-Lyttelton-Eccles depositional systems contact.

Traverses in the Selati Trough have revealed that shallow siliciclastic facies is only 30 m thick, instead of the 500 m thickness Button (1973b) proposed. This 30 m thick unit was deposited over a regional unconformity prior to the deposition of the Lower Oak Tree depositional system and is fluvial subfacies (Black Reef Quartzite). Paleocurrent measurements indicate that siliciclastics were shed from the northeast. It should be noted that the Selati Trough influenced the palaeotopography as far south as Sabie because several borehole cores from the Pilgrims Rest-Sabie area indicate that in the region more than 20 m of fluvial subfacies was deposited prior to carbonate sedimentation in the Upper Oak Tree depositional system (Appendix A). The tidal flat subfacies (Blyde River Quartzite), which overlies the Upper Monte Christo depositional system unconformity in the Selati Trough, pinches out to the south near Sabie and to the north of Potgietersrus (Fig. 2).

2.12 Carbonate Platforms

The various profiles supported Wilson's (1975) expanded ramp concept. Distinctive subfacies had developed down the gentle regional paleoslopes and facies were wide irregular belts. The profiles also allowed the various carbonate platforms, which developed within the Transvaal Seas, to be identified.

Beukes (1980a) pointed out that the Vryburg and Boomplaas depositional systems had faced an open ocean. With borehole from near Reivilo substantiating the lack of gravity flow deposits, development of an initial ramp-like platform was clarified (Figs. 14A, B). The depositional patterns of the Boomplaas depositional system support this clarification because ramps commonly develop over a basal siliciclastic unit (Read, 1985). Depositional patterns also revealed that the carbonate platforms developed in the Transvaal Sea were either ramps or distally-steepened ramps and that no shelf-like platforms ever developed. The calculation of the depositional slopes (Fig. 13), which had been used to characterize the epeiric nature of the Transvaal Sea, as well as the observational differences between the different depositional systems support this two fold classification of platforms.

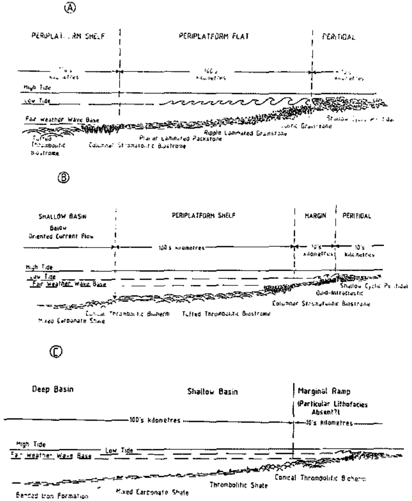


Figure 69. Cartoons of the distally-steepened ramps developed within the Transvaal Sea.

The following brief review of the depositional systems explains how the platforms changed with time. However, it should be noted that the cartoons of the various platform types are again only two dimensional reconstructions of the Transvaal Sea. As previously stated, the facies arrangement of the Boomplaas depositional system indicates ramp sedimentary patterns (Figs. 14A, B). With drowning during the Lower Oak Tree depositional system, shallow depositional slopes resulted in a distally-steepened ramp in the Transvaal, which was characterized by a periplatform shelf (Fig. 69B). Shallowing of this platform during the Lower Monte Christo depositional system did not develop a shelf-like platform with a barrier as previous workers had assumed. Shallowing simply transformed this deeper platform into a shallower variety which was characterized by a periplatform flat (Fig. 69A).

Following the Motiton depositional system, drowning re-established a distally-steepened ramp in the Transvaal during the Upper Monte Christo depositional system, which was again characterized by a periplatform flat. Shallow, nearly flat depositional slopes allowed lateral migration of lithofacies belts during regression and produced the shallowing-upward sedimentary prisms in the northern Cape at the end of the Upper Monte Christo depositional system. With retreat of a depositional system into the northern Cape, distally-steepened ramps, which resulted from drowning, re-evolved into ramps as the Transvaal region shallowed (Figs. 14A, B). This is purely interpretative; but in many depositional environments, lateral accretion of sediments is as important or more important than vertical aggradation (Miall, 1984). The shallow depositional slopes could allow lateral facies migration, without an abrupt facies transition.

Re-drowning with the initiation of the Lyttelton-Eccles depositional system, re-established a distally-steepened ramp in the Transvaal and subsequent deepening changed it from a periplatform flat into that of a periplatform shelf. Ramps re-evolved at the end of Lyttelton-Eccles depositional system as the sea retreated into the northern Cape. The see-saw pattern (Fig. 63) associated with deepening occurred again with the Frisco-Penge depositional system as a periplatform shelf in the Transvaal became a shallow basin plane (Fig. 69C). Although the carbonate platforms discussed are based on two-dimensional reconstructions, it should be remembered that such platforms developed in a shallow sea and not on a passive margin.

2.13 Margins and Compartments of the Transvaal Sea

A number of interpretations of the field observations and geological profiles need to be clarified before paleogeographical reconstructions of the Transvaal Sea are discussed. The first interpretation is that the presence of tidal flat subfacies through time and space marks the marine-fluvial transition. This subfacies is, therefore, considered an indication of the general area of a depository compartment margin. However, during early transgressions, exaggerated thicknesses of the shallow siliciclastic facies were deposited locally in parts of several

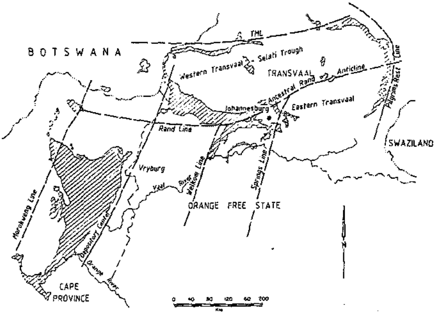


Figure 70. Preserved compartments of the Transvaal Sea as indicated by condensed sequences and major subfacies changes produced by thermal subsidence pattern. Compartment margins are indicated by name.

compartments when they were in a proximal depositional environment. At such times, shallow siliciclastic facies tended to smooth the paleotopography. Lenses of re-worked siliciclastic intraclasts in transgressive shales are indicative of overstepping, as the shallow siliciclastic facies was drowned.

The second interpretation is that the Transvaal Sea was compartmentalized and that to a large extent various compartments were structurally controlled. Structural barriers, which delineate various compartments, were overstepped as each compartment was progressively flooded by the next north-northeastward directed transgression. Three compartments are preserved on the craton, while another lay beyond the limits of the preserved outcrop pattern. This fourth compartment is known to have existed because of the overstepping depositional patterns and because minor outcrops of strata deposited in it are preserved in both the northwestern and northeastern Transvaal.

Based on these interpretations, several possible margins of the various compartments may be delineated and their approximate positions are shown by line in Figure 70. Four north-south and two east-west striking lines are identified, which were perpetuated through Transvaal Sea time and space. The four north-south lines have a general strike of N5°E and are named from west to east as the Morokweng, Welkom, Springs, and Pilgrims Rest lines respectively. The two east-west lines have a general strike of N85°E and are named from south to north as the Rand and Thabazimbi-Murchison lines.

Combinations of these lines define the areal extent of the compartments (Fig. 70). The Vryburg compartment is bound on the west by the Morokweng line, on the east by the Welkom line, and on the north by the Rand line. The western Transvaal-SelatiTrough compartment is bound on the west by the Morokweng line, on the east by the Springs line, on the southeast by eastward extensions of the Rand line, and on the north by the Thabazimbi-Murchison line. The eastern Transvaal compartment is bound by the Springs line on the west and the Pilgrims Rest line on the east; its northern limit is the eastward extension of the Rand line. Limits of the fourth compartment are unknown and may simply represent the dimensions of the Kaapvaal Craton.

Each known line or margin was eventually overstepped during the progressive north-northeastward transgressions. After overstepping, four lines were perpetuated and continued to have a pronounced influence on the depositional systems. They were the Morokweng, Thabazimbi-Murchison, Pilgrims Rest, and Rand lines (Fig. 70). The Morokweng line was perpetuated the longest and was not overstepped until the Upper Monte Christo depositional system. Both the Morokweng and Pilgrims Rest lines influenced the Lower Lyttelton grandcycle when they again acted as margins, but both were overstepped by later transgressions during the Lyttelton-Eccles depositional system. Mudstone-matrix breccias, which occur in almost every depositional system in the northwest Transvaal and which represent some form of slumping, are also an indication that activity on the Thabazimbi-Murchison line was long lived. The Rand line is the most interesting because at different times during the evolution of the Transvaal Sea it acted as a positive, arch-like structure, here termed the Ancestral Rand Anticline (Fig 70).

The Vryburg compartment is considered to be the protobasin of the Transvaal Sea. This was the first compartment to be flooded during various transgressions and the limits of this protobasin are those of the areal distribution of the Vryburg depositional system (Fig. 70). This interpretation is based on the relationships that the Vryburg and Boomplaas depositional systems are not present in the Transvaal, that transgressions were to the north-northeast, and that regressions were to the south-southwest into the northern Cape. It is evident that the Selati Trough is neither the protobasin nor the depocenter previously proposed by Button (1973a). The Selati Trough seems to have formed only part of a Transvaal compartment and it was apparently filled prior to the Lyttelton-Eccles depositional system. In many respects, the Selati Trough appears to have had a very passive character. These interpretations are based on the thicknesses of depositional systems over the Transvaal, on the presence of an unconformity in the Selati Trough, and on the presence tidal flat subfacies (Blyde River Quartzite), which marks a depository margin during the Lower Lyttelton grandcycle.

Stratigraphic thicknesses and skewed depositional patterns indicate that the center of the Transvaal Sea lay in the western Transvaal and northern Cape (Fig. 70). The depository center is juxtaposed over the western margin of the northerly-orientated Ventersdorp Supergroup which has been interpreted to have developed in a rift environment (Tankard et al., 1982; Burke et al., 1985). This resulted in a somewhat asymmetric depository configuration, with steeper depositional flanks to the north and west while gentler ones are to the east and southeast.

2.14 Paleogeographical Synthesis

Paleogeographical reconstructions of the Transvaal Sea are presented in Appendix B and are simplified due to the limitations of preserved outcrop. The following brief statements about these reconstructions are presented so that simplifications can be related to field work. The statements are based on a combination of field data, regional correlation, and interpretations, which reflect how the paleoenvironment was modified to accommodate the evolving depositional systems.

Marine units of the Vryburg depositional system are localized in the northern Cape and northwestern Orange Free State and represent a transition to carbonate sedimentation. These marine siliciclastic units are confined to the Vryburg compartment. Fluvial subfacies (Black Reef Quartzite) sedimentation characterizes the depositional system in the Transvaal (Fig. 52). Due to its passive character, the Selati Trough appears to have been merely a sediment sink as the lower siliciclastic units began to smooth the topography at the onset of deposition (Fig. 52). Two mafic lava flows are present in the Vryburg depositional system. These flows occur near the middle and the top of the depositional system and crop out towards the center of the Vryburg compartment in the northern Cape. The lava flows are of variable thickness; the upper one is locally over 10 m thick.

Carbonate sedimentation began with the Boomplaas depositional system and was a response to rapid transgressions, which drowned the Vryburg depositional system siliciclastic tidal flats. A 15 m thick mafic lava flow is locally present and occurs approximately 36 m above the contact with the underlying Vryburg depositional system (Appendix A). The lava flow appears to have an areal distribution similar to those in the Vryburg depositional system. The Boomplaas depositional system is restricted to the protobasinal area as is the Vryburg depositional system. Relationships are based on borehole core and on paleocurrent measurements, which are to the west in the Middlerand area and to the east at Schmidtsdrif (Visser and Grobler, 1972) (Fig. 2). In both areas, elongation of boundstone organosedimentary structures were used to interpret paleocurrent directions (Fig. 31). These measurements tend to confirm both previous interpretations of the position of the basin center and of the limited extent of marine inundation within the Boomplaas depositional system. Continued accumulation of fluvial subfacies (Black Reef Quartzite) in the Transvaal compartments, north of the Rand line, also supports the areal restriction of the Boomplaas depositional system.

The Lower Oak Tree depositional system followed rapid transgressions which overstepped both the Rand and the Welkom lines. The presence of interbedded lenses of cross-laminated tidal flat subfacies within overstepping shale beds in boreholes from the Koster area indicate that the transgressions were episodic. This depositional system was restricted in an east-west direction by the Springs line in the east and by the Morokweng line in the west (Fig. 70). Overstepping of the Rand line resulted in the flooding of the Western Transvaal-Selati Trough compartment, as is indicated by presence of the depositional system in the Selati Trough. Transgressions were restricted to the north by the Thabazimbi-Murchison line; restriction is indicated by the presence of tidal flat subfacies all along the northern margin of the compartment. Fluvial siliciclastic subfacies (Black Reef Quartzite) continued to accumulate in the eastern Transvaal compartment.

With continued transgressions, the Upper Oak Tree depositional system overstepped both the Thabazimbi-Murchison and Springs lines as a result of the collapse of these margins. Overstepping is also marked by the development of mudstone-matrix breccias along both of these lines and by color-banded rhythmites in the western Transvaal. Such large-scale collapse of marginal lines is likely to generate slumps and breccia debris flows, as well as aid in the erosional landward retreat of barriers (Mullens et al., 1986). Collapse of the Thabazimbi-Murchison caused major southward-directed debris flows, which are related to carbonate rhythmites in the western Transvaal (Fig. 60). Overstepping appears to have been episodic as is indicated by sporadic lateral retreat of the mudstone-matrix breccias up section to the north away from the Thabazimbi-Murchison line and by repeated re-establishment of tufted thrombolitic mound lithofacies between carbonate rhythmite units in the western Transvaal, as well as between units of tidal flat subfacies in the Sudwala Caves area. This was the first depositional system to deposit marine sediments over the eastern Transvaal compartment, as well as most of the Kaapvaal Craton. Expanded inundation drowned the fluvial subfacies and terminated this lower time transgressive unit (Black Reef Quartzite). Transgressions were correlated in the western Transvaal by the location of 15 cm thick ash bed marker (Fig. 53) and relationships have been previously described (See Section 2.9).

The Ancestral Rand Anticline became active toward the end of the Upper Oak Tree depositional system (Fig. 70). Comparisons between boreholes north and south of this arch-like structure indicate that up to 40 m of the stratigraphic succession was either eroded penecontemporaneously with deposition or was simply not deposited (Fig. 60). Disaggregation of oolitic grainstones (Fig. 54) suggests that the area was not sub-areally exposed because diagenetic alteration (chertification) seems to be closely associated with such exposure and not the disaggregation of lithoclasts. In the Sudwala Caves area, there is evidence of shallowing to tidal flat subfacies, but again there is no evidence of subaerial exposure. A lack of deposition over the Ancestral Rand Anticline, also, indicates that this structure may have temporarily separated the western Transvaal-Selati Trough compartment into a sub-basin, as local basin inversion took place. However, depositional patterns clearly indicate that there was active circulation across the structure (Fig. 60) and that the northern sub-basin was not restricted from the southern portion of the Transvaal Sea, but was simply separated from it.

At the beginning of the Lower Monte Christo depositional system, the Ancestral Rand Anticline was again passive. Overstepping was related to rapid transgressions as is indicated by a black carbonaceous shale unit, from 1-3 m thick, that was deposited over the Upper Oak Tree depositional system in the eastern Transvaal (Fig. 65). The general depositional patterns between the Upper Oak Tree and Lower Monte Christo depositional systems, which can be interpreted as a single event, support the interpretation of circulation over the passive Ancestral Rand Anticline, while the deposition of shale on this contact in the eastern Transvaal indicates depositional lag time before re-establishment of carbonate sedimentation. Shallowing over the Transvaal followed the resumption of carbonate sedimentation and resulted in the shoaled flat subfacies depositional character of this depositional system. However, the presence of PACs in the Lower Monte Christo depositional system in the eastern Transvaal implies that subsidence was not continuous, but consisted of a series of episodic deepening events.

Uplift occurred following the Lower Monte Christo depositional system, and a hiatus in deposition separated the Lower Monte Christo and Upper Monte Christo depositional systems. During this hiatus, the Transvaal Sea apparently abandoned the Kaapvaal Craton prior to the deposition of the Motiton depositional system. Abandonment of the Kaapvaal Craton and re-establishment of the Transvaal Sea is supported by the observations that the Motiton depositional system is tidal flat subfacies in depositional character, that marine units are restricted to the protobasinal area (Vryburg compartment) (Fig. 70), that fluvial subfacies channels are present over the western-northwestern Transvaal, and that to a large extent the Motiton depositional system has the same areal distribution as the older Vryburg depositional system. The Motiton depositional system would, thus, represent the thin siliciclastic veneer which is generally deposited prior to the onset of carbonate sedimentation (Read, 1985).

Rapid north-northeast transgressions at the beginning of the Upper Monte Christo depositional system drowned the Motiton "protobasinal" depositional system and re-established carbonate sedimentation over portions of the Kaapvaal Craton that were occupied by the Transvaal Sea prior to the hiatus. Facies distribution following this transgression was similar to that of the Lower Monte Christo depositional system as is indicated by the shoaled flat subfacies character of the Upper Monte Christo depositional system. These similarities indicate that transgressions were not episodic as they were below the regional unconformity and that, with deepening above the Motiton depositional system, the Transvaal Sea simply reclaimed it former depository in the Transvaal. However, some depository deepening, with possible associated expansion, occurred during the Upper Monte Christo depositional system because oolitic lithofacies was re-established some 100 kms north of its greatest accumulations began in the Lower Monte Christo depositional system (Figs. 61; 62). Basin expansion during the Upper Monte Christo depositional system also resulted in the initial overstepping of the Morokweng line (Fig. 70).

At the end of the Upper Monte Christo depositional system, the Transvaal Sea retreated out of the Transvaal and back into the Vryburg protobasinal compartment (Fig. 70). Erosion has removed any evidence of facies progradation, but shallowing upward sedimentary prisms mark the event in the northern Cape. Diagenetic alteration, chertification, and erosion affected the subaerially exposed carbonates in the Transvaal as the fluvial subfacies began to erode channels across the exposed surface. It is significant that fluvial siliciclastic subfacies channels are again developed only in the west and northwestern Transvaal.

Rapid north-northeastward transgressions inundated the Transvaal as the Transvaal Sea again reclaimed it northern and eastern compartments at the beginning of the Lyttelton-Eccles depositional system. There was an unknown lag time before carbonace deposition was re-established during the Lower Lyttelton grandcycle. Sediment starvation resulted in the deposition of a 1-3 m thick shale unit over the Upper Monte Christo depositional system unconformity. The formation of mudstone-matrix breccias over and into the unconformity in the western Transvaal suggests that the Ancestral Rand Anticline (Fig. 70) may have been acting as a barrier margin. Such a margin would have prevented rapid re-establishment of carbonate sedimentation in the Transvaal compartments and margin collapse, during subsequent stages of the transgression, produced the mudstone-matrix breccias. Tidal flat subfacies developed over the northern half of the eastern Transvaal, indicating that the Selati Trough had been filled, that part of the Pilgrims Rest line was again acting as a margin, and that a southwesterly tilt was influencing depositional patterns of the depository. Rapid transgressions occurred again at the end of the Lower Lyttelton grandcycle as the depository deepened and expanded. Submerged shelf subfacies (Figs. 64; 68) spread over the Transvaal during this deepening episode and established the character of this depositional system. The contact of the Lower Lyttelton and the depositional system's second grandcycle is a sharp, paraconformable-like angular unconformity over much of the Transvaal (Fig. 50). This suggests that no barriers existed at this time since a deeper subfacies simply overstepped a shallower one and that depositional lag time between grandcycles was less than that between depositional systems. Near the top of this second grandcycle, carbonate rhythmites appeared in the western Transvaal and were followed by rapid shallowing prior to the next grandcycle. Some shallowing of the depository occurred during the subsequent grandcycles as the percentage of deeper, tufted thrombolitic mound lithofacies began to decrease in subsequent grandcycles.

The sea left the Transvaal again at the end of the Lyttelton-Eccles depositional system and retreated into the Vryburg protobasinal compartment. In the northwestern Transvaal, mudstone-matrix breccias were produced in the upper

Lyttelton-Eccles depositional system prior to regional shallowing. These breccias have the appearance of those found near the base of the Upper Oak Tree depositional system in the Thabazimbi area (Figs. 2; 47). Shallowing-upward sequences also mark this retreat into the northern Cape as the Transvaal was exposed by uplift. Diagenetic alteration, chertification, and erosion followed subaerial exposure. Any fluvial subfacies channels, that may have formed during subaerial exposure, were probably not preserved.

Rapid north-northeastward transgressions of the Frisco-Penge depositional system overstepped progradational boundaries as the second major period of depository deepening and expansion began. The Lower Frisco grandcycle was deposited as the Transvaal was inundated, but only a limited occurrence of this grandcycle is preserved. Carbonate rhythmites were deposited near its upper contact in the western Transvaal prior to shallowing. With shallowing and exposure, the Transvaal Sea prograded southward again into the Vryburg compartment. Following the development of an unconformity, which marks the end of the Lower Frisco grandcycle, rapid transgressions associated with deepening and expansion reinitiated the depositional system as submerged shelf subfacies was re-established over the Transvaal. The repetition of depositional character in the Lower and Upper Frisco grand-cycles indicates that a pattern of rapid transgression could be followed by just as rapid regression. Such a pattern would result in a condensed cycle prior to depository equilibrium that allowed accumulation and preservation of the subsequent grandcycles. This second carbonate grandcycle was followed by a deepening event, which spread basin facies over the Transvaal. Carbonate sedimentation came to end over the preserved outcrop area as banded iron-formation was deposited by these transgressions.

Minor mudstone-matrix breccias and carbonate rhythmites mark the re-introduction of carbonate sedimentation in the Transvaal as shallowing developed the Duitschland depositional system. The Duitschland depositional system is unique in that it is the only carbonate depositional system introduced from the northeast, that it is characterized by both rapid regressions and transgressions and that volcanic flows re-appear for the first time since the Boomplaas depositional system. The Duitschland depositional system was terminated by uplift, which led to the production of regional pre-Pretoria Group, Transvaal Sequence, unconformity.

2.15 Interpretations of Interrelationships

Based on data presented in the previous section, paleogeographical reconstructions (Appendix B) point out a number of interrelationships between the stages of basin development, the sequential arrangement of the depositional systems on the craton, and the influence that expansion of the depository had on the depositional character of the depositional systems. A brief discussion is presented of these interrelationships.

The Transvaal Sea had two principal stages of development (Appendix B). The first stage consisted of the Vryburg through the Lower Monte Christo depositional systems, which is characterized by a dominantly north-northeastward transgressive depositional pattern and by overall depository expansion. The second stage consisted of the Motiton through the Duitschland depositional systems. This second stage is characterized by a re-initiation of the north-northeastward transgressive pattern, as well as a see-saw pattern of regression followed by depository deepening and expansion (Fig. 63).

These two stages represent the evolutionary development of a single depository. As such, they are not strictly first order cycles, as defined by Vail et al. (1977). However, since the stages consist of depositional systems or second order cycles and represent extended periods of maximum marine transgression, they are interpreted as first order cycles. The paleogeographic reconstructions (Appendix B) support this interpretation based on broad changes in the transgressive patterns. It is, also, supported by the relationship that the Motiton through Duitschland depositional systems rest on a cratonic scale unconformity, separating them from the older depositional systems.

If the depository is examined in the light of first order cycles, the repeated character of the transgressive patterns appears to have maintained similar depositional assemblages along older boundaries and trends. These older boundaries and trends within the Transvaal Sea delineate the various compartments which were perpetuated through time and space (Fig. 70). These relationships and the polyhistory of the first order cycles allows the Transvaal Sea to be classified as a resurgent basin.

Klein (1987) recently introduced this term to describe a basin with a polyhistory where the original basin-style is repeated, and maintained, along older tectonic boundaries and trends. A resurgent basin is different from the successor basin-type as described by Klemme (1975). Successor basins are characterized by changing basin-types along older trends while resurgent basins maintain original basin-styles.

Examination of the individual depositional systems also allows a number of interpretations to be made about the sequential arrangement of depositional systems. These interpretations are again based on the depositional patterns. Depositional systems are formed by a number of sedimentary processes. Within the Transvaal Sea, fluvial, wave, and tidal processes seem to dominate. The two principal controls on the spatial and temporal distribution of depositional systems is areal extent of marine inundation and climate (Klein, 1982). Since carbonates characterize the majority of depositional systems, the climate is considered to have been arid and/or tropical. This is supported by the apparent polar wander path for southern Africa published by Windley (1979) (Fig. 71). This plot indicates that southern Africa was in the low latitudes during the proposed 2,5 to 2,3 Ga time frame of deposition. However, increasing width of cratonic inundation by marine processes not only influences the sequential arrangement of the depositional systems, but it also determines their depositional

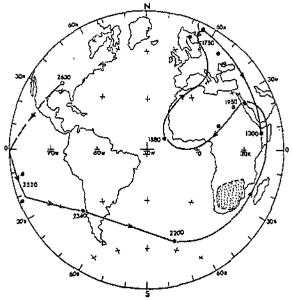


Figure 71. Late Archean to Middle Proterozoic apparent polar wander path for southern Africa. (After Windley, 1979)

character. Pitman (1978) has pointed out that the width of the zone of marine submergence is controlled by the rate of sea-level rise or fall and by the rate of subsidence and sediment fill. If any change occurs, the shoreline will move to a new equilibrium stand. The movement of the shoreline would, thus, determine the time-s ace variations of the different depositional systems. Such variations have been documented by Klein (1982), who has pointed out the following relationships:

1) During low stands of sea-level, fluvial depositional systems are dominant, but they are replaced by wave-dominated processes during early stages of transgression.

2) With sea-level rise, areal extent of cratonic inundation is expanded and tide-dominated processes are characteristic. The lithofacies arrangement is characterized by subtidal, tide dominated counterparts, which intertongue laterally with shallow, wave-dominated coastal varieties.

3) During regression, fluvial deposition once again takes place. It should, also, be obvious that with regression the areal extent of marine processes is decreased and wave-dominated processes replace tide-dominated ones. The depositional character of the various Transvaal Ser depositi al systems clearly follow Klein's (1982) relationships (Table 2). Water depth superimposed on these relationships would explain the periplatform flat nature of early depositional systems, which would require increased wave energy, and the periplatform shelf character of later ones, which had organosedimentary structures shaped by tidal currents.

Klein's (1982) predicted order of the sequential arrangement

Table 2. Depositional character of the various depositional systems within the Transvaal Sea

Depositional System	Transgressive-Regressive Pattern	Depositional Character	Sediment Processes	Stands of Sea Level	Number of Compartments Inundated
Dutschland	Regression	Dynamic	Fluvial-Tidal	High-Low	4-1
Frisco-Penge	Transgression Regression	Shallow Basin	Tidal Fluvial	High Intermediate	4 1
Lyttelton-Eccles	Transgression Regression	Submerged Shelf	Tidal Fluvial	High Intermediate	4 1
Upper Monte Christo	Transgression	Shoaled Flat	Wave-Storm	High	4
Mohlton	Regression	Tidal Flat	Fluvial-Wave Fluvial	Low Low	1 0
Lower Monte Christo		Shoaled Flat	Wave-Storm	High	4
Upper Oak Tree	Transgression	Submerged Shelf	Tidal	High	3
Lower Oak Tree		Submerged Shelf	Tidal	High	2
Boomplaas		Shoaled Flat	Wave-Storm	Intermediate	1
Vryburg		Tidal Flat	Fluvial-Wave	Low	1

Table 2. Depositional character of the various depositional systems within the Transvaal Sea

Depositional System	Transgressive-Regressive Pattern	Depositional Character	Sediment Processes	Stands of Sea Level	Number of Compartments Inundated
Duitschland	Regression	Dynamic	*Fluvial-Tidal*	High-Low	4-1
Frisco-*Penge*	Transgression	*Shallow* Basin	Tidal	High	4
	Regression		Fluvial	Intermediate	1
Lyttelton-Eccles	Transgression	Submerged Shelf	*Tidal*	High	4
	Regression		Fluvial	*Intermediate*	1
Upper Monte Christo	Transgression	Shoaled *Flat*	Wave-Storm	High	4
Motiton	Regression	Tidal Flat	Fluvial-Wave	Low	1
			Fluvial	Low	0
Lower Monte Christo		Shoaled *Flat*	Wave-Storm	High	4
Upper *Oak* Tree	Transgression	Submerged Shelf	Tidal	High	3
Lower Oak *Tree*		Submerged Shelf	Tidal	High	2
Boomplaas		Shoaled *Flat*	*Wave Storm*	Intermediate	1
Vryburg		Tidal Flat	Fluvial-Wave	Low	1

of depositional systems on cratons owes its origin to the known connection between platform width and increasing coastal tidal range and shelf tidal-current velocities. This leads to the conclusion that tides must have functioned in most ancient epeiric seas (Pratt and James, 1986). This is contrary to the accepted historic concept proposed by Irwin (1965) that tides are damped out by friction with shallow sea bottoms. Rather than being damped out, tidal height increases as the ocean tides approach shallow water over a wide platform (Klein ,1982; Pratt and James, 1986). It has been suggested that certain depositional systems smoothed the topography over which the Transvaal Sea transgressed (Button, 1973a; Beukes, 1980a) and the sea floor was being created, not inherited. Tidal waves and currents were therefore, not forced into an inherited, pre-existing array of obstructions and the hydrographic forces of the sea could create sea floor configuration. By creating such a configuration, the shape, areal extent, character, and distribution of lithofacies were then simply determined by water depth (Fig. 55). This is a major difference between epeiric seas and passive margins because the sea could not evolve into a shelf-type platform (Fig. 12). The hydrographic forces of an epeiric sea would not allow the development of any barrier that would overly restrict water circulation and sediment-generating capacity of subtidal areas.

The epeiric character of the Transvaal Sea, in conjunction with water depths, resulted in the broad subfacies belts. This hydrographic system also developed the mudstone-matrix breccias and rhythmites during shallowing events as excess sediment was shed to deeper water. Such a hydrographic system might eliminate the need for allogenic forces as the cause of most small-scale carbonate cycles (PACs ?) (Pratt and James, 1986). Any damping of tides within the Transvaal Sea was probably due to the columnar stromatolite lithofacies acting both as a baffle, as was suggested by Eriksson and Truswell (1974a), and as a sediment sink. This could account for the minor sediment starvation associated with tufted thrombolitic mound lithofacies.

The evolution of a depositional system within an epeiric sea may also explain progressive elimination of deeper water lithofacies from a second stage depositional system, while depositional character is maintained. The depositional systems consist of shallowing-upward grandcycles; and after a few cycles, carbonate sedimentation may reach an equilibrium stand of sea-level. *Such a stand would tend to progressively eliminate* any deeper water lithofacies from a depositional system, but the hydrographic forces would not allow sedimentation to overly restrict established circulation patterns. The depositional character of a depositional system would, thus, represent establishment of an equilibrium stand before the hydrographic forces totally controlled lithofacies assemblages of the depositional system.

The interpretations of the paleogeographic reconstructions and the interrelationships outlined above lead to several questions:

1) What were the structural controls on the depository that influenced the various compartments?

2) Why did the character of the depositional systems change with time?

3) What were the geodynamic influences on the underlying controls and the character of subsidence?

These questions require more data than has been presented here and will be addressed in subsequent chapters.

Chapter 3

Ventersdorp Rift System

3.1 General Statements

Backstripping of the paleogeographical reconstructions reveals a common relationship between the depositional systems, i.e., all depositional systems thicken to the west and southwest (Appendix B). Such sedimentary patterns imply that thickest sedimentary packages overlie the thinnest crust. This is typical of cratonic basins developed over rifts. Further backstripping reveals that the Ventersdorp Supergroup crops out extensively in this west-southwest area. The structural influence on the Ventersdorp Supergroup, along with its observed sedimentary *patterns, has led several authors* to suggest that the Ventersdorp Supergroup represents an Early Proterozoic rift system (Bickle and Eriksson, 1982; Tankard et al., 1982; Burke et al., 1985). Based on this relationship, a two stage *extensional system, i.e.* rifting followed by basin subsidence, was tentatively assumed as an interrelationship between the Transvaal Sea and the Ventersdorp Supergroup. Juxtaposition of the depositional axes of the Transvaal Sea over the western margin of the Platberg Group, Ventersdorp Supergroup (Fig. 70), and skewed sedimentary patterns suggest that the structural framework of the Transvaal Sea was inherited from the intraplate deformation that produced the Ventersdorp Supergroup.

3.2 Geological Relationships

The Ventersdorp Supergroup (approximately 2.7 Ga) accumulated in fault-bounded troughs and is estimated to have covered an area of 300,000 km^2 (Pretorius, 1976; Armstrong et al., 1986). Approximately 200,000 km^2 of this area is preserved over the central portion of the Kaapvaal Craton with about one fourth cropping out. Field evidence clearly indicates an interrelationship between the Transvaal Sea and the Ventersdorp Supergroup and support earlier, more general rift interpretations (Tankard et al., 1982; Bickle and Eriksson 1982; Burke et al.; 1985). Moreover, the compartmentalization of the Transvaal Sea (Fig. 70) suggests that the tectonic history of the Ventersdorp Supergroup is more complex than previously assumed. However, the structural style of extension of the Ventersdorp Supergroup has not been fully addressed. Further backstripping was required to examine the relationships preserved in the Ventersdorp Supergroup so that this structural style could be identified; this was accomplished using known geologic relationships. Such an approach was based on Harding and Lowell's (1979) statement that identification of structural style can be made with few data if based on the gross regional patterns of the structures.

Winter (1976) subdivided the Ventersdorp Supergroup into four sub-divisions: the Klipriviersberg Group, the Platberg Group, the Bothaville Formation, and the Allanridge Formation. These subdivisions will be continually referred to in the

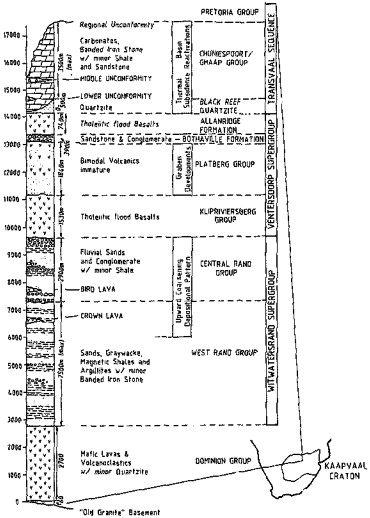


Figure 72. General stratigraphic section of the successor basin sequence developed on the Kaapvaal Craton from 3,0 to pre-2,2 Ga.

following discussion and a simple stratigraphic section is shown in Figure 72. Volcanic and sedimentary rocks of the Ventersdorp Supergroup rest somewhat conformably on Witwatersrand Supergroup strata in many places in the east and central Rand. Along the northwest margin of the preserved Witwatersrand Supergroup, there is an angular unconformity of up to 5° between the Supergroups.

Extensional block faulting was initiated during late Central Rand Group, Witwatersrand Supergroup, time; paleorelief produced by this faulting varied from 1 to 30 m (Tankard et al., 1982). Troughs and half-troughs strike north-south oblique to other Witwatersrand Supergroup structural features and faulted blocks acted as sediment sources prior to the extrusion of Klipriviersberg Group lavas. Thicknesses, shapes, and dispersal patterns of deposited fanglomerates suggest down-to-the-west faulting (Minter, 1978).

The Klipriviersberg Group consists of a repetitive sequence of alkali-rich, continental tholeiitic flood basalts in which lava flows of variable thickness filled irregularities on the underlying Witwatersrand Supergroup paleosurface (Tankard et al., 1982). However, locally at the base, high-Mg, komatiitic basalt flows are present (McIver et al., 1982). The lower flows, which filled the Witwatersrand irregularities, do not have the areal extent of some of the upper Klipriviersberg Group flows (K. J. Palmer, pers. commun., 1987). This suggests a widening propagation of volcanism during Klipriviersberg time, which could have been related to alternating periods of faulting. Overall, general chemical homogeneity of these extrusives, along with a general lack of intercalated sedimentary layers, suggests rapid extrusion which was penecontemporaneous with faulting (Tyler, 1979a). Extension faults are believed to have acted as conduits for the ascending magmas (Visser, 1957).

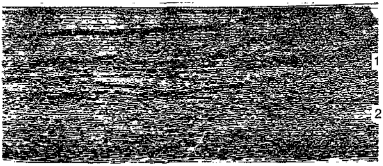
The principal development of the Platberg Group is located to the west of the preserved Witwatersrand structural basin and represents a shift in the position of both faulting and depocenters. A major phase of extensional block faulting became active in late Klipriviersberg time and was responsible for the formation of the Platberg Group grabens. Field relationships suggest that attenuation of the extended Ventersdorp terrane increased with the production of horst blocks and strike-slip faults (Buck, 1980; Tankard et al., 1982; Stanistreet et al., 1986). Graben development resulted in a pronounced unconformity between the Platberg Group and the underlying Klipriviersberg Group. The unconformity is along what has been termed in this research the Welkom line which is also the western margin of the preserved Witwatersrand structural basin (Buck, 1980) (Fig. 70). This is in sharp contrast with the general nonconformable contact between the Klipriviersberg and Central Rand Groups to the east. Fault displacement varies east to west across the extended Platberg region. Throw on faults differs from hundreds of meters along the eastern margin (Welkom line) of the graben to as much as 5 km along the western margin which is just west of the basin center of the Transvaal Sea (Visser et al., 1976; Buck, 1980) (Fig. 70). Differences in throw along these marginal faults have resulted in an overall skewed, if not asymmetric, pattern of extensional deformation. Lithologies within the Platberg Group are made up of an interfingering sequence of bimodal volcanics, immature clastics, and playa lake sediments (Buck, 1980). These sediments suggest that an interior or closed drainage system was present within the developing graben system. Fanglomerate shape is a reflection of penecontemporaneous faulting (Winter, 1976) and dispersion patterns again indicate a down-to-the-west pattern of faulting. By the end of Platberg Group time, faulting and graben development were virtually complete (Buck, 1980).

The Bothaville Formation is unconformable with the underlying Platberg Group and is dominated by clastic sedimentation. Lithologies vary vertically from conglomerate to impure sand and shales back to conglomerate (Buck, 1980). Winter (1965) suggested that this sedimentation was the initial phase of deposition of the Transvaal Sea; these relationships will be discussed later. The Bothaville Formation was not deposited over parts of the eastern Platberg Graben margin. Non-deposition suggests that the margin might have undergone differential uplift and was a positive feature at that time. The Allanridge Formation flood basalts buried both the Bothaville Formation and eastern marginal features (Buck, 1980). However, the Allanridge Formation is known to overlie older basement in other places (Button et al., 1981). The Vryburg depositional system overlies the volcanic units of the Allanridge Formation; relationships of this depositional system with the Ventersdorp Supergroup have been described in the previous section.

3.3 Geophysical Relationships

With much of the geology known from surface outcrop, mine development, or boreholes, seismic surveys have only recently been introduced to assist in the determination of hidden exploration targets and many of the surveys are presently confidential. Magnetic and gravimetric surveys have been utilized in gold field scale exploration of the Witwatersrand Supergroup, but many geophysical anomalies have yet to be described because the focus has not been on a cratonic-wide scale.

Only specific, regional seismic lines exist presently and very few descriptions of industrial seismic sections have been published. However, Weder (1987) recently described a number of section lines just to the south of Johannesburg in an area known as the Central Rand (Fig. 2). In these lines, he identified low-angle imbricate thrusts which verge to the northeast and deform both Central Rand Group, Witwatersrand Supergroup, and Klipriviersberg Group strata (Figs. 73A, B). Thrust blocks show independent block movement with both normal and reverse throws across individual structures bounding faulted blocks. Faults flatten into a sole thrust within a major shale unit in the upper West Rand Group, Witwatersrand Supergroup, just below its contact with the Central Rand Group (E. E. W. Weder, 1988, pers. commun.). The sole thrust is approximately 5000 m below the present surface. In two short lines in the Bothaville area, low-angle imbricate thrusts, which verge to the east, can also be identified. Normal and reverse throws across individual faults



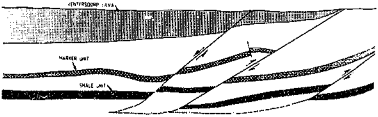


Figure 73A. Seismic profile across the Central Rand, south of Johannesburg.

73B. Interpretation of seismic profile showing low-angle imbricate thrusts which offsaet markers within both the Witwatersrand and Ventersdorp Supergroups. (After Weder, 1987)

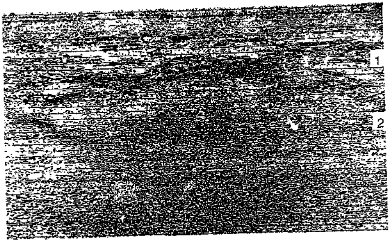


Figure 74. Seismic profile showing the antiformal arching of the sole fault west of Bothaville.

again indicate independent thrust block movement. These structures flatten into a sole structure at a depth of approximately 6000 m. Along one line, the sole fault is arched into an antiform and climbs to approximately 3000 m below surface before dipping down to the west to approximately a depth of 6000 m again (Fig. 74). In seismic lines further to the west, in the Vryburg area, deeper reflection surfaces show a similar arched geometry and may represent uplifted Moho (E. P. W. Swindell, 1988, pers. commun.).

