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Stratigraphy and sedimentology of the middle Permian Abrahamskraal formation (Tapinocephalus Assemblage Zone) in the southern Karoo around Merweville, South Africa.

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STRATIGRAPHY AND SEDIMENTOLOGY OF THE MIDDLE PERMIAN ABRAHAMSKRAAL FORMATION (*TAPINOCEPHALUS* ASSEMBLAGE ZONE) IN THE SOUTHERN KAROO AROUND MERWEVILLE, SOUTH AFRICA.

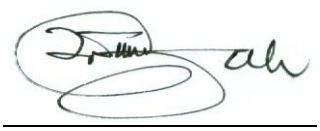
SIFELANI JIRAH

A Dissertation submitted to the Faculty of Science, University of the Witwatersrand, in fulfillment of the requirements for the degree of Master of Science.

Johannesburg, 2013

DECLARATION

I declare that this Masters project is my own unaided work, except as acknowledged in the text. Neither the substance nor any part of it has been submitted in the past, or is being submitted for a degree in any other University. The information used in this masters project was obtained by me while employed at the Bernard Price Institute for Palaeontological Research, Wits Uiversity, Johannesburg, during the period in which I was registered as a student in the school for Geosciences.



S. Jirah

26th day of June 2013

ABSTRACT

A study of the Abrahamskraal Formation in the area around Merweville, in the southwestern corner of the Karoo Basin has revealed the presence of traceable lithological units with lateral continuity throughout the study area. The stratigraphic section measured in this part of the basin matches the section measured by Jordaan, (1990) south of Leeu Gamka, with a basal arenaceous unit overlain by a predominantly argillaceous succession. The thickness of the Abrahamskraal Formation in this part of the Karoo Basin in 2565m, charactersized by a braided depositional environment in the lower 2075m and a meandering depositional environment in the upper 490m. Biostratigraphically the succession comprises a basal *Eodicynodon* Assemblage Zone which constitutes the lower 1104m and this is overlain by a 1461m thick *Tapinocephalus* Assemblage Zone whose upper limit is 21m below the Poortjie Member of the Teekloof Formation. This study has also corroborated the work by earlier authors who proposed a northeasterly palaeoflow direction as well as contributing to the global correlation of the Middle Permian terrestrial tetrapod faunas where the *Eodicynodon* Assemblage Zone correlates with the fauna from the Russian Ocher & Ischeevo; fauna of China's Xidagou Formation and Rio da Rosto fauna of Brazil while the *Tapinocephalus* Assemblage Zone fauna corrletaes with fauna from Mezen and Ischeevo in Russia, Posto Queimado fauna in Brazil and those from the Madumabisa strata of Zimbabwe.

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CHAPTER ONE: INTRODUCTION

1.1 Karoo Basin

The Karoo Basin is a retro-arc foreland basin developed in front of the Cape Fold Belt in relation to subduction of the Palaeo-Pacific plate beneath the Gondwana plate (Lock, 1978, 1980; Johnson, 1991; Winter, 1984). As the subduction took place underneath the basin, the Karoo qualifies as a retro-arc (Dickson, 1974) or retro-foreland setting (Johnson & Beaumont, 1995). During the Permian, the Karoo Basin comprised an east-west elongate foreland trough or retro-arc basin in which a thick sequence of molasse-type sediments accumulated under the controlling influence of the intrusive Gondwanide orogeny (Lock, 1978). The initial rapid down-warping of the basin in the Permian times was caused by isostatic compensation of crustal loading in the distant southern orogenic belt. Orogenesis had reached a peak during the Permian (Visser, 1978), and basin subsidence and sedimentation were accompanied by intermittent, weak volcanism (Martini, 1974). The balance between crustal down-warping in the depositional area and uplift of granitic and metamorphic core rocks in the source area is reflected in the thick pile of fine grained Lower Beaufort Group sediments that signifies no major change in palaeo-environment (Stear, 1983). Sedimentation within the Karoo foreland Basin was closely controlled by orogenic cycles of loading and unloading of the Cape Fold Belt (Catuneanu *et al*., 1998).

The main Karoo Basin forms the thickest and stratigraphically most complete mega-sequence of several depositories of Permo-Carboniferous to Jurassic age in south-western Gondwana (Catuneanu *et al.,* 1998) and is subdivided into five main groups, i.e. the Dwyka, Ecca, Beaufort (Adelaide and Tarkastad subgroups), "Stormberg" and Drakensberg (Figure 1.1). The maximum preserved thickness of this megasequence adjacent to the Cape Fold Belt exceeds 6km and the sedimentary succession reflects changing environments from glacial to deep marine, deltaic, fluvial and aeolian (Smith, 1990; Smith *et al*., 1993). Due to the lithological heterogeneity in different parts of the basin, different stratigraphic nomenclatures exist around the main Karoo Basin (S.A.C.S. 1980). Apart from the igneous rocks of the Drakensberg Group, the rest of the Karoo Supergroup is composed of sedimentary rocks. In the southwestern part of the basin, the continental rocks of the lower Beaufort Group were

deposited in a foreland basin which evolved between the Namaqua Craton in the north and the emerging Cape Fold Belt in the south (Loock *et al.*, 1994) which had a dramatic control on the fill of the sequence (Hancox & Rubidge, 2001; Catuneanu *et al*., 1998).