With the limitation on seismic profiles, indirect observations of the Ventersdorp Supergroup were based on regional aeromagnetic and Bouguer gravity expressions (Figs. 75A, B). Although data sets show a number of superimposed features, i.e. Bushveld Complex and Vredefort Dome, other prominent features can be identified from the geophysical data. A preliminary analysis using a similar data base has been presented by Corner et al. (1986), but their analysis primarily involved the northern and central portions of the preserved Witwatersrand structural basin.

Particular attention is drawn to a previously undescribed negative magnetic feature which occurs as a subdued trench-like zone and which extends northwards from the southern limit of the map (Fig. 75A). The western boundary of this trench-like zone is pronounced, while the eastern boundary is somewhat gradational with a regionally subdued magnetic area. The western boundary strikes about N5°E and coincides with the depositional axes of the Transvaal Sea. This boundary terminates against a northern linear magnetic feature, which is the Thabazimbi-Murchison line

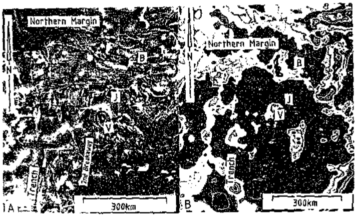


Figure 75A. Regional magnetic data over the central and western Kaapvaal Craton. Location of trench-like structure and second breakway are indicated.

75B. Regional bouger gravity field map over the central and western Kaapvaal Craton. Relationship between trench-like magnetic structure and major gravity anomaly are indicated. (J-Johannesburg; V-Vredefort Structure; B-Bushveld Igneous Complex) striking N85°E across the northern quarter of the map. The Thabazimbi-Murchison line has been previously mentioned as a compartment boundary of the Transvaal Sea. It is, also, a major, left-lateral transcurrent fault, which forms a long-lived zone of weakness in the Kaapvaal Craton.

The pronounced western and northern boundaries of the subdued trench-like zone indicate that magnetic basement is deeper adjacent to these boundaries and imply that the magnetic basement is down-faulted. Differences in the basement were ruled out as a reason for these linear magnetic expressions because the magnetic basement for the Kaapvaal Craton is considered to be the "Old Granite" basement and because this negative anomaly dominates the western half of the craton, regardless of any heterogeneities. The pronounced western margin, which grades eastward into a larger subdued magnetic expression, supports the observation of asymmetric fault configurations previously discussed (See Sec. 5.2).

If superimposed features are again ignored on the Bouguer gravity field map, the most prominent features on the map are two linear, positive anomalies which dominate the western third of the map (Fig. 75B). Both anomalies strike about N5°E and terminate abruptly against the Thabazimbi-Murchison line. The anomalies also appear to correspond with the aeromagnetic pattern (Fig. 75A). However, the larger Bouguer anomaly lies west of the subdued trench-like zone, while the second, smaller discontinuous anomaly is coincident with it. This asymmetric relationship between the larger anomaly and the trench-like magnetic expression suggests that separate mantle lithospheric thinning was offset from crustal extension.

3.4 Rift Thermotectonics

A certain amount of confusion has developed in the literature due to the usage of the term "rift." The writer considers the term rift or rifting to denote a sequence of tectonic responses of lithospheric magnitude and is, thus, not a specific structure. A reconstruction of the paleoenvironment of a rifted sequence can be based on lithological character and crustal response. However, such reconstructions must also address thermotectonic driving mechanisms of the rifted sequence. Perrodon and Masse (1984, p. 6) have distinguished such thermotectonic areas as:

1) convergent zones, dominated by compressive tectonics and weak heat flows in a thickened lithosphere;
2) continental platforms, characterized by strike-slip faulting and average heat flow; and
3) divergent zones, developed by extensional tectonics combined with high heat flow in a thinned lithosphere.

Rift structures can form in all three settings and interpretations of their development have been made without consideration of heat flow or extension rates. However, paleogeographical reconstructions must consider both of these factors. If heat flow is considered, rift zones can be divided into wet rifts (high volcanism) and dry rifts (low- or no *volcanism) (Barberi et al., 1982).* Extension rates are greater in wet rifts than in dry rifts, and this is linked to the dynamics of asthenospheric upwelling (Barberi et al., 1982). If asthenospheric upwelling *is considered, two modes of rifting* can be construed: "active" rifting, related to asthenospheric up-welling, or "passive" rifting, related to deviatoric stresses transmitted from distant plate interactions (Sengor and Burke, 1978; Ramberg and Morgan, 1984). The "active" mechanism differs greatly from "passive" rifting because in "active" rifting heat flow, magnitude of uplift, and volume of associated extrusives tends to be greater than in "passive" systems (Ramberg and Morgan, 1984). Since high heat flow and increased extension rates are characteristic of wet rift zones, wet rifts should be considered as part of a divergent thermotectonic zone driven by "active" rifting.

3.5 Interpretations of Normal Simple Shear

3.5.1 General Statements Mohr (1982) established a succession of tectonic and magmatic events resulting from rifting and he proposed that graben development was a late stage phenomenon of the succession. However, some authors consider late-stage graben development and rifting to be synonymous. It is this synonymous usage that has led to misinterpretations of *infra-graben tectonic and magmatic events. Since graben* development is considered to be a late stage response to infra-graben tectonic and magmatic events, many transformations within the rifting process develop during a pre-graben stage and lead to graben development. Episodic changes in heat flow, extension rates, uplift/subsidence patterns, and faulting occur in the pre-graben stage. These early thermotectonic processes influence the structural grain of the area, which localizes all sequential structural responses.

From a thermotectonic point of view, the Ventersdorp Supergroup can be linked to a divergent thermotectonic zone driven by "active" rifting, which results in a wet rift with greater extension rates. Graben development was a late stage phenomenon, and the stratigraphic subdivisions of the Ventersdorp Supergroup can be used to interpret the progressive evolution of the tectonic stages. One would assume that early interpretations of rifting (Bickle and Eriksson, 1982; Burke et al., 1985) were based on the accepted pure shear or symmetric extension model. However, the COCORP 40° Transect, across the Basin and Range province, western United States, has shown that any model of symmetric horst and grabens can be largely ruled out when applied to large areas of continental stretching (Allmendinger et al., 1987). The skewed pattern of the compartments of the Transvaal Sea indicates that a different style of extension produced the Ventersdorp Supergroup. Integration of backstripped geological and geophysical data suggests that the extended Ventersdorp terrane resulted from crustal scale simple shear along a detachment.

Such an interpretation of the skewed geological and geophysical relationships suggests that Wernicke's (1985) normal simple shear or asymmetric extension hypothesis provides insight into the formation of the Ventersdorp Supergroup. Although the COCORP 40° Transect did not completely support the Wernicke hypothesis, it did not rule it out. Moreover, interpretations of deep seismic reflection profiles across the North Sea (Beach, 1986); across the Gregory Rift (Bosworth, 1987); across the Ross Embayment, Antarctica (Fitzgerald et al., 1986/87); and across the Bay of Biscay (Le Pichon and Barbier, 1987) show striking similarities between the extensional geometries and the Wernicke hypothesis.

The interpretation of normal simple shear is generally based on the identification of low-angle (less than 30°) normal faults, which have a consistent sense of dip and which progressively flatten into a basal detachment (Wernicke, 1981). A basal detachment has been tentatively identified on seismic lines at depths between 5000 and 6000 m (Figs. 73B; 74). Several generalizations also support application of the Wernicke hypothesis to the Ventersdorp Supergroup. Such generalizations are that an absence of symmetric rift structures has been noted on seismic sections (Bally, 1982); that low-angle normal faults characterize areas of large continental stretching (Brun and Chockroune, 1983); that opposite margins do not exhibit identical structures (Lister et al., 1986); and that the nature of extension of the lower lithosphere provides clues to crustal shear systems which penetrate the entire lithosphere (Wernicke, 1985). Of the four, the last is crucial because crustal geology may provide few clues to the nature of extension of the lower lithosphere. It is the non-uniformity of extension between the

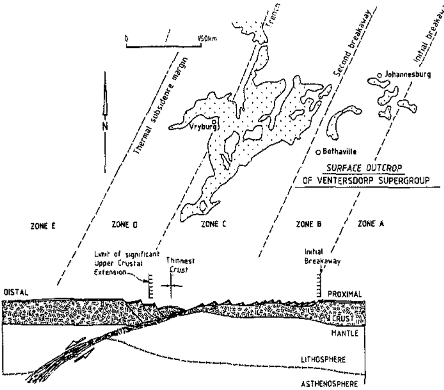


Figure 76. Wernicke's (1985) hypothesis as applied to the development of the Ventersdorp supergroup. Graphic shows location of initial and second breakaway zones, as well as thermal subsidence margin.

crustal and mantle lithospheres upon which the normal simple shear hypothesis is based (Wernicke, 1985). This non-uniformity of extension between the two lithospheric units is clearly recognizable in the presented geophysical relationships and is an indication of the structural style of deformation of the Ventersdorp Supergroup.

Wernicke (1985) proposed five zones across a hypothetically extended terrane (Fig. 76); and simply named them as A, B, C, D, and E, with zone A being the most proximal to the breakaway and zone E the most distal. Zone B defines a region of crustal, but not mantle, lithospheric extension and the zone undergoes mechanical subsidence. Zone C contains the locus of maximum crustal extension; both crustal and mantle lithosphere are thinned across the zone. Zone C also contains the region of maximum subsidence; the distal margin of this zone defines where the crust is no longer involved in the thinning process. Zone D involves only mantle lithospheric thinning and uplift occurs because the zone contains the locus of maximum lithospheric thinning. Zone A and Zone E are unstrained, but footwall rebound of zone A may develop a structural barrier near the breakaway.

3.5.2 Asymmetric Ventersdorp Supergroup Extension As shown in Figure 76, Wernicke's (1985) proposed zones of extension are clearly identified within the extended Ventersdorp terrane and support the interpretation of down-to-the-west lithospheric failure. Extension began in late Central Rand Group, Witwatersrand Supergroup, time and was characterized by normal down-to-the-west faulting, which is the interpreted structural style of Ventersdorp Supergroup. This early period of normal faulting without volcanism would represent an initial stage of passive rifting and could have been associated with some uplift. The fairly rapid appearance of volcanics in the Klipriviersberg Group following early extension faulting and initial outpouring of komatiitic flows (McIver et al., 1982) is an indication that extensional faulting accelerated with time. Nisbet (1984) points out that, if extension was rapid enough and country rock cool during the early stages of an Archean basin, some komatiite liquid might ascend directly from depth. *The occurrence of* komatiites would also indicate that magma at mantle temperatures *of as much as 1650° were extruded* at the surface and that the geothermal gradient was radically reduced over the region as heat was pumped into the crust. Such modifications of the thermal structure of the Kaapvaal Craton set the stage for the sequence of rifting events, which followed during the remainder of Ventersdorp Supergroup time.

A barrier of some sort along the Springs line retarded basin expansion to the east during the flooding of the Western Transvaal-Selati Trough compartment by the Lower Oak Tree depositional system (Fig. 70). The Springs line is, thus, interpreted as being the site of the initial breakaway and the boundary between zones A and B. Footwall uplift or rebound due to unloading of the hanging wall may have formed the Springs line barrier. E. E. W. Weder *(1988, pers. commun.) points out that* seismic lines are structurally quiet east of this line. West of the breakaway, the area between the Springs and the Welkom lines would define zone B. Low-angle imbricate thrusts, which splay from a sole thrust, are believed to be reactivated low-angle listric normal faults which initially joined the basal detachment in zone B (Figs. 77A, B). If these thrusts are reactivated listric normal faults, their vergence would indicate that initial normal faulting was down-to-west-southwest. Normal fault systems formed by substantial extension may have identical thrust fault geometries; and under a suitably orientated compressive stress field, normal faults should be reactivated as thrusts (Etheridge, 1986). These structures are in the West Rand Group, Witwatersrand Supergroup, and the location of such structures is consistent with faulting being restricted to the crustal lithosphere in zone B. However, the minimal displacement on the thrusts may be an indication that the early listric normal faults in zone B were only weakly rotational.

The Welkom line would separate zones B and C (Fig. 76). However, zone C is more interpretative than zone B. Its existence west of the Welkom line may be deduced from the observations that sedimentary thicknesses increase toward the basin center (Badley et al., 1984) and that opposite margins do not exhibit faults with identical throws (Lister et al., 1986). Thickest accumulations of sediment overlie the subdued trench-like magnetic zone in the western Transvaal and northern Cape (Fig. 75A). Gibbs (1987) pointed out that much of the basin

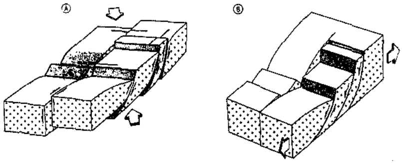


Figure 77A. Block reconstruction of Weder's (1987) interpretation of Central Rand imbricate thrusts (See Fig. 73B). Graphic also shows associated oblique-slip fault.

77B. Interpretation of listric fault geometry *developed by* Ventersdorp Supergroup extension prior to compressive stress reactivation. Graphic *shows transfer fault* developed within the extensional fault system.

(Cartoons modified after Etheridge, 1986)

floor on one side may be a fault surface and distribution of facies and stratigraphic fill is skewed to one basin margin. The smaller of the two Bouguer anomalies (Fig. 75B) to the west of the Welkom line is coincident with the trench-like zone. This anomaly implies that both crustal and mantle lithospheric are thinned in the distal portion of zone C, where the basin floor may have been only a fault surface. Maximum thinning can also be equated to maximum subsidence and this is indicated by the thicknesses of the overlying Transvaal Sea carbonates. The larger of the two Bouguer anomalies lies (Fig. 75B) to the west of the Platberg Group grabens and substantiates zone D, since the zone only involves mantle lithospheric thinning. An uplifted Moho in this area, also, supports this interpretation. Magnetic expressions and asymmetry of the depositional systems, which were influenced by the Morokweng line to the west, are additional evidence. However, without confirmation from regional seismics, the existence of a low-angle detachment fault, which penetrates the entire thickness of the lithosphere in zone D, is speculative. Nevertheless, Allmendinger et al. (1987) have indicated that such a structure may be healed relatively quickly by magmatic processes and ductile flow, which would make it difficult to detect. The assigned extensional zones of the Ventersdorp Supergroup are supported by the lithospheric deformation patterns Fitzgerald et al. (1986/87) have proposed for uplift and subsidence in the Transantarctic Mountains and Ross Embayment, Antarctica (Fig. 78).

3.5.3 The Platberg Group Graben Graben development is somewhat problematical because it is located in only the western half of the extended Ventersdorp terrane. This implies that the detached terrane was overprinted by large-fault block ranges. The evolution of faulting during Ventersdorp Supergroup time is shown in Figure 79.

The increase in faulting with time suggests that isostatic rebound resulted in antiformal warping of the basal detachment as the footwall was unloaded. In the parts of extended terranes that are hot and highly faulted, flexural rigidity should be low (Buck et al., 1988) and assists isostatic rebound. Antiformal warping could also develop due to stress amplification because the early normal faults are only weakly rotational and the amount of unloading prior to isostatic rebound is unknown. Gibbs (1984) points out that the original form of the basal detachment may have an arch-like geometry with ramps and flats. With high heat flow, upward warping of an extension ramp in the vicinity of the Welkom line may have resulted in the antiformal structure.

Antiformal warping produced a second breakaway zone and one sided denudation. A second breakaway, associated with maximum extension, may be located at a significant distance from the initial breakaway (Spencer, 1984). Such a sequence of events would explain the increase in faulting with time and the location of the Platberg Group graben in zone C. The rift zone should narrow with time if extension occurs preferentially in the weakest part of the lithosphere (Buck *et al.*, 1988). Zone C, which localized the Platberg Group graben, had a higher geotherm and thinner lithosphere due to the deformation geometries.

Antiformal warping of the basal detachment probably occurred during late Klipriviersberg Group time with the second breakaway forming along the western margin of the preserved Witwatersrand structural basin near the boundary of zone B and C (Figs. 70; 74; 76; 79B). With its development, faulting became inactive to the east preserving the Witwatersrand Supergroup and its major economic resources. Footwall-rebound, resulting from development of this second breakaway, formed a barrier along the Welkom line.

Related to the antiformal warping of the basal detachment and the development of a second breakaway is the De Bron Horst (Fig. 80). The De Bron Horst lies within the region of the Welkom line and was not buried until post-Bothaville Formation times (Buck, 1980). Continued warping, possibly due to rebound and heat flow, allowed the antiformal breakaway to reach surficial levels and is believed to formed the De Bron Horst. Associated footwall uplift and erosion imparts a characteristic rounded shoulder to extension fault blocks (Barr, 1987). These relationships are clearly evident in published cross sections of the horst by Buck (1980). However, the vertical scale on Buck's (1980) diagram is greatly exaggerated and a true scale representation is presented in Figure 80. The complex extensional fault array, which formed the second breakaway, dissected the arched basal detachment and left the De Bron

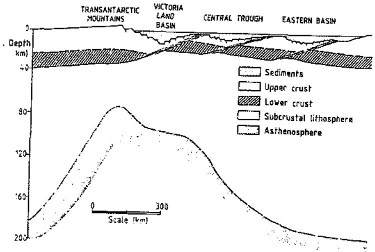


Figure 78. Cartoon of deformation patterns and extension geomery as interpreted from deep seismic profiles ascross the Transantarctic Mountains and Ross embayment. (Modified after Fitzgerald et al., 1986/87)

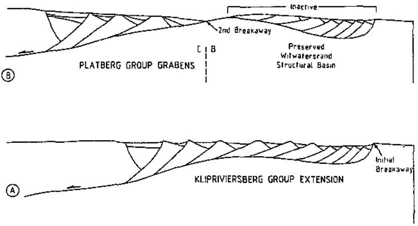


Figure 79A. Down-to-the-west, listric normal faulting developed *during Klipriviersberg Group* time prior to second breakaway.

79b. Development of second breakaway and one sided overprinting of large fault-block ranges on the detached terrane during Platberg Group time.

(Cartoons modified after Spencer, 1984)

structure as a footwall island (Barr, 1987). Reverse faults *have* been reported in the same area as the De Bron structure and have a minor component of strike-slip. Such oblique slip can develop on detachment faults with strike-slip, reverse faults, and folding components of deformation in the hanging wall plate (Gibbs, 1987). A second explanation for several of these structures might be that they represent a secondary effect of one-sided denudation. Continued uplift results in concave-upward flexure on the inactive flank of the antiform, which could lead to reverse faulting and folding increasing the antiform height (Spencer, 1984).

3.6 Observations of Margins

Interpretations of down-to-the-west normal faulting for Ventersdorp Supergroup extension indicate that the bounding lines or margins for the various compartments of the Transvaal Sea may not have been as linear as previously sketched in this research *(Fig. 70). Step-like margins are a normal* consquence of an extensional system. Longitudinal normal faults and orthogonal strike-slip faults were activated by the extension system which both developed and expanded the *Platberg Group graben.* Longitudinal normal fault arrays are perpendicular to east-west regional extension, while orthogonal strike-slip faults lie nearly parallel to it. East-west strike-slip faults have been described by Stanistreet et al. (1986) in the Central Rand, and local pull-apart basins along strike of these faults, during Platberg Group time, have been interpreted by them as due to a

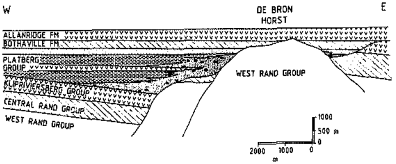


Figure 80. True scale graphic of the De Bron horst showing asymmetric horst development. (Modified after Buck, 1980)

wrench fault system operating in that area. However, these faults may well be transfer faults, as defined by Gibbs (1984), and not "true" basement-driven wrench faults. Transfer faults are a fundamental expression of extension rupture which produces the graben; they link extension structures of differing slip rates (Harding and Lowell, 1979; Gibbs, 1984). Both transpressional structures, i.e. Riedel-shears, folds, and flower structures, and transtensional structures, i.e. pull-apart basins, can develop depending on the orientation of transfer and extensional fault components in the overall extension system (Gibbs, 1984).

Formation of associated normal and transfer faults appears necessary to allow discontinuous slip, rotation of main basin elements, and integrated graben subsidence (Harding and Lowell, 1979; Gibbs, 1984). The gross geometry of the Platberg Group graben is that of a series of half-grabens with the hanging wall being segmented by strike-slip transfer faulting during the growth of the structure. Segmentation of the extended terrane resulted in step-like margins which were inherited by the Transvaal Sea.

Chapter 4

Subsidence of the Transvaal Sea Depository

4.1 Early Subsidence Patterns

4.1.1 General Statements As previously mentioned, the history of vertical crustal movements is recorded in the stratigraphy of a sedimentary basin (Beaumont, 1978). Crustal movements can be reconstructed from the stratigraphic record once a data base is analyzed. With an understanding of the architecture of the depository and its basement precursors, thermomechanical models can be used to predict subsidence patterns of the depository through time. Most models predict two stages of subsidence. The initial stage is one of mechanical thinning of crust and lithosphere and may be called the rift stage. Graben geometry developed by the rift stage is largely controlled by the fault pattern which results from the overall tensional stress regime (Badley et al., 1984). Graben development, during the rift stage, may have a polyhistory. The second stage is a post-graben, thermal subsidence stage, which is due to thermal contraction of a cooling lithosphere (Royden et al., 1980; Watts, 1982; Watts et al., 1982.). Thermal subsidence occurs because during lithospheric attenuation geothermal gradient is reduced and heat flow is increased, which heats and weakens the lithosphere. Thermal readjustment is required to return the lithosphere to its pre-stressed state. Since it is a readjustment, thermal subsidence is time dependent because cooling would increase the flexural rigidity of the lithosphere with age (Watts, 1982). For a depository to form, lithospheric attenuation has to be accompanied by mechanical subsidence (faulting). Without it, cooling, following a thermal disruption, would simply return the lithosphere to a pre-stressed state without the development of a basin. To form an extensive depository requires a divergent thermotectonic zone as defined by Perrodon and Masse (1984).

This general two-stage model of basin subsidence has come to be known as the McKenzie (1978) model, which has been systematically and widely applied to the development of continental basins (Dewey, 1982). However, basin or depository development is not quite as simple as the McKenzie model implies because the timing of thermal subsidence is highly dependent on heat flow. Royden et al. (1980) have considered this variable and have proposed an alternative or complimentary model. In this model, Royden et al. (1980) address character of graben development and subsequent thermal subsidence from an associated heat flow approach.

With two models available for comparative purposes, predicted subsidence patterns of a basin can be confused. Dewey (1982) carefully reviewed both models in his study of the evolution of the British Isles and has pointed out a number of specifics.

1) Listric normal faulting characterizes extension in the McKenzie model; while the Royden et al. model is typified by steep, basin margin normal faults which focus hypabyssal intrusion and volcanism that persists into the thermal subsidence stage.

2) The history of basinal geothermal gradients is fundamentally different in the two models and many of the thermal differences in the two models can be explained by the timing of the associated volcanism. It is these differences that influence the subsequent character of thermal subsidence. In the McKenzie model, all strata in the lithosphere gradually become cooler with time after the rifting stage because early rift graben development is assumed to occur without volcanism. Individual rock units within the lithosphere would, thus, enjoy a reduced overburden prior to heating by mafic volcanism in some advanced stage of graben development. However, in the Royden et al. model, magma at mantle temperatures comes to the surface. Heat is, thus, pumped into the crust with the effect that the geothermal gradient is reduced, and all strata become initially hotter before gradually cooling to equilibrium temperature. This is because the Royden et al. model assumes that mafic magmatism characterizes the entire history of the rift stage and the early parts of the thermal subsidence stage.

3) In both models, fault-controlled graben subsidence is followed by thermal subsidence which is enhanced by sediment loading. Such subsidence patterns produce the common "Steer's Head" basin geometry.

4) The time span, involving the transition from the fault-controlled rift stage into the thermal subsidence stage, is relatively short in the McKenzie model. It is more protracted in the Royden et al. model because the lithosphere remains warmer and weaker for a longer period of time, which allows local compensation (uplift) to persist into the thermal subsidence stage.

5) Heat flow will develop marginal thermal bulges earlier and more strongly in the McKenzie model. However, marginal thermal bulges, caused by lateral heat flow, will be more characteristic of the Royden et al. model causing early, fault-controlled rift shoulders.

Both the McKenzie (1978) and the Royden et al. (1980) models share a common assumption that thermal subsidence began at or below sea level. Such an assumption may be justified in order to model the geometry of syntectonic stratigraphic relationships. However, such an assumption creates difficulty in the differentiation of subsidence stages when either of these models are applied to the Transvaal Sea. Recently, Houseman and England (1986) discussed this problem and pointed out that a third component to the subsidence history existed, which was termed tectonic subsidence. In their view, tectonic subsidence represents a re-adjustment stage between mechanical fault-controlled subsidence (rift stage) and flexural thermal subsidence. During tectonic subsidence, the driving force of extension is removed prior to thermal subsidence. Houseman and England (1986) also point out that removal or decay of convection-related uplift can be episodic in character and that much of the subsidence during this re-adjustment stage takes place subaerially. Such a re-adjustment stage should be recognizable in the stratigraphic record. Since various thermotectonic models assume thermal subsidence starts at sea level, it is the tectonic subsidence stage, that is separated from the rift stage by an unconformity, instead of the thermal subsidence stage. Transition between tectonic and thermal subsidence stages can be assigned where the first marine sediments are first present in the stratigraphic record, regardless of whether they overstep the rift graben margins or not.

4.1.2 Discussion The geometry of the graben developed by the rift stage is largely controlled by the overall extensional stress system. Recognition of the character of extension is important because it has a direct influence on the patterns of subsidence. Since field relationships indicate that the Ventersdorp Supergroup was developed by uniform-normal simple shear, it is pertinent that Wernicke (1985) suggested thermal subsidence should occur to some degree in all zones across the extended terrane, with the maximum net subsidence occurring in zone C (Fig. 76). Barr (1987) re-examined Wernicke's model and indicated that, due to the complex interplay of upper- and lower-plate stretching, thermal subsidence can be partly or wholly decoupled in a geographic sense from the rift stage graben. This would mean that thermal subsidence of zone D (Fig. 76), rather than zone C, could dictate the geographical location of the basin. However, in quantitative models calculated by Buck et al. (1988), the effects of crustal thinning outweighed that of thermal uplift, resulting in maximum subsidence where the crust is thinned. Maximum subsidence would be in the distal parts of zone C where the area of nearly uniform depth of subsidence narrows. If both Wernicke's (1985) and Buck et al. (1988) conclusions are considered together, they tend to confirm Gibbs' (1987) statement that distribution of facies and stratigraphic fill are skewed to one basin margin.

After comparing the McKenzie (1978) and Royden et al. (1980) models, Dewey (1982) concluded that they were not exclusive alternatives. However, a combination of the two has fundamental implications for development of associated rift shoulders, peripheral bulges, and geometry of subtle stratigraphic features. If a combination of the McKenzie and Royden et al. models is applied to the Wernicke model, the following generalizations can be made:

1) The extended area of zone B is characterized by listric normal faults as predicted by the McKenzie model, while zone C, which is near the limit of significant upper-crustal extension, is characterized by steep, basin-margin normal faults as predicted by the Royden et al. model.

2) Due to the complex interplay between upper- and lower-plate stretching, zone C would have a lower geothermal gradient than zone B as predicted by the Royden et al. model.

3) Thermal subsidence, enhanced by sediment loading, produces a "Steer's Head" geometry, but the basin geometry would be asymmetrically skewed toward zone B, which would result in a "short horn" being developed in zone C due to the differences in the graben margins.

4) The time span for transition from a fault-controlled rift stage into a thermal subsidence stage should be short in zone B as predicted by the McKenzie model. However, it would be more protracted in zone C as predicted by the Royden et al. model because zone C would remain warmer for a longer time period due to reduced geothermal gradients.

5) Heat flow would create an early thermal bulge in zone B as predicted by the McKenzie model; but lateral heat flow, associated with doming in zone D, would enhance the steeply-dipping, normal faults of zone C . This would produce more prominent, fault-controlled graben shoulders in the distal part of zone C as predicted by the Royden et al. model.

The character and timing of subsidence is primarily due to changes in heat flow during the three stages of depository development. Since heat flow affects subsidence, both the Ventersdorp rift stage and the early depositional systems of the Transvaal Sea are reviewed in light of the previous general statements.

Crustal extension began in the upper Central Rand Group, Witwatersrand Supergroup, and was characterized by down-to-the-west faulting. This early period of faulting without volcanism would represent an initial stage of passive rifting and could have been associated with some uplift. The *fairly rapid* appearance of volcanics in the Klipriviersberg Group, Ventersdorp Supergroup following this early faulting and initial outpouring of komatiitic flows is an indication that extensional faulting was quite rapid under a high, regional tensional stress and the country rock cool. The occurrence of komatiites would also indicate that the geothermal gradient was radically reduced over the region as heat was pumped into the crust by temperatures up to 1650° (England and Bickle, 1984). Such a change in geothermal gradient could lead to an increased melt fraction beneath the continental lithosphere and to copious volcanic outpourings (Bickle, 1986). This appears to be the pattern of events during the remainder of the Klipriviersberg Group as processes in subcrustal magma chambers gave rise to voluminous tholeiitic flows, which were probably derived from komatiitic parents (Nisbet, 1984).

Formation of a second breakaway zone, along the Welkom Line *during Platberg Group time*, isolated zone B from active graben development further to the west (Figs. 79B; 81A). Zone B had undergone some crustal attenuation due to listric normal faulting. However, with separation from active graben development, this zone probably began to cool to some equilibrium temperature, following a period of reduced overburden due to attenuation. Cooling of zone B during Platberg Group time should have increased both the rock strength and flexural rigidity of this zone prior to the thermal subsidence stage. Graben development, which was restricted to the west, further modified

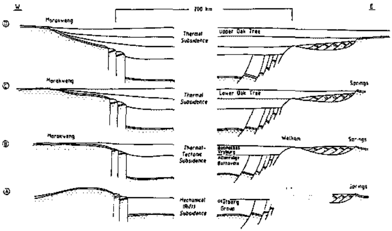


Figure 81. Cartoons showing asymmetric overstepping of Ventersdorp Supergroup rift structures during tectonic and early thermal subsidence.

the geothermal gradients as a result of the complex interplay between upper- and lower-plate stretching in zone C. Uplift associated with both doming and heat flow in zone D modified the western margin of the graben complex into one characterized by steeply dipping normal faults. Bimodal volcanism during Platberg Group time would indicate that volcanism occurred virtually throughout the rifting stage.

The rifting stage was virtually complete by the end of Platberg Group time, but the transition from that stage into the thermal subsidence stage appears to have been somewhat prolonged. Extension patterns during the rift stage were characteristically down-to-the-west, but the Bothaville Formation was deposited above an unconformity by a fluvial system flowing south-southwestward (Buck, 1980; Tankard et al., 1982). This would imply that this period of prolonged transition was the beginnings of the tectonic subsidence stage, that the unconformity between the Platberg Group and the Bothaville Formation was the rift unconformity, and that a regional tilt to the south-southwest followed rifting. The interpretation of tectonic subsidence following Platberg Group graben development is supported by Winter's (1965) suggestion that the Bothaville and Allanridge Formations represent the initial depositional stage of the Transvaal Sea (Fig. 81B). Tilting probably resulted from changes in the lithosphere as a consequence of rifting and would occur even in the absence of sediment loading as flexural processes gained in importance (Cloetingh, 1986, in press; Barr, 1987). The sedimentation of the Bothaville Formation could be related to substantial floods of clastics from the erosion of graben shoulders that would have been prominent along the western margin of the extended terrane. Tectonic subsidence was interrupted by the extrusion of the flood basalts of the Allanridge Formations, which buried the clastics of the Bothaville Formation. Re-appearance of mafic lava flows over the former area of the Platberg grabens is a good indication of the episodic nature of the tectonic subsidence stage.

The Vryburg depositional system contains the first marine units in the stratigraphic sequence above the Platberg Group and represents a stage of combined tectonic and thermal subsidence (Fig. 81B). Eruption of mafic lavas during deposition of the Vryburg depositional system indicates that heat flow controlled subsidence patterns during the early stages of thermal subsidence, as suggested by Royden et al. (1980). These mafic lavas are found only in the vicinity of the steeper, western margin normal faults. The transgression, which resulted in the deposition of the Boomplaas depositional system carbonates, can be related entirely to thermal subsidence as flexure initially overcame the effects of lateral heat flow. However, the 15 m thick mafic flow, which is present 36 m above the assigned contact of Vryburg and Boomplaas depositional systems (Appendix A), would indicate that mafic magmatism continued intermittently into the early stages of thermal subsidence.

The Vryburg and Boomplaas depositional systems were restricted the Vryburg compartment and represent a marine encroachment over only the southern half of the Platberg Group graben complex (Appendix B). This distribution could be due to a combination of the structural lines, which delineate compartment margins; lateral heat flow creating a thermal bulge in a cooled zone B; and/or a regional tilt to the south-southwest, which seemed to persist from Bothaville Formation time.

The Lower Oak Tree depositional system overstepped the northern margin of the Vryburg compartment (Rand line) (Fig. 70) and greatly expanded the basin to the north-northeast into the Western Transvaal-Selati Trough compartment. The Thabazimbi-Murchison line appears to have restricted basin expansion to the north. It may represent an equilibrium stand of the shoreline, stabilized as a result of an interaction between sedimentation and thermal subsidence (Pitman, 1978). East-west expansion during this transgression was asymmetric (Fig. 81C) with the basin expanding to the east, while being restricted to the west by the Morokweng line. However, eastward expansion was retarded by the Springs line; footwall uplift of the initial breakaway appears to have perpetuated this line as a barrier.

The Upper Oak Tree depositional system overstepped the Thabazimbi-Murchison line to the north-northeast and the Springs line to the east. This system was, however, restricted to the west by the Morokweng line (Fig. 81D). Overstepping of the Springs line resulted in the flooding of the Eastern Transvaal compartment. An equilibrium stand was reached near Sudwala Caves and is marked by the deposition of shallow siliciclastic facies. The Lower Monte Christo depositional system was deposited in a broad epeiric sea that occupied all four of the Transvaal Sea compartments (Appendix B). Thermal subsidence appears to have ended as the Transvaal Sea left the Kaapvaal Craton and retreated to the south-southwest prior to the deposition of the Motiton depositional system.

Cross sectional reconstructions of the progressive enlargement of the Transvaal Sea during thermal subsidence do indicate that the depository had a "short horn" configuration (Fig 81D). This configuration resulted both from the structural differences in the margins and from lateral heat flow. Lower-plate uplifts were much smaller than upper-plate uplifts because the lower plate side was carried further from the site of heating (Buck et al., 1988) and because of the development of the second breakaway. Thick basal shale units in the Lower Oak Tree depositional system in the northern Cape, also, probably enhanced lateral heat flow as a result of a thermal blanketing effect. Thermal subsidence was, thus, asymmetric and episodic as flexure overcame various marginal barriers (Appendix B).

In many respects, thermal subsidence appears to have been quite short if the preserved thickness of carbonate sediments, approximately 600 m in the western Transvaal, is considered against a potential 100 Ma time frame. Cooling may have been related to an anomously high heat flow in a thin crust, as well as rapid loss of heat by hydrothermal circulation (Jowett and Jarvis, 1984). If the rift and tectonic subsidence stages are augmented by additional lateral heat loss, the thermal subsidence stage will be diminished (Buck et al., 1988). However, with the effects of thermal blanketing, the attainment of the cooling equilibrium temperature, which represents the end of thermal subsidence, may have also been reached in a shorter time because the upper crust could cool conductively while the lower crustal boundary was maintained at a higher temperature (Royden et al., 1980). This could mean that the steady state Moho temperature at the end of thermal subsidence would be higher than the initial Moho temperature, thus rendering the depository more liable to subsequent tectonic activity (Houseman and England, 1986).

4.2 Reactivation of Subsidence

4.2.1 General Statements Basin studies are generally preoccupied with the initiation of subsidence and such subsidence is only considered in terms of passive thermal recovery of the rifted lithosphere (Lake and Karner, 1987). However, reactivation of basin subsidence has to be considered in the light of Button's (1973a) statement that the Transvaal Sea was characterized by expansion with time. Many basins are often characterized by renewed subsidence; neither structural evolution of rifts nor early thermal subsidence may have had a significant influence on such subsidence (De Rito et al., 1983; Lake and Karner, 1987). Basins, which exhibit this type of behavior, are often situated over the axes of ancient rift zones and reactivation by any regional mechanism will cause subsidence following thermal recovery (De Rito et al., 1983)

If the basin is semi-dormant, the only widespread mechanism for reactivation of subsidence is some polyphase extensional process that reduces the effective thickness of the lithosphere (De Rito et al., 1983; Lake and Karner, 1987). The only two processes that are likely to reactivate paleorift basins are an increase in the temperature of the lithosphere and a change in the regional stress field (De Rito et al., 1983). To significantly increase the temperature of the lithosphere, a decrease in geothermal gradient would be required, and some of the load-carrying capacity of the upper lithosphere would, thus, be removed (De Rito et al., 1983). However, an increase in heat flow from the asthenosphere or upper mantle might lead to renewed mechanical subsidence instead of reactivated basin subsidence. A single thermal episode, with which an increase in temperature might be associated, cannot alone account for polyphase reactivations. Furthermore, if the asthenosphere or upper mantle were responsible for increased heat flow, the presence of volcanics above a regional unconformity marking end of thermal subsidence could be expected.

The application of horizontal regional stresses caused by distant plate interactions may result in the in-plane stresses necessary for reactivation of subsidence (De Rito et al., 1983; Karner, 1986). With a change from an extensional into a compressional regional stress field, the application of compressive in-plane stresses into a hot lower lithosphere will reactivate subsidence, and rapid stress-relaxation will take place as the lithosphere undergoes another period of rapid thinning (De Rito et al., 1983). As previously mentioned, thermal blanketing may also be important because, if the equilibrium temperature at the end of thermal subsidence is higher than the pre-stressed temperature at the time of rifting, the basin is likely to react to subsequent tectonic activity (Houseman and England, 1986). Such subsequent tectonic activity may be related to the application of compressive in-plane stresses from processes operating at distant plate margins.

Compressive in-plane stress, with a magnitude of only a few percent of the buckling strength of the lithosphere, may be the cause of reactivated subsidence (De Rito et al., 1987). Maximum stress differences occur in the basement within downwarped areas (Lambeck, 1983) and account for reactivation of basins situated over the axes of paleorifts. Introduction of compressive stress would cause a deflection of the lithosphere at the edge of a basin, while a removal of compressive stress would cause the relative subsidence of the edge (Cloetingh et al., 1985; Cloetingh, 1986; in press; Karner, 1986) (Fig. 82). Uplift due to compression would have a basic pattern of marginal uplift and basin interior subsidence, while it would manifest itself as a stratigraphic offlap which could cause subaerial exposure and produce weathered surface (Cloetingh, 1986, in press; Karner, 1986) (Fig. 48). Removal of compressive stress would be characterized by an apparent rise in sea-level, renewed deposition with a corresponding facies change, and a widening or

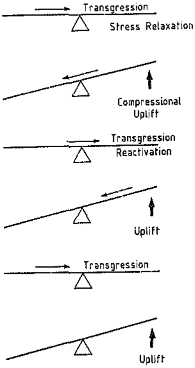


Figure 82. Cartoon of see-saw regressive-transgressive sedimentary patterns produced by the application and removal of in-plane compressive stress. Fulcrum is stationary through time.

expansion of the basin. However, there would also be an associated fall in base level or pseudo-uplift of the basin interior (Cloetingh, 1986, in press; Karner, 1986) (Fig. 82). Net subsidence, resulting from relaxation of compressive in-plane stress, would be approximately 90 to 100 m as compared to the subsidence of the basin if it had remained unperturbed (De Rito et al., 1983: Cloetingh et al., 1985; Cloetingh 1986, in press). However, the amount of subsidence, resulting from each reactivation phase, would be a direct function of time required for the lithosphere to regain its pre-stressed, semi-dormant subsidence rate (De Rito et al., 1983). A repetition of this process by an episodic application of compressive in-plane stress may yield a large amount of renewed subsidence. Accumulation of subsidence in this fashion would require a region of the lithosphere with a slightly decreased geothermal gradient (De Rito et al., 1983).

4.2.2 Discussion The preserved stratigraphy indicates that the Transvaal Sea left the craton prior to the deposition of the Motiton depositional system. This is the only period in which the entire depository appears to have experienced uplift, non-deposition, and erosion. This event is believed to represent the end of thermal subsidence prior to subsequent periods of basin reactivation. When considering the reactivation of subsidence, several other generalizations about the response of the lithosphere need to be understood. De Rito et al. (1983) have enumerated the following effects of reactivated subsidence on basin sratigraphy:

1) Initial effects of applied compressive in-plane stress would remove any re-equilibrated stress (strength) in the lower lithosphere, resulting from thermal recovery and reactivate subsidence. However, this initial phase of subsidence may not have any real cumulative effects.

2) A single reactivation pulse may yield only minor deflections, but repeated pulses within a particular period of reactivation would yield increased subsidence.

3) The lithosphere should warm up as it descends; this would also progressively decrease its effective thickness. The additional load deposited during a reactivation period would not be completely eroded away during rebound and recovery would be incomplete. This should allow additional subsidence to accumulate with each cycle.

4) A reactivation period should proceed until some degree of isostatic compensation is attained, after which time subsidence returns to a semi-dormant rate.

The following general observations of the depositional systems of the Transvaal Sea above the regional unconformity are comparable with these generalizations (Appendix B; Fig. 83):

1) Each depositional system began with a rather abrupt drowning, which resulted in both basin expansion and subsequent overstepping of margins.

2) Depositional systems (second order cycles) are made up of two to six grandcycles (third order cycles).

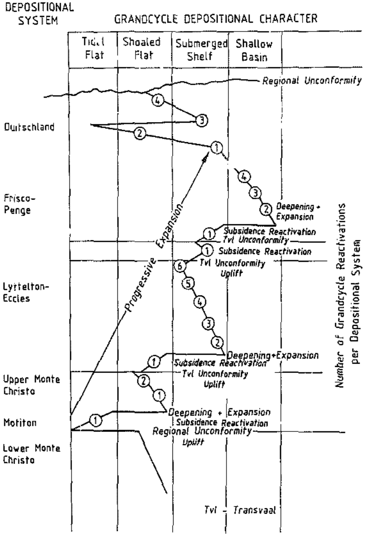


Figure 63. *Grandcycles* within the reactivated depositional systems and their progessive change in depositional character.

3) Grandcycles within these various depositional systems range in thickness from 100 to 150 m, with an average of approximately 120 m.4) The second grandcycle of a depositional system represents a deepening expansion of the basin with a major facies change.

5) Depositional systems are separated by subregional unconformities which resulted in non-deposition over part of the depository.

An abrupt *drowning event followin*· a *period* of semi-dormancy or rapid shallowing indicates reactivated subsidence during the Upper Monte Christo, Lyttelton-Eccles, and Frisco-Penge depositional systems (Appendix B; Figs 63; 83). Differential epeirogenic movements of continental interiors associated with sea level rise are probably an indication of tectonics rather than eustatic sea level change (Cloetingh et al., 1985; Cloetingh 1986, in press; Sahagian, 1987). Following reactivation, the depositional character of the initial grandcycle is similar to the previous depositional system. Reactivation would imply that any re-equilibrated stress (strength) had been removed. With removal of this stress, the depository simply became a clone of the previous depositional system. The initial reactivation phase had no real cumulative effects and reactivation could only return the depository to its former state.

The following brief review of observations of the initial g¨andcycle of reactivated depositional systems is presented as *field evidence* for these interpretations (Fig. 83). Although facies distributions onlapped slightly to the north-northeast, the initial grandcycle of the Upper Monte Christo depositional system was charaterized by shoaled flat subfacies, similar to that of the Lower Monte Christo depositional system. The Lower Lyttelton grandcycle of the Lyttelton-Eccles depositional system has the same shoaled flat subfacies character as the Upper Monte Christo depositional system. This grandcycle has a somewhat limited areal distribution over the Transvaal, being influenced by the Morokweng line on the west and the Pilgrims Rest line on the east-northeast (Fig. 70). The localization of tidal flat subfacies (Blyde River Quartzite) (Appendix B) over the east-northeast portion of the Pilgrims Rest line indicates that an onlap equilibrium stand had been reached by the shoreline and that a south-southwest tilt continued to influence facies distributions. The Lower Frisco grandcycle of the Frisco-Penge depositional system has the submerged shelf subfacies character of the Lyttelton-Eccles depositional system. Thinning of the preserved lithologies of this grandcycle by approximately 50 per cent to the northeast indicates that a south-southwest tilt continued to influence the depository. The Upper Frisco grandcycle, also, has the submerged shelf subfacies character of the Lyttelton-Eccles depositional system.

The Duitschland depositional system is slightly different from the other reactivated depositional systems because it represents a cycle of offlap and depository shallowing (Fig. 83). Nevertheless, the four grandcycles within the Duitschland depositional system indicate that shallowing was not continuous and periods of reactivation influenced subsidence of this offlapping depositional system. Shallowing of the depositional system from the northeast and localization of shallow siliciclastic facies over the northeast portion of the Pilgrims Rest line again indicates that a south-southwest tilt to the depository influenced both onlap and offlap depositional patterns.

Reactivated depositional systems are made up of two to six grandcycles. This would support the generalization that multiple pulses occur during a period of reactivation and that they are responsible for subsidence instead of a single reactivation event. Cumulative effects of these various grandcycles within a depositional system would represent the total subsidence of a period of basin reactivation. These interpretations are, also, supported by the 120 m average thickness of a grandcycle, which is in agreement with the modeled net subsidence of 100 m for a reactivated, third order cycle (De Rito et al., 1983).

Since the depository would gain some degree of isostatic compensation with time, reactivation periods would be punctuated by periods of semi-dormancy, while the stratigraphic record would appear to be mainly continuous A reactivated depositional system, therefore, would represent the time required for the lithosphere to regain a semi-dormant subsidence rate. The various subregional unconformities indicate that a period of reactivation had been completed and that a state of isostatic compensation had been achieved prior to the next period of reactivation. Any additional sedimentary load not eroded away at the end of a reactivated *depostional system* would allow additional subsidence to accumulate with each depositional system.

Expansion and deeping of the depository during the second grandcyle of each reactivated depositional system. *Reactivation*, which resulted in the inital grandcycle, effectively removed any strength in the lower listhosphere gained during a period of semi-dormant subsidence. However, the additional sedimentary load deposited during the initial grandcycle did not completely erode away during rebound at the end of the grandcycle. This additional load reintroduced stress into the lower lithosphere by increasing the net load (DeRito et al., 1983) and allowed additional subsidence to occur with the second grandcycle. Such additional subsidence allowed the basin to deepen and expand. However, baselevel fall of the depositiory interior associated with marginal overstepping resulted in expansion, while it maintained a constant water depth over large regions, which dictated the development of distally-steepened ramps (Figs. 69; 82).

Field relationships indicate that a see-saw stratigraphic pattern of northeast onlap-southwest offlap is present (Figs. 63; 82). The south-southwest tilt, *which started* to influence facies distributions in the Motiton depositional system, was probably a direct result of northeast uplift. Northeast uplift may also be the reason that fluvial channels are found only in the western Transvaal above two subregional unconformities, separating reactivated depositional systems, and that the Transvaal Sea continually retreated into the Vryburg compartment (Appendix B). Localization of tidal flat subfacies over the northeastern portion of the Pilgrims Rest line during the Lower Lyttelton grandcycle onlap indicates that, in this instance, the Transvaal Sea only reclaimed a portion of the areal distribution of the Upper Monte Christo depositional system. The Lower Frisco grandcycle may represent the opposite; a short-lived onlap was followed by a rapid offlap of the facies.

Expansion of the Transvaal Sea with time is better explained by compressive in-plane stress than be eustatic sea level change. Removal of compressive in-plane stress would cause subsidence of the margins, which would induce onlap. At the same time, a relatively constant water depth would be maintained over a large region because of the associated fall of baselevel in the basin interior. This type of accumulative subsidence through the various reactivated depositional systems resulted in the progressive north-northeast advancement of the more distal facies until they covered the Transvaal region and produced the pattern of basin expansion with time that Button (1973a) had proposed. Abandonment of the Transvaal during a reactivation offlap would have almost the opposite effect with marginal uplift and basin interior subsidence. Such stress induced offlap could satisfactorily account for the retreat of the Transvaal Sea into the Vryburg compartment during offlaps or lateral shallowing events. The onlap-offlap pattern would account for the see-saw stratigraphic pattern developed by later depositional systems (Fig. 63) and resulted from the repeated application of compressive in-plane stress from the northeast.

Two other field observations support the conclusion that reactivation was driven by northeast compressive stress. They are the 1.5° to 2° angular unconformities, which separate the depositional cycles (Figs 48; 50), and the presence of the mudstone-matrix slump breccias and rhythmites prior to rapid shallowing events.

The two locations where the angular unconformities were identified in the field are along a northwest-southeast line that appears to separate northeast thinning from south-southwest thickening of the depositional facies. Uplift of the depository margin should produce an angular unconformity because offlap would result in subaerial exposure of the margin prior to any subsequent phase of reactivation. Karner (1986) pointed out that unconformities should be expected only during middle stages of basin development and that in-plane stress can explain termination of a sedimentary cycle. Since unconformities produced during the middle stages of a basin can be related to the increasing flexural rigidity of the lithosphere, any other unconformities provide important constraints on the structural and tectonic development of a sedimentary basin (Lake and Karner, 1987). Presence of angular unconformities within the stratigraphy can, thus, be interpreted as a natural consequence of mechanical narrowing and widening of the depository by fluctuations in intraplate stress, following a period of thermal readjustment (Cloetingh, 1986, in press).

Mudstone-matrix slump breccias (Fig. 47) are only found along the northwest margin of the preserved outcrop and rhythmites flow direction is to the south-southwest. With uplift, gravity instability across the margin created by high rates of sediment accumulation could trigger collapse and the formation of local slump breccias or debris flows (Mullins et al., 1986). Newly deposited sediments would be expected to be saturated, and excess pore pressures would reduce the static yield strength of the debris, allowing both collapse and movement (Hiscott and James, 1985). However, it is also expected that the breccia flow would move as a result of deformation in a basal zone of high-shear stress and this may be the reason that modern submarine debris-flow deposits are present on slopes of less than 1° (Hiscott and James, 1985). Such slopes were characteristic of the Transvaal Sea. Rapid denudation rates would also generate rhythmite sequences as sediment is yielded to the basin. Tectonic uplift is a significant factor in controlling rhythmite frequency (Klein, 1984). The appearance of both slump breccias and rhythmites in the sedimentary sequence prior to a rapid shallowing of the depository is, therefore, considered evidence for tectonic uplift. Generation of these lithofacies during a period of reactivated onlap would again be related to gravity instability and collapse would aid in the retreat of any exaggerated marginal feature.

Although a northwest-southeast line across the depository appears to separate northeast thinning from south-southwest thickening of depositional facies, the Ancestral Rand Anticline (Fig. 70) separates the eroded Transvaal depositional systems from the continuous depositional systems of the northern Cape. This would suggest that the Ancestral Rand Anticline acted as a fulcrum for the see-saw pattern of reactivated onlap-offlap (Fig. 63). It should be noted that boreholes in the Potchefstroom and Pilgrims Rest areas (Appendix A) and geologic profiles around the Johannesburg Dome are the only sections that contain erosional breccias and other unconformity reference criteria between the grandcycles. The localized presence of erosion between grandcycles is an indication that the Ancestral Rand Anticline was subjected to differential uplift during periods of applied compressive in-plane stress. The onlap collapse of the Rand line at the beginning of the Lower Lyttelton grandcycle is also an indication that the Ancestral Rand Anticline was acting as a margin during basin semi-dormancy. The tidal flat subfacies of the Motiton depositional system and the Kamden member, which spread the banded iron-formation lithofacies over the northern Cape during the basin-expanding second grandcycle of the Lyttelton-Eccles depositional system, are only present south-southwest of the Ancestral Rand Anticline. These field relationships are support the interpretation that the Ancestral Rand Anticline was the location of an onlap-offlap fulcrum. This fulcrum does not appear to have moved during basin evolution and it may have been inherited from the basement. This fulcrum also influenced the Vryburg, Boomplaas, and Upper Oak Tree depositional systems during thermal subsidence (*Appendix B*).

Chapter 5

Geodynamic Influences on the Transvaal Sea

5.1 General Statements

Reactivation of subsidence is interpreted as the reason for Button's (1973a) observation that the most striking feature of deposition was expansion of the Transvaal Sea with time. While compressive in-plane stress is capable of inducing basin margin uplift, it is the removal of this stress that accentuates basin margin subsidence (Cloetingh et al., 1985; Cloetingh 1986; Karner, 1986) and basin expansion. Interplay between application and removal of regional stresses influences and modifies basin stratigraphy by superimposing a "geodynamic-induced noise" onto the basin (Karner, 1986). Although evidence of this "noise" has been identified in the stratigraphy, an explanation of these stresses is necessary.

Sleep and Windley (1982) have attributed the development of marginal basins in the Archean-Early Proterozoic to disruption of the lithosphere by stresses related to subduction and by flow induced in the asthenosphere by the subduction process. These explanations are quite applicable to the Ventersdorp Group graben and the Transvaal Sea. However, Vlaar (1986a) also pointed out that another consequence of the Proterozoic plate tectonic regime is the compressive state of the overall protocontinent, counteracting easy penetration of the crust by ascending magmas. Identification of subduction processes, that influenced the development of the Transvaal Sea, and the explanation for the existence of a regional extensional stress regime, during a time when protocontinents should have been under a compressive state, are addressed in the following sections.

5.2 Other Related Stratigraphic Sequences

In order to identify changing styles of intraplate deformation, which might fingerprint possible related subduction processes, understanding of the architecture of the basin is not only essential, but characterization of its basement precursors is vital to interpretations (Gibbs, 1987). Stratigraphic units older than the Ventersdorp Supergroup (Fig. 72), which lie on the Archean "Old Granite" basement, were reviewed so that any vertical movements recorded in the stratigraphy could be scrutinized. In this study, it is assumed that the initial topography of the "Old Granite" basement was an imperfectly peneplaned surface and that any vertical movements of this surface would be recorded in the overlying stratigraphic record. This assumption is based on Vlaar's (1986a) suggestion that Archean continental crust had a moderate surface relief and stood only slightly above sea level.

The Dominion Group is oldest of these stratigraphic units that rests on the "Old Granite" basement (S.A.C.S., 1980) (Figs. 72; 84A). Button et al. (1981) have suggested that the Dominion Group represents a *proto-basinal* phase to the Witwatersrand Supergroup and is made up of mixed volcano-sedimentary lithologies. Volcanics and volcanoclastics constitute the bulk

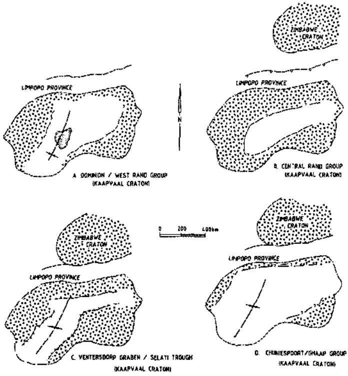


Figure 84. Paleogeographical reconstructions of the successor basins developed on the Kaapvaal Craton from 3,0 to pre-2,2 Ga. Inferred depositional axes of the basins are also shown.

of lithologies and overlie 60 m of basal siliciclastics (Button et al., 1981; Tankard et al., 1982). The succession crops out in only three small areas in the western Transvaal (S.A.C.S., 1980, p. 99); borehole data show a larger, but still restricted, areal distribution. The Dominion Group volcanics are overlain by clastics of the Witwatersrand Supergroup.

The Witwatersrand Supergroup is divided into a lower, West Rand Group and an upper, Central Rand Group (S.A.C.S., 1980) (Figs. 72; 84A, B). Each Group is reviewed separately because sediments of the West Rand Group have been interpreted as representing a more distal, lower energy, depositional environment than those which characterize the overlying Central Rand Group (Button et al., 1981). Based on this interpretation, each Group represents a somewhat independent depositional sequence, which was possibly controlled by differing tectonic events.

Reworked orthoquartzite, ferruginous shale, and minor iron-formation suggest that more distal depositional environments in a basin opening to the south-southwest influenced the lower, West Rand Group (Tankard et al., 1982) (Fig. 84A). This basin appears to have been progressively modified with fluvial and lacustrine sedimentation becoming more prominent in Late West Rand into Central Rand time (Button et al., 1981). The West Rand Group varies in thickness with greatest stratigraphic accumulations located west of Krugersdorp, and these outcrops show little evidence of a proximal shore line (Tankard et al., 1982). Pretorius (1981) proposed that the West Rand Basin covered an area nearly 2.5 times that presently preserved; this suggests that the depository may have been a broad, relatively shallow depression.

The Central Rand Group, in general, conformably overlies the West Rand Group and consists primarily of coarse clastics (Button et al., 1981) (Figs. 72; 84B). Characteristics of these sediments indicate a more proximal depositional environment than the West Rand Group and a progressive shrinking of the basin (Button et al., 1981; Tankard et al., 1982). The Central Rand Group contains numerous upward-fining packages separated by shallow disconformities (Tankard et al., 1982); these marginal *features pass basinward into conformable sequences* (T. S. McCarthy, 1985, pers. commun.). Marginal disconformities indicate that episodic uplift and progressive shrinking of the basin occurred throughout Central Rand time. Periods of folding, and both compressive block and strike-slip faulting, have, also, been interpreted as having occurred episodically throughout Central Rand time (Button et al., 1981; Stanistreet et al., 1986; Charlesworth et al., 1986; McCarthy et al., 1987). However, extensional block faulting characterized the upper Central Rand Group (Tankard et al., 1982).

The pattern of regression, which was initiated in the West Rand Group, continued through Central Rand time. Nevertheless, increased subsidence during Middle Central Rand time resulted in deposition of a basin-wide shale (Booysens Formation) which is used as a regional marker (Tankard et al., 1982). Although the basin was restricted during Middle Central Rand time (Fig. 84B), episodic subsidence allowed communication with outer seas as represented by this shale (Booysens Formation). However, progressive regression resulted in a general coarsening upward of lithologies through the two Groups, with deposition of the most proximal, higher energy clastics of the Central Rand Group above the regional shale marker (Button et al., 1981). Two mafic lava flows also lie within the Witwatersrand Supergroup: the Crown lava of the upper West Rand Group and the Bird tuffs and amygdaloid of the Central Rand Group (Fig. 72). The Crown lava is the thicker of the two and, locally, attains thicknesses of 250 m along the northern margin of the preserved basin (Burke et al., 1986). However, the upper lava unit of the Bird sequence many be as much as 170 m thick and both mafic lava flows are absent in the south-southeast portion of the preserved basin (Tankard et al., 1982). Volcanic and sedimentary rocks of the Ventersdorp Supergroup rest both conformably and unconformably on Witwatersrand Supergroup strata and their relationships have been described earlier in this research.

Other stratigraphic units, which lie nonconformably on the "Old Granite" basement and that either have an unconformable or questionable conformable relationship with the Black Reef Quartzite (Fig. 52), are: the Uitkyk Formation, the Godwan Formation, the Groblersdal Group, the Buffalo Springs Group, and the Wolkberg Group (Fig. 85). At various times in the geological literature, these units have been correlated with either the Dominion-Witwatersrand or the Ventersdorp Supergroup; a brief summary is presented on such suggested correlations. Van Rooyen

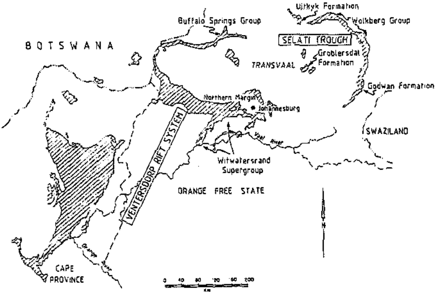


Figure 85. General location map of the various other stratigraphic units which are correlated with the successor basin sequence. Major structural elements are also shown.

(1947) proposed that the Uitkyk Formation was a correlative of the Witwatersrand Supergroup and Button (1973b) tended to support this interpretacion. Button (1977) also suggested that the Godwan Formation was part of the Witwatersrand Supergroup and that the Godwan Formation is unconformable with the younger Black Reef Quartzite. Little is known about the Groblersdal Group, other than it overlies the "Old Granite" basement and has an apparent conformable (?) contact with the Black Reef Quartzite (S.A.C.S., 1980).

Present correlation between the Wolkberg Group and the Buffalo Springs Group is questionable, as well as the correlation of both Groups to stages of other basin sequences. Tyler (1979b) proposed that the Buffalo Springs Group and the Black Reef Quartzite were conformable; he correlated the Buffalo Springs Group with the Wolkberg Group based on this relationship. However, field observations in the northwest Transvaal indicate that an unconformable relationship exists between the Buffalo Springs Group and the overlying Black Reef Quartzite. Based on these new observations, any correlation between the Buffalo Springs Group and the Wolkberg Group, which is based on an apparent conformable relationship proposed by Button (1973b) between the Wolkberg Group and the Black Reef Quartzite, is not justifiable. Based on Tyler's (1979b) stratigraphic descriptions, it is suggested that the lower Buffalo Springs Group, with its overall upward coarsening siliciclastics and low-angle discordances, can be correlated with the Witwatersrand Supergroup; while the upper Buffalo Springs Group bimodal

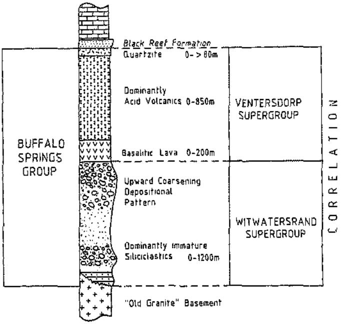


Figure 86. Stratigraphic section of the Buffalo Springs Group and its correction with the successor basin sequence.

volcanics (basaltic lavas followed by dominantly acid volcanics) is tentatively correlated with the Ventersdorp Supergroup (Fig. 86). Button (1973b) identified an erosional contact between the Wolkberg Group and Black Reef Quartzite and then ignored it as a regional feature because the Wolkberg Group is found primarily in the rift-like Selati Trough (Fig. 85). Field evidence indicates that an unconformity does exist in the Selati Trough between these stratigraphic units. The presence of this unconformity makes any proposed conformable relationship between the Wolkberg Group and Black Reef Quartzite also suspect. Correlation of the Wolkberg Group with other stratigraphic units, which lie on the "Old Granite" basement, will be discussed in a subsequent section. Regardless of their exact correlation, the five preserved fragments are consistent with the suggestion by Matthews (1982) that the various basins extended well beyond their presently preserved limits.

5.3 Phanerozoic Analogues

Based on a subjective division of the various stratigraphic units, a number of Phanerozoic analogues are presented and many conclusions throughout the remainder of this research are based on such Phanerozoic examples. These comparisons are justified because during Proterozoic times a number of volcano-sedimentary basins formed that in style, form, and rock content are close to Phanerozoic "geosynclines" (Kroner, 1981).

The Dominion Group accumulated in the earliest of the proto-basin depressions and represents a major thermal anomaly. This anomaly is manifest as 2700 m of bimodal volcanics and it localized a number of successive events (Figs. 72; 84A). Thermally weakened crust is more susceptible to slow plastic deformation and active horizontal extension, which promote rifting (Mohr, 1982). Characteristics of the Dominion Group indicate that this sequence developed in a rift environment (Bickle and Eriksson, 1982). Although there is no field evidence of graben development, the structural complexity of a region may prevent recognition of early extensional structures (Etheridge, 1986). Stratigraphic thicknesses indicate the general location of the rift graben may have been west of Krugersdorp (Fig. 84A). Allmendinger et al. (1987) have also used such field relationships to identify initial, Late Proterozoic rifting in the Basin and Range Province.

Dominion Group volcanic activity diminished as the West Rand Group began to accumulate in an expanding, southwesterly opening basin (Fig. 84A). General character of West Rand Group sediments indicate a subdued landscape and absence of "high" relief. An analogy can be drawn between the Dominion/West Rand Group and the first evolutionary stage of development of the Baikal Rift System. In the Baikal Rift System, volcanics are associated with the earliest of the proto-basin valleys; but as a vast, shallow basin surrounded by subdued highlands developed, volcanism diminished (Logatchev and Florensov, 1978). In both instances, the early proto-basin depression appears to have been localized by an earlier thermal anomaly (rift) and was later expanded by related thermal subsidence.

Episodic uplift began in Late West Rand time and the early basin began to be restricted (Fig. 84B). Periods of coarser sedimentation, due to increased erosion, correspond to this episodic uplift. Gradual subsidence continued until Middle entral Rand time and, in compensation, sedimentation may have been relatively slow. However, local uplift, due to compressive block fault inversion of Dominion Group extension structures in the Central and West Rand areas, seems to be dominant structural style during Central Rand time (Stanistreet et al., 1986; McCarthy et al., 1987). Sharp morphological contacts were developed along basin margins by this faulting as the West Rand Group depository shrank and became tectonically influenced. As a result of continued compressive stress, the basin closed to the southwest and became a restricted, asymmetric, shrinking basin (Button et al., 1981). Compressive block faulting can essentially emplace a load onto the footwall side of the faults with the footwall basement flexing to produce a number of "mini" foreland basins (Lake and Karner, 1987) (Fig. 87). Numerous merging unconformities along the shrinking margins and upward coarsening clastics within the Central Rand Group indicate that associated uplift was somewhat continuous and that a subdued landscape did not exist. Coarsening clastics were fed into this restricted basin during the various evolutionary stages via a number of shallow depressions or faulted valleys. The axis of

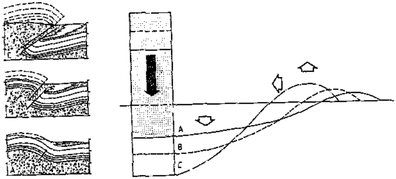


Figure 87. Evolution of a compressive block fault as it loads the *footwall* developing a "mini" foreland basin. Possible migration and enlargement of the peripheral bulge due to progressive supracrustal loading during compressive block faulting. (Modified after *Quinlan and* Beaumont, 1984)

this later restricted basin was also oblique to subparallel to the axis of the underlying West Rand depression (Figs. 84A, B). Unlike the simple model for basin development, the shifting of depocenter and axis indicates that basin shape does not remain constant during evolution (Watts et al., 1982).

The Central Rand Group is analogous to the second stage development of the Baikal Rift System. As the Baikal Rift System closed, the proto-basin became an asymmetric or one-sided graben with an active northwestern faulted margin (Sherman, 1978). Superimposition of the one-sided graben on the earlier Baikal depression is, also, asymmetric on one flank as is the Central Rand Group. Numerous faulted valleys fed coarser siliciclastics into the second stage Baikal Rift System, but subsidence outpaced sedimentation in this progressively shrinking system (Logatchev and Florensov, 1978). The Pannonian Basin System shows a similar sequence of events. Uplift and associated erosion triggered deposition of coarser, more proximal clastics as the Central Paratethys Sea gradually disappeared (Royden et al., 1983). Uplift finally isolated the Central Paratethys Sea from the Mediterranean and sediments accumulated in asymmetric troughs (Royden et al., 1983). Faulting began and ended during various stages of the Pannonian Basin System with displacements along both normal and strike-slip faults (Royden et al., 1982; Royden et al., 1983).

Continued tectonic activity, during Late Central Rand time, resulted in extensional block faulting and this period of extension was probably associated with the accelerated erosional sequence in the upper Central Rand Group. The rapid appearance of flood basalts of the Klipriviersberg Group transformed this early extensional phase from a relatively "passive" one (dry rift analogy) to an "active" system (wet rift analogy). This "active" system generated a second thermal event. General character of the Klipriviersberg volcanics is alkali basalt (Tankard et al., 1982). Morgan (1982) has pointed out that magma forms at shallower levels on young continental margins and that this magma is extruded as alkali basalt. The rapid extrusion of Klipriviersberg basalt was penecontemporaneous with faulting. This phase of extension, which may have cover several hundred thousand square kilometers, was succeeded by graben formation.

Graben formation during Platberg time was a late-stage phenomenon as it is in most "continental" rift sequences (Mohr, 1982). Bimodal volcanics, immature clastics, and playa lake sediments were deposited during graben development and accumulated in numerous, half-grabens (Buck, 1980). As graben development proceeded, there was a shift in the depocenter to the west; shift of depocenter produced a second, asymmetic superimposition of basins (Fig. 84C). Shifts in the locus of tectonic activity and re-expansion during active graben formation from the flanks to the center of the basin has also been interpreted to have occurred in the North China Basin (Ye et al., 1985).

The size, structural style, and depositional systems of the Ventersdorp Supergroup are not characteristic of a continental rift system, which is usually only 50 km in width. However, the

Ventersdorp Supergroup does compare to both the Cenozoic Basin and Range Province, western United States, and the Permian Rotliegendes troughs, central Europe. These systems have been called foreland rifts, and characteristics include: extensive crustal thinning, bimodal igneous activity, normal to listric faulting, high heat flow, regional uplift, and immature clastic and evaporitic sediments rapidly deposited within subsiding rift grabens (Jowett and Jarvis, 1984). Block faulting and major rift graben development follow the main period of volcanism and extension in the foreland (Jowett and Jarvis, 1984).

Graben development was essentially complete by the end of Platberg Group. The unconformity between the Platberg Group and the overlying Bothaville Formation is considered the rift unconformity which represents an excellent marker between mechanical and subsequent periods of tectonic-thermal subsidence (Etheridge, 1986). Periods of tectonic, thermal,and reactivated subsidence in the Transvaal Sea are comparable to the North Sea Basin. Rift-generated thermal subsidence, overall transgressive nature of sedimentation, and periods of reactivated subsidence associated with expansion have also been recorded in the North Sea Basin (Watts et al., 1982; Badley et al., 1984; Gibbs, 1984). Excessive flexure on pre-existing faults during tectonic and thermal subsidence has induced renewed faulting following the flexure front in the North Sea Basin (Badley et al., 1984), but such a period of reactivated faulting in the Transvaal Sea has not yet been recognized.

Continued expansions allowed the Transvaal Sea to cover most of the Kaapvaal Craton prior to a pre-Pretoria Group, Transvaal Sequence, regional unconformity, which abruptly terminated the continuance of the Transvaal Sea (Fig. 84D). Several analogues might be presented for this termination; but without an understanding of other regional relationships, which will be presented later, any comparisons would be only speculative.

5.4 Identification of Tectonic Style

These Phanerozoic analogues illustrate that the evolution of various basins, which lie on the "Old Granite" basement, are not unique and can be interrelated. Although the basins are superimposed and interrelated, they are dissimilar because each was characterized by particular lithologies; each was subjected to episodic evolution; and each was dominated by specific styles of deformation. Klemme (1975) recognized that changing tectonic styles develop a succession of basin types along zones of pre-existing tectonic weakness and named these changing basin types successor basins. Before any Kaapvaal successor basin sequence can be outlined, more fundamental questions of causation need to be understood so that a progressive modification of tectonic style can be interpreted from the stratigraphy.

Tectonic style results from changing intraplate stress systems that are imposed on the thermomechanical properties of the crust (Cross and Pilger, 1982). Molnar and Atwater (1978) have proposed that tectonic styles can be divided into three broad categories: extensional, compressional, and simple. The category of simple tectonic style is not self-explanatory and is a tectonic style in which neither extension nor compression dominates. Simple tectonic style should be expected to characterize successor basin evolution because differing basin types, developing along zones of pre-existing tectonic weakness, would be influenced by changing regional stress systems. However, a particular successor basin may be dominated by specific intraplate stresses, as well as reflect changes within the stress systems through time.

Modification of tectonic style is the result of a combination of two major types of superimposed lithospheric stress, which have been referred to as renewable and non-renewable (Bott, 1982). Renewable-type stresses are those generated by plate boundary forces, or by loading, and are fed by re-application of boundary or body forces, even though the strain energy is continually relieved by tectonic activity (Bott and Kusznir, 1984). Renewable-type stresses due to plate boundary forces can be either compressional or extensional, and changes in plate motion interactions probably cause intraplate deformation. All renewable stress systems are particularly susceptible to stress amplification because stress decay in the lower lithosphere results in stress amplification in the upper lithosphere (Kusznir, 1982; Mithen, 1982) and subsequent modification of structural style. In contrast, non-renewable-type stresses are those either due to lithospheric flexure or resulting from thermal stresses and are stress systems that are dissipated by release of the strain energy present (Bott and

Kusznir, 1984). Non-renewable stresses also differ from renewable types in that non-renewable types are strongly time dependent. Any combination of renewable and non-renewable stress systems can be generally distinguished by tectonic analysis because of the time dependent nature of non-renewable systems. Nevertheless, non-renewable stress may be of some importance in creating fundamental zones of weakness within the lithosphere, which may be subsequently exploited by renewable stresses (Bott and Kusznir, 1984). In addition, combinations of renewable and non-renewable stress may amplify the effectiveness of non-renewable stress in creating zones of weakness. However, the effect which combin[illegible] non-renewable and renewable stresses have on one anothe[illegible] the type of stress system responsible for produ[illegible] tectonic style at any given time.

If the lithosphere contains a pre-existing tectonic weakness, i.e. thermal anomaly, sedimentary basin, or large wrench fault zone, the perturbation will localize the combination of stress systems. The perturbation will be amplified and amplification will perpetuate the perturbation, as well as allow it to grow with time (Lambeck, 1983). It should be emphasized that changing regional stress systems are interpreted to have developed the Early Proterozoic successor basins on the Kaapvaal Craton, while zones of pre-existing weakness influenced their location. It is the intent of this discussion to propose a causal mechanism that genetically and chronologically links these events.

Having reviewed the stratigraphy of the successor basins, a number of specific changes within the sequence can be directly related to local and regional intraplate stress systems, while others have to be inferred. Volcanism is generally associated with thermal uplift and is followed by time-dependent thermal subsidence. Thermally induced vertical movements would represent changes in the thermomechanical properties of the crust and indicate periods of non-renewable thermal stress. From the stratigraphic record (Fig. 72), periods of non-renewable thermal stress can be related to major periods of volcanism during Dominion and Ventersdorp time and to periods of thermal subsidence during Early Witwatersrand Supergroup and Transvaal Sea times.

Matthews (1982) pointed out that periods of alternating volcanism and non-volcanism can be related to the evolution of an overall expanding basin and has proposed that periods of volcanism can be related to extensional stress systems, while periods of non-volcanism are due to compressional ones. Dewey (1980) also pointed out that under a compressional stress system volcanism will be inhibited because feeders will close. Although it might be a rather simplistic approach to renewable stress systems, alternating periods of volcanism within the stratigraphic record would indicate a chronology of changing intraplate stresses due to distant plate interactions, as well as the tectonic style. As just mentioned, major periods of volcanism occurred during Dominion and Ventersdorp times and these periods alternated with substantial periods of non-volcanism during

Witwatersrand and Transvaal Sea times. Due to these alternating periods, a simple tectonic style is interpreted as having produced the early Proterozoic Kaapvaal successor basins. However, the reader is reminded that this definition of tectonic style based on volcanism is an overview of changing regional stress systems and that initiation of changes within the stress systems cannot be simply correlated with the first appearance of volcanism.

5.5 Identification of Geodynamic Processes

Hunter (1974) pointed out that the Limpopo Belt is fundamental in the evolution of the Kaapvaal Craton. This somewhat linear belt or province has been attributed to convergence and collision between the Kaapvaal and Zimbabwe Cratons (Light, 1982; Burke et al., 1985, 1986; Winter, 1986a, 1986b) (Fig. 88). Driving and resisting forces produced at a converging margin would cause the cratons to be stressed and transmission of these plate boundary forces into intraplate regions would generate different renewable stress systems (Bott and Kusznir, 1984).

A number of authors have interpreted the Kaapvaal Craton as the overriding plate (Light, 1982; Burke et al., 1985, 1986; Winter, 1986a, 1986b), even if it has only been implied from the graphics associated with their publications. If this interpretation is accepted, renewable in-plane stress would be transmitted into the Kaapvaal Craton by convergence and collision. This transmitted stress would affect both tectonic

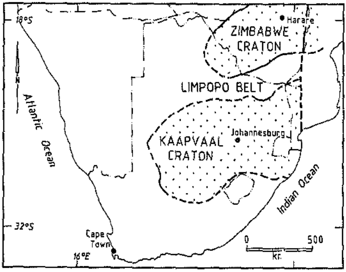


Figure 88. Regional relationships of the Kaapvaal and Zimbabwe Cratons and location of the separating Limpopo Belt.

style and resulting intraplate deformation. Changes in renewable stress systems within the Kaapv l Craton can, thus, be related to the history of the Limpopo Belt.

Light (1982) proposed the following chronology of events for the Limpopo Belt within the 3,0 Ga to pre-2,2 Ga time frame of this study. The zone was static around 2,9 Ga; collision occurred about 2,6 Ga; and culmination of convergence resulted between 2,5 Ga and 2,3 Ga when the Kaapvaal and Zimbabwe Cratons formed a stable unit. On a broad scale, effects of each of these events can be identified and attributed to changing renewable stress systems within the Kaapvaal Craton and are shown graphically in Figure 89.

With removal of compressional forces at about 2,9 Ga, the static nature of the zone can be related to a period of extension within the Kaapvaal Craton because removal of compressive stress could lead to extensional stress systems. This period of extension at about 2,9 Ga localized Dominion Group rifting (Fig. 89A). Periods of extension at this time are supported by Light's (1982) interpretation that a series of igneous centers intruded along a major zone of release (extensional) fractures in the old cratonic crust at about 2,9 Ga. This zone of fractures can be related to a resurgent Precambrian taphrogenic lineament extending from the Afar triangle to the Orange River, South Africa (McConnell, 1980) and possibly represents oldest of the pre-existing zones of weakness that influenced the successor

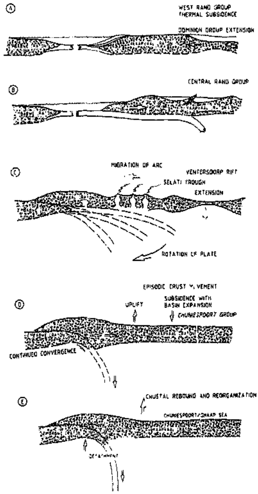


Figure 89. Cartuons of intraplate deformation and successor basin development prior to and following collision of the Kaapvaal and Zimbabwe Cratons, 3,0 to pre-2,2 Ga.

basin sequence. Weakening of the crustal lithosphere, due to changes in the thermal structure, perpetuated and expanded the pre-existing crustal flaw.

Light (1982) interpreted a *recommencement of convergence* between the Kaapvaal and Zimbabwe Cratons following the 2.9 Ga period of static or extensional stress. The understanding and interpretation of this period of convergence is critical in the identification of the geodynamic processes and the subsequent tectonic styles outlined in this research. Although Light (1982) and others have readily used terms such as convergence and collision, invariably they have implied or suggested subduction. Recently, Shackleton (1986) challenged this implied subduction between the Kaapvaal and Zimbabwe Cratons even though he supported an interpretation of collision. However, as he pointed out, one must tread lightly in the minefields of Archean-Early Proterozoic geodynamics. As with most geodynamics, this challenge and warning may be due to a pre-occupation with marginal processes at the expense of the identification of intraplate deformation, which may assist in the recognition of the marginal processes, and in particular, subduction.

Four relationships within the Witwatersrand successor basin provide evidence not only for subduction, but also for an initial shallow angle of subduction (Fig. 89B). These relationships are:
1) the *cessation of volcanism* at the end of Dominion time;
2) the development of basement-involved compressive block faults during Central Rand time;
3) a basin fill composed of *continental clastics;* and

4) a depositional basin larger than its presently preserved structural limits.

The first two points indicate that the extensional stress system, which operated in Dominion time, changed to one of compression at the beginning of assigned Witwatersrand time. It has been proposed previously that, under a compressional stress system, volcanism will be inhibited and that non-volcanic periods can be equated with compressional stress. The transmission of compressive in-plane stress can be related directly to the angle of subduction because low-angle subduction results in more effective coupling between the subducting and overriding plates than does steeper subduction (Cross and Pilger 1978a, 1978b). Low-angle subduction is induced by rapid absolute motion of the upper plate toward the trench, rapid relative convergence, and subduction of young lithosphere (Cross and Pilger, 1982). Low-angle subduction and effective transmission of compressive in-plane stress has been invoked to explain Laramide-style, compressive block faults in the western United States, some 1000 km from the trench (Cross and Pilger, 1978a, 1978b, 1982; Dickinson and Snyder, 1978) (Fig. 90A). A similar style of compressive block faulting developed in Central Rand time (McCarthy et al., 1987) (Fig. 90B). Compressive block faulting along the northern margin of the preserved Witwatersrand structural basin was more than 300 km from the Limpopo Belt. Fault-bounded uplifts provided a flood of coarse clastics that filled adjoining sites of deposition and maintained [illegible]llow water

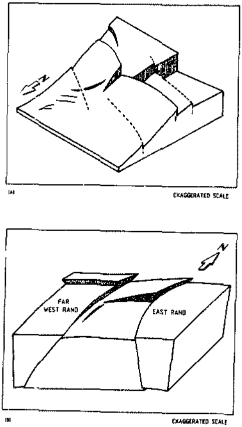


Figure 90A. Laramide-type compressive block faulting, Beartooth Range, Montana. (Modified after Foose et al., 1961)

90B. Character of compressive block faulting in Central Rand Group, Witwatersrand Supergroup. (Modified after McCarthy et al., 1987; With permission of T. S. McCarthy, 1987) or emergent conditions. A similar fashion of sedimentation has been defined by Kluth and Coney (1981) for the Ancestral Rocky Mountains.

Low-angle subduction would also induce regional subsidence due to isostatic subsidence by subcrustal loading and thermal subsidence by subcrustal cooling (Cross and Pilger, 1978a). Such regional subsidence would develop a depositional basin larger than any particular site of deposition, e.g. the preserved Witwatersrand structural basin. Subcrustal loading would result in rapid subsidence associated with compressive stress transmission soon after establishment of low-angle subduction (Cross and Pilger, 1978a). However, with thinner crusts, effects of compressive shortening may be delayed due to flexural rigidity being a function of thermal structure (Allen et al., 1986). Subcrustal cooling, resulting from subcrustal loading, produces a subsequent slower subsidence pattern, which modifies the thermal structure of the region (Cross and Pilger 1978a, 1978b). Modifications of the thermal structure would increase the density of the continental crust (Cross and Pilger, 1978a) and produce a relatively cold, elastic region at great distances from the trench, that would be susceptible to Laramide-style, compressive block faulting (Cross and Pilger, 1982). Disruption of the geothermal state by low-angle subduction can also be inferred from the large drop in temperature indicated by retrogressive metamorphism in the Limpopo Belt just prior to collision about 2,6 Ga (Light, 1982).