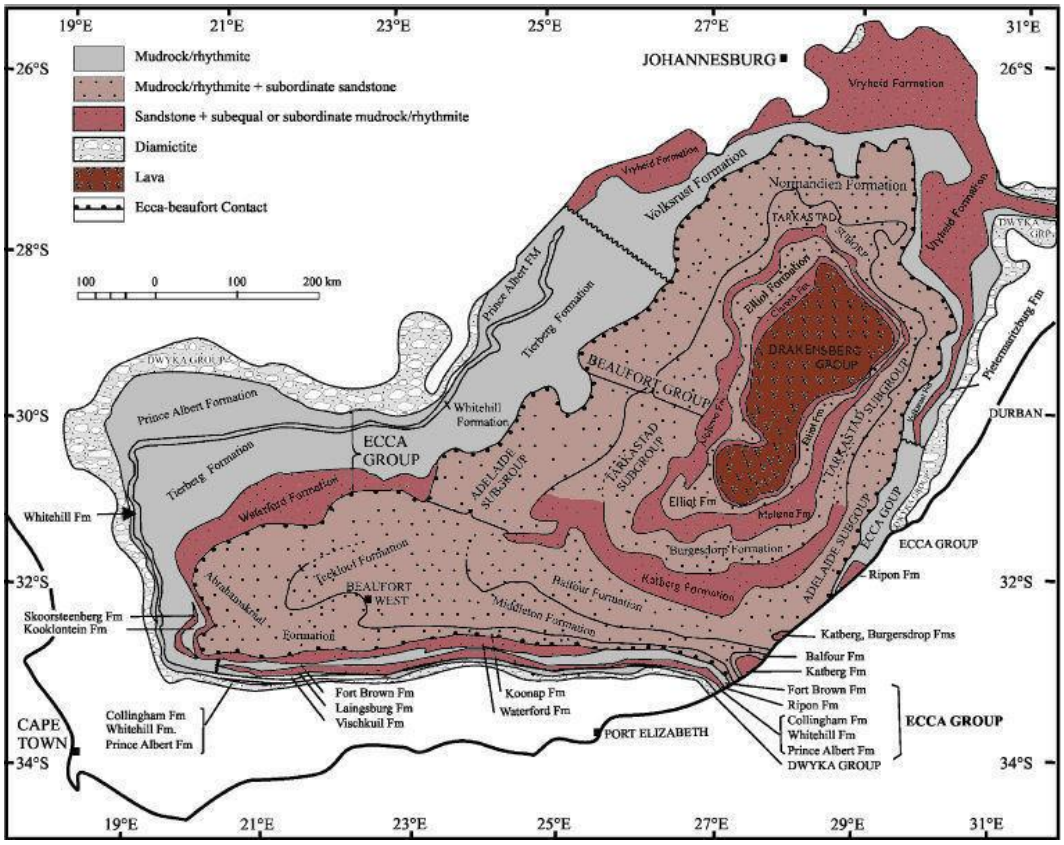


Figure 1.1: Map of the lithostratigraphic units of the Karoo Supergroup of South Africa (after Catuneanu *et al*., 2005).

1.2 Beaufort Group

1.2.1 Stratigraphy

The Beaufort Group is characterized by a monotonous sequence of mudstones, siltstones and lenticular sandstones. In the southwestern part of the Karoo Basin, various attempts have been made to define mappable units in the Lower Beaufort. The Karoo Working Group of S.A.C.S. (1980) accepted a two-fold subdivision comprising the Adelaide and Tarkastad Subgroups. West of 24°E the Adelaide Subgroup was further subdivided into a lower Abrahamskraal and an upper Teekloof Formation by Keyser & Smith (1977/78) who tabled a number of criteria distinguishing these two formations (Jordaan, 1990). The Abrahamskraal and Teekloof formations grade eastwards of longitude 24°, into the Koonap, Middleton and

Balfour formations of the eastern Karoo Basin (Figure 1.2) over a palaeohigh known as the "Willowmore Arch" (Van Eeeden, 1972).