It is pertinent that no fold-thrust belt or magmatic arc has been positively identified even though these two features, like subduction, have been implied (Winter, 1986a, 1986b; Burke et al., 1986). However, it is suggested that these seemingly negative points can also be used as evidence for the proposed initial shallow-angle subduction. Dickinson and Snyder (1978) pointed out that the Laramide structural style, characterized by from low-angle subduction, results in suppression of arc magmatism and absence of an integrated system of nappes. Sleep and Windley (1982) pointed out that at places where young Archean crust was subducted the slab would dip shallowly and Cordilleran tectonics should be expected. Thus, the absence of both arc magmatism and an integrated system of nappes during Central Rand time would support a Laramide- style comparison.

The interpretive evidence for subduction presented here is also supported by Vlaar's (1986a, 1986b) interpretations that lithospheric doubling (low-angle subduction) was common in the Archean-Early Proterozoic and by Nisbet and Fowler's (1983) suggestions that Archean subduction not only occurred, but was easy and rapid. It is interpreted that Nisbet and Fowler's (1983) easy and rapid Archean subduction implies low-angle subduction associated with both rapid absolute motion and rapid relative convergence.

Modification of geothermal state and lithospheric rheology due to low-angle subduction resulted in the wholesale brittle failure of the Kaapvaal Craton about 2,6 Ga, which Light (1982) has used to define collision. Collision at about 2,6 Ga would be penecontemporaneous with the Ventersdorp Supergroup extensional stage and its associated volcanism. As long as low-angle subduction continued, an extensional stage could not develop. With removal of compressive stress, extension in the overriding plate would be facilitated and would be associated with basaltic volcanism (Cross and Pilger, 1978b). Periods of extensional block faulting occurred in late Central Rand time and were followed by the extrusion of Klipriviersberg Group mafic lavas, which were associated with faulting. The initial extrusion of komatiite flows in the Klipriviersberg Group is, also, supportive of a cool geothermal state due to low-angle subduction prior to the Ventersdorp time. Komatiite lava could not penetrate from depth to surface unless the country rock cool (Nisbet, 1982).

With a collision occurring at about 2,6 Ga, the subducted lithosphere would have been acted upon less by horizontal forces and more by vertical gravity forces so that it would roll back increasingly toward a vertical orientation producing a regional extensional stress system (Fig. 89C). Models for this type of roll-back geodynamic process have been proposed by Royden et al.(1983) and Murrell (1986). These models are supported by a well-defined, near-vertical zone of intermediate-focus earthquakes that are associated with subducted, but not totally assimilated, remnants of Tethys lithosphere along the Carpathian Arc in Romania and the Hindu Kush region of India (Royden et al., 1983; Gupta and Bhatia, 1986). With roll-back of the subducting plate, the asthenosphere would rise to maintain isostatic conditions. By maintaining isostatic conditions, large, relative, and absolute vertical displacements of the continental crust are possible (Vlaar, 1986a).

It should be noted that initiation of extension could be *before the cessation of subduction* (Cross and Pilger, 1978b). Such extension may have be amplified by collision, due to the relatively rapid roll-back of subducted lithosphere combined with a deceleration of absolute upper plate motion. *With development* of such a regional extensional stress system, the resulting deformation would be confined to pre-existing zones of tectonic weakness (Cross and Pilger, 1978b). Extensional stress, resulting from roll-back, modified tectonic style, as localization of this stress led to rifting. Crustal extension, episodic uplift, and faulting associated with volcanism characterize the rift system during Late Central Rand and Klipriviersberg time. As with most rift systems, the development of the Platberg Group graben was a late stage response. With development of the graben being virtually complete by the end of Platberg Group time, tectonic subsidence, during the Bothaville, Allanridge and lower Vryburg Formations, episodically removed the effects of asthenospheric upwelling prior to thermal subsidence.

Continued convergence between the Kaapvaal and Zimbabwe Cratons is proposed by Light (1982) to have occurred between about 2,6 and 2,5 Ga (Fig. 89D). Following collision, subduction should be expected to continue as long as the force pulling the continental crust down is not balanced by buoyancy effect (Molnar and Gray, 1979). However, resistance to subduction by young *lithosphere may have generated the regional compressive stress* system which replaced the extensional one during Late Ventersdorp time. In Early Ventersdorp time, a lower angle of subduction, a faster convergence rate, and a thinner plate would cause a *smaller resistive force at the convergence zone* (Nisbet and Fowler, 1983; Vlaar, 1986b); but with a near vertical angle during Late Ventersdorp time, resistive forces and friction should have increased considerably. *Episodic uplift followed by* basin expansion during Transvaal Sea time indicates that renewable compressive in-plane stress existed and was being relieved. Compressive in-plane stress, due to transmitted boundary forces, would induce marginal uplift (Cloetingh et al., 1985; Karner, 1986), while rapid stress removal would occur as the lithosphere undergoes another period of rapid thinning that causes basin expansion (De Rito et al., 1983). The episodic nature of compressive in-plane stress transmission, also, suggests that subduction resistance was a stick-slip process and that periodic readjustments between the Kaapvaal and Zimbabwe Cratons resulted in stress removal, as well as basin expansion.

As the buoyancy effect overcomes downward pull, convergence and subsidence would stop, but gravity would continue to act on the vertical excess lithosphere of the downgoing slab (Molnar and Gray, 1979). Under this continued force, the excess lithosphere would detach itself and such detachment will be followed by rapid isostatic uplift (Murrell, 1986). Detachment is interpreted to have occurred and appears to be the geodynamic process, which led

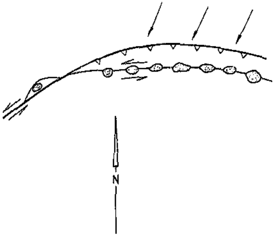


Figure 91. Cartoon of Sunda-style oblique convergence and the development of an associated strike-slip fault-subduction pair.

to the pre-Pretoria Group regional unconformity (Fig. 89E). Detachment could also explain crustal thickening being preserved only in the Limpopo Belt (Shackleton, 1986).

5.6 Thabazimbi-Murchison Line

The Thabazimbi-Murchison line is a prominent east-west linear structure within the northern portion of the Kaapvaal Craton and parallels the Limpopo province, which lies to the north. The Thabazimbi-Murchison line marks the northern margin of the the preserved Transvaal Sea compartments (Fig. 70) and geophysics imply that the Platberg Group graben terminates against it in the west-nothwest Transvaal. In the eastern Transvaal, the Thabazimbi-Murchison line appears to have influenced the Pietersburg and Murchison Greenstone Belts. These relationships indicate that the Thabazimbi-Murchison line has been a long-lived zone of weazkness in the Kaapvaal Craton.

A number of granite bodies, also, parallel the Thabazimbi-Murchison line in Botswana and in the Murchison Greenstone Belt. Duplication of Chuniespoort Group (Transvaal Sea) stratigraphic units have led to thrust interpretations, but field relationships in the Thabazimbi area indicate that the structure is a [illegible]-lateral strike-slip fault.

In light of the previous discussion on geodynamic processes, a long-lived zone of weakness can be explained by Sunda-style tectonics being operative on the Kaapvaal Craton prior to collision with the Zimbabwe Craton at about [illegible],5 Ga. Sunda-style *tectonics were first identified in* Sumatra and result from oblique convergence (Beck, 1986). Such convergence develops a parallel strike-slip fault-subduction pair (Fig. 91) and new analysis show that 59 per cent of plate boundaries have associated strike-slip faults as a result of oblique convergence (Woodcock, 1986). Strike-slip faulting develops inland and detachment of crustal slivers takes place along the margin to accommodate oblique convergence (Beck, 1983, 1986). Due to parallelism, faulting leaves the margin virtually intact as large slivers are translated along the margin (Beck, 1986). However, a curving outer belt seems necessary to accommodate "escape" of slivers.

When subduction is low-angle, strike-slip faulting is localized by zones of earlier weakness. Faulting occurs prior to collision and localizes later San Andreas-type transform faults. However, the ease with which faults cut the overriding plate depends on the thermomechanical properties of the rocks involved (Beck, 1986). Oblique convergence of a shallowly subducted slab may only result in zones of weakness or localized fractures due to the absence of a magmatic arc. The important point here is the timing of the development of the magmatic arc and the angle of subduction. Prior to subduction heating of the overriding lithosphere, there is little potential for strike-slip faulting; but with thermal softening, a "master fault" cuts through the magmatic arc and can detach the entire forearc region (Beck, 1983, 1986). The inland location of the "master fault" and later transform would, thus, be determined by the location of the magmatic arc.

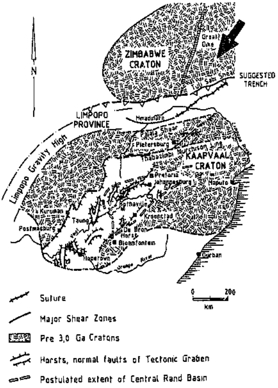


Figure 92. Paleogeographical reconstruction of the oblique collision between the Kaapvaal and Zimbabwe Cratons and of the major structural features developed on the overriding Kaapvaal Craton prior to thermal subsidence. *(Modified after Burke et al., 1985)*

The recognition of low-angle subduction and Sunda-style tectonics would again allow intraplate deformation to assist in the identification of marginal process. The Limpopo province is interpreted to be the suture zone between the Kaapvaal and Zimbabwe Cratons (Fig. 92). The province is delineated by a somewhat linear belt of deformation along the northern boundary of the Kaapvaal Craton, but the Limpopo gravity high appears to curve to the southwest. Any linearity of an ancient suture is 1983, 1986). The inland location of the "master fault" and later transform would, thus, be determined by the location of the magmatic arc.

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This would imply that the ancestral zones of weakness of the Thabazimbi-Murchison line, developed by possible oblique convergence and collision, had a left-lateral sense of movement. Left-lateral movement would also suggest north-northeast oblique convergence between the Kaapvaal and Zimbabwe Cratons. Escape of a detached sliver would be away from the converging cratons and would result in left-lateral translation along the margin. The granite bodies, which parallel the Thabazimbi-Murchison line, are probably the eroded remnants of a magmatic arc (Burke et al., 1986). Such parallelism implies that the Thabazimbi-Murchison line represents the "master fault". Based on these relationships, the collision between the Kaapvaal and Zimbabwe Cratons is interpreted to have been oblique from the north-northeast (Fig. 92) instead of north-northwest as interpreted by Light (1982).

Oblique collision along the Carpathian arc, that influenced the Pannonian Basin System, offers a close comparison to Kaapvaal Craton tectonics. In the Pannonian Basin System, regional extensional stress is related to differential motion between crustal blocks, to shortening around an irregularly shaped outer belt with major strike-slip faulting to the south of it, and to roll back of a subducted slab (Royden et al., 1983). Oblique collision of the Kaapvaal and Zimbabwe Cratons along the southwesterly-curving Limpopo Province reflects similar geodynamic processes were in operation. Other examples of structures developed by oblique tectonics are the active rifts of the *Rio Grande and Basin and Range Province*. Both systems have been interpreted as due to extension developed by oblique rotation of North American plates and roll back of shallowly subducted plates (Burke, 1978; Sengor and Burke, 1978; Barberi et al., 1982; Cross and Pilger, 1982; Cross, 1986).

5.7 Opening of the Selati Trough

The Selati Trough is an east-west trending, *rift-like* structure which has a pronounced coincidence with the *Thabazimbi-Murchison line (Figs. 84C; 85)*. It is probably one of the most ignored structural features on the Kaapvaal Craton (Fig. 85). However, field relationships and sections (Button, 1973a, 1973b) indicate that the Selati Trough was a rather passive structure.

Several characteristics of the Selati Trough allow tectonic correlation with the successor basin sequence. The passive, rift-like nature of the Selati Trough suggests that this structural feature opened along pre-existing zones of weakness in the "Old Granite" basement. These zones of weakness could have been inherited from the Thabazimbi-Murchison line, or could have been the result of a penecontemporaneous proto-fault *system* produced by oblique convergence, or both. The development of a *proto-fault system would take up part of* the oblique relative motion between plates and tend to cut through the weakened magmatic arc.

Convergence between the Kaapvaal and Zimbabwe Cratons has been interpreted as oblique and relatively rapid, but a magmatic arc is not clearly identified. The east-west trend of the Selati

Trough parallels both the Limpopo Belt and a line of granitic bodies, which have been interpreted as an eroded remnant of a magmatic arc (Burke et al., 1986). A closer examination of these granitic bodies to the north of the Selati Trough reveals that they form several parallel lines, that the exposed bodies decrease in size toward the Limpopo Belt, and that they young progressively in the same direction from about 2,6 to 2,4 Ga (Barton et al., 1983). It is suggested that the magmatic arc proposed by Burke et al. (1986) existed to the north of the Selati Trough; but it evolved during Ventersdorp time, instead of during Witwatersrand time as proposed by Burke et al. (1986). Development of this magmatic arc is equated with steepening of the angle of subduction, while the migration of the arc supports the interpretation of flexural roll-back following collision (Fig. 89C). Since arc magmatism decreases as the cont'-ntal plates involved in collision are welded together (D' son 1977), the decreasing size of the granitic bodies wo support roll-back. The rate of convergence, also, dire...y influences the volume of magmatism; a decrease in the rate of convergence would result in less magma being produced because less material was being subducted (Verplanck and Duncan, 1987).

Based on these descriptions and relationships, it is proposed that the Selati Trough developed as a consequence of interarc spreading as regional extension began to exploit a weak, ductile area previously heated by arc magmatism. Molnar and Atwater (1978) suggest that interarc spreading results in largely passive openings along lines of pre-existing weakness within the overriding plate in response to divergent motion. Slowing of absolute plate motion, combined with slower convergence, should create extensional stresses or divergent motion in the overriding plate and both are associated with steeper angles of subduction (Cross and Pilger, 1982).

Opening of the Selati Trough interarc basin probably began during early Ventersdorp time *following the expansion of* Klipriviersberg Group volcanism. Following spreading, the Selati Trough was bounded to the north by an active, but migrating, magmatic arc. The Wolkberg Group began accumulating in this rift-like interarc basin which represented a localized depocenter. Spreading expanded and deepened the Selati Trough interarc basin throughout the Ventersdorp extensional stage, but spreading probably ceased as crustal reorganizations due to tectonic subsidence developed an erosional surface over the area. Based on these relationships, the Wolkberg Group could be correlated with the Ventersdorp Supergroup, as well as the upper Buffalo Springs Group. The Selati Trough continued to be a passive downwarp until it was filled at the end of the Upper Monte Christo depositional system. Button (1973b) proposed that the Selati Trough was the basin center, but its filling implies that it was only a temporary arm of the depository.

5.8 Interpretations of Regional Relationships

The Dominion Group was deposited in rift grabens on the "Old Granite" basement and represents a local thermal anomaly developed under a regional extensional stress system. Rifting resulted because a thinner and thermally weakened crust, which probably existed in the Archean-early Proterozoic, would have lower cohesion and less resistance to deformation under a *regional extensional stress system.* It should be noted that a granite basement would have a lower density than a metamorphic one and form a significant mass deficiency which could be compensated by magmatic upwelling (*Logatchev and Zorin, 1984*). With the replacement or removal of extensional stress in Late Dominion time, compression would have aborted the progressive rift process, while preserving an expanded linear zone of weakness, which would be amplified and perpetuated for as much as 500 Ma (Fig. 84A).

The onset of regional compressional stress suggests that re-initiation of convergence and subduction (Light, 1982) had modified the boundary forces influencing the transmitted in-plane stresses. The general character of the West Rand sediments indicates both a subdued landscape and an absence of "high" relief. The character of the basin, also, appears to be simply flexural (Fig. 84A) and is an indication that thermal subsidence followed Dominion Group rifting. With changes in the thermal structure due to Dominion Group volcanism, thermal stress would have exerted a greater influence on the development of the early Witwatersrand successor basin than did the regional compressive stress system. This may explain the apparent delay of the effects of in-plane compression until Late West Rand time. Changes in sedimentation in Late West Rand time suggest that the earlier subdued landscape had been tectonically modified and imply that regional compressive stress possibly began to influence tectonic style even before the end of thermal subsidence. Cross (1986) recently proposed that stress transmitted into the overriding plate would be relieved along the zone of least strength; this zone would be coincident with the junction between a double and a single thickness of lithosphere. The position of greatest contrast of mechanical properties and zone of least strength would have been along the northern margin of the preserved Witwatersrand structural basin (Fig. 84B). Localized deformation within this narrow zone would have been due to the modifications of thermal structure induced by the subducted slab (Cross, 1986) and compressive block faulting might represent a form of supracrustal loading (Figs. 87; 90B). This narrow zone of deformation with its greatest contrast of mechanical properties may have also modified the structural architecture of the basement and determined the location the Ancestral Rand Anticline (Fig. 70).

Restriction of the basin during Middle Central Rand time indicates that time-dependent thermal subsidence had ended and regional compressive stress dominated. Restriction of the basin could have been due to a rising peripheral bulge (Fig. 87) along the south-southwest margin of the presently preserved Witwatersrand structural basin (Fig. 84B). Development of a peripheral bulge indicates the development of foreland-type tectonics as suggested by Winter (1986a, 1986b) and Burke et al. (1986). The numerous disconformities in the Central Rand Group would support the suggestion of foreland-type tectonics for the evolving basin, since unconformities *should be developed* throughout foreland basin development (Karner, 1986). Quinlan and Beaumont (1984) have reported that loads on a viscoelastic lithosphere gradually evolve toward local isostatic equilibrium with the result that the evolving basin becomes deeper and narrower as the peripheral bulge is uplifted and broadened (Fig. 87). However, no potential supracrustal loads of the right age, i.e. penecontemporaneous magmatic arc or integrated system of nappes, other than compressive block faulting, have been identified during this stage of successor basin development and these are critical assumptions that both Winter (1986a, 1986b) and Burke et al. (1986) have made.

The characteristics of the Central Rand Group are similar to those of Chinese-type basins documented by Bally and Snelson (1980). Chinese-type basins are bound by either distal compressive block faults or wrench faults and develop without an associated A-subduction margin or fold-thrust belt (Bally and Snelson, 1980). Their origin appears to be similar to both Laramide- and Ancestral Rocky Mountains-type basins of the western United States, which are filled mostly with continental clastics (Bally and Snelson, 1980). These relationships would certainly support the interpretation that the Central Rand Group was a type of foreland basin developed by low-angle subduction. However, it is not the type of foreland basin proposed by either Winter (1986a, 1986b) or Burke et al. (1986).

Karner and Watts (1983) have also suggested that an extra driving force is necessary for foreland flexure; such an extra driving force could be due to transmitted compressive stress (Allen et al., 1986). The transmission of compressive or extensional in-plane stress would either amplify or decrease the height of the peripheral bulge (Cloetingh, 1986). The Central Rand Group was actively influenced by compressive *in-plane stress* as indicated by compressive block faulting; and with amplified uplift, the peripheral bulge should have broadened and begun to restrict the basin. However, periods of extensional stress, as indicated by the extrusion of the Crown and Bird lavas (Fig. 72) and followed by minor thermal subsidence, as indicated by the deposition of shale or very fine-grained quartzite (subdued landscape sedimentation), punctuated the regional compressive stress system. Thermal subsidence, following the extrusion of the Bird lavas, may have downwarped the peripheral bulge and supports the interpretation that the basin was merely restricted, not closed, to the outer southwestern sea.

Major changes in sedimentation and initiation of extensional block faulting during Late Central Rand time point to a change in the renewable stress systems before the extrusion of the Klipriviersberg Group lavas. The gradual, widening areal distribution of the Klipriviersberg Group lavas and acceleration of faulting with time indicate that, with the rising geotherm, stress amplification resulted in the propagation of rift-type tectonics under a regional extensional stress field. Stress amplification should be expected since areas of high geotherm and *thinner lithosphere* are more susceptible to faulting (Kusznir, 1982; Kusznir and Karner, 1985; Mithen, 1982). With major graben formation a late stage event and often preceded by uplift and volcanism, stress amplification would also lead to graben development. The reason is that once initiated stress amplification would accelerate with time. Further amplification would be due to the release of stress by brittle failure; re-stressing of the lower lithosphere would result in creep and stress transmission again to the upper lithosphere (Kusznir and Park, 1982, 1984; Bott and Kusznir, 1984). With the lack of sediments recording tectonics in Platberg time, bimodal volcanics in the Platberg and Buffalo Springs Groups support extensional stresses generated by roll-back. Intermediate and felsic volcanism following mafics have been attributed to a slowing of absolute upper plate motion and reduced convergence rates (Cross and Pilger, 1978b). Such plate motion has been interpreted as occurring following collision in Ventersdorp time.

Tectonic subsidence in Bothaville, Allanridge and Early Vryburg Formation time represents a change from a regional extensional stress system to a compressional one. A change in the character of transmitted in-plane stress would be due to resistance to convergence between the Kaapvaal and Zimbabwe Cratons. However, extensional stress alternated with compression on at this time and such an interpretation is suggested by volcanics in the Allanridge and Vryburg Formations. The regional unconformity between the Bothaville Formation and the Platberg Group is the rift unconformity and would represent a plate reorganization into a new geodynamic regime (Bally, 1982). The Platberg Group grabens are a type of failed rift; and with slightly elevated mantle temperatures during the Archean-early Proterozoic, a regional compressive stress system would resist fragmentation of the cratonic mass (Vlaar, 1986b). Compressive stress systems seem to have prevailed during the Proterozoic (Vlaar, 1986a, 1986b) and may be the reason why the Proterozoic is characterized by large intracratonic basins.

Following tectonic subsidence, thermal subsidence began to dominate over any regional renewable stress systems and the Transvaal Sea depository (epeiric sea) began to subside. Thermal subsidence was time dependent and episodic because lateral heat flow from the cooling rift can disrupt the pattern of marginal flexure and overstepping (Watts, 1982; Vlaar, 1986a). However, flexure soon overcomes the effects of lateral heat flow and younger sediments progressive onlap, due to flexural rigidity with age (Watts, 1982). Arching and the development of local unconformities during these periods of early subsidence would suggest regional compressive stress was also operating and developed a peripheral bulge-like structure (Ancestral Rand Anticline) that divided the basin. Stresses during this period did not exceed the strength of the upper crust and flexure resulted, instead of faulting as is evident in Central Rand time. Such an arch structure (Ancestral Rand Anticline) might be expected at this time since the effectiveness of compressive in-plane stress in producing deflections is greatest on young margins subject to rapid loading (Cloetingh et al., 1985) and might represent perpetuation of a crustal flaw developed during Central Rand time. Enlargement of the basin following arching suggests that removal of renewable stress amplified the effects of non-renewable thermal stress. In a hotter Archean-Proterozoic earth, it is assumed that thermal subsidence equilibrium was reached within the same or a shorter time frame (Vlaar, 1986b) as compared to Phanerozoic basins.

The regional unconformity at the end of the Lower Monte Christo depositional system would represent another major crustal reorganization. This unconformity represents the end of thermal subsidence as uplift and erosion resulted in siliciclastics replacing carbonates. Continued convergence between the Kaapvaal and Zimbabwe Cratons, following the end of thermal subsidence, episodically transmitted compressive in-plane stress into the Kaapvaal Craton (Fig. 89D). Stress removal resulted in subsidence reactivation and progressive enlargement of the basin following periods of semi-dormancy (Figs. 63; 82). Stress differences associated with the Platberg Group graben initiated basin reactivation. Following three major periods of basin reactivation and expansion, the successor basin sequence was terminated by rapid uplift and development of the pre-Pretoria Group unconformity. Such a major crustal reorganization, which would both terminate and partially erase a sedimentary depository, may be a modification of the Wilson Cycle when failed rifts are involved in basin development.

Chapter 6

Summary and Conclusions

Throughout this research, the objective has been to use genetic stratigraphy, based on observations and tractable questions, to establish a regional framework for the development of the Early Proterozoic Transvaal Sea. By taking this approach, the focus has been placed on interpretations of interrelationships between the carbonate and siliciclastic depositional environments and the syndepositional tectonics, which influenced their development.

Eight subfacies were identified as being developed by the depositional environments of the Transvaal Sea and their spacial interrelationships were used to identify syndepositional tectonics. Although specific observations were made of outcrop, borehole core, and geophysical evidence, data was simplified to identify interrelationships in terms of depositional systems and broad paleogeographical reconstructions. With interrelationships identified in those terms, vertical crustal movements, which influenced the Transvaal Sea, were recognized and interpretations of the regional stress fields and/or thermal effects, which influenced the crustal movements, were made.

Ten depositional systems were identified as the regional framework was developed and correlations were made between the Transvaal and the northern Cape. The paleogeographical reconstructions of the depositional systems through Transvaal Sea time and space indicated:

1) The depository was compartmentalized, had a north-northeast striking depositional axes, and had a somewhat westerly skewed, asymmetric configuration.

2) The depositional axis lay over the western margin of the Ventersdorp Supergroup in the western Transvaal and northern Cape.

3) The depositional systems were developed in two principal stages of subsidence, which were characterized by continued depository deepening and expansion.

4) The depositional systems were influenced by tidal processes on a sea floor created by the hydrographic forces.

5) The depositional systems were developed on distally-steepened ramp-like platforms which never evolved into a shelf-like platform.

6) The distribution of subfacies, the areal extent, and the depositional character of a depositional system was simply a function of water depth.

The episodic transgressions, which developed the early depositional systems, followed the pattern proposed by Visser and Grobler (1972) that early transgressions covered only a limited area and that subsequent transgressions covered most of the Kaapvaal Craton. However, this research has indicated patterns of sedimentation that, during periods of regression, the Transvaal Sea either retreated completely off of or abandoned large areas of the craton. Moreover, unconformity bounded packages developed due to these regressions and could be correlated throughout the preserved outcrop area. Correlation, thus, indicated that Button (1973a) was mistaken in his assumption that unconformities in the eastern Transvaal had no apparent counterparts in the western Transvaal. However, distribution of lithofacies within the various depositional systems confirmed Button's (1986) summation that sedimentation was on a very wide, flat, gently shelving marine platform. The telescoped range of environments, which developed the lithofacies distributions, also supported Eriksson and Truswell's (1973) suggestion that this marine platform was an epeiric sea. The ten depositional systems also confirmed that sedimentation was cyclic as proposed by Eriksson (1972), Button (1973a), and Beukes (1977). However, both the character of the depositional systems and the reconstructions have indicated that there were only two first order cycles of sedimentation, instead of three as proposed by Button (1973a). Of all the early generalizations, the reconstructions clarified those of Visser and Grobler (1972) that depositional environment was controlled both by macro-influences (tectonic) and micro-influences (hydrographic) and that the two were superimposed on each other.

Basement precursors were scrutinized to identify what structural influences the Transvaal Sea compartments had inherited from the basement architecture. The north-south trending Ventersdorp Supergroup developed in a rift environment just prior to the opening of the Transvaal Sea, and Wernicke's (1985) hypothesis of normal simple shear best explained the down-to-the-west pattern of faulting due to the rifting event. High heat flow and stress amplification were interpreted as the causes for the development of a second breakaway, which superimposed large block ranges over the western half of the extended Ventersdorp terrane. Under this same regional extensional stress field, the east-west trending Selati Trough opened and this opening was subsequently interpreted as due to interarc spreading. However, the Selati Trough was not the depositional axes of the Transvaal Sea as proposed by Button (1973a). The geographical interrelationships between the Ventersdorp rift and the Selati Trough created the structural boundaries of the Transvaal Sea compartments, while asymmetric rifting determined its skewed configuration.

By identifying rifting prior to the Transvaal Sea, backstripping of the stratigraphy through the Ventersdorp Supergroup identified three stages of subsidence. Initial mechanical subsidence, due to rifting, was followed by subaerial tectonic subsidence and this intermediate stage was followed by subaqueous thermal subsidence which developed the first phase of the Transvaal Sea. Tectonic subsidence, which could have been rather protracted, had not been previously recognized. Thermal subsidence was relatively short and was followed by periods of basin reactivation, which produced the second and major phase of subsidence of the Transvaal Sea.

Compressive in-plane stress was the driving mechanism for basin reactivation and dominated syndepositional tectonics. However, a simple tectonic style, in which neither extensional nor compressional stress predominates, was interpreted from the changes in the regional stress fields from Ventersdorp Supergroup through Transvaal Sea time. Thermal subsidence, which produced the initial phase of subsidence, was recognized as a non-renewable-type of stress; while compressive in-plane stress, which produced basin reactivations during the second phase of subsidence, was determined to be a renewable-type. Renewable-type stresses were attributed to the continued convergence of the Kaapvaal and Zimbabwe Cratons following collision. However, Vlaar (1986a, 1986b) pointed out that compressive regional stress systems prevailed during the Proterozoic. With the recognition that the Ventersdorp Supergroup developed under a regional extensional stress system, simple tectonic style was the preferred explanation for the Proterozoic stress systems.

Craton boundary conditions for the 3,0 to pre-2,2 Ga time reference were examined. The stratigraphy of both the Witwatersrand Supergroup and the Dominion Group were backstripped to the "Old Granite" basement to identify changes in the regional stress fields, which would result in a regional extensional stress field. When combined with the known Ventersdorp Supergroup and Transvaal Sea relationships, backstripping identified the following changes in the regional stress systems:

1) The Dominion Group developed under an extensional stress field and developed the structural architecture of the basement. This basement architecture was to be perpetuated by the changing regional stress systems and influenced the succession of later basins.

2) Regional compressive stress began to dominate during Late West Rand Group, Witwatersrand Supergroup, time and it continued through Central Rand Group, Witwatersrand Supergroup, time. Under the regional compressive stress system, compressive block faults resulted from the inversion of Dominion Group extension faults. "Mini" foreland-type basins formed during Central Rand time as compressive block faults loaded their footwalls.

3) Regional extensional stress began during Late Central Rand time and led to the development of the Ventersdorp Supergroup.

4) Regional compressive stress affected intraplate deformation patterns again during Early Transvaal Sea time and continued until the evolution of the Transvaal Sea was terminated by uplift which developed the pre-Pretoria Group, Transvaal Sequence, regional unconformity.

The recognition of compressive stress during Transvaal Sea time confirmed Button's (1986) suggestion that the tectonic framework of the Kaapvaal Craton remained essentially constant throughout the evolution of the various depositional systems.

These interrelationships tend to substantiate the Proterozoic stress systems by indicating that a simple tectonic style could be related to the angle of the subducting slab prior to and following oblique collision between the Kaapvaal and

Zimbabwe Cratons; that this simple tectonic style influenced a number of Early Proterozoic successor basins on the Kaapvaal Craton, which climaxed in the development of the Transvaal Sea; that the Transvaal Sea inherited its initial regional margins from the basement architecture developed; and that basin reactivation due to the transmission of compressive in-plane stress is the reason that the Transvaal Sea was characterized by continued deepening and expansion.

This last interpretation is important because the Proterozoic was characterized by large epeiric seas. When dealing with a hotter earth, thermal subsidence of a basin should be reached in a shorter time. It was the reactivation of basin subsidence under a regional compressive stress regime that allowed these seas to expand and to cover the stabilized Proterozoic cratons. It is through the identification of reactivated subsidence that the evolution of Proterozoic and Phanerozoic epeiric seas can be compared. The same geodynamic processes probably affected both, although those in the Proterozoic may have been slightly accelerated. Geodynamic comparisons could also lead to a better understanding of Proterozoic intraplate deformation and help identify marginal processes, which led to the evolution of the Proterozoic epeiric seas. Lithological comparisons between the Proterozoic and Phanerozoic, on the other hand, would fail because the subtidal-below-wavebase lithofacies of the Phanerozoic are strikingly different, due to the evolution of predators and reef builders.

Once dates are determined for the stages of subsidence of the Transvaal Sea, subsidence curves can be calculated to quantify these interpretations. The characteristics and subsidence curves for the tectonic subsidence stage can also be developed to substantiate its intermediate relationship to the mechanical and thermal subsidence stages. However, in the interim, it is suggested that research on Proterozoic basins and epeiric seas in southern Africa be from a genetic stratigraphic approach, so that the geodynamic forces influencing the basins can be determined simultaneously with the lithostratigraphic descriptions.

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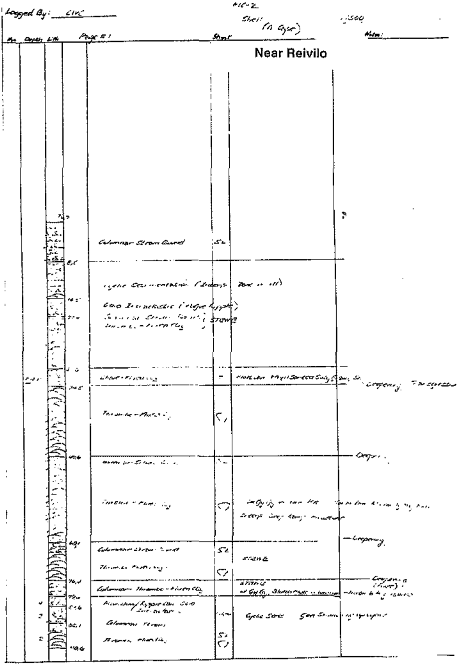
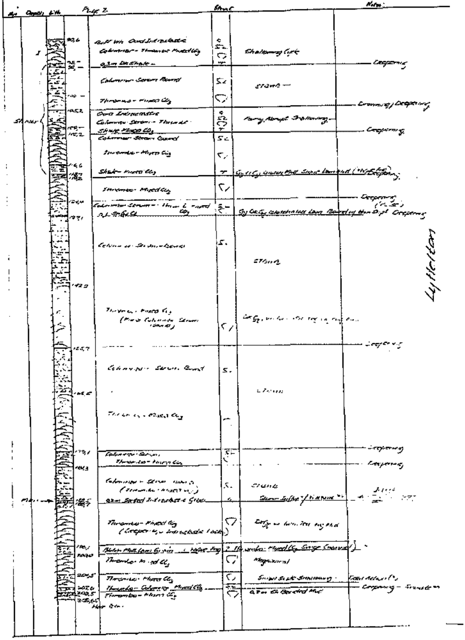
Appendix A


Logged By:
Depth
Lith
Near Reivilo
STONE

MC-2
Shell
Northern Cape
1:500

Logged By: CWC



Logged By: CWC

K-1 Shell (Northern Cape)

Page #1

Near Reivilo

Top of Hole

Lyttelton - Eccles

Logged By: CWC

F-1

Shell (Northern Cape)

1:500

No.	Depth	Lith.	Page #2	Struct.	Notes:
	264.0				
	267.-				Motiton
	270.7				
	273.6				
	28?.?				
	29.7-				
	29?.?				
	31?.?				
	33?.?				
	335.?				
	34?.?				

Lower Monte Christo

Logged By: CWC. E-1 Shell (Northern Cape)

Page #3 1:500

Ag	Depth	Lith.		Description	Struct.		Notes
			3460	Shale - Mixed Clg	T		Erosional / "Transformal"
5			3593	— Poss. Transgressive Surface			
4			3610	Gy Lt Gy Mass. can Banded Intraclastic / S. by Calcareous Grain		— Cyclic Sed	
3			3647				
2			3713				
1			3751	Gy Lt Gy Banded Intraclastic S.C. Lt Gy [illegible] Calcareous [illegible] @ Contact —		"Bedding [illegible]"	
			3760	Calc Intraclastic Thrombo - Mixed Clg Shale - Mixed Clg	T	Cards have sh. frag. cores.	Deepening — Poss. [illegible] - Erosive Cont. Paraconformity
			3817	Lt Gy Gy Banded Intraclastic Grain — Large Thrombo - Mixed Clg		Deep Ramp	
			3915 / 3940	Dk Shale — Gy Calcareous S.C. → Large Thrombo - Mixed Clg	—	Deep Ramp —	
			3952	Shale - Mixed Clg	T	Basin Lithofacies —	25.00 46.00 [illegible]
			4467	Gy Lt Gy Mass. Frag. [illegible]		Shale Mixed Clg	
			4465	Lt Gy [illegible] Banded [illegible] Intraclastic Grain		Shale - Mixed Clg	
Cycle			4520	Lt Gy [illegible]			
			4532 / 4541	Mass. Banded Calcareous S.C. Lt Gy Black [illegible]		Cyclic Sed. [illegible]	
			4563	Thrombo - Mixed Clg [illegible] Gy [illegible] Grain		[illegible] Ramp	[illegible]
			4591	Dk Gy Black [illegible]	—	[illegible]	
			4573	Lt Gy Black Intraclastic [illegible]		Basin [illegible]	
			4609	Dk Gy Black Shale [illegible]		[illegible]	
			4630	Lt Gy Black Banded [illegible] Calcareous [illegible]		[illegible]	
			4637 / 4640 / 4646	T.D. Lt Gy Black Shale — Bottom Hole —			

Lower Oak Tree

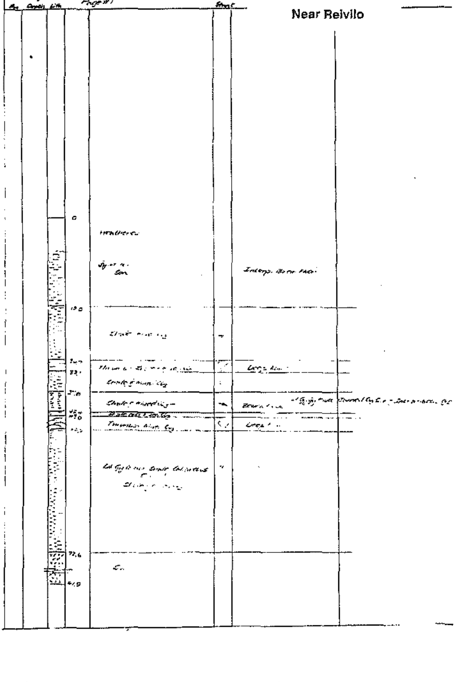
Logged By: CWC

22-1

Shell (Northern Cape)

:500

Near Reivilo

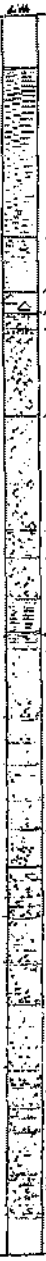


Logged By: CIVC

ZZ-1 Shell (Northern Cape)

1:500

Page #2

An	Depth	Lith		Description	Show		Notes
			519	Lt Gy/Black Shale/Calcareous Silt; Dark & mixed [illegible]			Lower Oak Tree
			1102	Tan [illegible] Calcareous Silt [illegible]		Transgression	
			1164	[illegible]		Regional [illegible]	
			1181	[illegible] (Intraclasts)			Boomplaas
			1231	[illegible]			
			1270	[illegible]		Intraclastic [illegible]	
			[illegible]	[illegible]		[illegible]	
			1526	[illegible]		[illegible]	
			1543	[illegible]		[illegible]	
			[illegible]	[illegible]		[illegible]	
			1720	[illegible]		[illegible]	
			1909	[illegible]		[illegible]	
			2159	[illegible]		[illegible]	

Logged By: SMC

ZE-1
Shell (Northern Cape)

Page #3 — 1:500

Depth	Description	Struc	Notes
215,4	Ooid Intraclastic		Rapid Shallowing 3cm Sh. Mud @ Ct.
218,4	Thrombo - Shale Mixed CO_3 Lt Gy Uniform [illegible]		Note: 219,7 - 20 Tuff
220,9	Thrombo - Mixed CO_3 Shale Mixed CO_3	→	Lt Gy [illegible] Calcareous Slt. Shale
227,9	Andesitic Lava - "		Volcanic'
237,9 / 237,3	Shale & Mixed CO_3	→	Often randomly Similar as: Gy-Lt Gy, Shale, Calcareous Slt & Sort Intraclastic GS.
240,9 / 241,3	Thrombo - Mixed CO_3	▽	STBMG
	Shale Mixed CO_3	→	Note: 250,7 - 250,9 Sand. Zebra Rock. Lt Gy Gy Uniform Txt. Banded Sh & Calcareous Slt.
251,9	Thrombo - Mixed CO_3 (Minor Mud & Sh)	▽	STBMG —
258,2	Shale Mixed CO_3	→	Zebra Rk' Lt Gy Gy Fining Up Seq. STBMG'
260,6	Lt Gy Sorted Sand w/ Minor Sh. [illegible]	→	
262,4	[illegible] Calcareous Shale	→	
263,1 / 263,7	Thrombo - Mixed CO_3 Shale Mixed CO_3 (Lower Bump)	⊤	Lt Gy Shale Sand Mud
265,8	Shale - Mixed CO_3 Gy. Dk Gy. Well Sorted Uniform Txt. Interbedded Calcareous Slt w/ Sh.	→	
276,5	Lt Gy Mixed [illegible] Thrombo Mixed CO_3		
278,2	Buff White Gy Green Sorted 'uniform' Txt Sandstone. [illegible] upper Ct pass [illegible] silt [illegible]		Note: Pass Ash @ 279,5" Clean Sand @ Ct' Note: 278,5/279,0 2 upper fining Seq — [illegible] Slt.
285,7 / 287,4	[illegible] Gy Green Slt. [illegible] "Ash" [illegible] Reworked?"		
290,2	Buff White/Lt Gy Sorted Sandstone. [illegible] Graded from pea gravel [illegible] lower Ct		
293,7			
297,2 / 298,5	Lt Gy Buff White (slight green tint) [illegible] Sandstone [illegible]		Note: Zone has a Reverse Graded to Mixed [illegible] Sort [illegible]
303,6			
312,9	[illegible] Dk Gy [illegible]		
313,9	[illegible] Poorly sorted [illegible] Sandstone		
317,7			
323,2	Lt Gy Green Poorly Sorted Sandstone - Siliciclastic Greywacke		Siliciclastic — Appears to be a number of fining upward cycles. Cycle starts w/ Greywacke → pea gravel(?) Sandstone → Sandstone. Sorting is variable → poor to fairly uniform. Note: Unit has a "[illegible]" look about it.'
328,2			
330,5			
341,6			
348,1			