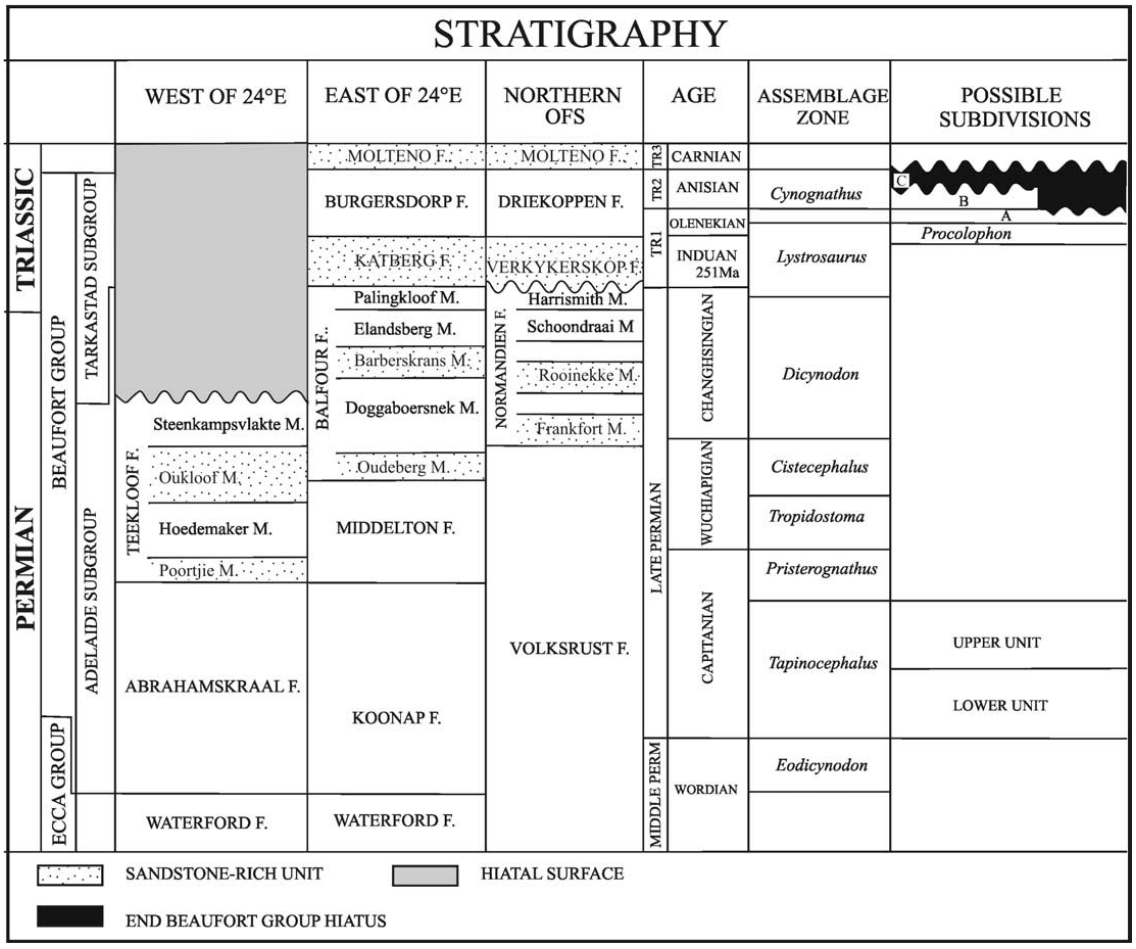


Figure 1.2: Relationship between lithostratigraphy west & east of longitude 24° (after Catuneanu *et al*., 2005).

Keyser & Smith (1978) place the contact between the Abrahamkraal and Teekloof formations above the Poortjie Sandstone. This was influenced by their observation that there is a change in faunal content between these two formations. Johnson and Keyser (1979) on the other hand used mudstone color to demarcate the contact and the base of the Poortjie sandstone is the contact.

In the southwestern Karoo Basin, sedimentation of the Beaufort Group was initiated in the middle Permian by uplift in the Gondwanide mountain-lands (Hälbich, 1983; Cole, 1992; Veevers *et al*., 1994c; Rubidge, 2005) and this resulted in the deposition of a fining upward succession of sandstones and blue and purple mudstones containing numerous thin "chert" bands and rich fossil fauna (Catuneanu *et al*., 2005). The presence of calc-alkaline volcaniclastic detritus and "cherts" of tuffaceous origin (Ho-Tun, 1979) suggests that the

provenance rocks in the southwest may have included an active andesitic volcanic chain located on the eastern side of the Andean Cordillera in South America and West Antarctica (Veevers *et al*., 1994c). This thick succession was deposited mainly by overbank flooding of large meandering rivers of variable sinuosity, draining an extensive alluvial plain sloping gently towards the northeast in the direction of the receding Ecca shoreline (Turner, 1978). Deposition in this part of the basin occurred under semi-arid climatic conditions as evidenced by the presence of pedogenic carbonate horizons and gypsum desert-rose evaporates (Keyser, 1966, Smith, 1990).

Various attempts have been made to recognize mappable lithological units of the lower Beaufort in the southwestern part of the Karoo Basin. The first attempt at a lithological classification of Beaufort beds was by Schwarz (1897) who referred to certain sandstone beds along the Nuweveld escarpment as either defining or intermediate sandstones. More recently "chert" beds have been used to demarcate stratigraphic units (Haughton *et al*., 1953; Rossouw & De Villiers, 1953). Rossouw & De Villiers (1953) mapped the area around Merweville and mapped out the Poortjie sandstone which has since been used as a marker bed. SACS (1980) considered the lower Beaufort in the southwestern part of the basin to comprise a lower Abrahamskraal and upper Teekloof formations.

1.2.2 Abrahamskraal Formation

The Abrahamskraal Formation forms the basal stratigraphic unit of the Beaufort Group in the south of the main Karoo Basin and follows conformably on the upper Waterford Formation (of the Ecca Group) with an abrupt basal contact which marks the Palaeo-shoreline (Rubidge *et al*., 2000). This formation (Abrahamskraal Formation) is distinguished from the overlying Teekloof Formation by a higher percentage of sandstone, less red mudstone, and the presence of chert bands (Keyser & Smith, 1978). Keyser & Smith (1978) summarized the criteria used to differentiate between the two formations and this is presented in Table I. Turner (1979b) suggested that the basal contact of the Teekloof Formation be placed at the top of the Poortjie Member, which he termed the Paalhuis Member and not at its base as proposed by Keyser & Smith (1979). SACS (1980) accepted the base of the Poortjie Member as the base of the Teekloof Formation.

Table I: Comparison of the Abrahamskraal and Teekloof formations (after Keyser & Smith, 1978).