Boomplaas

Vryburg

Logged By: CWC

MTV-1
Monte Cristo Fm

page #1

Near Bothaville

Depth	Description		Notes	
4479	Regional unconformity			NK / Eccles Fm. contact
4481	Brecciated Columnar Chert			
4490,1	Columnar Stom.			Max. Compact Zone
	Thrombolite - Mixed Clay			Drowning
4498,1	Intraclastic Grain. Columnar Strom.		Shallowing Up Seq.	
4499	Slump ?		Origin ??	
4505,0	Thrombolite - Mixed Clay			
4513				

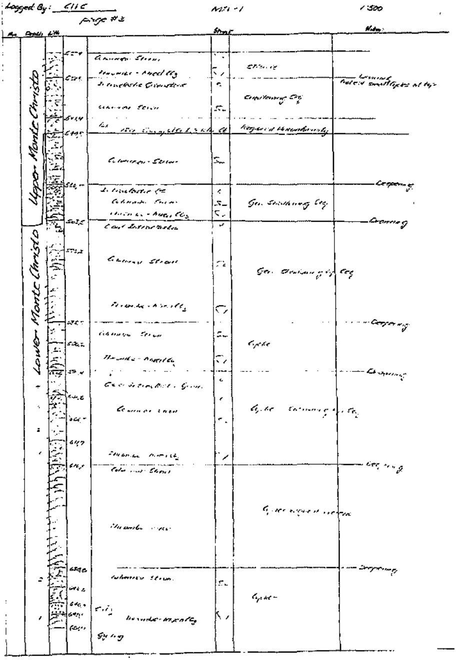
Logged By: CIYC

MTV-1

1:500

page #2

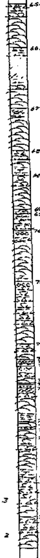
Cy	Depth	Description	Struc		Notes
3	403.3				
	406.7	Columnar · Strom —	SZ		
2				Cyclic Sed.	
	413.–				
1		Thrombo - Mixed CC_3			
5	419.–	Ripple Lam Grainstone	o		Crowning
4	421.5				
3	424.–	Intraclastic Grainstone			
2	427.–				
1	429.3	Columnar Strom	Sz	Cycle — Well Obscures Detail -	
	432.2				
		Thrombo - Mixed CC_3			
	441.7	Gy Ng, Columnar Strom	Sz		Deepening
		Thrombo + Mixed CC_3			
4	445.9	(Intraclastic Gs)	o		Deepening
3	448.7				
	455.5	Columnar Strom			
2	459.9			Cycle Sedimentation	
1		Thrombo - Mixed CC_3			
4	467.–	Gy Ng Columnar Strom			Deepening
3	470.7				
2	473.0	Columnar Strom	Sz	Cyclic Sed.	
1	475.3	Thrombo - Mixed CC_3			
	479.9	Ng Gy Columnar Strom + Thrombo - Mixed CC_3 Slumped		Strom —	
	491.– 492.1	Thrombo - Mixed CC_3			
6	495.5	Columnar Strom	Sz	Strom	Deepening
4	505.–	Gy Ng. Thrombo - Mixed CC_3		Cycle Break?	
3	510.6	Intraclastic Grain	o		Deepening
2	514.6	Columnar Strom		Generally Cyclic Sed — Well obscures detail.	
1	520.0				
	523.4	Thrombo - Mixed CC_3			


Logged By:
page #3
1:500
Strat
Notes
Upper Monte Christo
Lower Monte Christo

Logged By: CWC

page # 4

MITV-1
1:500



Bx	Depth	Lith	Description	Struct	Interpretation	Notes
	651.9		Gy Fng Columnar Strom			
	661.4		Columnar Strom Board (Gy Gr Matx)	SZ	Cyclic Seal Seq.	
			663 – 668.4 Ft. disruption			
	674.5		Thrombo – Mottled Ls	◯		
	682.9		Columnar Strom	Sc		
			Thrombo – Mottled Ls (Mbd)	C		
	689.3		Gy Fng Columnar Strom	Sc	STACK	
			Thrombo – Mottled Ls	C		
	697 – 698 –		Intraclast. Gr.		Inc Cycle.	
	701.5		Columnar Strom		Shallowing Up. Seq.	
			Thrombo – Mottled Ls			
			Lam. Mud			Coarsening
	712.7		Intraclastic Grain			
			Columnar Strom.			
			Gy Fng	S	Cyclic Shallowing Up	
	726.5		Gy Fng. Thrombo – Mottled Ls	C		
	731.2 / 731		Silt]			Coarsening
			Intraclastic Grain			
	734.9 / 735.2 / 735.6		Silt] Columnar Strom.		Cyclic Shallowing Up	
			Thrombo – Mottled Ls			
			Gy + Mud			
	742.1 / 744.6 / 744.8		Silt] Thrombo – Mottled Ls	C		
	746.5		Gy Fng Columnar Strom	S	Shallowing Seq	
			Thrombo – Mottled Ls	C		
			"Layer Mud"			Coarsening
	755 –		Gy Fn Columnar Strom	SZ		
3			Columnar Strom		Cyclic – Shallowing Up	
	764.5					
2			Thrombo – Mottled Ls	▽		
	770.5					

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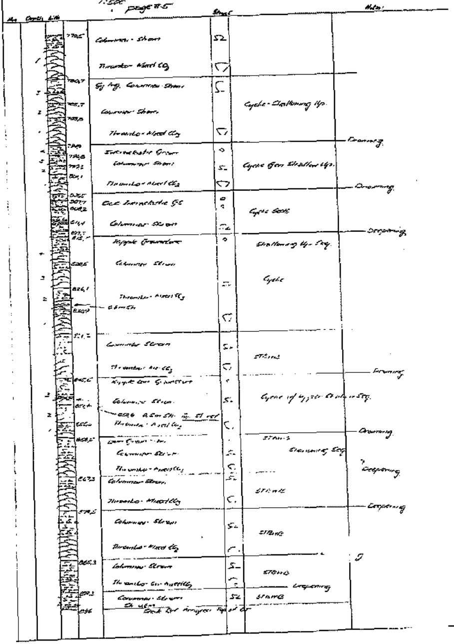
Monte Cristo Section

MTV-1

Near Batesville.

1:500 page # 5



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Mt1-2
Black Reef Contact & Transition

1:250

Near Bothaville

Bn | Depth | Lith | | Sh

BEG - Lower Oak Tree Transition

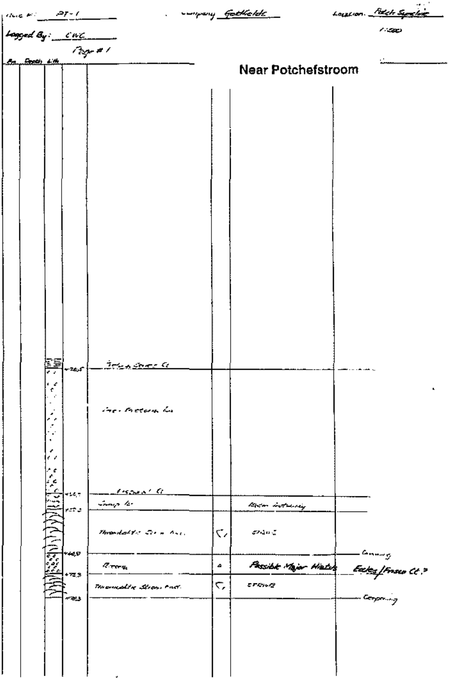
[illegible] of [illegible] Mer is [illegible] below main base (stone)
[illegible] Megacmal
[illegible] of deeper Shale - MeCO3 basinal facies -

[illegible] Thrombo - MnCO3 -

Top of [illegible]
[illegible] regression

3.6 [illegible] St
[illegible]
[illegible]
[illegible] Glyde [illegible]
1.5 Thrombo - MnCO3
1.25 Black Shale
0.0 [illegible] - MnCO3 Cy
3.95 Black Shale
9.6 [illegible] Gy [illegible] Nom. Grade
2.5 Buff white - Lt Gy Well sorted quartz arenite
(partly [illegible] — overall uniform bed — [illegible])

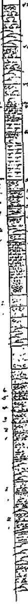
[illegible] Contact w/ [illegible]


PT-1
Logged By: CWC
Page # 1
1:500
Near Potchefstroom
Possible Major Hiatus
Eccles/Frisco Ct.?

Hole #: DT-1 Company: Goldfields Location: Potch Syncline

Logged By: CWC 1:500

Page #2



Depth	Description	Struct	Interpretation	Notes
478.3	Oncoid Intraclastic Columnar Stromatolite		Shallowing Up Cycles	
482.0				
485.0	Thrombolitic Stromatolite		Rapid Shallowing, Intraformational [illegible]	
499.0 / 499.0	[illegible] Tectonoclastic			3 Best Pick
505.3	Cyclic Peritidal Stromatolite		Gen. Shallowing Up. Mud & [illegible]	
	Oncoid Intraclastic Columnar Stromatolite		Rapid Shallowing	
516.2	[illegible]	T	Interpreted Major Change	Deepening 2
518.7, 520.0, 522.0, 524.2	Oncoid Intraclastic Columnar Stromatolite Cycles		STRONG Shallowing through [illegible]	
528.2	Thrombolitic Stromatolite Mud			Coarsening 1
529.7	Cyclic Position		Shallow Sequence	
538.1	Oncoid Intraclastic		[illegible]	
541.2	Oncoid Intraclastic Columnar Stromatolite		Shallowing Cycles	
543.7, 544.0	Oncoid Intraclastic, Columnar Stromatolite; Thrombolitic Stromatolite Mud		Rapid Shallowing Up; [illegible]	Coarsening
552.4	Oncoid Intraclastic		[illegible]	Deepening
557.2	Oncoid Intraclastic		STRONG	
559.5, 560.3				
563.3, 565.0, 566.2, 568.4	Repeated Oncoid Intraclastic & Columnar Stromatolite		Cycles in Progressive Shallowing	
570.6	Oncoid Intraclastic, Columnar Stromatolite		Shallowing Up. Shallowing [illegible]	
576.4	Thrombolitic Stromatolite, [illegible]		STRONG [illegible] Columnar	Coarsening
581.4	Oncoid Intraclastic / Columnar Stromatolite		Shallow [illegible]	Deepening
583.5	Oncoid Intraclastic, Columnar → Thrombolitic Stromatolite		Rapid Shallowing, Thrombolitic	Coarsening
586.3	Oncoid Intraclastic → Columnar Stromatolite		Cycle	Deepening
587.7	Oncoid Intraclastic / Columnar Stromatolite		[illegible] → Shallowing Up	
590.1	Tectonoclastic		[illegible]	[illegible]
590.3	Thrombolitic Stromatolite Mud			Deepening
593.6	Columnar Stromatolite		Shallowing Up	
604.5	Thrombolitic Stromatolite Mud			Deepening

#7 End of Depo Cycle

K. [illegible] Contacts

Hole # PT-1 | Company Goldfields | Location: Patch Syncline

Logged By: CHC | | 1:500

Page #3

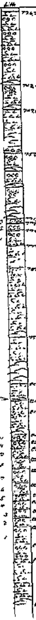
Depth	Lith	Strat	Notes
604.5	Columnar Strom / with coal Ooid Intraclastic	S	Algal Columnar Strom. Stg #2 Cycles Not Located
623.1			Lithology Major Change — Drowning
623.0	Cycle Terminal Stromatolites	SS	
	Ooid Intraclastic	O	Rapid Shallowing Up Seq.
636.0	Columnar Strom. (Is … ?)	S	— Deepening
	Ooid Intraclastic	O	Shallowing Up
649.0	Columnar Strom.	S	Small Flat Type — Deepening
	Ooid Intraclastic (Complete)	O	Ooid Fracture
	Columnar Strom.	S	
650.0	Thrombolitic Strom. Mud	T	Top of Thrombolite Unit; Shallowing Up; Ditto
662.2			— Drowning
	Ooid Intraclastic	O	
666.0			
667.5	Ooid Grainstone		Interp. Thr. Upper Ooid Cont. Ramp
	Columnar Strom.	S	Gen. Shallowing Up
	Thrombolitic Strom. Mud	T	
676.0			— Deepening
	Columnar Strom.	S	Gen. Shallowing Up
683.0	Thrombolitic Strom. Mud / Ooid Grainstone	T	Gradational w/ Columnar ? Columnar Strom.
	Thrombolitic Strom. …	T	Ditto
705.0			Abrupt … Major Upper … Line
	Minor Ooid Intraclastic	O	
710.7			
	Columnar Strom.	S	Strong Cycles — General Shallowing Up
720.0	Thrombolitic Strom. Mud	T	
726.5			

End of Depo Cycle #4

Core #: PT-1 Company: Goldfields Location: Patch Syncline

Logged By: CHC 1:500

Page # 4

Ac.	Depth	Lith			Struct.		Notes	
			726.2	Columnar Strom Band. w/ Interbedded lenses of G.S.		Appears to be Ha... Zone STRWE / STRMG Smooth - Nodular Wet ...		
				Note: There are ... Uniform				Deepening / ...
			742.4	Card Intraclast, Columnar Strom, Thrombolitic Mats		Gen Shallowing through Lith faces		Deepening
			747.6	Columnar Strom		Gen Shallowing		
				Thrombolitic Strom ...				
				Chert ... Scale Bx				Depo. Hiatus
3			757.2	Cycles: Card Intraclastic, Columnar Strom		Gen Shallowing Up - Inter through Lithofacies		
2								
1				Thrombolitic Strom Mats				Drowning
3			771.3					2 deepening Cycles
2			777.6	Card Intraclastic		Mud (E) G.		
1			779.5	Columnar Strom		Shallowing Cycles		Deepening
				Thrombolitic Strom, Mud		Mud (E) G.		Drowning
			782.3	G.S., ... Card Intraclastic		Chert increases ... Gen Shallowing Up		
				Columnar Strom Thrombolitic Mats				Deepening
			795.4	Columnar Strom		Larger Up Cycle		
				Thrombolitic Strom, Mud				Deepening
			807.5	Columnar Strom, G.S. + Intraclasts		STRW		
			811.3	Columnar Strom				Deepening
			817.5	Card Intraclastic		Gen Shallowing Up Seq.		
				Columnar - Thrombolitic Strom. Mud				Deepening
11			822.0					
10			824.6					
9			827.0					
8			830.2	Card Intraclastic				
7			832.3			Cyclic Depo Cycles → Gen Shallowing Up Cycles		
6			835.5	Columnar Strom Band		Cycle ... w/ ... G.S.		
5			837.1					
4			837.5					
3			838.5					
2			839.1					
1			840.0					
			847.5	Changed Card Intraclastic, Columnar Strom		General Shallowing Up		
			850.0					
				Columnar - Thrombolitic Strom				Drowning
			855.8					

End of Depo Cycle

Hole #: PT-1 Company: Goldfields Location: Potch Syncline

Logged By: CIVE 1:500

Page # 5

Depth	Description	Struc	Interpretation	Notes
[illegible] / 865,6			Top of Shallowing Seq.	Drowning.
[illegible] / 866,6				
868,0	Sed. Intraclastic	o	General Shallowing up. Cycles	
[illegible]	Columnar [illegible] [illegible]			
[illegible]				
			Deepening [illegible]	Tectonic Basin Re-expansion. Subsidence Cycle Begins
875,5 / 876,5	0,2m [illegible]			Drowning End of Depo. Cycle
	Cyclic [illegible] [illegible]		Shallowing Upward Cycle	
887,4				Hy/[illegible]
	Sed. Intraclastic		General Shallowing Seq.	
	[illegible] [illegible]			
[illegible]	[illegible] [illegible] [illegible] [illegible]			
[illegible]	Tectonic [illegible]			
	[illegible] [illegible] [illegible]			
[illegible]	[illegible] [illegible] [illegible]		[illegible] [illegible] [illegible]	[illegible] Seq.
905,4	[illegible] (...)		[illegible] [illegible] [illegible]	[illegible] [illegible]
[illegible]	[illegible] [illegible] [illegible] Tectonic [illegible]		[illegible] [illegible] Seq.	
[illegible]				[illegible] [illegible]
	Tectono-[illegible] [illegible] [illegible] [illegible] [illegible]		[illegible] [illegible] [illegible]	
977,1				

End of Depo Cycle

Core # PT-1 Company Goldfields Location: Patch Syncline

1:500

Logged By: C.H.C.

Page #6

Fm Depth Lith Struct Notes:

977.1

Thrombolite Stromatolite Mud-Mound

Deepening Seq. ... Transgressive-Regressive

1003 Grainstone/Intraclastic

Columnar Stromatolite

Deepening w/ Gen. Shallowing Seq.

Thrombolite (...) Stromatolite and

Transgressive-Regressive Cyc.

Regional Drowning

1030

#5 End of Cycle

Grainstone ... Columnar ...

Gen. Shallowing Up Cyclic Sedimentation

1045.5

1048.3

Top of ... Unit

Grainstone Intraclastic ... Columnar Stromatolite

1056

1062.9

Grainstone Intraclastic ... Columnar / Thrombolite / Stromatolite

Cyclic Sedimentation

Shallowing Cycles

4

3

2

1

Deepening

Lower Patch Member

General Shallowing

1092

Chert ... Shale

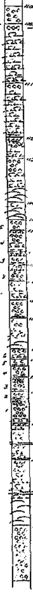
Regional unconformity

1097

Hole #: DP-1 Company: Goldfields Location: [illegible]

Logged By: CWL 1:500

Page #7

Fm	Depth	Lith.		Description	Struc.		Notes
Lyttelton: [illegible]			1100,2	Chert-in Shale Pz		Abu. [illegible] of Chert [illegible] Lyttelton M.C. [illegible]	[illegible] Unconformity
[illegible] (Thomas [illegible])	#2. End of Depo Cycle		1103,7	Note: Core highly [illegible]			
			1116,5	Key: [illegible]		[illegible] Columnar Strom.	
				[illegible]			Deepening
			1130,0	[illegible] Intraclastic			
			1133,5	Columnar Strom.		General Shallowing Up	
				Thrombolitic Strom Mud			Deepening
			1142,2	Columnar Strom		STRAND	
				Thrombolitic Strom [illegible]			Deepening
			1146,0	Cycle [illegible]		General Shallowing Up Seq	
				[illegible] FAC's		Upper [illegible] Change	
				([illegible] Columnar Strom.		[illegible]	
				[illegible] Intraclastic		STAND	Deepening
			1157,2	[illegible] Intraclastic		General Shallowing Up	
				Columnar Strom. [illegible]			
				Thrombolitic Strom. [illegible]		[illegible]	Deepening
				[illegible] Intraclastic		6 [illegible] Cycles	
				[illegible]			
				[illegible]			
				[illegible]		[illegible]	
				Cycle [illegible] Intraclastic		[illegible]	
			1209,9	Columnar Strom.		[illegible]	Deepening
				Core jumbled & highly fractured		Approx. [illegible] Gen. Shallowing Up Sequence	
				[illegible]			
			1224,2	[illegible] Intraclastic		[illegible]	Deepening
			1236				

Core # PT-1 Company Gulf[illegible] Location: Peck Syncline

Logged By: CWC 1:500

Page #2

Depth	Description	Struct	Notes	
1236.5	Ooid Intraclastic		Recall	
	Columnar Stroms (Multi-[illegible])			Deepening
1240	Cyclic Horizontal Stroms		Smooth Mat	
	Ooid Intraclastic			
1242.5	Breccia		[illegible] — [illegible]	
1243.2	[illegible], [illegible], Mtn. Strom. Bound		Interpreted: Columnar Strom Based on [illegible])	General Shallowing up Seq
1262.9	Ooid Intraclastic		Poss. 2 Cycles	
	Columnar Stroms (Mtn.)			Deepening
1269.2	Cyclic Horizontal (Shallowing Seq) Ooid Intraclasts → Columnar Stroms Thrombolitic Strom [illegible]. 0.3m [illegible]		Seq Smooth Mat. [illegible] Shallowing	
1274.2	Ooid Intraclastic → Columnar Stroms			Deepening
1279.1				
1282.1	Ooid Intraclastic Columnar Strom		General Shallowing Sequence	
1287.7				
	Thrombolitic Strom. Mnd.			Deepening
1290.5	Ooid Intraclastic → Columnar Strom.		[illegible]	
1292.1	Ooid Intraclastic			
1297.1	[illegible] Columnar Strom		General Shallowing Seq.	Deepening
	Thrombolitic [illegible] Strom. [illegible]			Deepening
1303.5				
1306.4	[illegible], Columnar Strom		[illegible]	
1309	Thrombolitic Structure		(Thrombolitic [illegible])	
1312.0				
1316.7 1316.4	[illegible] Strom. [illegible]		[illegible] Columnar Strom	
1325	[illegible]		[illegible]	Deepening
1329	[illegible] Ooid Intraclastic [illegible] Strom)		[illegible]	
1330.1	[illegible]		General Shallowing Up.	Gen. Shallowing Up.
	Columnar Strom. Thrombolitic Strom. [illegible]			Deepening
1334.5	Ooid Intraclast,		4 Cycles [illegible]	
1336.1	[illegible] Columnar Strom ([illegible]) Thrombolitic [illegible]		[illegible]	
1339.8				
1347.2	[illegible] Ooid Intraclastic Columnar Stroms Thrombolitic Strom. [illegible]		[illegible]	
1351.0	Ooid Intraclastic [illegible]		[illegible] Algal Glory	Deepening
1353.2	Ooid Intraclastic Columnar Strom		[illegible]	General Shallowing Up.
1358.0	Mottled Ctr. Gr. Thrombol. Fog Mud			Deepening
1365.0				

#1

End of Deep Cycle

Core #: DP-1 [illegible]

Logged By: [illegible]

Location: Pebble Cypress? (Spitzberg? Spr.) 1:200?

Page # 9

Fm.	Depth	Lith.		Description	Struc.		Notes
Basin Centralization?			1345.5?	[illegible] Intraclastic			Deepening – Drowning
				Columnar Stroms [illegible]		Gen. Shallowing Up	
	1372.3		1368.3	[illegible] Mott. Thrombolitic Strom. Mud		Basin Herdstones?	
				Middle M.C. [illegible] Gy			End of T.E.?
	1385.5		1371.5	[illegible] Gy. Coral Intraclastic; [illegible] Gy. Mott. Columnar Stroms; [illegible] Stroms			
	1378.2		1376.2	Dk. Gy. Columnar Strom. w/ Clast [illegible]			Deepening
				Mott. Thrombolitic Strom. Mud			
	1380.9		1381.0	Columnar Strom – Grain		At Colonized G.S.	Deepening
3m Mistake in Core blocks				[illegible] Thrombolitic Mud			
Thermal Subsidence			1390				
				[illegible]		Origin Questionable	
			3356?	Lt. Gy. Columnar Strom.			
			3360.7?	Thrombolitic Strom. [illegible]			Drowning
				Mott. Gy. or Gy. Strom. [illegible]		Intclasts [illegible] Columnar Strom – At Colonized Grain; An Apparent [illegible] for Shallowing Intclasts.	
			[illegible]	Gy. Mott. Mud			Deepening?
			[illegible]	[illegible] Strom [illegible]; Thrombolitic Strom [illegible]		[illegible]	
			[illegible]	[illegible] Mott. Mud		[illegible]	
			[illegible]	[illegible]			Drowning
			[illegible]	Columnar Strom. w/ Intraclastic [illegible]		Lt. Gy. (Core Here) [illegible]	
			[illegible]	[illegible] Columnar [illegible]; [illegible]		[illegible] Shallowing Up [illegible]	
			[illegible]	Coral Intraclastic; Fragile Columnar Strom; Thrombolitic Strom [illegible]; [illegible]		[illegible] Change.	
			[illegible]	[illegible] of the Shallowing [illegible]		[illegible]	Deepening
			[illegible]	Coral Intraclastic			
				[illegible] Thrombolitic Strom. Mud			Deepening
				[illegible] Stromatolite w/ [illegible]		[illegible]	
			[illegible]				Deepening
			[illegible]	Cyclic [illegible] Coral Intraclastic		Shallow [illegible]	
			[illegible]	Cyclic [illegible]			Deepening

Well #: PT-1 Company: Goldfields Location: Palah Syn.

Logged By: CIVC 1:500

Page #10

Fm	Depth	Lith	Depth (m)	Description	Struct.	Interpretation	Notes:
5			1488,1	Cool Intraclastic – At Elongated Grain – Columnar Stroms	o	Shallowing Up Cycle	
				Thrombolitic Cap Stromatolite			
			1494,4				Drowning
14	5 4 3 2 1		1499,1 1500,6 1502,2 1505,2 1506,8	Cyclic Peritidal – Cool Intraclastic PAC'S			
			1509	Grainy Gy. Well Bioturbated Mottled		Interp. Shallow Ramp Wave by STEVE?	
			1510,0	Cool Intraclast	o		
13 12 11 10	10 9 8 7 6 5		1514,5 1516,1 1517 1521,3 1525,7 1526,3	Cyclic Peritidal – Cool Intraclastic PAC'S	[illegible] o c	Interfingering of Lithofacies Stacks of Intertidal	
9	4		1530,1	Cyclic Peritidal	[illegible]	SMF –	
	3			Rippled Coc. Intraclastic	o	Peritidal → [illegible]	
8	2 1		1534 1536,2	Cyclic Peritidal – Cool Intraclastic	[illegible] c	General Shallowing Up.	—
			1539,1	Cycle of Columnar Stroms	[illegible]		Deepening
				Coc. Intraclastic	c	[illegible]	
7			1541,7 1542,1	[illegible] Cyclic [illegible] Cool Intr.	[illegible]		Deepen
			1546,3	Cyclic Peritidal Strom. Cool Intraclastic	[illegible]	[illegible]	Deepening [illegible] Cycles
6			1548,3		c		Deepening
			1551,0	Cyclic Peritidal Stroms	[illegible]	[illegible]	
				Coc. Intraclastic	o	[illegible] – [illegible] G. S. [illegible]	
				Columnar Strom [illegible]	S	[illegible]	
			1556,6	[illegible] Cool Intraclastic (Columnar Strom [illegible])	c	[illegible] Type	Deepening
				Thrombolite [illegible]			
5			1561,7	Coc. Intraclastic	o	[illegible] (Stacks [illegible] Cycle [illegible].)	Drowning – Deepening
				[illegible] Columnar [illegible]	S	Rapid Shallowing Up – 3 [illegible]	
				Thrombolite [illegible]		[illegible]	
			1566,0	Cyclic Peritidal Cool Intraclastic – [illegible] Columnar Strom. [illegible]	[illegible] o		Drowning
			1570,0	Cool Intraclastic → Columnar Strom	o S	Algal Columnar	Drowning
3			1574,0	Cool Intraclastic [illegible] Thrombolite – [illegible]	o c	[illegible] (Interp. [illegible])	Deepening General Shallow
			1578,1	Coc. Intraclastic Columnar Strom → Thrombolite Strom [illegible]	o S S	[illegible] Type	Deepening
2			1582,5	Cool Intraclastic Columnar Strom	[illegible]	Gen. Shallowing [illegible]	Drowning
1	2 1 2 1		1587,0 1589,4 1593,1 1596,9	Cool Intraclastic (Upper Columnar Strom)	o S	Deepening – 2 cycles	Deepening
				Cool Intraclastic Columnar Stroms w/ Intraclast Grain. Thrombolite Strom Mud	o S	Deepening Deepening 2 cycles Columnar Overlies Thrombolite Strom	Gen. Shallowing Up.
			1600,0	Cool Intraclastic Columnar Thrombolite Strom.	c S	Algal Strom Up	Drowning
	1 2		1602,7 1604,0	Coc. Intraclastic	o	2 cycles	Deepening
			1606	Cool Intraclastic Columnar Strom. Thrombolite Strom Mud	o S	Smooth Mat Type	Gen. Shallowing Up.
			1611,3				Drowning

PT-1 Gebflirkir Location: Fatch in clue

Logged By: CIVC 1:500

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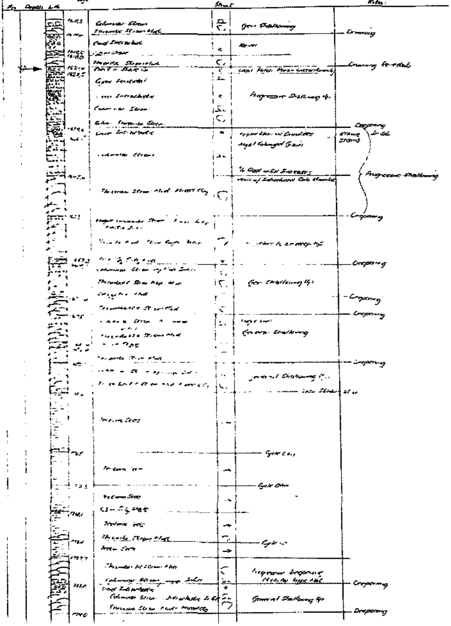
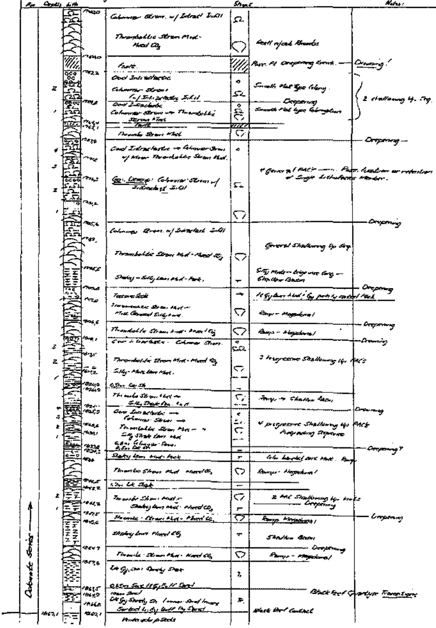


Hole # PT-1 Company Goldfields Location: Petch Syn

Logged By: EWC

1:500

Page #12

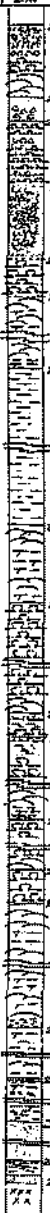


Hole # Bos-7 Company Goldfields

Logged By: CWC

Near Potchefstroom

Oak Tree (General Section) 1:500



Depth	Description	Struct	Interpretation	Notes
2166,4			— Drowning —	
	Con. Intraclastic		Shallowing up Seq.	Lower MC
	Thrombolitic – Mixed CO_3			
2172,6	Quartzite.		— Drowning	
2176,5	Cx Shale Hosted Clast Bx		Adm CO_3 – Silcrete	Unconformity
	Shallow Cyclic Horizontal			
2187,5	Cond Intraclastic (Non Graded – In Situ!)		General Shallowing-up Sequence	
2190,3	Columnar Thrombo – Mixed CO_3			
2194,2	Thrombo – Mixed CO_3			
2212,7	0,7m Shale – Mixed CO_3			Deepening (Invest. CO_3 Basin)
	Shallow Basin – Silty Mud w/ very minor Thrombo – Mixed CO_3 (Tecloraceels)		Basin Expansion — Silty CO_3 Units of Turbidites	
2269,0	Thrombolitic – Mixed CO_3 Shallow Basin Shale – Mixed CO_3		CO_3 thin mud interp. a shallow basin	Tree
2290,3	Columnar Thrombo – Mixed CO_3			— Drowning
2305,1	Thrombo – Mixed CO_3			— Drown
2307,6	Cond – Intraclastic w/ Algal Colonization		? Cratonal Interp.	
	Columnar Thrombolitic – CO_3		Gen Shallowing Up Seq	
2317	Thrombo Shale – Mixed CO_3 0,3m Sh.			
2326,2	Columnar Thrombo Mixed CO_3			— Deepening
2334,5				— Deepening
2342,2	Columnar Thrombo Mixed CO_3			
	Thrombo – Mixed CO_3 w/ Shallow Basin Banded Muddiness			
	Int. Dk Shale			
2370,7	Shallow Basin Marls + Silt (minor Thrombo CO_3)			Deepening w. Expansion
2382,1	Transition Zone — Sh. + Mixed CO_3		Initial Transgression	BR
2388,1	Black Reef Qtz			
2397,4	Mine Cong.		Post Tectonic Readjustment.	
2399,3	Kaaterdorp Supergroup			V V

Near Potchefstroom

Hole #: Bcs-7 — Company: Gold

Logged By: CWC — 1:250

Observations of Tectofacies

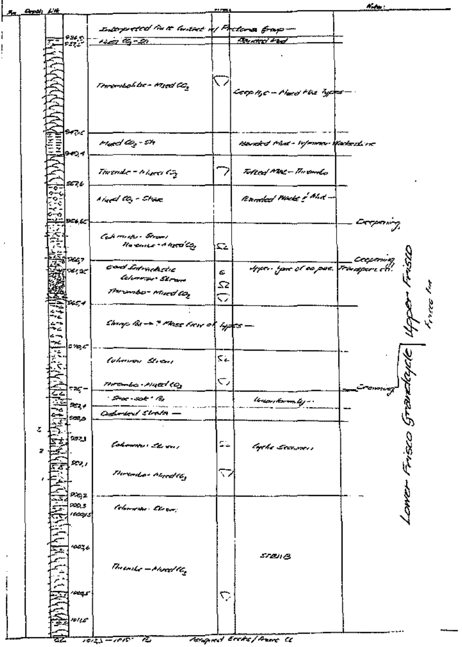
Cyc	Depth	Lith	Description	Struct	Notes
	2232,7		Q&7m Sh / Cly-mud Sh. Gy/d Gy Vaguely Lam Gran		Tectonosede have been termed Calcisiltites & Silty muds — both terms refer to both siliceous & Cly turbidites.
			Gy/d Gy Mud Lam Thread-Mud w/ Interlam Lt Gy Sort Indistinct Gran		
	2237,8		Lt Gy Gy well Sorted Vaguely Lam Gran – minor Stringers, Erosive Conglomerate		
(1)	2243,6		Base of Cycle		Distinct Bdn w/ Lt Buff White poorly sorted, fine Siltstone
(2)			Dk Gy Gy Mottled Color-Banded Fine Sort Gran – Lam/or Lam		
			Lt Gy Gy fine-medium Fine-sorted Lam not Fresh Gran		Note: All Silty Mud Tectofacies are fining up sequences.
(3)	2252,8		Base of Cycle		
	2257,0				
	2258,5		Thrombolite/Stromatolite		Base Stromatolite.
(4)					
	2258,5		Base of Cycle		Distinct Bdn w/ light Buff ...
(5)					Note: Bdn of 5 assigned on ... banding
	2265,2		Base of Cycle. Fine, sorted ... silty Gran → fine, sort vaguely lam Gran		
(6)	2268,5				Base Expression of Stromatolite
	2271,1		Thrombolite end		
			Fine, sorted vaguely laminated Gran ...		
	2272,1				... Base Stromatolite
			Thrombolite		
	2276,0				Major Deepening Event

Logged By: CMC

1:250

Koster E

JTF-1



JCI — Ka **Koster E**

Logged By: CIVC

9/66

Page #1

(W.Tvl.)

General Section N. of Rand Anticline

1:500

Depth		Strat.		Note:
5 / [illegible] / 3525	Ooid Intraclastic; Ripple Mud [illegible]; Columnar Ooid Intraclastic		Top — Core [illegible]	Top of Hole —
4 / 3540 / 3	Columnar Stromatolite		General Cyclic Shallowing Up Seq. (Progressive)	
2 / 3550 / 3455 / 1	Thrombolitic — Mixed Clay		Greater [illegible]	
3574 / 2	Ooid Intraclastic; Columnar Strom.; Thrombolitic — Mixed Clay	⁰ Σ∟ ⟨⟩	Deepening	
3632 / 1	Rippled Ooid Intraclastic; Columnar Strom. — Thrombolitic; [illegible]		Shallowing Up; [illegible]	
3646 / 3696	Rippled Ooid Intraclastic; Columnar Stromatolite; Thrombolitic — Mixed Clay	⁰ Σ∟ ⟨,	Gradual Shallowing Up. Major Drowning, Tectonic Break.	
3696 / 5 / 4054 / 4 / 4102 / 3 / 4137 / 2 / 4164 / 1	Cycle [illegible] Band; Rippled Ooid Intraclastic; Columnar Stromatolite; Thrombolitic — Mixed Clay; Mixed Clay [illegible]	⁰ Σ∟ ⟨,	Cycle Sedimentation; Progressive Shallowing Up. Top of Shallowing [illegible] Drowning	Summary log only — Faulted
4220	(Ground [illegible]) Ooid Intraclastic; Columnar Strom.; Thrombolitic — Mixed Clay	⁰ ⟨,	[illegible] Shallowing Up Seq. [illegible]	
4326	(Ground [illegible]) Ooid Intraclastic; Columnar Strom.; Thrombolitic — Mixed Clay	⁰ ⟨, ⟨,	Shallowing Up Sequence	
4791	Ground [illegible]		[illegible] Shallowing Cycles	
5079 / 5120	Columnar Stromatolite; Thrombolitic — Mixed Clay	Σ. ⟨,	[illegible] Shallowing? Deepening [illegible]	
5196 / 5212	[illegible]		Tectonic [illegible]	
5276	Rippled Ooid Intraclast.; Columnar Strom. — Thrombolitic Mixed Clay; [illegible]		[illegible]	
5341 / 5342	Rippled Ooid Intraclastic; Columnar Strom.; Thrombolitic — Mixed Clay	⁰ Σ ⟨,	Deepening [illegible]	Deepening
5362 / 5433	Cycle [illegible] Band; Ooid Intraclastic; Columnar Strom.; Thrombolitic — Mixed Clay	Σ. ⟨	Cycle Strat. Rapid Shallowing Up	

Intop 6th Bout (Drowning Event) →

Intop 5th Bout →

Logged By: LMC

1:500

Page #2 RMC-1

Depth	Description	Struct.	Interpretation	Notes
				Deepening Top of Shallowing Cycle
549.3	Cycle Horizontal Bound			
55.9	Ooid Intraclastic			
560.–	Algal Coated Intraclastic			
	Columnar Strom			
565.–	Thrombolitic – Mixed Cl_2			
567.7	Algal Coated Ooid Intraclastic		0.2m for Cl [illegible]	Increase in % Chert
	Columnar Stromatolite			
	Thrombolitic – Mixed Cl_2			Top of Cycle Growing
566.2	Ooid Intraclastic			
568.8	Algal Coated Ooid Intracl		General Cycle — Shallowing Up Sedimentation	
572.–				
576.6	Columnar Stromatolite			
578.4	Thrombolitic Mixed Cl_2			
589.8				
592.2	C in Intraclastic		Rapid Shallowing	Top of General Cycle
	Columnar Strom → Thrombolite			
595.7	Coated Grain Intraclastic			
	Columnar Strom		Shallowing Up	
	Thrombolitic – Mixed Cl_2			
598.4	Algal Coated Apple [illegible] Intraclastic			
602.7	Columnar Strom		Cycle Sedimentation → Gen. Shallowing Up	
606.6	Thrombolitic – Mixed Cl_2			
612.3	Apple [illegible]			
621.1	Columnar Strom		Cycle Scale → General Shallowing Up	
	Thrombolitic – Mixed Cl_2			
632.–	Columnar Strom Slump Bottom		Gen. Shallowing	Deepening
634.4				
636.–				
638.2	Columnar Strom Thrombolitic – Mixed Cl_2		Cycle Scale Gen. Shallowing Up	Top of Cycle
644.7	Ooid Intraclastic – Columnar Strom & Thrombolitic Mixed Cl_2		Rapid Shallowing	
646.4	Columnar Strom (Thrombolitic Mixed Cl_2) [illegible] shale		Gen. Shallowing up Algal Cake, Grow [illegible]	Deepening
651.1				
651.2	Breccia Mixed Columnar Strom.		Note: Unit has probably been [illegible] by Cycle [illegible]	
663.5	Ooid Intraclastic	C	Top of Progressive Shallowing	Deepening
669.6				

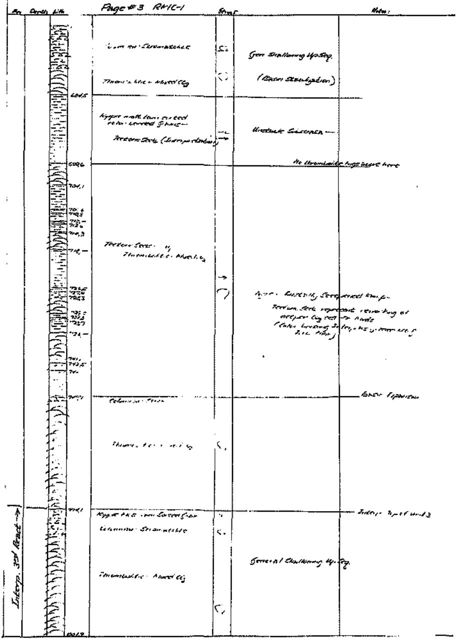
Interp. 4th Road → Lyttelton Eccles

RMK-1

Logged By: CMC
6/06

1:500

Page #3 RMC-1



RMC-1

Logged By: CNC
E/84

1:500

Page #4 - RMC-1

Fm | Depth | Lith | Struct | Notes

6019
Columnar Strom

Thrombolite - Mud Clg

620.1
Interp Top of 3rd Unit

624.3

627.2
627-640 Feed/Broken Ground

(Minor Agal Mat Lam Sorted GS)
Columnar Stromatolites
Thrombolites - Mud Clg
Cyclic Sedimentation — General Shallowing Up Seq

640.7

652.5
Drowning
Top of 1st Unit

661.0

664.1
Ooid Intraclastic
(Cortices & Agal Mat Lam Sorted GS)

669.5
Cyclic Sedimentation
(Progressive Shallowing Up Seq)

676.4
Columnar Stromatolites

Interlayering - Lower Break

677.0
Dolomite GS
Intraclastic GS
Aerial Exp.
Lyttleton : MC Fm Ct

681.0
Columnar Stromatolite

685.2
Lag Zone

687.0

Lyttleton

Lt / MC

Monte Cristo

Interp #2nd Reef

686.6
Ooid Intraclastic
(Algal Coated Grains)

694.6
Columnar Strom Boxwork
Cyclic Sedimentation
(Cont. of Shallowing Seq)

696

699

701.8
Static

704.8
Ooid Intraclastic
(Cortices on Intraclasts)

5

711.1
Cyclic Sedimentation
(Progressive Shallowing Up Seq)

4

712.2
Columnar Stromatolites

3
Static

713.3
Thrombolite - Mud Clg

2

722.4
Chip Breccia Highly Altd
(Lag prior to Reefs)

1

Chip Br
724.6
Ooid Intraclastic - [illegible]
Sheets Cl
Clg

727.7
Basal Disconformity

RMC-1

Logged By: ______

1:500

Page #5 - RMC-1

Depth	Description	Struct.	Interpretation	Notes
939.7 – 946.5	Ooid Intraclastic; Columnar Stromatolite; (Minor Thrombolite - Mixed Log)	c, S	Cyclic Sedimentation (Gen. Shallowing Up. Seq.)	
946.5	14 m Chert in Shale [illegible]			
946.5 – 962	Flat Ooid Intraclastic; Columnar Strom.; Thrombolite Mixed Log; Ripple [illegible] GS w/ [illegible]; 0.7 m Chert in Shale [illegible]		Gen. Shallowing Up.; Increased Current Activity Assoc. w/ Deepening	Deepening Event
962 – 966.7	Ooid Intraclastic → Columnar Str.; Thrombolite Mixed Log; 0.7 m Gr. Shale		General Shallowing Up	
966.7 – 977.4	Ripple [illegible] GS Ooid Intra.; Columnar Strom.; Thrombolite - Mixed Log		Cyclic Sed. — Gen. Shallowing Up.	Deepening
977.4 – 991.3	Ooid Intraclastic; Columnar Stromatolite		Gen. Shallowing Up. Cyclic Sed.	Block? [illegible] Deepening
991.3 – 1002.0	Cyclic [illegible]; Ooid Intraclastic; Columnar Stromatolite; [illegible]		Gen. Shallowing Up. Cyclic Sed.; Deepening [illegible]	Block [illegible] Event
1002.0 – 1012.2	[illegible]; Columnar Strom.; Thrombolite Mixed Log; [illegible] Shale [illegible]		General Shallowing	Note: Major Shallowing Events [illegible] Event
1012.2 – 1025.5	Ooid Intraclastic; Columnar Strom.; Thrombolite Mixed Log		Cyclic Sedimentation (Gen. Shallowing Up Seq.)	Deepening
1025.5 – 1050.0	Ooid Intraclastic Cycles (minor [illegible] Cyclic [illegible]); Note: Cyclic Grain. [illegible] Ripple [illegible] [illegible] Intraclastic GS; Columnar Strom.		Cyclic Sedimentation. (General Shallowing Up Sequence Cyclic [illegible] defined by [illegible])	
1050.0 – 1052.1	[illegible]		[illegible]	[illegible] Shale [illegible]
1052.1 – 1054.3	Cyclic [illegible]; [illegible]		Gen. Shallowing Seq.	

RMC-1 Complex: FCF

Logged By: CIVC

Page #6 - RMC-1

Run	Depth	Lith.		Description	Struct.		Notes:
			1056.2	(Minor Cycle Peritidal Events)			
			1062.1				
			1064.2	Coarse Intraclastic (Ripple Rolled but Best well sorted Grainstone)		Cyclic Sedimentation (General Shallowing Sequence Bases of Cycles Marked by [illegible])	
			1067.5				
			1069.1				
			1074.1	Cyclic Peritidal + Rippled Grain		[illegible] Rapid Shallowing	
			[illegible]	Columnar Stromatolite [illegible]			Drowning
2			1080.2	Cyclic Peritidal Coarse Intraclastic		Deepening [illegible]	
1				Columnar Stromatolites		[illegible]	
			1084.0	Ripple Rolled [illegible] Coarse Intraclastic		Deepening [illegible]	
			1086.1	Cyclic Peritidal Boundstones		Shallowing Up. Seq.	
			[illegible]	Coarse Intraclastic			
1			1090.7	Cyclic Peritidal [illegible] Coarse Intraclastic		V. Rapid Shallowing Up Seq.	
6							
5			1095.4	(Rippled well [illegible] sorted Intraclastic Grainstone)		General Shallowing Up.	Part of Same Seq?
4			1099.0	Columnar Stromatolite			
			1101.5	0.75m [illegible] Shale - Tectonic Zone			
3			1104.0	(Rippled) [illegible] Intraclastic		Highly [illegible] — Cycle [illegible] Ppt. Changes	
2			1105.5	Columnar Stromatolite [illegible]			
1			1108.5	[illegible] Tectonic Seq.			
			111[illegible]				Overall Shallowing Up, return to Peritidal
				Columnar [illegible]		[illegible]	
			1127.0	[illegible]		General Cyclicity [illegible]	
			1137.2	Coarse Intraclastic		[illegible]	Deepening
				Columnar Stromatolite [illegible]			
3			1144.1				Deepening
2			1146.0	[illegible]		Cyclic Sedimentation [illegible]	
1			1151.2	[illegible]			
			1154.7				Deepening
0			1156.2				
9			1158.7	Cyclic Peritidal [illegible] & Ripple Rolled Grain[illegible]		Cyclic Sedimentation	
8			1162.2			(General Shallowing Cycles	
7			1164.0	Coarse Intraclastic		(Generally Larger Cycles Defined [illegible] — [illegible] of Cycles defined by [illegible])	
6			1165.3				
5			11[illegible]				
4			11[illegible]				
3			11[illegible]				
2			1175.0				
1				Columnar Stromatolite [illegible]		[illegible]	[illegible]
			11[illegible]	Coarse Intraclastic			
3			1180.7				
2			1182.2	Columnar Stromatolite + [illegible]		[illegible] Deepening ([illegible] Cycle)	
1			1183.2	[illegible]			

Interp. #1 Read. →

RMC-1 JCI

Logged By: CMC 1:500

Page #7 RMC-1

Tectonic Reactivations / Intorp. End Thermal Subsidence

Depth	Lith. / Description	Interpretation	Notes
1189,2 – 1190,4	Ripple Cord Intraclastic	Deepening Rise	
1193,7	Ooid Intraclastic	Cyclic Seds →	
1196,5	Columnar Strom	Gen. Shallowing Up Seq	
1200,3	Thrombolitic → Mixed CO_3		Deepening
1205,7	Ooid Intraclastic; Columnar Strom → Thrombo; Shale CO_3 Mud (Mott. banded)		
1208,2	Columnar Strom	Deepening Rise	
1211,2	Ooid Intraclastic; Columnar Strom	General Shallowing Strom → Strom	
1215,4	CO_3 Mixed Strom mud (Dol)	Log invaded by Mud	Drowning
	Cyclic Peritidal → "smoothed" Grains; Ooid Intraclastic	Shallowing Up Seq.	
	Columnar Strom	Entire Cycle of Return to original CO_3 platform condition	
1224,5	Thrombolitic – Mixed CO_3		Drowning
1229,5	Cyclic Peritidal → Ooid Intracl; Columnar Strom → Th Mix CO_3	Rapid Shallowing	Deepening
1234,0	Ooid Intraclastic; Columnar Strom → Thrombo Mix CO_3	General Shallowing	Deepening
1237,5 – 1237,9	Ooid Intraclastic → Thrombo Mixed; 0.35 m CO_3 Black Shale	CO_3 Dissolution → Gen Shallowing	
	Columnar Strom.		
1243,1	Thrombolitic – Mixed CO_3	← 1239,5 Major General Shallowing Up in STROM	Deepening
1244,1	Ooid Intraclastic → Columnar Strom	Deepening Rise	
1244,2	[illegible]	Unconformity	Regional Unconformity
1247,6	Ooid Intraclastic → Thrombolitic Mix CO_3	Rapid Shallowing	Deepening ↔ Interp. Extension ? CO_3 [illegible]
	Ooid Intraclastic		
	Columnar Strom / Algal Laminated Strom		
	Thrombolitic mixed CO_3	General Rise [illegible]	
	Mixed CO_3 [illegible]	Deepening & Shallowing Seq	
1267,2	Thrombolitic → Columnar Strom		Deepening → Shallowing
1264,6	Ooid Intraclastic → Columnar Strom	Cyclic [illegible]	
	Ooid Intraclastic; Columnar Strom → Laminated CO_3	Gen. Shallowing; Rapid. Reactivation	?? Regional Unconformity
1276,5 – 1274,7	Columnar Strom →	Gen. Shallowing of [illegible]	
1279,4	Thrombolitic Mixed CO_3; → 0,2 m Sh/Cl		
	0,12 Sh/Cl; Deepening rise – Columnar Strom → Mix CO_3 [illegible]		Drowning
1282,7	Cyclic Peritidal → Ooid Intracl	Rapid Shallowing Up Cycles	
1284,1	Cycles; Ripple Lam Grainstone (Major reorganization)		Deepening
1290,0	Columnar Strom →	General Drowning	
1292,6	Thrombolitic Mixed CO_3		
1296,0	Cyclic Peritidal Bands; Ooid Intraclastic; Columnar Strom → Thrombolitic Mixed CO_3; 0.3 m Sh/Cl	Rapid Shallow Cycle	Drowning
1302,6	Columnar Strom / Lam Grains; Thrombolitic Mixed CO_3	Strom Infill between [illegible]	Deepening
1312,7	Columnar Strom / Lam Grains; Thrombolitic Mixed CO_3	Deeper H_2O Lithofacies	Deepening
1320,6			Deepening

Well: RMC-1 Company: JCI Location: Kesler

Logged By: CWC 1:20

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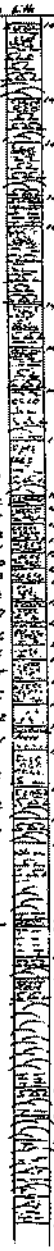
Depth	Description	Struct	Notes
1320.6	Dk Gy, Columnar Strom.	SL	Mottled Dk Gy, Siltstone / Dolomites
			Drowning
1337.2, 1337, 1340.6, 1341.0	Coral Intraclastic / Rippled Mud GS.	o	Cycle Bases marked by Lt Gy Gy Mud
	Coral Intraclastic, Rippled mudd. Grainstone, Columnar Strom., w/ Thrombolitic Mudd CO3	o, SL	Shallowing Seq. 1 Ape Breaks.
1350.3			Drowning
1352.7, 1355.5, 1358, 1360.4, 1361.6, 1364.4, 1364.6	Cycles of Coral Intraclastic (Bases Deepen into Columnar Strom)	o, SL	General Shallowing Up. Bases of Cycles Marked by Lt Gy Mud.
1370.9			Deepening
1374.6, 1376	Cycles of Coral Intraclastic	o	Cycles marked by Lt Gy Mud
1379.5	Columnar Stromatolites		Deepening
1381, 1382.8, 1385, 1386.2, 1387.7, 1389.5, 1392.5, 1394.1, 1396.0, 1397.5, 1400.5, 1401.5, 1403.0	Cycle Coral Intraclastic (Minor Shallowing Cycles) w/ Cycle Mudstone / Lt Mud.	o	Investigation Important of Laminated Carbonates — Cycle Bases w/ Lt Gy Gy Mud.
1407.5, 1409.0	Minor Deepening Cycle Columnar Strom		
1411.2			Intrap. Bases of Coral Cycles
	Coral Intraclastic, Columnar Stromatolite	o, SL	Gen. Shallowing Up
1416.7, 1417.5	Coral Intraclastic → Columnar Strom.	SL	Deepening Into
			Deepening
	Cycle Mudstone / Laminates, Coral Intraclast, Thrombolite Mudd CO3	o	Ripple Shallowing of Seq in Gen. Are Columnar Strom Capping
1426.7			Drowning
1428.7, 1431.7, 1433.9, 1436.3	Cycle Sediment Intra..., Coral Intraclastic → Rippled Grain Strom, Columnar Strom	c, SL	Gen. Shallowing Cycles (Long line between of laminated of Lt Gy Gy Mud Deposited)
	Coral Intraclastic, Rippled Grainstone, Columnar Strom → Thrombolitic Mudd CO3	o, SL	Gen. Shallowing
1444.4			Deepening
1446.2, 1447.6, 1449.4	Cycle Sed., Coral Intraclast → Columnar Strom	o, SL	Gen. Shallow Cycles Interfingering
			Drowning

Hole #: RMC-1 Company: JCI Location: Kadar

Logged By: CWC 1:500

Page #9 — RMC-1



Depth	Description	Struct.	Notes	
1449.4	Cycle Pericratal / Coral Intraclastic Algal-Coloured G.S. Columnar Stroma → Thrombolitic Mixed CO₂		Gen Shallow Up — Intensive core STA/C#13.	Drowning
1457.5	Coral Intraclastic & Rippled Intraclastic Grain		Cycle Sets — Gen Shallowing	
1462.2	Columnar Stroma → Thrombolitic Mixed CO₂		Minor Deepening Pulse —	Drowning
1468.0	Cycle Pericratal — Coral Intraclastic — Mixed Cy-Mud			Deepening Pulse
1471.0	Coral Intraclastic Columnar Stroma w/ Infill		General Shallowing Seq.	Deepening
1479.5	Coral Intraclastic Columnar Stroma & Mixed CO₂ Mud		General Shallowing Up. [illegible]	
1484.3				Deepening
1488.0	Rippled Coral Intraclastic Columnar Cl. Thrombolitic — Mixed CO₂ Mud		Shallowing Up Seq.	Drowning
1491.3	Rippled [illegible] Gal Coral Intracl. Columnar Stroma — Thrombolitic Mixed CO₂		Shallowing Up Seq.	
1497.2	Cycle [illegible] Pericratal Growth			Deepening Sequence
1497.3	Columnar Stroma → Coral Intraclastic		[illegible] deepening [illegible]	
1502.2				
1505	[illegible]			
1506.4				
1509				
1509.5				
1511.4	Coral Intraclastic w/ (minor cycle Pericratal [illegible])		General Shallowing Up Cycles (Cycles [illegible] Gy [illegible]) (Cycles [illegible] Intraclast [illegible] cycle [illegible]) ([illegible]) Interp. [illegible] Coral Intraclastic Lithology	Deepening
1513.6				
1514.3				
1517.8				
1518.0				
1522.5				
1525.0				
1529.6	Cycle [illegible] Algal Coloured Coral Intracl. Columnar Stroma Thrombolitic / Mixed Cy		General Shallowing Up Seq. [illegible]	
1531.7				
1534.7				
1537.7	[illegible] Columnar [illegible] Columnar Stroma Thrombolitic — Mixed Cy [illegible]		[illegible] Shallowing Up Seq.	Deepening
1546.1	[illegible]			Transgressive Surface
1546.5	Mixed Cy and		Basal Lithofacies	Drowning
1550.1	Columnar Stroma / Thrombolitic [illegible]		Shallowing Event	Drowning
1552.5	Coral Intraclastic Columnar Stroma Thrombolitic — Mixed Cy Mixed Cy Mud		Rapid Shallowing Up [illegible] Gen Shallowing	Note: [illegible] — [illegible]
1564.2	Columnar Stroma → Thrombolitic Mixed Cy — Mud		Shallowing Up Seq.	Deepening
1567.4	Thrombolitic — [illegible]		[illegible]	Deepening
1568.0	Shale — Mixed [illegible] Marl [illegible] Thrombolitic [illegible]		Basal Lithofacies	General Shallowing
1576.6				

Monte Cristo — Oak Tree Depo. Package

Monte Cristo

Oak Tree

Well #: RMC-1 Company: JCI Location: Koster

Logged By: LWC

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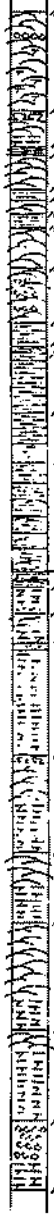

Depth	Description	Strat	Notes	
1570.6	Deep H_2O Thrombolitic - Mixed CO_3 Ripple Mott Lam Grain			
	Thrombolitic - Mixed CO_3 Mud Dk Gy, Fossil Undefined Text Mud/Bound			Deepening
1588.4	Columnar Strom - Thrombolitic Mixed CO_3 - Mud.		Gen. Shallowing Seq	
1593.3 / 1594.0	6.72 m Wackest Shale			Transgressive Surface
	Thrombolitic - Mixed CO_3		B & B — Interp Gen Shallowing	
1597.6 / 1598.9 / 1600.3 / 1601.6	Tectonic Seds (Magnetite) & Thrombolitic - Mixed CO_3		Mixed Environment (Deeper Ramp)	
	Thrombolitic - Mixed CO_3 (mixed Grainstone)		Deeper H_2O Environment	
1606	Thrombolitic - Mixed CO_3 interbedded w/ Lt Gy Calc at Grd Interval		Interp. STRWB w/ Strong Current Flow Influence	Deepening
1612.0 / 1614.7 / 1615.2	Interlam Tectonoseds			
1621.2	(minor Thrombolitic - Mixed CO_3)		Cycles based on Color etc. - Interp. Gen. Shallowing Up.	
1625.0 / 1627.0	Lt Gy Calcsilt ... Lam Grain w/ Thrombolite ...		Interp. (Tectonic - Thrombolite) ...	
	Lt Color Ct			
	Tectonoseds → Thrombolitic Mixed CO_3 Mud.		Basin Destratification / Gen Shallowing Seq.	
	... Silt/Lam ...		Poss. ... 1624.6 - 24.9 ...	
1640.2				...
	Mixed CO_3 ...		... Contact	
1645.2	Thrombolitic - Mixed CO_3, Mixed CO_3 Mud			Deepening
1646.5 / 1647.0	... Columnar Strom		Shallowing event followed by Deepening	
	Mixed CO_3 - Mud.		Deeper H_2O ... (Gen. Shallow up.)	
	Strom ... Mixed CO_3 ...			
1653.7	Columnar Strom.			Deepening
	Thrombolitic - Mixed CO_3		...	
	Mixed CO_3 ...			
1670.3	Thrombolitic - Mixed CO_3		B & B ...	Deepening
	Mixed CO_3 Mud			
1677.8	Thrombolitic - Mixed CO_3		B & B ...	Deepening
	Mixed CO_3 Mud			General Shallowing Up. Seq
1689.2	Thrombolitic - Mixed CO_3		Bread & Butter ...	Deepening
	Mixed CO_3 Mud			
1699.1	Lam. Intraclastic Grain		Shallowing Up ... into More Agitated/... Setting	Deepening
1704.9	Mixed CO_3 Mud			Deepening

Cycle numbers beside the column (top to bottom): 5, 4, 3, 2, 1

Core #: RMC-1 Company: JCI Location: Kostar[illegible] 1:500

Logged By: CHC Gen. Section N of Ekron Anticline

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Fm	Depth	Lith	Description	Struct	Interpretation	Notes
		1706.9	Columnar Strom. Thrombo. Mixed CO_3		Shallowing Seq.	Deepening
		1711.1	Columnar Strom. – Thrombolite Mixed CO_3; Mixed CO_3 Mud – Shale Lam.		Shallowing Upward Subtidal/Intertidal Lithofacies	Major Deepening / Drowning
		1722.5	Cycle Mdst. Laminated Intertidal (Mixed Columnar Strom.)		Fe Stained [illegible]	Rapid Shallowing
		1724.1				
Ext.		1725.2	Dolostone & Shale Lam. Mud		[illegible]	Basin Destabilization
	3	1733.3	Thrombo. – Mixed CO_3 / Mixed CO_3 Mud		General Shallowing Up Sequence	
	2				% of mixed CO_3 Mud decreases w/ Each Cycle.	
		1740.[illegible]			(Both Log & Deeper Strom. [illegible])	
	1	1748.0 / 1748.2	Green Ripup & Shale			
	3		Thrombo. – Mixed CO_3; Mixed CO_3 Mud		Deepening Upward [illegible]	
		1751.2				Deepening
	2		Thrombo. – Mixed CO_3; Mixed CO_3 Mud		Shallowing Up Sequence	
		1757.0				Deepening
	1		[illegible] – Mixed CO_3; Mixed CO_3 Mud			
		1765.2				? Deepening
			Thrombo. – Mixed CO_3; Mixed CO_3 Mud; [illegible]		[illegible] Shallowing Up Seq.; Subtidal Lithofacies	
		1774 / 1775.3	[illegible]		[illegible]	[illegible]
			Mixed CO_3; [illegible]		[illegible]	
		1780.[illegible] / 1786.9	Shale – Mixed CO_3		[illegible]	Deepening
			Thrombolite [illegible]		[illegible] Shallowing Sequence	
		1793.8	[illegible]		[illegible]	Deepening
		1796.[illegible] / 1797.1 / 1797.[illegible] / 1799.0	Cycle Sedimentation; Thrombo. Mixed CO_3 [illegible]		[illegible]	Deepening
		1804.4	Shaley Mixed CO_3 [illegible]		[illegible] Shallowing Seq.	Deepening
		1805.[illegible] / 1807.[illegible]	Cycle Strom. [illegible]; [illegible]		Shallowing Up Seq. Basinal Facies; [illegible]	Deepening
		1809	Thrombo. – Mixed CO_3		Shallowing Up Sequence	
		1811.3	[illegible]		[illegible]	[illegible] Dist. Steep Ramp.
		1811.[illegible] / 1812.[illegible]	Cycle Sedimentation; Thrombo. – Mixed CO_3 Mud w/ Gr. Shale		Shallowing Up Cycles – Basinal Facies	
		1812 / 1813			Stacks Completed	1st Strong CO_3 Unit
			[illegible] Shale [illegible] Green CO_3 [illegible]		[illegible] Transgressive [illegible]	
		1817.3				
		1818.5	[illegible]		Interpretation – [illegible]	Note – [illegible]
		1821.0	[illegible]		[illegible]	
			[illegible] Shale		[illegible]	
		1826.2	Shale [illegible]			
Bh. / Wat	1830.7	1830.7 / 1830.2	[illegible]		Early Transgressions Assigned on [illegible]	
			[illegible] Supergroup			

Hole #: 7TF-1/72

Logged By: CWC

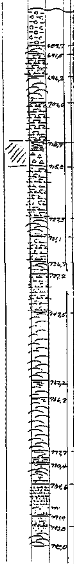
Company: Geol. Survey Strat Hole K.W

General Stratigraphic Section N. Trl.

Location: Treefontein

1:500

Koster W

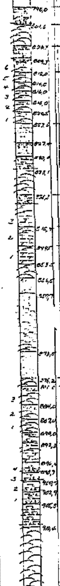


Bevets Br Cong.

Depth	Description	Sym.	Remarks	Trend
681,8	DkGy, V. Uniform Red. Sst. Lam. Intraclastic Grain		Poss. Turbidite? Unit could be deep H_2O Mud — In ripple or x-ll. Lam. Known.	
689,7	DkGy Thrsm/Strom Bound Mud.		Megadomal	Deepening.
691,6	Gy-DkGy, Blebh Matt Vaguely Strat. Strom Bound			
696,5	DkGy, Gy, Matt Mud/Thromb Strom. Bound Mud + Imn Flowage & Mud & Stm.		Megadomal	
702,0	Gy-DkGy, Blebh Matt Vaguely Stratified Strom Bound		STBWC	Deepening.
710,7	1,4 m Sh. Bx — Rounded Subr. Frags		Hiatus Disconformity. Minor Ind. Chert & Cl.	Lower/Freneo Unc.
715,8	Gy-DkGy, Blebh Matt Vaguely Strat. Strom Bound		STBWC	
727,5	DkGy Laminated Thromb Strom Mud		R-B Megadomal	Deepening Shallowing Cl.
731,1	Gy. DkGy, Vaguely Strat. Strom Boundstone		STBWC	
736,7	DkGy, ind. Mud → Gy, Thrm + Strom Mud		Gy Megadomal	
737,2	Gy DkGy, Blebh Matt Vaguely Strat. Strom Bound		STBWC	Deepening.
742,5	DkGy, Gy, Blebh Matt Thromb. Frag. Strom Bound Mud. Minor Cycles end w/ Ripple Grain		Megadomal — STBWC	
757,2				
756,2				
777,7	DkGy, Uniform Blebh Matt Mud → Gy-DkGy, Thromb Frag Mud		Shallowing, Up Sq. STBWC	Deepening.
780,4				
784,6	Gy, Sed. Matt. Lam. Intraclast. Gr. → Cyclic Horizon Boundstones & Grainstones		Shallowing, Up Sq.	Drowning/Deepening.
791,9	Gy, Strom Bound → Intraclastic Grain			
792,0	DkGy, Gy, Blebh Matt Thromb Frag. Strom Mud → Lt. Gy, Ripple Matt Strm.			
795,0				

Hole #: 77F1/72 Company: Geol. Survey Location: Tweefontein

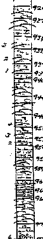
Logged By: CWC General Stratigraphic Hole (W Tvl) 1:50 [illegible]



Depth	Description		Interpretation	Notes
796,0 – 801,6	Lt Gy/Gy, Mott → Intraclastic or Grain & Strom Bound	Sc	STAWB ? Cycle Portal	Shallowing Up. Seq.
801,6 – 803,7	Dk Gy/Gy, Blotch Mott, Thrombolitic, Strom Mud		Megadome / STBWB	Deepening / Drowning
803,7 – 808,3	Cycle Portal ? Grain	Sc	Shallowing Up.	
808,3 – 812,0	Lt Gy, Strom Mud → Gy, Intraclastic Grain			
812,0 – 823,0	Dk Gy, Gy, Blotch Mott, Thrombolitic, Strom Mud → Lt Gy, Gy Ripple Mott Lam. Intraclastic Grain		ST(?)/(E)WC	Deepening
823,0 – 835,2	Shallowing Up. Dk Gy/Gy, Thrombolitic, Strom Mud → Gy, Lt Gy, Mott Strom Bound → Lt Gy, Gy/Gy, Ripple Mott Lam. or Intraclastic Grain → Cycle Portal / Brecciated Grain		Cycle Portal. STAWB. STBWC	Shallowing Upward Seq.
835,2 – 845,9	Lt Gy, Mud → Dk Gy, Gy, Thrombolitic, Mott, Strom Mud → Gy, Gy Grain or Intraclastic Grain		Initial Shallowing → Prograding Seq.	Deepening
845,9 – 849,5	Lt Gy, Uniform Text Mud → Gy, Lt Gy, Thrombolitic Mud		STBWB – [illegible] Shallow Water	PAC Cycle
849,5 – 853,5	Lt Gy, Uniform Text Mud → Lt Gy, Gy, Thrombolitic Mud		STBWC	Deepening
853,5 – 856,5	Dk Gy, Gy, Blotch Mott, Thrombolitic, Strom Mud		STBWB	Deepening
856,5 – 859,7	Buff, Lt Gy, Sorted Uniform Grain		Clay Band – STAWC, [illegible]	
859,7 – 872,5	Gy, Buff, Gy, Sorted Ripple Mott Lam. Intraclastic Grainstone (Lower Ag. Comp.)		Cycle Nature Vague. ST(B)/AWC – [illegible]	Deepening
872,5 – 876,2	Lt Gy, Gy, Ripple Mott Lam. Intraclast Grain		ST [illegible]	
876,2 – 881,0	Lt Gy, Gy, Thrombolitic Mud, Strom Mud		[illegible]	Deepening
881,0 – 890,0	Cycle. Lt Gy, Blotch Mott, Thrombolitic, Strom Mud → Lt Gy, Gy, Vaguely Ripple Mott Lam. Graded Grain		Cycles begin or end w/ ripple [illegible] – Lost [illegible] PAC – Sequences	
890,0 – 892,3	Gy, Lt Gy, Mott, Strom Mud → Ripple Mott, [illegible] Grain		Shallowing Sequence	
892,3 – 896,4	Dk Gy, Gy, Mott Mud [illegible] Gy, Thrombolitic, Strom Mud		STBWC	Deepening / Drowning
896,4 – 905,5	Cycle. Gy, Lt Gy, Blotch Mott, Strom. Boundstone / Mud / Shallow Int. Lt Gy, Buff Ripple Lam. Grain		ST(?)/(E)WC	PAC's Sequence
905,5 – 910,6	Lt Gy, Gy, Blotch Mott. (Vaguely Banded) Strom Bound	Sc	STBWB	Color Band = Shallow H_2O ??
910,6 – 924,7	Lt Gy, Gy, Uniform Text, Blotch Mott, Thrombolitic, Strom Mud / Bound		STBWC	

Hole #: 77F1-72 Company Geol. Survey Location Treefontein

Logged By: CHC Gen. Strat Section (Hn Tvl) 1:50



Depth	Description	Struct.		Notes
924,7 – 927,2	Lt Gy, Gy, Ripple Lam, Intrad. Grains & Cemented Thromb. Cal Mud		STRE WC	Shallowing Up: Lt color & Intraclasts
927,2 – 931,0	DkGy, Gy, Uniform Text Mud → Banded Gy Thrombo Mott Mud, Laminated		STRWC	Deepening
931,0 – 937,3	Gy, DkGy, Mott. Thromb Strom Mud → Lt Gy, Buff, Ripple Mott Lam. Intraclast Grain		STRWC → ST@/AWC PAC's Seq.	
937,3 – 940,1	Lt Gy, Ripple Mott Intracl. Grain		ST@/AWC	
940,1 – 948,0	DkGy, Uniform Text Mud → DkGy, Gy, Thrombo Mott Strom Mud & Mott Strom Boundstone		Megadome — STRWC	Shallowing Up Sequences Deepening
948,0 – 953,1	DkGy, Thrombo Frag, Mott Strom Mud → Lt Gy Lam Intracl. Grain/Pack		PAC Cycles	Deepening → STRWC
953,1 – 957,4	Lt Gy, Gy, as → Intraclastic Grain, F Lt Gy Buff Mott. Strom Bound			Shallowing Up Seq.
957,4 – 959,4	DkGy, Gy, Unif. Text Mud / Th Str Mud			
959,4 – 966,8	DkGy, Gy, Thrombolitic Mud, Strom Frag Mud → Lt Gy, Planar Lam Crt (Vague), Ripple Mott Lam Grain → Pack		STRWC → ST@ WC	
966,8 – 974,7	DkGy, Uniform Txt. Thrombo Frag, Mott Strom Mud & Lt Gy, Gy, Plan Lam, Mud, Strom		Megadome	Drowning/Deepening
974,7 – 981,0	Lt Gy, Gy Mott. Lam. Sorted as — Intraclastic Pack → Grain — Cycles on Lepo. Separated by thin beds; lower units grade → Pack		STAWC → Cycle Peritidal PAC Cycles — Shallow Up.	
981,0 – 982,3	Gy, Lt Gy, Lam & Mott Lam Intracl. Grain		Shallowing Up Seq.	
982,3 – 984,1	DkGy, Gy, Thrombolitic Strom. Mud		Megadome	
984,1 – 992,5	DkGy, Gy, Thrombolitic Mott Frag Strom Mud → Gy, Lt Gy, Plan & Ripple Mott Lam, Intracl Pack/Grain		STRWC → Ripple Lam ST@ WC	
992,5 – 1013,1	DkGy, Uniform Clotted Text Vaguely Frag, Strom Bound Mud –		Megadome I. Propagation of Deep H₂O Seq.	Drowning
1013,1 – 1019,5	DkGy, Gy, Mott. Vaguely Frag, Throm. Strom. Mud		Megadome I → DkGy, Ripple Sort Grain	Deeping; Shallows up to Rip. Gr.
1019,5 – 1026,5	Gy Lt Gy, Clotted, Mott Bound, Strom. Bound		STRWC Shallowing Up Seq.	
1026,5 – 1030,6	DkGy, Gy, Vaguely Frag, Thromb Mud & Gy Sort Intraclastic Mud Gr		B = B	
1030,6 – 1037,0	DkGy, Gy, Mott. Vaguely Frag Thrombo/Dig. Strom Bound		STRWC.	Drowning/Deepening
1037,0 – 1046,2	Lt Gy, Gy, Mott Strom Bound & Lt Gy, Gy, Ripple Mott Lam as — Intracl. Grain		Peritidal — Smooth Mat cw @ 1041,0	
1046,2 – 1048,8	DkGy Uniform Text Strom Bound. → Ripple Lam Grain		Shallowing Up Seq	

1042,8

Core # 77F-1/72 Company Geological Survey Location Tweefontein

Logged By: CIVC Gen. Strat Section (W Tvl) 1:500

Depth	Description	Struct	Interpretation	Notes
1048,2 / 1051,0 / 1052,1 / 1053,4	DkGy,Gy, Blotch Mott. Mud → Gy Thromb Frag Strom Mud.		Pac's ↑ Shallowing Up Seq. — Deeping	
1057,2	Gy-Lt Gy, Blotch Mott. / Mott. Band. Strom Bound		Shallow Up.	
1066,0	DkGy,Gy, Blotch Mott Lrg. Thrombo / Frag Strom Mud.		STRMB — Megadome / R-B	
1068,9	DkGy,Gy, Blotch Mott. Frag Strom Mud → Gy / Silt. Mott Mud	↓	Deeping Up Seq. — Turbid. Current — Chnps	Deeping.
1069,3 / 1072,4	DkGy,Gy, Blotch Mott. Thrombo Mud → LtGy. Lam Strom Bound	up	Shallowing Up Cycle —	
1074,4	Lt Gy,Gy, Ripple Mott. Lam. Sort Grain		STR/BWB — Nuc Ag.	Deeping / Drowning
1077,7	DkGy,Gy, Band. Strom Bound.		STBWB Shallow Up Seq.	
1079,3	DkGy,Gy, Sort Mott. Lam. Deg/H2O. Intrncl Grain	Banded Uniform Look. DkGy...	Interp As Deep Ht Seq	
1084,0	DkGy,Gy, Broken Mott Thrmb. Lam. Mud → Intrncl Strm Grain.			
1091,0	DkGy,Gy Uniform Text Mud Thromb. Frag. Strom Mud / Gy-Lt Gy Mott. Band Strom Bound.		General / Shallow Up Seq	
1101,1	Gy-Lt Gy, Blotch Mott Lam / Sort Intraclastic Grain & Coat. Frag Lam. Strom. Bound.		Interp — STBWB Non-... Poss. Shallowing Up	Deeping
1109,4	Gy-Lt Gy, Vague Blotch Mott Strom Grain / Intrcl. Grain		Algal Colonization STBWB	
1116,1	DkGy,Gy, Uniform Text. Thromb. Frag. Mud → Gy-Lt Gy Wackstone Mud		Megadome / Shallow Up, STBWB	
1121,5	Gy-Lt Gy, Blotch Mott Frg Thromb. Strom Mud		Mud w/ Intcl — STBWB	Deeping.
1124,8	DkGy,Gy Unif. / Thrombo Mud Intl Gy-Lt Gy Band Strom Mud		STBWB BrB Ht Lop.	
1128,1 / 1129,0	DkGy Uniform Mud → LtGy,Gy Mott. Band. Frag Strom...	up	STBWB	Deeping.
1131,3	Gy-Lt Gy, Ripple Mott Laminated Grain		Shallow Up Near Algal Colony	Drowning,
1136,0	DkGy,Gy, Blotch Mott. Throm. Frag. Thick Lam ; Strom. Bound		Megadome / — STBWB. Gen Shallow Up. — Deeping, or Drowning Event.	
1139,0	Lt Gy,Gy, Blotch Mott. Strom. Bound / Vaguely Banded. w/ Lt Gy Bott. Ripple Mott Lam. Grain		Residual. Environment Here? ... Stable Environment — No Uniformity. Shallowing Seq. Appr. to be repeat of Ag. Am.	
1156,9 / 1160,0	DkGy,Gy, Blotch Mott. Strom. Mud → Gy-Lt Gy, Sort Vaguely Lam. Al. Colonized Grain		Pal. Shallowing Up Seq. Appears to Shallow Into Residual w/ Rapid Al. Colonization — ...	
1166,5	Gy-Lt Gy Vaguely Lam. Strom Colony Grain		STBWB / AWB	Shallowing Up Seq
1168,3	DkGy,Gy, Blotch Mott Uniform. Text thrombo Strom. Mud			
1174,0	DkGy,Gy Blotch Mott. Frg. Strom Bound		STRWB Next Core Common Strom	
1180,0				

File #: 77F-1/77 | Company: Geol. Survey | Location: Frechtown

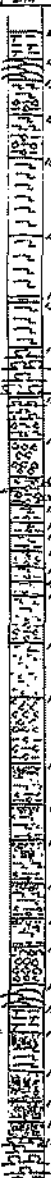
Logged By: CWC | General Strat. Hole (w/el) | 1:500

Depth	Description	Env.	Notes
1100.0 – 1150	DkGy, Gy, Uniform Text. Banded Mott. Inter. Gy, DkGy, Blotch Mott. Banded. Strom. Bound Mud		Maybe Part of Same Underlying Seq. STBWB — Deeping,
1180.3 – 1193.2 (1190.65)	DkGy, Uniform Text. Mud into Gy, DkGy, Blotch mott. Lamd Strom. Bound → Mud.		Part Shallowing Upward. STBWB Cycles. B & B. Megadune
1193.2 – 1197.7	DkGy, Gy, Strom. Thromb. Mott. Horiz. Lamd → Gy, Blotch Mott./Mottled Strom. Bound.		STBWB, B & B — Shallowing Up → Ripple Grain at color & contact. Drowning or Deeping
1197.7 – 1214	~1205 Alum. Strom. Gy, Lt Gy, Blotch Mott Lam., Al Strom Colony, Grainstone, & Dk Gy, Mott. Columnar Strom. Bound.		Peritidal — Al Colony ? Shallow Up Character. Eccles/Lyttelton Depo Break.
1214 – 1442.2	Lyttelton Fm (See Field Notebook for Details)		Lyttelton — Monte Cristo Paraconformity
1442.2 – 1464.4	Lenses or Layers of Lt Gy, Unif. Ripple Mott. Sort. Intraclastic Grain separated by DkGy, Blotch Mott. Wacke — Pack. (Very local Minor Al. colony). Rip Up Breccia		STBWB → & Pkt. Repetitions. All Shallowing Upward Cycles. Paraconformity
1465.9 – 1477.3 (1471.1)	DkGy, Gy, Blotch Mott. Dig./Thrombo. Frag. Strom. Bound & Minor Lt Gy, Mott. Lam. Intracl. Grain.		Mott. Frag. — ST. Poss ST — Flat / no common relationships. Drowning/Deepening
1477.3 – 1484.9 (1482.6)	DkGy, Mott. Lam., Blotch Text. Wacke/Pack → Lt Gy, Mott. Lam. Intracl. Grain. Rip Up Br.	o	1480–81 ex Grain. Paraconformity
1484.9 – 1495.2 (1488.6, 1491.2)	DkGy, Gy, Frag. ST Strom. Bound Grades into Lt Gy, Sort. Mott. Lam. Intraclastic ex-Grain		Shallow Upward Cycles
1495.2 – 1499.1	Lt Gy, Gy, Blotch Mott. Vague Frag. Wkd. Strom. Bound		
1499.1 – 1503.3	Lt Gy, Gy, Mmm Frag. Strom. Bound & Strom. Mud.		STBWB — Deep. Blunt Frag. Drowning or Deep.
1503.3 – 1507.7	Lt Gy, Buff. Sort. Ripple Mott. Lam. Intraclastic Grain	o	STBWB Color = local Subaerial Exp.
1507.7 – 1511.0 (1508.1)	DkGy, Blotch Mott. PoorSort. Pack → Lt Buff Gy, Lam. Intracl. Grain		Interfing. = 2 small Cycles
1511.0 – 1514.4	DkGy, Gy, Thromb. Frag. Mud → Gy, Lt Gy, Strom. Bound		STBWB Shallowing Up Seq.
1514.4 – 1519.5	DkGy, Gy, Bound — Thrombo. Frag. Lcf Mud & Gy, Lt locally, Ripple Lam. Mud — Pack.		Broad & Taller. Megadomal Cycle Dev. Drowning or Deepening.
1519.5 – 1523.1	Lt Gy, Gy, Uniform Text. Ripple Mott. Lam. Intracl. Grain	o	STBWB — Wave Ag.
1523.1 – 1526.0	Gy, Lt Gy, Strom. Mott. Lam. Bound		STBWB
1526.0 – 1534.1	DkGy, Gy, Blotch Mott. Thromb. Frag. Strom. Bound Mud.		Megadomal

Left margin: 1214; 1442.2; 1, 2, 3, 4, 5; 15; 1534.1

Hole #: 77F1/77 Company: Geol. Survey – Pretoria Location: Trechardtson

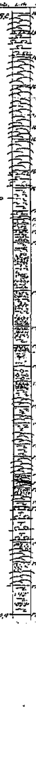
Logged By: CWC Gen. Stratigraphic Sect (W-Tu) 1:500