Parameter	Abrahamskraal Formation	Teekloof Formation
1.Ratio of sandstone to mudrock (argillaceous sediments) by volume	1:2-1:3 (Turner 1975; Rossouw & De Villers, 1952)	1:4-1:6, locally 1:3 (Kübler 1977)
2.Mudstone colour	Blue-grey, purple and red. Reddish colours subordinate	Predominantly reddish-purple and brown. Grey blue-grey and green subordinate
3. Chert	Numerous discreet but laterally continuous lenses of green (red weathering) "chert"	Occasional small discrete lenses of cream coloured "chert". No lateral continuity
4.Lime-rich horizons	Present as beds of brown-weathering carbonate rich nodules (Rossouw & De Villiers 1952)	No carbonate rich "lime stone" beds recorded
5.Sandstone a.Geometry and size of lithosome	Lenticular plano-convex and tabular sheet sands. Individual outcrops up to 2km in length. Few small 1m thick developments	Lenticular plano-convex and biconvex sands. Individual outcrops less extensive with rapid tapering and splitting. Numerous small 1m thick developments
b.Texture	Predominantly fine grained. Some medium to coarse grained developments	Generally fine to very fine grained. No coarse sands
c.Boundaries of lithosome	Erosive base, shallow smooth scour profile, gradational upper and lateral boundaries	Erosive base, deeper scour more irregular (multiple scour), profile gradational and interlaminating upper and lateral boundaries
d.Organic content	Generally high content of coalified remains fragmented and disseminated throughout matrix	Platy carbonaceous minerals generally distributed through sandstone body
6.Vertebrate bones	Fossilised vertebrate bones commonly found in basal parts of larger sandstones	Fossilised vertebrate bones rarely found in sandstones
7.Clay-pebble conglomerate	Thick continuous developments occur covering the basal erosion surface of larger sandstone bodies. Bone fragments and calcareous nodules common and no extrabasinal material	Rapid fluctuation of thickness in accordance with irregular erosion surface. Bone fragments rare, intraformationally derived calcareous nodules common. Extrabasinal material rarely recorded
8**.** Broad depositional environment	Deposition by and in a high-sinuosity channel system with lateral flood plain. High rate of channel migration and abandonment, much crevassing and erosion of flood plain deposits	Predominantly flood-plain deposition. More permanent meander belts with large low-lying lateral flood plains drained by a network of ephemeral streams.

1.2.3 Lithostratigraphy

Lithostratigraphic investigation of the Abrahamskraal Formation has been neglected in the past mainly due to the vast thickness of this stratigraphi unit with estimates varying from 1400m (Stear, 1980) to 1810m (Keyser & Smith, 1979), its lithological homogeneity as well as intense folding of the strata to the south of the basin. Accordingly more focus was directed at biostratigraphic investigations (Jordaan 1990).

The first attempt at a lithological classification of Beaufort beds was by Schwarz (1897) who referred to certain sandstone beds along the Nuweveld escarpment as either "defining" or "intermediate" sandstones. The Poortjie sandstone has been used as a marker bed since it was first mapped in the Merweville area by Rossouw & De Villiers (1953).

With the recognition of megacycles in the Lower Beaufort (Winter & Venter, 1970; Le Roux *et al*., 1979; Stear, 1980), the possibility of dividing the Abrahamskraal Formation into mappable units emerged (Le Roux, 1985).

Stear (1980) made a detailed study of the sedimentology in an area bounded by longitudes 21°25'E-22°35'E and latitudes 32°15'S-33°00'S. He identified 7 upward fining megacycles in the Lower Beaufort. A megacycle is a regionally definable first-order cycle consisting of smaller second and third-order cycles (Stear, 1983). Each megacycle is hundreds of meters thick and consists of an arenaceous zone overlain by an argillaceous zone whereas the second-order cycles are local units, tens of meters thick that comprise the regular alternations of channel sandstone with overbank shale and smaller third-order cycles occur mainly in the overbank facies (Stear, 1983). Arenaceous zones are definable sandstone packages that consist of complex lenticular and sheet-like channel sandstone bodies traceable over tens of kilometers, inter-bedded with varying amounts of overbank siltstone and mudstone. Overbank deposits in these zones are often proportionally greater than the channel deposits and consist of siltstone and mudstone with only minor amounts of sandstone (Stear, 1983). These sandstone bodies in argillaceous zones usually occur as single-channel and splay bodies isolated in overbank deposits (Stear, 1983).

Stear (1980) named the uppermost of these megacycles the "Moordenaars Member" which contains a predominance of tabular shaped sandstone bodies up to 60m thick (Jordaan ,1990)

and caps the Great Escarpment from Komsberg Pass to Verlatenkloof in the Sutherland area. Palaeocurrent direction of this package is northeasterly (Cole & Wipplinger, 2001).
Le Roux (1978 , 1984) undertook an in-depth analysis of the lithostratigraphy of the area around the Klipbankskraal Uranium prospect on the farm Bullekraal 251 about 30km NE of Merweville as well as a 35km wide strip from the Steenkamsberg south of Fraserburg to the Moordenaarskaroo north of Laingsburg. This area covers the complete stratigraphic succession of the Lower Beaufort in the southwestern Karoo. The results of his work confirmed the presence of megacycles below the Poortjie Member. Overlying the Waterford Formation of the Ecca Group is an arenaceous unit which Le Roux (1985) proposed as the Combrinkskraal Member. Overlying this is an argillaceous Leeuvlei Member. The sequence continues with the Koornplaats, Wilgerbos, Moordenaars and the Karelskraal members and this sequence capped by the Poortjie Member of the Teekloof Formation. Le Roux's study covered only the lithostratigraphy and ignores biostratigraphy.

Jordaan (1990) measured a section on the farm Combrinkskraal, south of Leeu-Gamka. He proposed the Combrinkskraal and Leeu Gamka members as making up the Abrahamskraal Formation in this part of the basin. His Combrinkskraal member is an arenaceous unit attaining a thickness of 1916m. The Leeu Gamka member constitutes the upper part and is about 600m thick and just like the Combrinkskraal member it becomes indistinct northeast of Fraserburg where they both eventually grade into the Ecca Group (Jordaan 1990). Overlying the Leeu Gamka member is the Koup member which correlates with Stear's (1980) 6^{th} megacycle (Poortjie sandstone) and Le Roux's Poortjie Member. Jordaan's subdivisions were based on lithology alone and did not consider biostratigraphy. Figure 1.3 shows the comparison of Stear's (1980), Le Roux's (1985) and Jordaan's (1990) work.