Fm	Depth	Description	Struct	Notes
	1531,1 – 1534,0	DkGy Uniform Text. Lam. (Vaguely Alg.) Mud.	T	Deep.
	1534,0 – 1536,4	DkGy Blotch Mott. Thrm. SL Band	▽	Megadomal / STAWB; Drowning or Deepening Seq.
	1536,4 – 1540,0 – 1544,6	DkGy Blotch Mott. Mud/Pack Grades into Lt Gy Uniform Text. Intracl. Grain	⊤, –o–	Interfing. of Litho's; ETA/BWB; 2's of small Ryp's @ 0,5–0,75m
	1544,6 – 1553,4 – 1557,4 / 1560,2	Lt Gy Gy Sort Uniform Text Ripple Mott. Lam. Intraclastic Grain; DkGy Type; Minor local Algal Colonization & Stablization; Mudstone	○	1550–54 — Fault Brecciation; STAWB
	1566,2	Lt Gy Gy Blotch Mott. Dig. Ing. Vaguely Thrm. Strm. Bound	Ω	STAWB → may be also delta / or ? poss. ST Fine — ST Deepening
	1570,5	Lt GyGy Sort Uniform Text. Intracl. Grain & Interbd. Lam. Strm. Bound	Ω, ○	Shallowing Up Seq.
	1575,2	Lt Gy Gy Vaguely Banded Lam Grain. Sup. ?Al. Colony	○	STA/AWB — ? Al Colony.
	1579,2	DkGy Gy Blotch Mott. Strm. Pack / Mud & Lt Gy Lam. Grains		STB/AWB — ? ST Algal Colonization
	1583,2 – 1584,3 – 1585,7 – 1587,2 – 1589,0 – 1590,4	DkGy Gy Blotch Mott. Banded Intraclastic on Throm. Mud/Pack Into Lt. Gy Gy Mott. Ripple Lam. Intracl. Grain	⊤, –o–	Interfingers of Lithologies → Shallowing Upward Cycles. Shallows w/ ?Lt. Color = ? Subaerial Ex; STA/AWB → STAWB.
	1592,2	DkGy Uniform Text. Sort Pack → Mud Into Lt Gy Sort Intracl Grain	○	Shallowing Up Seq. STA/AWB → STAWB
	1597,3	Lt GyGy Sort Uniform Text Ripple Mott. Lam. Intraclastic Grain	··	Shallowing Up Seq; STAWB — Minor Algal Grain
	1605,4	DkGyGy Vague Lam Pack → Mud Grades into Lt Gy Mott. Lam Uniform Text Grain	○, –o–	STAWB → STAWB; Minor Algal Colony & Shallowing Up Seq.
17	1610,4 – 1614,7 – 1618,4 – 1623,8 – 1627,1	0,1–2,5 Thin DkGy Uniform Text Mud → Lt Gy Gy Uniform Text Ripple Mud. Lam. Intraclastic → Grainst; (Minor strong, Local Algal Colony)	○, ⊤, ○○	MAC— Shallowing Upward Cycles. Gen. ? Thinness ? Continuous Sed. up to end; STAWB → Minor Agitation.
	1630,7	Lt Gy Gy Mott. Text Sort Intracl. Grains	○	STAWB; Minor Algal Colonization; Shallowing Up Seq. Asso. 1627,7
	1634,1	DkGy Shale Bands Blotch Mott. Throm. Strm. Mott.	▽	STAWB w/ Slpt.
	1636,7	DkGy Gy Blotch Mott. Strm. Mud.	⊤	Drowning
1639m	1639,4	Gy Lt Gy Ripple Mott. Lam Sort Uniform Text Intracl. Grains → Mud Graded to Grain	○	STAWB
16	1643,3 – 1647,8 – 1649,0	GyGy Mott. Thrombo Ing. Mud Shallows Upwards Into Lt GyGy Mott. Lam. Ripple Intraclastic Grain	○○, Ω, –o–	Cyclic Sedimentation — Shallowing Up MAC's; STAWB → STAWB
	1650,8	DkGyGy Mott. Lam. Strm. Al. Boundstone	Ω	STAWB — Shallowing Up Seq; Hummocky & Columnar Ing. Hd's
1659,8	1657,2 – 1659,8	DkGyGy Blotch Mott. Vague Ing. Strm. Bound w/ ?? Infill	▽	1652–57 ? Slump Fault — Disturb. STAWB Interp. Megadomal

Hole # 77F1/72 Company Geol. Survey Location Trachfontein

Logged By: CWC. General Strat. Hole (WTM) 1:500



Box	Depth	Depth	Description	Struct.	Interpretation	Notes
	1659.8	1659.8	DkGy, Gy, Blotch Mott. Pseudo Band / Lam. Sh. infill Strom Bound	◡	STRMS → Intrp. Mod.	
		1662.6	Lt. Gy, Gy, Blotch Mottled Lam / Vague Banded Strom. Bound / Strom. Grain (Local Frag)	SZ	STRMS → Inc. in More Agitation & Destabilization of Al colony.	
		1669.5	DkGy, Gy, Blotch Mott. Uniform Text. Vaguely Frag. Strom Bound. Thrombo Strom Mott.	◡	STRMS → Megadome / Al colony. Less Stable w/ more Uniform Mott Text.	
		1675.5	Gy, LtGy, Blotch Mott. Vague Frag. Strom. Bound. (minor Banding & DkGy Mott Shale Infill	◡	STRMS — Megadome / Note: Unique Text w/ Mott frag — Lt. Gy. Colour — & Shale / Silt Mud Infill	
		1680.0				
		1682				
		1684.4	Gy, DkGy Blotch Mott Vaguely Banded Strom. Bound & minor Intraclast Grain	◡	Brecci & Rubble (Local Vague Frag) Interp. Mixed → STRMS	
		1687.1	Gy, DkGy, Blotch Mott. Consistently Text. Vaguely Frag. Thrombo Strom. Bound (Minor Lam)	◡	STRMS Algal Colonization Interp. As Megadome!	
		1694.2	DkGy, Gy, Blotch Mott. Vaguely Frag Thrombo Strom Bound → Intraclastic Grain Infill		STRMS → Vague Colour. SZ	
1700		1697.8	Lt Gy, Gy, Mott. Lam Grain, Ripple Lam Grain → Sort. Grain	~	Poor Al colony in unstable subst.	Appears to be Shallowing Up Seq.; Drowning or Deep.
		1703.0	DkGy, Blotch Mott. Thromb Strom. Bd.	◡	STRMS	
		1704.7	Lt/Gy, Gy Blotch Mott Strom Bd.		STRMS Strom	
		1706.6	Lt. Gy Buff, Sort. oo Intracl. Grain	o	STRMS.	
		1707.8	Lt Gy Buff. Strom Bound		Pen tide!	
		1709.6				
15		1720.3	Minor LtGy Wacke → Pack Gradational w/ Lt. Gy Buff Sort. Ripple Mott Lam. oo – Intraclastic Grain. minor Algal Stab.	◇	Cyclic Shallowing Up Cycle STRMS	
		1728.2	Lt Gy Buff Gy Sort. Ripple Mott Lam Intraclastic Grain / oo Grain		Minor Al Stabilization STRMS	
		1732.4	1732.5 Al Colonization. Lt Gy Sorted oo – Intraclastic Grain		Shallowing Up Seq.	
		1737	DkGy Blotch Mott Lam Oncolitic Mud → Pack		STRM or STRMS	
14		1741.1	DkGy Blotch Mott. Strom Bound → Lt. G. Buff. Ripple Mott Lam Intraclastic Grain / oo Grainstone		Top cycle not shown → oo Grain. Shallowing Upward Cycles + Pack's	
		1745.9				
		1749.2				
		1753.9	Lt Gy Buff Sort Ripple Mott Lam. Intraclastic Grain	◇	STRMS Contact Abrupt	
		1756.8	LtGy, Gy, Uniform Text. Frag. Thrombo Strom. Bd. Mott.	◡	Megadome!	
13		1761.9	Gy / Gy, Blotch Mott Frag. Strom Bound → Lt. Gy Sort. Gr., Graded → Intraclastic Grain		Cyclic → STRMS Al colony → Hard by STRMS.	
		1763.4				
		1766.8	Lt. Gy Ripple Lam Grainstone Up Bed Agg. Grad.			
		1767.8	DkGy, Blotch Mott. Pseudo-Mott Banded Strom Bound / Mott Mud.	◡	STRMS — minor Mud & Wacke Megadome / @ Low Ct.	
12		1775.0	LtGy, Gy, Blotch Mott Vague Frag. Thrombo Mott → Lt. Gy Buff Sort. Well Graded oo Grain	◡	Shallowing Up Cycles.	
11		1779.5				
		1784.4				
10	1790.4	1790.9	Lt Gy Buff. Gy Sorted Ripple Mott Lam. oo-Grainstone & Intraclast. Grain	◇	Com. STRMS — Hard Agit.	

Hole #: 7771/72 Company: Geol Survey Location: Tweefontein

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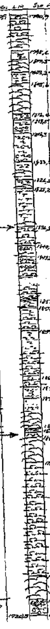
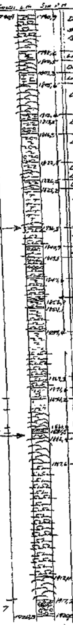


Depth	Description	Symbol	Interpretation
1790,7	DkGy Gy, Mott. Fng. Thrombo Strom Laminated Mud → DkGy Gy, Blotch Mott. Fng. Strom Band.	Ω	Shallowing Up STGWB
1798,6	Lt Gy Sort Ripple Mott Intracl. Grain	○	Sharp Contact Abrupt.
1800,5	DkGy Blotch Mott. Fng. Thrombo Mud.	▽	Megadomal.
1803,2	Lt Gy Mott Mud & Gy Thrombo Strom Mud		0,3 Cycles
1805,6	DkGy Blotch Mott. Thrombo Strom Band Mud	▽	Megadomal.
1812,4 / 1813,5	Dk Gy Blotch Mott Lam Thromb Mud & Strom Band → Lt Gy Ripple Mott Grain		Shallowing Up Seq
1816,3	Lt Gy Gy, Ripple Mott Lam Sorted Intraclastic Grain	○	Wave Agit. — STGWB; 0,3m Regrep or Paraconformity Rz
1822,5	DkGy Mott Lam Mud / Throm. Mud → Lt Gy Lsoft Ripple Mott Lam Grain		Shallowing Up Seq.
1824,5	DkGy Thromb Mud → Lt Gy Soft Intraclast. Grain		Shallowing Up
1825,2	DkGy Gy Wavy Mott Banded Mud — local small Strom		Deep H_2O Tiger Stripe Mud.
	Deep H_2O Thrombolitic Mud		Drowning Very Deep
1836,5	DkGy Gy, Mott Lam / Blotch Banded Strom Band	Ω	STGWB
1840,9	DkGy Mud → Lt Gy Banded Grain	○	Shallow Up; Minor Regrep or Paraconformity.
1433	Gy DkGy, Blotch Mott. Mainly Fng Strom Band & Lt Gy Banded Grain		
	0,2m Dk Sh.		Depo Cycles
1857,7 / 1854,1	DkGy Gy Thrombo Strom Mud & DkGy Mott St Band. [illegible] up into Lt Gy Lsoft Ripple Mud Lam Intraclastic Grain.		Shallowing Upward.
1859,4	Gy Lt Gy, Mott Lam Blotch Text Strom Fenes. w/ Minor Lt Gy Text. Ripple Lam Intraclast Grain		Shallowing Upward Cycle → Part not [illegible]
1869,3	DkGy Gy Blotch Mott Strom Band		STGWB
1871,6	DkGy Mud → Lt Gy Soft Intracl Grain		Shallowing Up Seq
1874,2	DkGy Gy, Mott Blotch Text Thrombo Fng Strom Band Mud [illegible] Lt Gy Graded [illegible] 0,5m [illegible] Grainstone [illegible] Graded	○	Shallowing Up Seq; Paraconformity
1884,6 / 1884,5 / 1886,4	Shale Mud Fragments Br.		
	DkGy Gy, Blotch Mott thrombo Strom Band Mud	▽	Megadomal Thrombolite Fng outlined by [illegible]
1882,6	Gy DkGy, Blotch Mott / mud Text Thrombolitic / Dig Strom Domal minor Fng & Wavy Lam		STGWB — Massive Algal Colonization
1912,4	DkGy Massive Uniform Text Mud → Largely Fng Thrombo Mud	▽	Megadomal Very Massive Deepening & [illegible]
1917,2	DkGy Gy Mott Clastic [illegible] Shale [illegible] Lt Gy [illegible] Intracl Grain		Shallowing Up Seq.
1920,0			

Hole #: 7TF1/72 Company: Tool Survey Location: Twee fontein

Logged By: MIC Gen. Strat. Section (WTs) 1:500



Fm / Depth	Description	Symbol	Notes
1790.9	DkGy/Gy Mott. Frag. Thrombo Strom Round Mud → DkGy/Gy Blotch Mott. Frag. Strom Round.	SL	Shallowing Up STDWB
1797.6	Lt Gy Sort Ripple Mott Intracl. Grain	○	Stand Contact Abrupt.
1800.5	Dk Gy Blotch Mott. Frag. Thrombo Mud.		Megaflonal.
1803.3	Lt Gy Mott Mud & Gy Thromb Strom. Mud		0.3 Rip Up.
1805.6	DkGy Blotch Mott. Thrombo. Strom Round Mud		Megaflonal.
1812.6 / 1813.5	DkGy Blotch Mott Lam Thromb Mud c Strom Round → Lt Gy Ripple Mott Grain		Shallowing Up Seq
1816.5	Lt Gy/Gy Ripple Mott Lam Sorted Intraclastic Grain	◇	Prone Agt. — STDWB; 0.3m Rip up or Paraconformity Bx
1822.5	DkGy Mott Lam Mud / Throm Mud → Lt Gy Lam Ripple Mott Lam Grain		Shallowing Up Seq.
1824.5	DkGy Thromb Mud → Lt Gy Rdd. Intracl. Grain		Shallowing Up.
1825.2	DkGy/Gy Wavy Mott Banded Mud — local small strom		Deep H_2O Tiger Stripe Mud.
	Deep H_2O Thrombolitic Mud.		Drowning, Very Deep
1834.3	DkGy/Gy Mott Lam / Blotch Banded Strom Round	SL	STDWB
1843.9	DkGy Mud → Lt Gy Graded Grain	◇	Shallow Up; Minor Rip up or Paraconformity.
1845.3	Gy/DkGy Blotch Mott Irregularly Frag Strom Round & Lt Gy Graded Grain		
1847.6	0.2m Crsh. DkGy/Gy Thrombo Strom Mud & DkGy Mott Sh Lam. [illegible] Lt Gy Mott Ripple Mott Lam Intraclastic Grain		Depo Cycles; Shallowing Upward.
1852.7 / 1854.1 / 1859.4	Gy/Lt Gy Mott Lam Series Thin Strom Round w/ Minor Lt Gy Mott Ripple Lam Intracl Grain		Shallowing Upward Cycle → Part not [illegible]
1869.3	DkGy/Gy Blotch Mott Strom Round		STDWB
1871.6	DkGy Mud → Lt Gy Rdd Intracl Grain		Shallowing Up Seq
1874.2	DkGy/Gy Mott Blotch Tect Thrombo Frag Strom Round Mud → Lt Gy Core Gr. Graded → Grain; 0.5m of Grainstone Gr. Graded	○	Shallowing Up Seq.
1881.0 / 1881.5	Shale Mott Fragments Gr.		Paraconformity
1882.4	DkGy/Gy Blotch Mott Thrombo Strom Round Mud		Megaclonal; Thrombol. Lc Frag outlined by Sh infill
1887.6	Gy/DkGy Blotch Mott / Mott Teet Thrombolites / Dig Strom Round minor Frag & Wavy Lam		STDWB — Massive Algal Colonization
1912.4	DkGy Massive Uniform Teet Mud → Irregularly Frag Thrombo Mud		Megadomal Very Dense; Deepening Upward
1917.2 / 1920.0	DkGy/Gy Mott Oolitic Mud → Thick Lam Lt Gy & Intracl Grain		Shallowing Up Seq.

File # TF1/72 Company GSO Location Twee fontein

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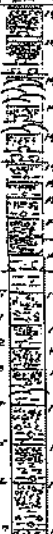
General Strat Section (WTW)



Fm	Depth	Description	Struc.	Notes
	1920.8 – 1924.0 – 1924.2	DkGy, Gy, Blotch Mott Lam Strom Bound → Lt. Gy, Srt Mott Ripple Lam. Grain. → Topped by sort Rev Graded m–Grainstone.		Shallowing Up Seq.
	1924.2 – 1926.6	DkGy, Gy, Blotch Mott. Thrombo Frg Strom Bound Mud.	▽	Megadomal — Drowning
	1926.6 – 1934.6 – 1936.0	DkGy, Blotch Mott. Thrombo Strom Bound Mud → Lt. Gy, Buff Srt Rev. Graded m–Grain		Slightly Deeper Water. Shallowing Upward Cycles
6	1936.0 – 1942.6	DkGy, Gy, Small Intraclastic Wacke → Gy Mott Ripple Lam Grain → Rev Graded Gy, Buff m–Grain		Shallowing Upward Cycles
	1942.6 – 1947.7	DkGy, Dark Mott. Nodular Gy Mott Srt & Gy Srt Rev Graded m–Grain.		
	1947.7 – 1951.7	DkGy, Gy, Mott Intracl. Mud Wacke → Gy DkGy Blotch Mott Strom Bound		STBW — Apparent Deepening
5	1951.7 – 1955.4 – 1957.0 – 1960.6 – 1964.0 – 1966.3 – 1972.2 – 1977.5 – 1980.4 – 1984.5 – 1988.4 – 1991.3	DkGy, Mott. Intraclastic Mud → Wack into Lt Gy, Gy, Buff Ripple Lam. Intraclastic Grain → Mott Lt. Gy, Rev. Graded m Intraclastic Grain (Cycles vary, & may be terminated at one lithology or another — Cycles deepening into Thrombo Strom Mud in places)		Interfingering or PAC System of 11 Shallowing Upward Cycles. STBWG → STMWG More Agit. Elevations = Lighter Color = Shallow Cond. + Winnowing. General lighter color may = removal of [illegible]
	1991.3 – 1997.8	DkGy, Gy, Uniform Text Frg, Thrombo Strom Bound Mud	▽	Zone in self appears to Shallow Up from Upper Cutter → Thrombo Mud. Down ↓
	1997.8 – 1999.1	DkGy Strom Bound Sel. Gy Ripple Lam. Intracl Grain	Z	Episodic or Interfinger of STMWG & STBWG
	1999.1 – 2004.3	DkGy, Gy, Mott & Blotch Lam Randomly Silicified Frg Thromb Strom Bound Mud	▽	Generally Megadome w/ Series of Intraclastic Wacke → Mud Storm / Episodic Event. } Shallow Up
	2004.3 – 2007.4	Lt Gy, Gy, Blotch Mott Strom Lam Strom Bound Grain		
	2007.4 – 2011.0	DkGy, Gy, Uniform Text Incl Blotch Mott. Vague Thrombolite Strom Mud	▽	Megadomal } Shallowing Upward Cycle.
	2011.0 – 2017.3	Gy, DkGy, Uniform Text Mott Intraclastic Pack (Has Mud Looks) minor Ripple Grain & Up Lt		Shallowing Upward Sequence → Generally Starts of Mottl, Wacke into Ripple Mott Grain [illegible]
	2017.3 – 2019.1	Lt Gy, Srt Mott Lam Intracl Grain	≈	} Shallowing Seq.
	2019.1 – 2021.1	DkGy, Gy, Mott Vague Thromb Strom Mud	▽	
	2021.1 – 2023.4	Lt Gy, Gy, Srt Ripple Intracl Grain	≈	
	2023.4 – 2027.2	DkGy, Gy, Blotch Mott Text Thrombo Frg Strom Bound Mud	▽	Megadomal } Possible PAC Shallow Seq.
	2027.2 – 2029.6 – 2033.8	Lt Gy, Gy, Vaguely Mott Frg Thrombo Strom Bound Mud Into Graded Srt m Grain	≈ ▽	Cyclic Sed. — Shallowing Upward PAC's
	2033.8 – 2038.0	Lt Gy, Buff Ripple Mott Lam Srt Intraclastic Grain	?	More Ag. — STMSW
	2038.0 – 2040.0	Gy Lt Gy, Blotch Mott Mud/Pack & DkGy Vague Frg	▽	Interp. as Megadomal
	2040.0 – 2044.3	Gy DkGy, Blotch Mott Vaguely Frg Dig/Thrombo Strom Mud	? ▽	(Onset Ripple Lam Grain) Megadomal → STBWG
	2044.3 – 2049.9	DkGy, Gy, Uniform Text Shale Lam Mud → Into Gy Thrombo Mud		STBWG Interp. Based on only Color + Vague Text
	2049.9 – 2051.7 (2051.7)	Lt Gy, Gy, Blotch Mott Mud → Pack Vague Frg. Thromb Mud		

Hole # TF1/72 Company GSO Location Tweefontein

Logged By: CMC. Gen. Strat. Sect. (m.b.l) 1:500

Fm	Log	Depth	Description	Struct.	Notes
4	2051,7 – 2052,0		Lt Gy Gy. Int-bed Ripple Grain	c	
	2052,0 – 2055,7		Lt Gy Gy Mansor & Ripple Lam Intraclastic Pteam Grain		overall zone has a muddy look
	2055,7 – 2062,0		DkGy Gy Blotch Mott. "Uniform Text" Vaguely Fig. Thrombo Strom Mud		Interpretat. = Megadom.
	2062,0 – 2062,1		Gy DkGy Wavy Lam, Strom Band		
3	2062,1 – 2067,0		Lt Gy Gy Mott Lam Sort Intraclastic (Lam. cg) Grain	c	STANB.
	2067,0 – 2072,0		Gy DkGy Gy Gy Banded Mansor Lam Strom Banded Mud/Mott Intraclastic Grain		
	2072,0 – 2074,2		DkGy Gy Blotch Mott Fig Strom Mud		Minor Band of Lt Gy Grain = Cycles 0,5m Strom Mound — Swash Mud 0,1m Grain @ 4.
2	2074,2 – 2077,3		Lt Gy Gy Ripple Mott Lam Grain		STANB
	2077,3 – 2080,2		DkGy Gy Blotch Mott. Text. Fig. Thrombo Strom Band Mud		Megadomal
	2080,2 – 2082,2		Lt Gy Gy Mansor Lam Pseudo Banded Mud		
	2082,2 – 2085,0		DkGy Gy Blotch Mott Vaguely Fig. Thrombo Strom Band Mud		Megadomal
	2085,0 – 2090		DkGy Gy Uniform Text Vaguely Fig. Thrombo Strom Banded Mud		Stratigraphic break Ripple cg 0,1m Bar Graded cg-Grain
	2090				— Drowning
	2092,3 – 2104,7	2095, 2097,0, 2099,8, 2101,0, 2102,8, 2103,9	Shale Lam Mud & Muds Inte. Lt Gy Vaguely Mott. Intraclastic & Lam Mock & Marker Intra. Lt Gy Mott. Cont. Xer. Graded & Strom/Ripple Lam Intraclastic Grain (Very local ? Thrombo Strom. Mud)		Cycle Sedimentation — Interpretation & Shallowing Up Mud Mats. STANB → STANB (More Agitated)
1	2105,7 – 2116,0	2107,0–7,7; 2108–10,3; 2114,0	Lt Gy Gy Cont. locally Xer. Graded cg Intraclastic Grain & Mud & Gy Lt Gy Ripple Up Intraclastic Grainstone. Minor Strom Grainy	c	STANB
	2116,0 – 2116,4		Lt Gy Gy Grainy/Parted Shale		
	2116,4 – 2122		Lt Gy Gy Banded Mott Lam. cg Intraclastic Grainy Mud	c	Lt Grain bands Xer. Graded. STANB — More Agitated.
	2122 – 2122,8		Lt Gy Gy Ripple Mott Lam Grain		
	2125,7 2122,8 – 2126,2		DkGy Strom Mott Text. Thrombo Mud → Gy Lt Gy Lam Mud. Lam Strom Band		Note: Below 2122,8 The change sequence due to change in STANB.
	2126,2 – 2129,8		Gy Lt Gy Mott. Mott. Lam Color & Fabric, Intraclastic Strom. Grain		Shallowing Upward Cycle —
	2129,8 – 2133,2		DkGy Gy Uniform Text. Vaguely Graded Mud	T	
	2133,2 – 2133,6		Lt DkGy Blotch Mottled Strom		Deepening. Interpreted as 1.7 transgressive Surf. 0,4m Lt Gy Ripple Lam Grain Up. Cont.
	2133,6 – 2152,3		DkGy Gy Blotch Mott Lam. Vaguely Color Banded Strom. Locally Vaguely Fig. Thrombo Strom. Band Mud		Deeper H₂O Full Algal Colonization
	2152,3 – 2156,7		DkGy Uniform Text. Vaguely Fig. Thrombo Strom Band Mud		Megadomal
	2156,7 – 2158,0		Lt Gy Gy Ripple Lam Grain		
	2158,0 – 2161,3		Gy Lt Gy Uniform Text. Intracl. Mud & Grain	o	Possible Shallow Up Seq.
	2161,3 – 2164,4		DkGy Gy Uniform Text Vaguely Fig. Thrombo Strom Band Mud		Megadomal
	2164,4 – 2165,0		Lt Gy Ripple Lam Gy Band Grain Gy Lam		Interp. STANB — Poss Shallowing Up Seq.
	2165,0 – 2166,8		Lt Gy Gy Blotch Mott. Strom Band		
	2166,8 – 2175,8	2169,6, 2175,5	DkGy Gy Uniform Text Vaguely Fig Thrombo Band Mud/ DkGy Gy Uni. Text. Vaguely Color Band Mud – Fig Thrm.	T	Degree of Diff. very Slight.
	2175,9	2175,8	2,5m Massive DkGy Glace Sh		

Hole # 781/72 Company GSO Location Trucfontein

Logged By: LWC General Strat Section 1:500

Depth	Description	Struct.	Notes
2178,9	Gy/Lt Gy, Mott. Thrombo Strom. Mud.		
2185,5	Dk Gy/Gy Mud c Lt Gy Strom Band		Bread & Butter
2187,6	Lt Gy/Gy, Uniform Text. Vaguely Fing. Thrombo Strom. Band Mud.	▽	Megadomal.
2189,8	Gy/Lt Gy/Gy, Bleb, Mott. Curr. Color Band. Vaguely Fing. Strom Band. / Minor Mud c CO_3 Clasts	[illegible]	Poss. Deep Hz. Al. Colony
2197,5	Gy/Lt Gy, Mott. Curr. Sort. Intraclast. Mud. Passes into lenses of Arcel Uniform Text. Thrombo. Strom Mud. Minor Color Banding		
2206,0	Lt Gy/Gy, Uniform Text. Vaguely Fing. Thromb. Strom. Bound Mud. (Randomly Banded)	▽	Megadomal
2213,2	Lt Gy/Gy, Vague Color Banding Mott. Lam. Intraclastic Grain		Wave or Current Agitation = — Alg. Colony.
2216,6			
2218,2	Dk Gy, Mudstone to Lt Gy, Sort. Intraclast. Grain		Cyclic Sed. ? Small PACS
2219,3	Lt Gy/Gy, Uniform Text. Thrombo Strom. Bound	▽	Megadomal — Contact = Sharp.
2222,4	Dk Gy/Gy, Uniform Text. 'Massive' Vaguely Mott. Fing. Thrombo Strom. Mud.	▽	Megadomal
2227,5	Dk Gy, Banded, Uniform Text. Silt to Mud		Pass. Silt to Sh. Text
2230,0	Gy/Dk Gy, Thrombo Strom. Mud c Lt Gy/Gy Lam. Mud Packs.	▽	Cyclic Sedimentation
2232,0			
2233,9	Gy/Dk Gy, Uniform Text. Thrombo Mud.	▽	Megadomal
2236,3	Lt Gy/Gy, Intraclast. Wacke to Pack.		
2237,0	Lt Gy/Gy, Uniform Text. Mud c Band Lam. Dk Gy, Silty Sh. Mud.		Diff. in 2 color banding for each unit.
2240,2	Gy/Lt Gy, Color-Mott. Bound Mud (Ribbed Flowage Mud Lam.)		
2243,1	[illegible]		Bread & Butter.
2244,2	Gy/Lt Gy, Uniform Text. Bound Mud.		
2246,3	Gy/Lt Gy, Sort. Mud. [illegible] c Ripple. Intraclast. [illegible]		Storms — [illegible] Agitation = — Alga. Colony.
2249,6	Lt Gy/Gy, Mott. Vaguely Fing. Thrombo Strom. Mud.	▽	[illegible] Megadomal.
2253,0	Dk Gy/Gy, Uniform Text. [illegible] Mud.		[illegible] Massive [illegible].
2254,4	Dk Gy/Gy, Uniform Text. Thrombo Mud. c Lt Gy/Gy Mud [illegible]	▽	Bread & Butter. Megadomal Strom. Bound
2257,2	Gy/Lt Gy/Gy, Uniform Text. [illegible] Lam. Mud / Thrombo Strom Mud		[illegible] Shale [illegible] random Still [illegible] color banding
2262,5	Dk Gy/Gy, Uniform Color. Thrombo Strom. Bound and c Lt Gy, Gy. Bleb. [illegible] Text. Vague Fing. Strom. Bound.	▽	Bread & Butter — Megadomal Bound Mud. In which the strat. can be quite large — [illegible]
2274,8	Dk Gy/Gy, Mott. w/ vague bleb. Mott. Mud / Thrombolitic Strom. Bound Mud. (Vague Dig. Fing.)	▽	Minor Color Banding. Interp. Megadomal. — Environment very questionable ?
2282,6	Gy/Lt Gy/Gy, Mott. Text. Poorly Sorted Intraclastic Wacke-Pack — Lt Gy Columnar Strom.	⋒	Note: Poss. Shallow Sea or Deep Environment, [illegible] — vague [illegible] shape 0,2m Vague Mott. [illegible] — Major Interp. Break
2284,5	Lt Gy/Gy, Bleb. Mott. Lam. / Pseudo Bound Algal Colonized Mud w/ lenses of Thrombo. Strom. Bound		General Shallowing Up Cycle — Dep. Environment questionable.
2295,4	Lt Gy, Uniform Text. Intraclast. Wacke to Mud.		Lt Gy Mud.
2297,5	Lt Gy/Gy, Bleb. Mott. Lam. Alg. Colonized Mud. — Shale Wavy Lam. Mud / Packs.		Storms — Colonized Mud.
2306,1	Igneous Sill (Gen. La Contact)		
2332,0			

Core # TF1/72 Company GSC Location Tree [illegible] E of [illegible]

Logged By CIYC General Strat. 1:500

Fm	Depth	Lith	Size etc.	Description	Struc.	Notes
	2332.0		2335.4 / 2337.5	DkGy, Gy, Mott Lam Uniform Text. Mud – Algal Laminations & Strom Boundstone Mud.		Cyclic Sedimentation. Each cycle begins w/ Strom Lam Mud, & into vague banded Megaloidal Texture. Each Cycle appears to Shallow Up.
			2344	DkGy, Gy Uniform Text. (Rather Massive) Mud / Local vague Thrombo Lag frag)		
			2352 / 2352.3	Lt Gy, Gy Mott Lam Mud		U. Calc – Agitation
			2355.2 / 2357.5	DkGy Uniform Text (Rather Massive) Planar Lam Mud (Tiny vague Thrombo Lag frag).	T	Poss. Megaloidal / ?
				DkGy, Gy Unif. Text. Thrombo Mud → Lt Gy, Gy Ripple Mott Lam Grain → Pack.		Cyclic Rys. Appears to be Shallow Up. Sequence.
			2360.7	DkGy, Gy Mott Lam Grain / Thromb Mud.		Large Current Ripple Lam
			2362.1	DkGy, Gy Uniform Text, Vaguely [illegible] Mud	T	Strom [illegible] Lower Cont.
			2365.1	DkGy Uniform Text Mud → Gy Lt Gy Str & Unif Text Mud – Pack		Minor Lam. Deep H_2O Clastic.
	2369.3			DkGy, Gy Cont. Uniform Text Intraclast Grainstone Interbedd w/ Thrombo Mud		Deep H_2O Co. Clasts. / [illegible] Pack → Mud.
	2376.0		2371.2 / 2376.2	Gy, DkGy, Color Mott, Laminated, Bkdd Alt [illegible] Uniform Text Mud / Bound		Minor Thrombo Mudstone Interpret. as Megaloidal
				DkGy, Gy Uniform Text Mud. Interbedd. w/ vague Current Thrombo Strom Mud.		Subtidal Below W.B. / Litho Contact @ in DkGy [illegible] / Transgressive St. (Interp. & Cont.)
			2384.2	DkGy, Gy Uniform Text Mud. (Minor Thrombo Mott Lam Mud & Ty. M)		Uniform – Full to abdominal features. Deeper Mud?
			2389.7 / 2391.2	DkGy, Gy Uniform Text Mud / Gy Lt Gy Burrowed Silty Mud St.	T	Thinnish Strom. Mud @ Ky Id. / Minor Fences of Mud, Slumps suggest separate Gy Color Lam
	2393.4		2395.4	Gy Lt Gy, Mott. Large Ckkld Lam Text Sort Uniform Text Mud / Silty Grain		Mott Slumps looking Text.
			2402.4 / 2404.5 / 2406.7	DkGy Green Gy, Thrombo Mud / Big Strom Bound Interbedd w/ Unit [illegible] of Greater Color Banded Lam Grain		Cycle Subtidal to Mid Sedimentation.
	2411.4		2412.4	DkGy, Gy, Mott Thrombo Mud / Strom Boundstone		Megaloidal / Int. 0.15m Uniform Text Mud / Grain to Cont
			2413.1	DkGy, Black Banded Silty Shale		[illegible] ---- Deepening upward
			2414.7	Gy, Green Gy Uniform Text Mott / Grain		[illegible]
			2415.7	DkGy [illegible] Gy Lt Gy Grain		Poss PAC – Shallowing Up Cycle. [illegible]
			2418.1	DkGy Gy Green Mott Thrombo [illegible]		Megaloidal.
			2420.7	Gy Lt Gy Mott Lam [illegible] Grain		
			2423.1	Gy, DkGy Uniform [illegible]		Poss. PAC → Shallowing Upward Cycle.
	2426.5		2426.5	DkGy Green Gy, Thrombolite Mott. / Strom Bound.		Megaloidal —— Lithologic → Shallowing Contact
				DkGy Black Mud, Planar Lam. Silty Shale w/ Lenses of Dk Green Gy, Mud Thrombolitic Mud.		Thrombolitic or Nodular Gy Mud.
				% of Green Gy Mud Inc. Upward.		
	2449.2 / 2449.5			Lt Green Gy [illegible]		
				DkGy, Black Uniform Text [illegible] Shale [illegible] pebble [illegible]		Early Transgressive
BR. / KR.	2452.3			Ventersdorp [illegible]		[illegible] contact [illegible] pebble [illegible]

Hole #: LE2

Company JCI

Location: Thabazimbi

Leeuwbosch

Logged By: CWC

Scale 1:500

Fm. | Depth | Lith | Str | P | M

North of Thabazimbi

0

6.55

66.6

94.7

110.5

Lyttelton

2nd

1st Grandcycle

LE 2

Logged By: CWC

May, 1987

Scale 1:250

Gancor

BH-1777-16

~10 km ESE

Col.

Note:

Near Springs

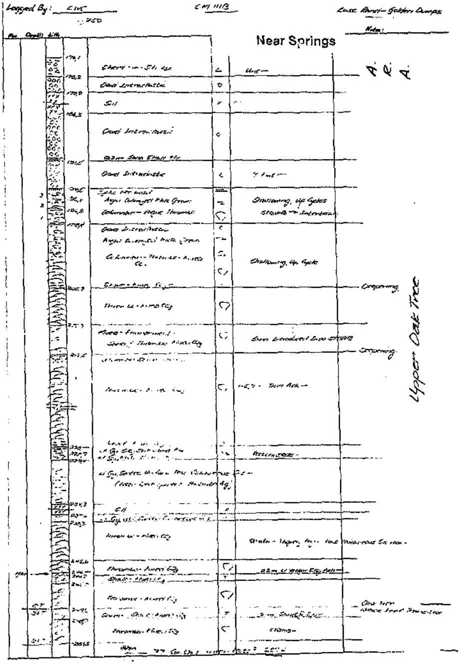
Bu | Depth | Lith

Depth	Description	Symbol	Remarks	
178.0	Intraclastic Grain	◊		
182.7	Interp. Ragged Disconformity — Chan-nel Fill By			
184.1				
185.1	Good Intraclastic			
186.6 / 186.8	Ripped Intraclastic GS	◊		
	Sill	x	~2.0	
188.0				
190.7	Columnar Strom.	Ω		
192.—				Deepening
	Intraclastic Grain	◊		
196.8	Cyclic Fenestral / Good Intraclastic		Cyclic @ Top	Deepening
197.9	Columnar Strom		Rapid Shallowing	
	Thrombolite - Mixed CG			
200.6	Cyclic Fenestral			Deepening
	Ripple Cross Grainstone			
	Columnar Strom		Rapid Shallowing	
	2005-2016 Sill			
	Thrombolite - Mix/CG			
206.0	Gy Frag Columnar Strom			Deepening
	Thrombolite - Mix/CG		Shallowing Seq.	
210.1	Sill	x	~1.5	
211.0				
	Thrombolite - Mix/CG			
221.1 / 221.4	[illegible]			
	CG & Mix - Thrombolite Barrel			
	[illegible]			
226.3				
	Thrombolite Barrel - CG Mix			
230.0 / 230.5	Ash Marker			
233.6	Recrystallised Sand			
234.3				
	Sill	x	~32	
237.5	Recrystallised Gy			
239.—	Thrombolite - Mixed -			
239.7 / 239.2	Recrystallised Glyte			
	Glyte [Crossed Ctng Bhm]			
241.6	Wide Bhm			

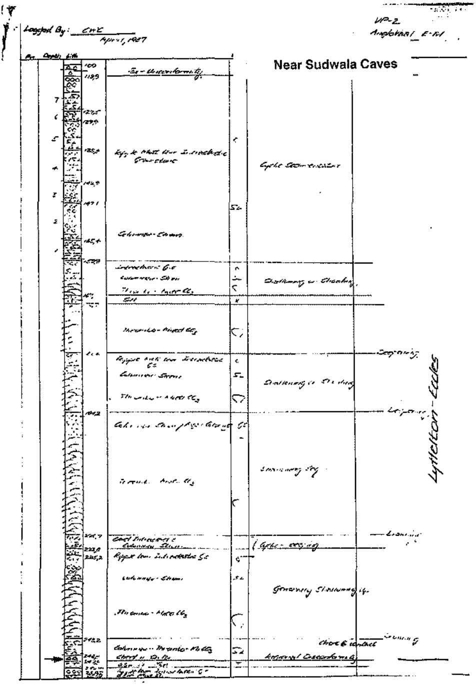
Upper Oak Tree

[illegible]

Cl+Cr.



Logged By: EWC
CM 11B
Near Springs
Notes:
Sill
Shallowing, up Cycles
Shallowing, up Cycle
Sill
Upper Oak Tree


Logged By: CNE
April, 1987
VP-2
Near Sudwala Caves
Lyttelton - Eccles

YP-2
A+ E. Tel.

Logged By: CWE
April 1987

Depth	Description	Struc.	Interpretation	Notes
252.2 – 258.7	Coar Intraclastic	o	Cyclic Sedimentation (Shallowing Up.)	
	Columnar Strom.			
258.7 – 264	Coar Intraclastic	o	Cyclic Sed.	
264 – 266.9	Cyclic Pentalad / Intraclastic GS	o	Gen Shallowing Up.	
266.9 – 272.4	[illegible] Intraclastic GS			
272.4 – 277.6	Silt			
277.6	Intraclastic GS			
	[illegible]			Deepening
	Intraclastic GS / Columnar Strom.	o	Cyclic Sed	Deepening
288	Intraclastic GS / Columnar Strom. / Thrombolite – Hard Gy	o	General Shallowing Up. Seq.	Deepening
297.7 – 306.2	Sand Intraclastic (Minor type [illegible] Columnar Strom)	o	Cyclic Sedimentation	Note: [illegible] thicker and [illegible] deepening [illegible]
306.2	Sand Intraclastic GS / Columnar Strom / Thrombolite – Hard Gy	o	Gen Shallowing Up. Seq.	Deepening
315.7 – 317.5	Silt			
317.5 – 349.7	Coar Intraclastic [illegible]	o	Cyclic Sedimentation [illegible] — Note [illegible]	
349.9	Oncol [illegible]		Apparent Unconformity	
351.0 – 355.7	Intraclastic Grain / Columnar Strom	o	Shallowing Up.	
355.7	Intraclastic Grain / Columnar Strom – Elongated GS / Thrombolite – Hard Gy	o	Gen Shallowing Up. Seq.	Deepening
365	Lt Gy Uniform Fed. Intracl. GS	o		
370.6	AT [illegible] Intraclastic Grain Cycles / Seq. [illegible]	o	Cyclic Sed – Intertidal [illegible]	

Upper Monte Christo

Logged By: LWC

April, 1987

TP-2

Arg. [illegible] E-Tul.