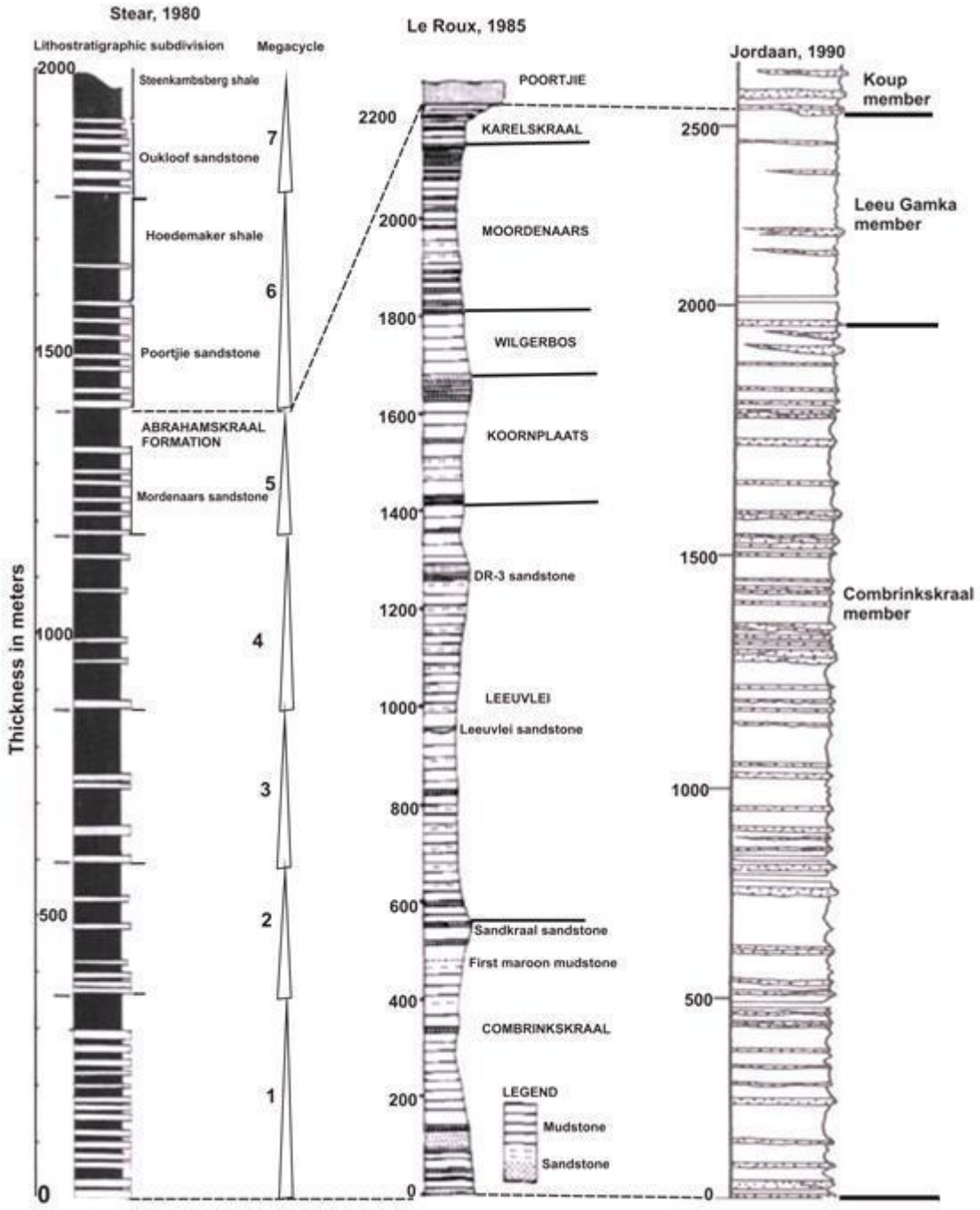


Figure 1.3: Comparison of the lithostratigraphic schemes for the Abrahamskraal Formation Stear 1980: (section measured in the Moordenaarskaroo); Le Roux, 1985: (section measured north of Merweville); & Jordaan's 1990: (section measured on the farm Combinkskraal, south of Leeu Gamka).

1.2.4 Biostratigraphy

Numerous tetrapod fossils have been collected in the Beaufort Group since their initial discovery more than a century ago. Seeley (1892) was the pioneer in establishing a biozonation for the Beaufort Group and this scheme has subsequently been refined (e.g, Kitching 1977; Keyser & Smith 1978; Rubidge 1995). By far the thickest biozone is the *Tapinocephalus* Assemblage Zone (Loock *et al*., 1994). Rossouw & De Villiers (1953) proposed a threefold subdivision of the *Tapinocephalus* biozone. Boonstra (1969) confirmed this threefold subdivision and considered the uppermost division to be characterized by a low diversity of vertebrate taxa, with therocephalians and the dicynodont *Diictodon* forming a major component of the fauna but no dinocephalians present at this level (Figure 1.4). This uppermost division now constitutes the *Pristerognathus* Assemblage Zone (Keyser & Smith, 1978, Keyser, 1979). The middle division is characterized by a relative abundance of dicynodonts and therocephalians but few dinocephalians and pareiasaurs. The lower division has a relative abundance of dinocephalians and therocephalians while dicynodonts are less abundant (Boonstra 1969).