Fm	Depth	Lith		Descr.	Struct		Notes
			372.5	Mott. Intraclastic Grain	o		
				Stack – [illegible]	Sc.		
				[illegible] G.S			
			387.9	Intraclastic Grain [illegible]		Chert [illegible]	Transition Surface
				Thrombo- [illegible]		[illegible] Shallowing Up. Seq.	
			395.2	Silt	x		
			416.9	[illegible]			
			429.4	[illegible]		Note: [illegible] No Cycles [illegible]! [illegible] Environment ? Could be [illegible] G.S ([illegible])	Lower Monte Christo
				Columnar Strom.? [illegible]			Deepening ???
				[illegible]	o		
			438.4	Intraclastic Grain Columnar Strom. – (Solitary)		Shallow Cycles	
				Thrombo [illegible]		[illegible]	
			449.0	Stack – [illegible]			Drowning
				Intraclastic Grain [illegible]		Shallowing Up. Seq.	
			452.5	[illegible]		Regional Disconformity	Erosional, [illegible]
			456.4	Thrombo- [illegible]		Intergr. [illegible]	
			462.7	[illegible]		[illegible]	Deepening
			464.8	[illegible]		Cycle Set	
			466.5	Graded – [illegible]		[illegible]	
			469.4				
			470.4				
			471.7			[illegible] (A [illegible] cycle)? Top	
			475.6				
			476.1	Clean, [illegible] Grainstone		Sed. Change ? Tectonic Influence	
			479.0	Silt	x		Upper Oak Tree
			483.4	Clean, [illegible] Grainstone			
			497.9	Silt	x		
			504.9	[illegible]		[illegible] Surface [illegible]	
			507.5	Stack – [illegible]		Cycle Sets — not Shallowing Sequence [illegible]	Contact Abrupt
			511.1	Graded – [illegible]		[illegible]	
			516.3	[illegible]			
			516.9			Intergr. Back Reef / [illegible] Contact. Note: [illegible]	

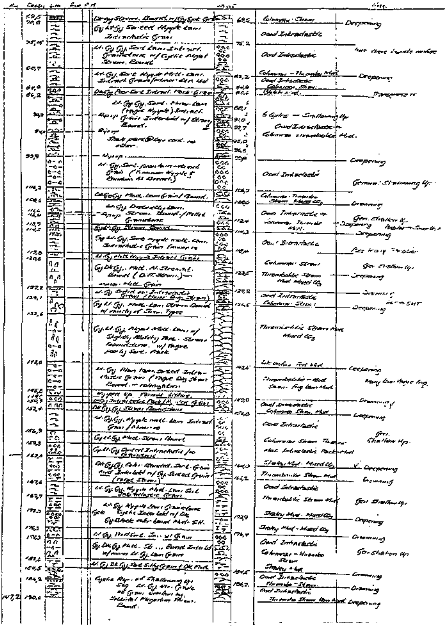
Core #: 7F-5

Company: [illegible]

Location: [illegible]

Logged By: CWC

Near Pilgrims Rest



Hole #: 7F-5   Company: E...d Exler   Location: E-Timiskami... / Pilgrims Rest

Logged By: CIYC   Page #2   Gen. Strat. Section / Long Hole   1:500

Fm	Core	Description
	190,0	Lt Gy-Gy, Mott. Strom. Bound w/ Gy Gyl. Mott/Pack infill
	192,4	Dk Gy Silt & Color Banded Sort. Grain
	193,4	Gy Sort. plan. Inv. Grains upward to Lt Gy Sort. Strom. Bound
	195,7	Gy Lt Gy, Mott. Strom. Bound.
	197,0	Dk Gy Silt. Mud / Color Band Sort. Gra...
140,5	198,0	Lt Gy Sort. Ripple Grainstone
	199,0	Lt Gy Gy Strom. Bound & Gy Mott. Grainstone
	202,5	Lt Gy Strom. Bound into Gy Sort. Mott. Grain
	204,5	Gy Lt Gy Strom. Bound into Gy Sort. Mott. Lam. Grain
	208,2	Dk Gy Columnar Frag Strom & Gy Mott. Grain
	213,2	
	214,2	Minor Strom. Bound & Sh. cont.
	217,0	Dk Gy, Well Sorted Intraclastic Gr...
		Lt Gy Gy, Mott. Uniform Crystalline Changing ... to ... Grainstone
110,5	225,0	Dk Gy Black Silty Shale / Laminated
	227,1	Lt Gy Gy Sort. Uniform Text. Int. Grain
	229,0	Gy Lt Gy Gy, Mott. Rbbls Lam. Algal Columnar Grain / Strom Bound (Knoblau Hum...)
	235,8	Lt Gy Gy, Mott. Lam. Uniform Text Sorted Intraclastic Grain
	239,2	Lt Gy Gy, Rbbls Mott. / Rbbls Lam. Vague Strom. Bound / Gy Sorted Uniform Text. Intracl. Grain
	241,6	
	246,1	Lt Gy Gy Uniform Text Sort. Vaguely Lam. Intraclastic Grain (Local Dev. of Vague Strom Frag)
Not to Scale	257,1	Gy Lt Gy Rbbls, Mott. Vague Strom. Bound
	259,8	Gy Lt Gy Sort. Uniform Text. Grain
	261,0	Dk Gy Gy Strom. Boundstone w/ Lt Gy Gyl. Wacke / Pack infill
	264,0	Lt Gy Gy Sort. Uniform Text. Mott. Intraclastic Grain
	267,6	Dk Gy Gy, Mott. Strom Bound w/ Gyl. Wacke / Pack Infill
	271,1	Lt Gy Gy, Sort. Mott. Rbbls Lam. Intraclastic Grain Minor Strom. Bound
	276,1	Dk Gy Lt Gy, Rbbls Mott. Lam. Strom. Bound / Grain
	278,0	Lt Gy Uniform Text. Sort. Intracl. Grain
	281,7	Gy Dk Gy Mott. Strom. Bound / Grain
	283,5	Lt Gy Gy, Mott. Lam. / Rbbls Intraclastic Grain / Strom. Bound
297	287,5	Dk Gy Frag Columnar Strom. Bound / Ripple Lam. Intraclastic Grain
	290,8	Dk Gy Col. Strom. Bound / Grain
	292,2	Dk Gy Col. Strom / Grain
	294,3	Lt Gy Mott. Strom. Boundstone
34,8	298,4	Lt Gy Gy Sort. Uniform Text. Minor Lam. Intraclastic Grain
	305,5	Dk Gy Rbbls Mott. Strom / Grain
	307	

Strat.	Interpretation	Notes
190	Columnar Thrombolitic Strom. Mud / Shaley Lam. Mud	
193,4	Thrombo. Strom. Mud / Shaley Lam. Mud	Deepening
198,1	Algal laminated - Grain / Columnar Strom / Mott. Lam. Mud Thrombo	Shoaling; Smooth Mat
207,7	Cond. Intraclastic / Columnar Thrombo. Strom. Mud	Shoaling
214,2	Shaley Lam. Mud	Deepening
	"Intraclastic" / Shaley Mott. Lam. Mud	
221,7	Thrombolitic Mud / Shaley Mott. Lam. Mud	Deepening
225,1	Lt Gy Mott. Lam. Chalky Mud	Deepening
232,7		Shoaling ? ←
235,0	Thrombolitic Strom. Mud - Micrite	
242,6	Cycle Period / Cond. Intraclastic / Columnar - Thrombo	Major Shoaling — Upper
249,0	Cond. Intraclastic	Deepening
257,2		
255,6	Columnar Strom. F.I. / Cond. Intraclastic	Deepening
265,9	Columnar - Strom / Thrombolitic Strom. Mud	
279,4	Cond. Intraclastic	Shoaling
280,7	Columnar Strom / Thrombolitic Stromatolite	
291,5	Columnar Strom / Thrombolitic Strom	Deepening
305		

Hole #: 71-5 Company: Rand E Location: E-7v1

Pilgrim's Rest

Logged By: CWC

Page #3

Re-evaluation of Monte-Cristo/Oak Tree

General Strat Section

Long Hole

1:500

Lyttelton/Leckie

Monte Cristo/Oaktree Depo Package

Depth	Description	Struct. depth	Interpretation	Notes
307,0	Lt Gy Dig/Strom Bound Grain			
308,4	Gy/Lt Gy Irregularly Ripple Lam. Srt Intraclastic Grainstone	308,5	Columnar Strom	stable
313,2				
315,7	Dk Gy, Mott. Bladed Text Strom Bound / Lt Gy, Lam with Sorted Intraclastic Grainstones	318,5 / 318,7	Stromatolite Sand	Deepening
318,6			Coarse Intraclastic	
320,3		320,8	Columnar Strom	Deepening - Cycle
322,6	Gy Dk Gy Sorted Uniform Text. Shale Mott / Lam Intraclastic Grainstone.		Thrombolitic Strom Mud.	
		324,1	Thrombo - Shaley Lam Mud	
		327,0		
		329,3	Shaley Lam Mud	
332,7	Lt Gy Gy Gritty Strom Bound.		Thrombolitic Mud	Deepening Up
334,6	Dk Gy "Massive" Silty Shale	334,7	Columnar Strom	
337,2	Gy Dk Gy Thrombo. Mud	337,2	Shale	Transgressions
338,2	Lt Gy Silicified/Sub-L Quartzite	338,2	Thrombolitic Mud	
341,0	Dk Gy-Lt Shale (Qtz Band)		Black River Gp / Black Edge type Contact.	
342,0	Lt Gy Gy Strom. Lam & Crinkle Lam, Boundstone (Minor Lt Gy Sorted Grain	345,6	Coarse Intraclastic → Thrombolitic Mud.	Deepening
		348,2	Columnar Strom → Thrombolitic Mud	
350,7	Lt Gy Gy Ripple Mott Lam. Sorted Intraclastic Grain 1-2 mm Pepper grains.	351,7	Coarse Intraclastic Depo Cycles 352,7 / 358,4 / 361,4	Drowning
361,7	Lt Gy, Mott. Layers of Strom Bound Interbeds w/ Lt Gy, Buff. Sorted Intraclastic Grainstone.	361,7 / 364,3 / 367,2 / 369,9 / 371,3	Mott Cycle Peritidal Strom & Ripple Mud. Coarse Intraclastic	Deepening; ← General Shallowing Up Cycle
364,3				
367,2				
369,8				
373,9	Intrusive Ig. Sill	373,9	Sill.	
375,3	Lt Gy, Mott. Lam Rippled on Intraclastic Grainstone	375,2 / 380,3	Coarse Intraclastic; Coarse Intraclastic (Ripple Mott)	Deepening; Minor High pts ? MK
383,5	Lt Gy Gy Strom / Crinkle Lam Bound	384,1	Columnar Strom → Al. elongated Grain	Small Mat type
385,0	Lt Gy Bleached Intracl. Grain	385,6		Deepening
387,7	Lt Gy Lam (Lam & Grainy) Strom Bound	387,7	Coarse Intraclastic	
391,0	Gy Lt Gy Crinkle Lam Bound/Grain	391,0	Columnar → Al. elongated Grain	Hist. type mat
392,3	Dk Gy Dig Fig Strom Bound/Grain		Columnar - Lam Thrombolitic Strom Mud	Grain. Shallowing Up
394,4	Gy Lt Gy Irregular Fig Srt Intracl Grain			
396,5	Dk Gy Columnar Strom Bound & Gy Sorted Grainstone	396,5	Columnar Strom Minor Thrombo. Mud	Deepening; Stable
409,8	Lt Gy Gy Sort. Mott/Ripple Lam. Intracl. Grain	409,8	Coarse Intraclastic 406,6	Drowning; Cycle
408,2	Gy Lt Gy Bladed Mott Lam Strom Grain / Lt Gy Fig Strom Bound	409,5 / 412,1	Columnar → Al. elongated Grain	Smooth Mat type
			Thrombo - Strom Mud Cy	
416,7	Gy Lt Gy Dig Strom Bound	416,6	Shaley Mud	Deepening
422,2	Lt Gy Gy Mott. Strom Bound	422,2	Thrombo Strom - Mixed Cy	? Shallowing
424,6	Lt Gy Buff White Srt Mar Lam. Intracl fine Grain	423,5	Thrombo Strom Mixed Cy	Break & Sudden Drowning
			Coarse Intraclastic	
436,4	Lt Gy Gy Lam Grainy Strom Bound	436,7	Al. elongated Columnar	Smooth Mat type — Deepening
439,6	Lt Gy Gy Dig Strom Bound		Coarse Intraclastic Columnar Strom	Smooth Mat type; Stable
440,7	Lt Gy Buff White Bleached Intracl. Grain	441,8	Thrombo Mud - Mixed Cy	Drowning
445,2	Lt Gy Buff Strom Bound.		Coarse Intraclastic	
446,6		446,6		Smooth Mat

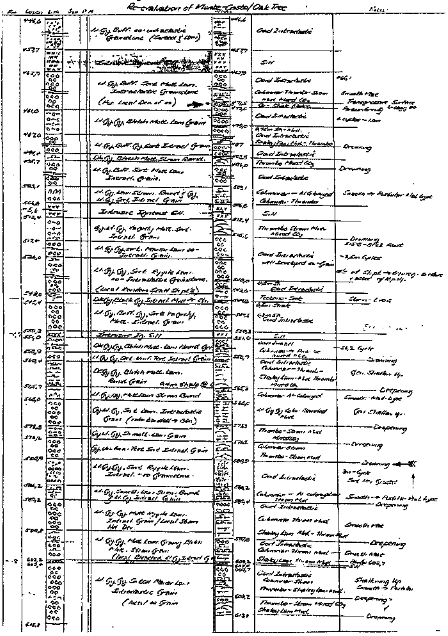
Well #: 7F-5 Company Rand Exter Location E-7x1

Pilgrim's Knot

Logged By: CWC Gen. Strat. Hole 1:500

Page #4

Re-evaluation of Monte Cristo/Oak Tree



Core #: 7F-5 Company Knud Lieder Location E-T1

Logged By: EWC General / Strat. Section 1:250

Page #3

Re-evaluation of Monte Cristo / Oak Tree

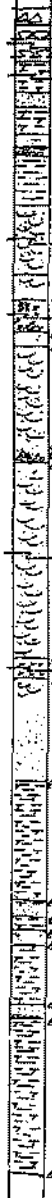
Depth	Description	Strat. depth	Strat.	Notes
615,8	Lt Gy Gy, Rblcls Mott Lam. Strom. Bound	613,2	Ooid Intraclastic – Columnar Strom	
619,2	Gy Lt Gy Lam. Pseudo Banded Pell Ost. – Mot Intraclast Grain	615,8	Ooid Intraclast. Columnar Strom. Thrombo Intraclastic	Deepening
		619,2	Shaley Mud	
624,1	Gy Lt Gy, Lam Strom Mound Mud; Lt Gy, Lam Sorted Intraclastic Grainstone	624,1	Thrombo – Mixed Cly; Shaley Mud	Draining – Deep. Pisolitic Type Mat
626,3		628,2	Shale, Mud – Deep Smooth Mat	Draining
631,9	Dk Gy, Wavy Shaley Lam Mud-Wack w/ Lenses of Grainstone	630,5 / 631,6	Ooid Intraclastic	
633,9 / 634,3	Gy Lt Gy Clastic Wacke-Pack.		Shaley Mud – Thrombo – Mud	Reverse Cycle Shallow Deep → Shallow Deepening
636,3	Dk Gy, Lam. Lt Mott. Grain Strom.			
	Gy Lt Gy, Sort Mott Ripple Lam Grain – Lenses of sorted, sub-rounded Intraclasts	639,3	Ooid Intraclast. → Thrombo Mud	
644,7		639,8	Columnar Strom	Deepening Smooth Mud –
5,9	Intrusive Igneous Sill	644,7	Sill	
647,6	Lt Gy Gy 'Grey' Lam Strom Bound	647,6 / 648,6	Thrombolite Strom Mud; Columnar Strom	Deepening
651,0	Gy Dk Gy Mod Lam 'Pseudo-banded' Intraclastic Pack-Grain	652,0	Shaley Pack – Mud	Deepening
654,2	Lt Gy Gy Delicately Lam. Strom Bound – Mud Lam – Intraclastic Grain	654,2	Shaley Lam Mud	
658,4	Gy Lt Gy, Wavy Mott Lam Intraclastic Grainstone.	659,6	Shaley Lam Mud.	Deepening
			Thrombo Mixed Cly	? Sand 662,5
664,2	Lt Gy Delicate Lam Strom Bound; Gy Lt Gy Intraclastic Wacke-Pack.	662,6	Thrombo Mixed; Shaley Burrowed	Deepening?
665,5	Gy Dk Gy Mott. Planar Lam. Intraclastic Pack-Wack			
670,4	Lt Gy Very Uniform Text. Mott w/ Traces of Grain & Ins Shale bnd Mud	670,5 / 671,0	Ooid Intraclastic	Draining Diastem?
673,	Lt Gy Gy Mott. Lam Strom Bound		Shaley Lam Mud	Go Transgr
675,4	Lt Gy, Mott. Mud-Wacke			
677,5	Lt Gy Gy Lam. Mott Mud-Pack	677,4		Deepening
683,4	Dk Gy Dk Shale / Lam Mud.	683,4	Shaley Lam Mud – Shale	
685,7	Black Reef Graded Quartzite	685,7	Black Reef Quartzite	
		691,7		

Logged By: C. Henry & CWC

1:250

Near Pilgrims Rest

Kn Depth Lith



Strat

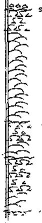
- 759,1 / 759,6 — Qz Qv?ein; Calcimagan St
- 764,0 — Gy/Gy Matt Lam Mdst — CC_3 T
- 770,4 — Gy Gritty Glyerenite
- 771,1 — Lt Gy/Gy Matt. Lam Mdst — CO_3
- 772,5 / 773,4 / 773,6 — Mx Ty-Dk Gy Lam Glyerenite & Silt; Gy Pebble Cong 2-5mm Py
- Gy-Black Silty Mud
- 776,2 — Gy-Dk Gy, M-Gritty Trough lam Glyerenite — small rd peb + lam.
- 783 — Grit — Inc.
- 794,4 — Sill — x
- 814,7 / 815,4 — Coarsening up Silt - Glyerenite
- White, Gritty Glyerenite — Trough lam — Small (2-3mm) pebbles on foresets ? Coarsening up
- 821 / 821,4 / 821,9 — Sm. Pebb Cong — Black Reef / Ilokberg
- Gy-Dk Gy Trough x/lam f-med gr Glyerenites
- 843,6 / 845,1 — Sill — x
- Gy-Dk Gy M-fn gr Glyerenite
- 850,4 — Gy-Dk Gy, Wavy-Matt lam Mdst Silt — "Iclimo Rk"
- 857,1 / 858 / 858,6 / 859,4 — 0,2m Gy; 6mm Gy
- On thick unit + silty knees of loral conc @860,6
- Common 'desiccation cracks'
- 863 / 863,7 — Sm pebble Cong + Glyerenite — Short flushes + fining up seq.
- 870

Upper Oak Tree Bdg

May 15, 1987

Gen. Notes on Ly. Fm.   KRB-1

Near Bothaville



971.2   Bx-clast @ base.

Brief Stabling

Threnke-Mixed Cg (Mud-lk)

1097   Major Textural Change

Cyclic.

1140   Assigned

Mixed Environment. — Cyclic between Columnar Strom & Thrombolite

1178   Erosional Contact

pprox 230 m thick — slightly thicker one sections to N.

Note: Hole appears to have erosional contact of ~30° w/ under-lying MC. Fm.

There is an inc. in chert content toward contact, but slump bd's & chert-in-shale bx's are not present (Both are in MTV-1)

Note: Two lower units are present (1 assigned on texture change)

Cyclic transgression into p. applies.

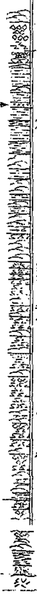
Note: Upper contact placed on Bx not on chert content.

Near Bothaville

March 5th, 1987

Anglo-Am. [illegible]

Oak Tree Section: So Vaal Rv. — No Stak to Log —



1913,0 — Thrombo - Mx CO_3 Transgression — Stand. Drowning

Ood Intraclastic - Gs. — Stand. Gen Shallowing Up. Seq.

1926 — Ood Intraclastic Col. Strom - Thrombo

1932,6 — Basin Stable

Silty Gs.

1946,5 Thrombo - Mxed CO_3

1947,3 Silty Gs

1949,44 - 49,56 Ash Mkr

Silty Gs

1953,8 Sh. - Silty Gh.

1954,4

Silty Gs. — Basin Floor Seds Storms & Turbs

1959,5 Thrombo - Mx Silty Gs.

1962,4 Thrombo - Mx CO_3 — Interp. Texture Seds by Comparison

1968,-

1973,6 Silty Gs Thrombo - Mx CO_3 1977,7 Sh. Brec.

1974,8 Silty Gs

1979,0 Thrombo - Mxed CO_3

1981,7 Silty Gs. — Float

1982,7 Thrombo - Mixed CO_3

1988 — Slump — Db - Flow — Basin Unstable

1989,5 — [illegible]

Thrombo - Mxd. CO_3 — Deepening (slot?)

2001,9 — Intracl GS/Col Strom — Drowning Cycle Seds Deepening

2005

2007,5

2011

Col Strom, Thrombo Mx CO_3 — Stand

Mxd - Mx CO_3

2021,3 Col Strom, Thrombo Mx CO_3 — Deepening

2035,1 Col Strom Thrombo Mx CO_3 — Cycle Seds Stand

2036 0,21 Rip-up Br

2041,2 Col Strom, Thrombo Mx CO_3

2047,5 — Drowning Up Strata

Intraclastic Gs

[illegible], Thrombo - Mx CO_3

2053,7 — Deepening

Colum. Strom, Intracl Gs.

2069

2071,4 Thrombo [illegible] — Drowning

Intracl Gs [illegible] Strom.

2076,2 — Cycle Seds

Intracl Gs - Thrombo.

2081

Intraclastic Gs.

[illegible] Strom - Thrombo

[illegible] Mx CO_3

2089,2 Thrombo Mx CO_3 — Deepening

2090,9 Sh - Mxd CO_3

2092,7 — Intraclastic Gs, Col Strom — Drowning

2096,3 — Deepening

2099,2 [illegible]

2096,3 Intraclastic Gs — Thrombo - Mxed CO_3

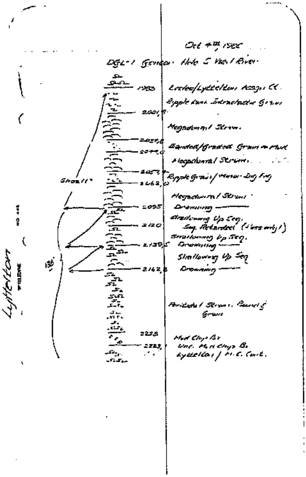
2204,8 Sh - Mx - CO_3 —

2214,5

2207,6 Sh - fam Sand — No dist. bds

Ventersdorp Lavas —

Near Bothaville

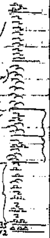


Koster W

Oct 14, 1985

Syndepositional Tectonics based on
Superposition of Eq. Lithotypes

BH 77/4/72 drilled E of Koster
on farm Zeekoeiesfontein



Uniform Contact
1213 – Lyttelton / Eccles Cont.

U. Gy. Ripple Mud Lam Gran.

1248

1284 (Mn Shallow)

Subtidal Below W.B.

Megaflora / Dig Mud.

Regional Event

1326,2 – Drowning

Shallowing Up Seq.

Pass. Single Event

1353,1 – Drowning

Shallowing Up Seq

~1372 – Drowning

115,3

Polch Member

1385,6 – Drowning ??

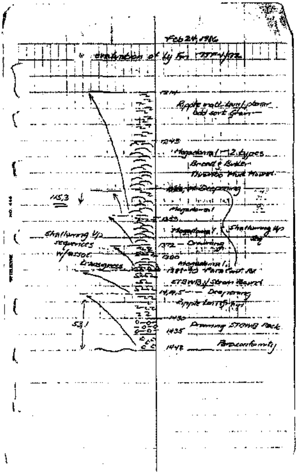
U. Gy. Ripple Gran. / Round
Shallow Peritidal Platform

1435
1442

Mud Clys Bx

Lyttelton / Mk

Koster W


Feb 24, 1986
Ripple xstl. lam / planar
1245
Brand & Baker
115.3
Shallowing Up sequences
Shallowing Up
1372 — Ondrinng
1380
ETB W/B / Strom Board
1441.5 — Deepening
1430
1435
53.1
1442
Paraconformity

Near Pilgrims Rest

Tues June 9th, 98

Pilgrims Rest

[illegible]

Lateral correlations in [illegible] upper [illegible]

[illegible] to E.

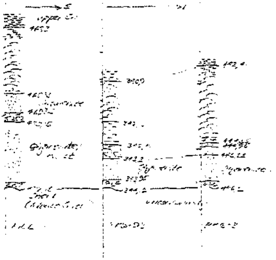
Note: upper Sh [illegible] in field, but [illegible]

[illegible]

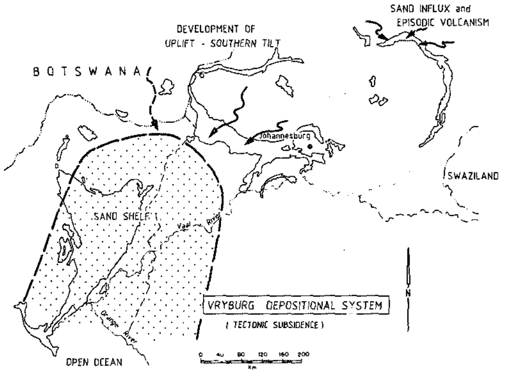
Note: A reworked erosion [illegible]

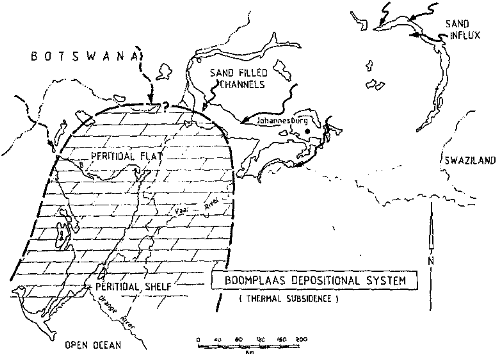
[illegible]

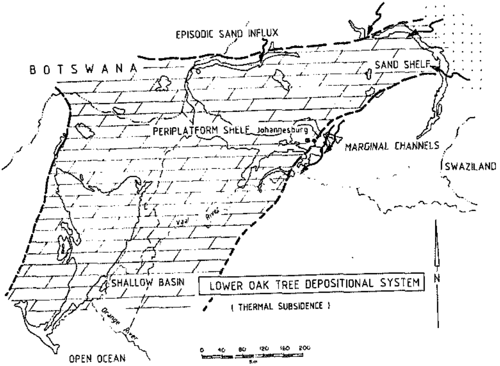
Interp. — [illegible] transgressed & reworked onto [illegible] floor.



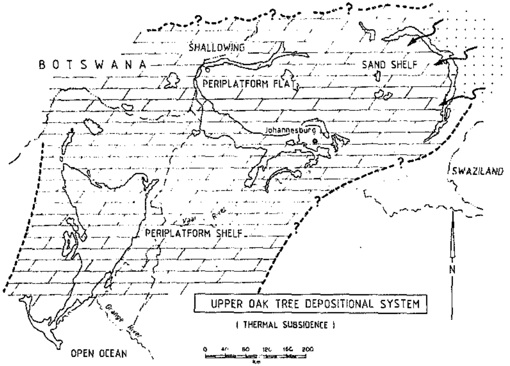
Appendix B


SAND INFLUX and
EPISODIC VOLCANISM
DEVELOPMENT OF
UPLIFT - SOUTHERN TILT
B O T S W A N A
Johannesburg
SWAZILAND
SAND SHELF
Vaal River
Orange River
OPEN OCEAN
VRYBURG DEPOSITIONAL SYSTEM
(TECTONIC SUBSIDENCE)
0 40 80 120 160 200
Km
N


BOTSWANA
SAND FILLED CHANNELS
SAND INFLUX
Johannesburg
SWAZILAND
PERITIDAL FLAT
Vaal River
PERITIDAL SHELF
Orange River
OPEN OCEAN
BOOMPLAAS DEPOSITIONAL SYSTEM
(THERMAL SUBSIDENCE)
N
0 40 80 120 160 200
Km

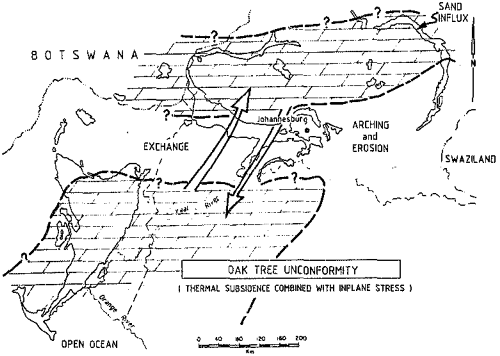


EPISODIC SAND INFLUX
BOTSWANA
SAND SHELF
PERIPLATFORM SHELF
Johannesburg
MARGINAL CHANNELS
SWAZILAND
Vaal River
SHALLOW BASIN
LOWER OAK TREE DEPOSITIONAL SYSTEM
(THERMAL SUBSIDENCE)
N
Orange River
OPEN OCEAN
0 40 80 120 160 200

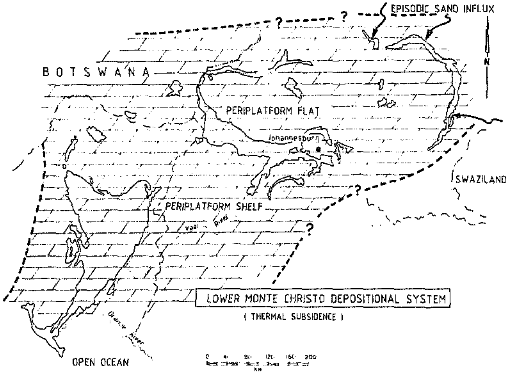


UPPER OAK TREE DEPOSITIONAL SYSTEM

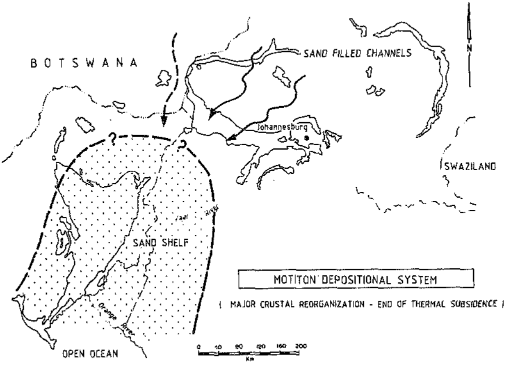
(THERMAL SUBSIDENCE)



SAND
INFLUX
N
BOTSWANA
Johannesburg
ARCHING
and
EROSION
EXCHANGE
SWAZILAND
Vaal River
OAK TREE UNCONFORMITY
(THERMAL SUBSIDENCE COMBINED WITH INPLANE STRESS)
Orange River
OPEN OCEAN
0 40 80 120 160 200
Km

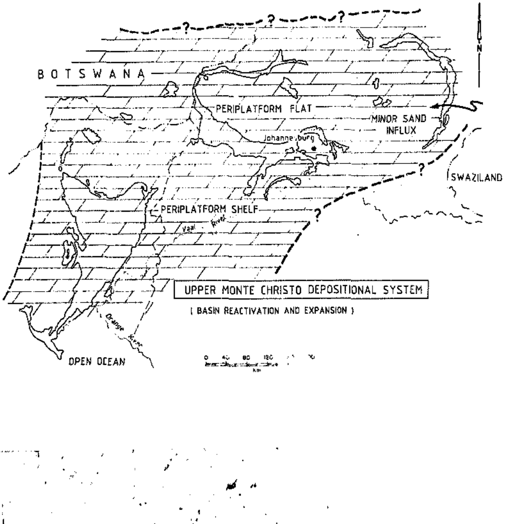


EPISODIC SAND INFLUX
N
BOTSWANA
PERIPLATFORM FLAT
Johannesburg
SWAZILAND
PERIPLATFORM SHELF
Vaal River
LOWER MONTE CHRISTO DEPOSITIONAL SYSTEM
(THERMAL SUBSIDENCE)
OPEN OCEAN



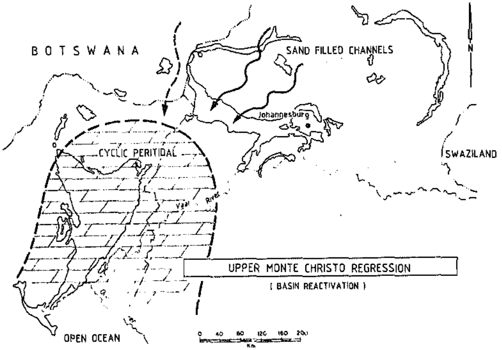
MOTITON DEPOSITIONAL SYSTEM

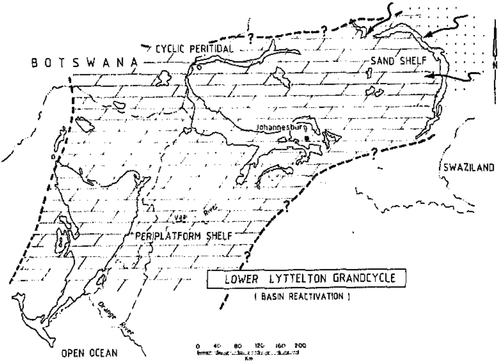
(MAJOR CRUSTAL REORGANIZATION - END OF THERMAL SUBSIDENCE)

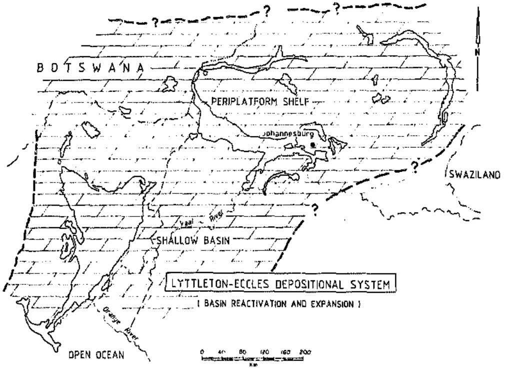


UPPER MONTE CHRISTO DEPOSITIONAL SYSTEM

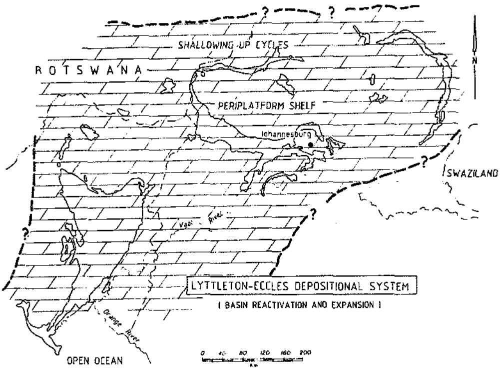
(BASIN REACTIVATION AND EXPANSION)

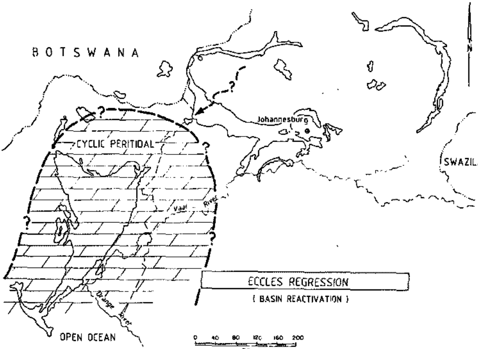

BOTSWANA
SAND FILLED CHANNELS
N
Johannesburg
CYCLIC PERITIDAL
SWAZILAND
Vaal River
UPPER MONTE CHRISTO REGRESSION
(BASIN REACTIVATION)
OPEN OCEAN
0 40 80 120 160 200
Km


CYCLIC PERITIDAL
BOTSWANA
SAND SHELF
N
Johannesburg
SWAZILAND
Vaal River
PERIPLATFORM SHELF
LOWER LYTTELTON GRANDCYCLE
(BASIN REACTIVATION)
Orange River
OPEN OCEAN
0 40 80 120 160 200
Km

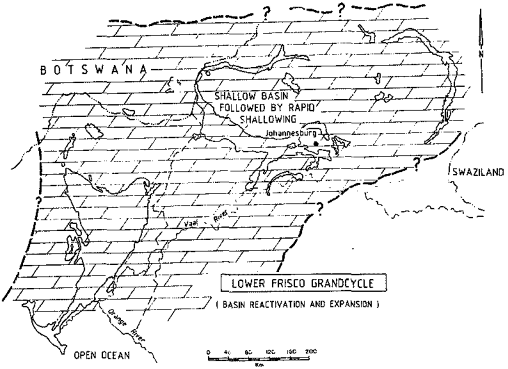


BOTSWANA
PERIPLATFORM SHELF
Johannesburg
SWAZILAND
Vaal River
SHALLOW BASIN
LYTTLETON-ECCLES DEPOSITIONAL SYSTEM
(BASIN REACTIVATION AND EXPANSION)
Orange River
OPEN OCEAN
0 40 80 120 160 200
Km
N

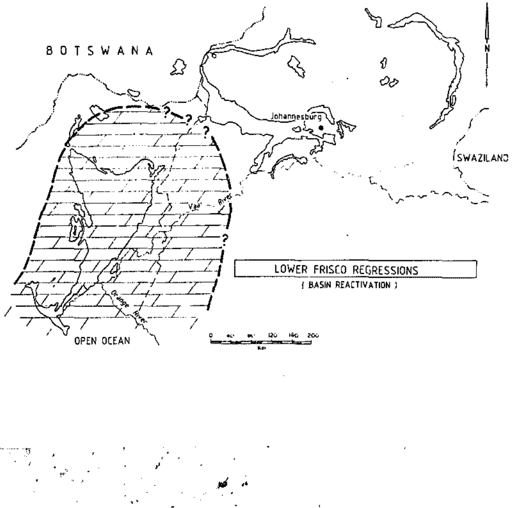

SHALLOWING-UP CYCLES
BOTSWANA
PERIPLATFORM SHELF
Johannesburg
SWAZILAND
Vaal River
Orange River
OPEN OCEAN
N
0 40 80 120 160 200
Km
LYTTLETON-ECCLES DEPOSITIONAL SYSTEM
(BASIN REACTIVATION AND EXPANSION)



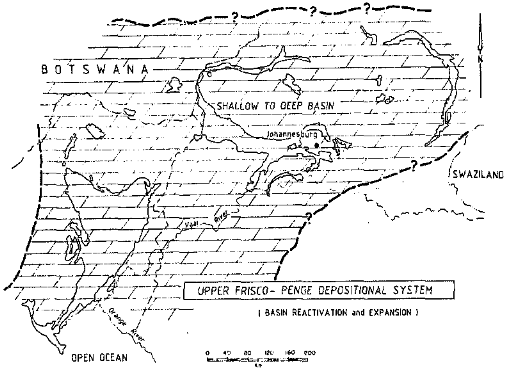
BOTSWANA
Johannesburg
CYCLIC PERITIDAL
SWAZILAND
Vaal River
ECCLES REGRESSION
(BASIN REACTIVATION)
Orange River
OPEN OCEAN
0 40 80 120 160 200
Km
N



BOTSWANA
SHALLOW BASIN FOLLOWED BY RAPID SHALLOWING
Johannesburg
SWAZILAND
Vaal River
Orange River
OPEN OCEAN
LOWER FRISCO GRANDCYCLE
(BASIN REACTIVATION AND EXPANSION)
0 40 80 120 160 200
Km
N

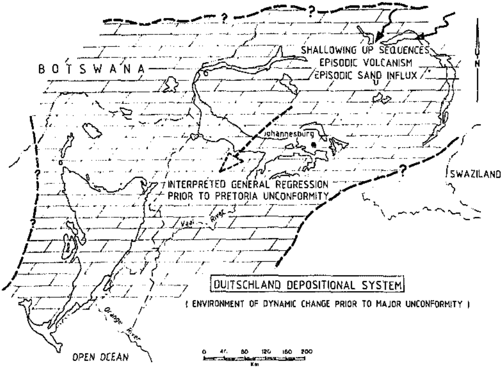


BOTSWANA
Johannesburg
SWAZILAND
N
Vaal River
Orange River
OPEN OCEAN
LOWER FRISCO REGRESSIONS
(BASIN REACTIVATION)
0 40 80 120 160 200
km



UPPER FRISCO- PENGE DEPOSITIONAL SYSTEM

(BASIN REACTIVATION and EXPANSION)



DUITSCHLAND DEPOSITIONAL SYSTEM

(ENVIRONMENT OF DYNAMIC CHANGE PRIOR TO MAJOR UNCONFORMITY)

Appendix C

Details of publications based on this text.

Full length papers:

Clendenin, C.W., Charlesworth, E.G., and Maske, S., 1988. An Early Proterozoic three-stage rift system Kaapvaal Craton, South Africa. Tectonophysics, 145, 73-86.

-----, 1988. Tectonic style and mechanism of Early Proterozoic basin development, southern Africa. Tectonophysics, 156: 275-291.

Clendenin, C.W., Charlesworth, E.G., Maske, S., Martin, D.McB., and de Gasparis, A.A, In Press. Structural evolution of the Early Proterozoic Ventersdorp Supergroup, southern Africa. Precambrian Res.

Extended Abstracts:

Clendenin, C.W., and Maske, S., 1986. Identification of syndepositional tectonics within the Transvaal sedimentary basin. Geocongress '86, Geol. Soc. So. Afr., p. 501-504.

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