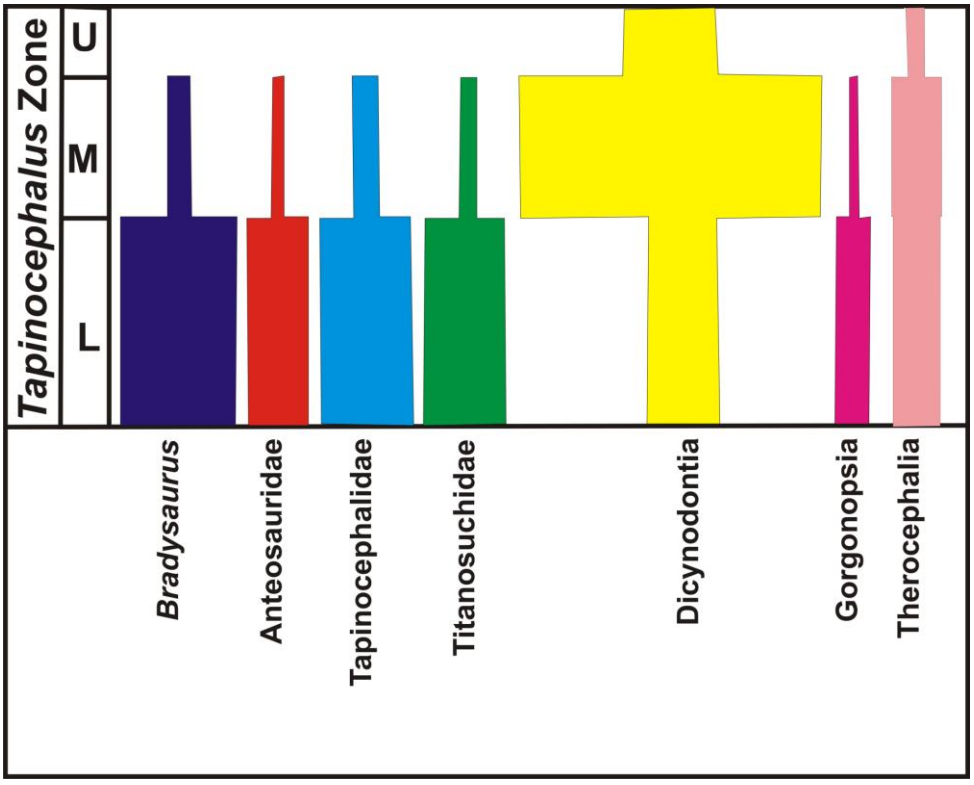


Figure 1.4: Biostratigraphic scheme of Boonstra (1969) showing a threefold subdivision of the *Tapinocephalus* biozone into Lower, Middle and Upper subdivisions) and illustrating relative numbers of various taxa during *Tapinocephalus* Zone times.

Loock *et al.* (1994) were the pioneers at integrating the biostratigraphy with the lithostratigraphy, in an area north of Laingsburg. They adopted the lithostratigraphic scheme of Le Roux (1985) and observed that the lower members (Combrinkskraal and lower Leeuvlei Members) were almost barren of fossils. Much of what these authors considered barren, have subsequently yielded fossils and this is now assigned to the *Eodicynodon* Assemblage Zone. These authors pointed out that dinocephalians are relatively plentiful in the lower horizons of the *Tapinocephalus* Assemblage Zone, achieving a maximum in the Upper Koornplats Member and decreasing in the Wilgerbos Member upwards. Dicynodonts on the other hand show a reverse trend.

Three biozones correspond with the Abrahamskraal Formation, namely the *Eodicynodon*, *Tapinocephalus* and the overlying *Pristerognathus* Assemblage Zone which extends upwards into the Teekloof Formation.

***Eodicynodon* Assemblage Zone**

The *Eodicynodon* Assemblage Zone was proposed by Rubidge (1990) as the lowermost biozone of the Beaufort Group to include rocks containing the primitive dicynodont *Eodicynodon* and the primitive dinocephalian *Tapinocaninus*. This biozone is currently considered to occur only in the southwestern margin of the Karoo Basin (Mason, 2007). Initially, the rocks in which fossils of the *Eodicynodon* Assemblage Zone occur were included in the Ecca Group (Barry, 1970) but are now considered to form the base of the Abrahamskraal Formation (Rubidge 1988, 1990, 1995) and directly overlie the Waterford Formation (Ecca Group). The tetrapod fauna in this biozone is considered to be the most primitive present in the rocks of the Karoo Basin (Rubidge 1987, 1988). Fossils in the *Eodicynodon* Assemblage Zone occur in argillaceous layers, usually associated with brown-weathering calcareous nodules (Rubidge, 1995). The Ecca-Beaufort boundary, which is the base of this biozone ranges from 331 to 663m below the first maroon mudrock of the Beaufort Group (Jinnah & Rubidge, 2007).

***Tapinocephalus* Assemblage Zone**

According to Keyser & Smith (1978) the upper limit of this biozone is defined by the last occurrence of dinocephalians and coincides with an extensive green “chert” band about 120m below the Poortjie Sandstone. The *Tapinocephalus* Assemblage Zone overlies the *Eodicynodon* Assemblage Zone and underlies the *Pristerognathus* Assemblage Zone and

corresponds with the middle part of the Abrahamskraal Formation. This biozone principally comprises dinocephalians, large pareiasaurians, pristerognathid therocephalians and small dicynodonts (Keyser & Smith, 1978).

***Pristerognathus* Assemblage Zone**

This zone comprises the upper 300m of the Abrahamskraal Formation and entire Poortjie Member as presently understood and is equivalent to Boonstra's (1969) Upper *Tapinocephalus* Zone. The lower boundary is defined by the last occurrence of dinocephalians (Smith & Keyser, 1995). The top of the *Pristerognathus* biozone occurs some 180m above the Poortjie Sandstone Member and often coincides with thick and paired sandstones, marking the base of the overlying *Tropidostoma* Assemblage Zone (Keyser & Smith, 1978).

This is the current state of litho and biostratigraphy of the Abrahamskraal Formation, now I have identified a gap and I am filling it by doing this study. From this literature review it is evident that it is difficult to correlate the different lithostratigraphic sections measured by previous researchers and there is very little understanding of the correlation between the bio and lithostratigraphy in the Formation. As the Abrahamskraal Formation is thickest in the southwestern part of the Beaufort Basin and numerous fossils have been recovered from this part of the basin it is pertinent to undertake such a study in this part of the basin.The aim of this study was to accurately document the lithostratigraphy and facies of the entire Abrahamskraal Formation in the study area as well as document palaeontological occurrences, their exact stratigraphic positions and ranges.

CHAPTER TWO: MATERIALS & METHODS

The purpose of this chapter is to establish clearly the methodology used during the course of this study. This investigation was intended to bridge the gap in our knowledge of the sedimentology and stratigraphy of the Lower Beaufort, as a background to a basin analysis of the southwestern Karoo Basin.

This project aims to:

- Compare accuracy of previous measured sections
- Measure a continuous section through entire Abrahamskraal Formation outcrop, logging bed thicknesses, bounding surfaces, sedimentary structures, palaeocurrents and fossils
- Measure 2-D panel sections of selected sandstone cliff exposures
- Group the lithologies into lithofacies
- Apply architectural element analysis to panel sections
- Interpret depositional processes
- Draw up a palaeoenvironmental reconstruction
- Establish biostratigraphic ranges of all fossils found
- Compare with existing ranges to see if the new fossils extend any of the known ranges

2.1 Study Area

The study area is situated in the southwestern corner of the Karoo Basin in the Western Cape Province and covers parts of both the Beaufort West and Prince Albert districts (Figure 2.1). It is bounded by the longitudes 21º 19' and 21º 45' east and latitudes 32º 20' and 33° 00' south and underlain by a monotonous succession of sandstone, blue and purple shale and mudstone intercalated with bands of siliceous rocks “chert”, as well as bands and lenses of brown calcareous and marly rocks (Rossouw & De Villiers, 1953).

2.2 Methodology

Stratigraphic profiles were used as a basis for the present investigation. Because of the folded nature of the Abrahamskraal Formation coupled with the fact that sandstone bodies are lenticular, it is difficult to recognize and trace out marker beds over a long distance. Accordingly, the best way to understand and make sense of the Abrahamskraal Formation is by measuring stratigraphic profiles which can be used to compare the lithology at different localities. In order to ensure that sections are stratigraphically continuous, individual beds were traced between anticlines and synclines by walking them out in the field and by aerial photographs and satellite imagery.

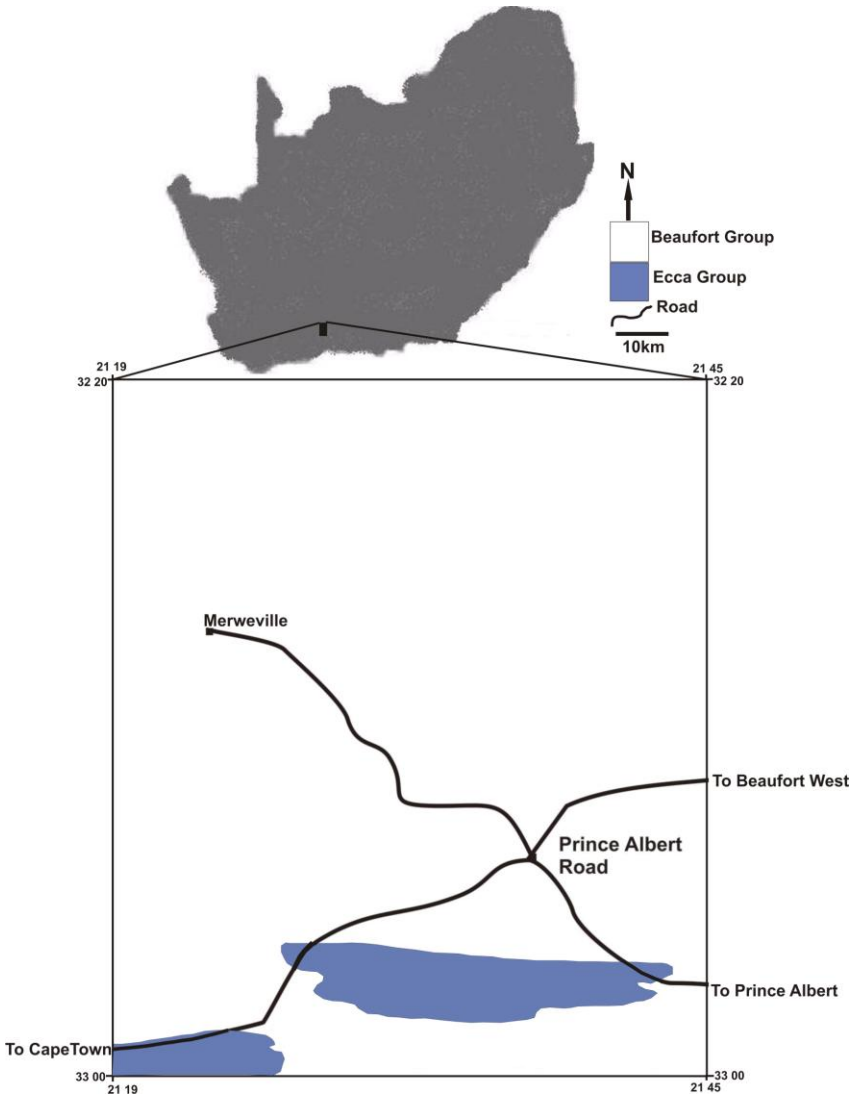


Figure 2.1: The position of the study area in the context of South Africa. The sketch is drawn from the 1:50 000 topographic maps of Dwyka, Prince Albert Road and Merweville and 1:250 000 Ladismith geological map.

2.2.1 Geological mapping

Systematic mapping of the area was accomplished in the laboratory with the aid of aerial photographs at a scale of 1:50 000 which were viewed under a stereoscope, as well as mosaics of Google Earth satellite imagery in order to recognize prominent lithological units. This map of the study area was successfully checked through fieldwork. Mapping is essential for the gathering of basic geological information such as the direction of dips of beds as well as structures such as synclines, anticlines and monoclines.

Once a reliable lithological map of the study area had been set up, two stratigraphic sections were measured through the entire Abrahamskraal Formation in the study area, using a Jacob's Staff and Abney level. The first section extended from the Ecca-Beaufort contact to the Poortjie Sandstone on Elandsberg on the farms Tuinkraal and Vlakkraal south of Prince Albert Road. The second section extended from one of the prominent sandstones (sandstone **G)** north of Prince Albert Road to the Poortjie Sandstone at the Nuweveld Escarpment on the farms Elandsfontein, Bullekraal and Springfontein in the Merweville district. Information documented on the stratigraphic sections includes lithofacies type, sedimentary structures, grain size, palaeocurrent directions and ranges of vertebrate fossils (see Chapter 4: Palaeontology)

2.2.2 Palaeocurrent studies

Many hydrodynamic structures contain internal evidence of the current which formed them, and a study of such evidence therefore yields useful clues as to the orientation of the palaeo-slope and hence the direction from which the sediments were derived (Miall, 1977). To obtain the maximum amount of information from palaeocurrrent analysis it is therefore essential to relate each observed structure to its position within the structure hierarchy and the sediment body (Maill, 1977). Orientation data should be displayed for easy visual interpretation. Data are first grouped for outcrops or areas according to the level of interpretation required.

Palaeocurrent directions were recorded with a Silver Compas. At each data point, a minimum of 10 readings were taken. Parting lineation, symmetrical ripple marks (Figure 2.2a) as well

as rib and furrow structures (Figure 2.2b) were used for these measurements. However, it is understood that not all palaeocurrent indicators are of the same magnitude. At each station it was essential to record structural dip and strike. In the southern part of the study area, there is structural tilting of the original horizontal primary bedding which complicates the procedure for measuring palaeocurrent directions. Where the beds dipped less than 10°, palaeocurrent directions were read directly with a compass. Where beds dipped more steeply than 10° the following data were measured:

- strike and dip of the bed in which, or on which the current indicators lie,
- The strike and dip of planar indicators,
- The sense of palaeocurrent direction relative to the dip.

These readings were then corrected on a stereographic net about strike to restore beds and palaeocurrent indicators to horizontal about strike (Potter & Pettijohn, 1977, Lewis & McConchie, 1994).

For each data point, the orientations of the sedimentary structures (ripples) were recorded, including both the azimuth and dip of planar structures that needed stereographic correction. For linear/planar structures in outcrops of low tectonic dip, only the azimuth was recorded. The arithmetic mean palaeocurrent direction was calculated by adding all the individual azimuth readings and dividing the sum by their number (Selley, 2000). These mean palaeocurrent directions were plotted at their respective positions in the stratigraphic succession (Appendix A). The mean vector direction is a reasonable estimate of palaeo transport direction and palaeoslope (Kurtz & Anderson, 1980). Usually palaocurrent data is presented in the form of rose diagrams but for the purposes of this study, a simple azimuth mean was recorded since palaeocurrents are not a major component of this project.

Palaeocurrent measurements were taken in order to characterize palaeo-flow; determine the down channel direction; outline the palaeocurrent system of the Karoo Basin; determine the distribution of fluvial transport systems in the southwestern part of the Karoo Basin and identify the sandstone packages associated with these systems in order to produce a better lithological and stratigraphic correlation.

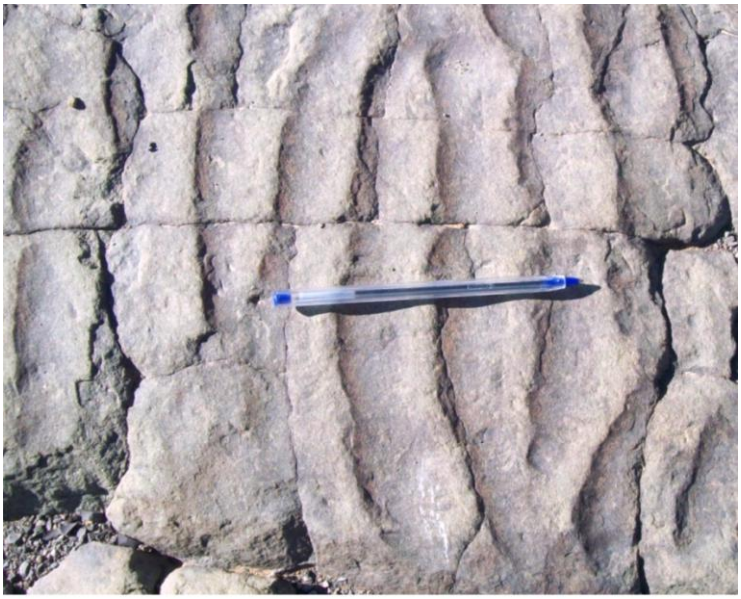


Figure 2.2a: Palaeosurface showing ripple marks. (Pen used for scale is 15.5cm long).



Figure 2.2b: Rib & furrow structure. Arrow shows palaeocurrent direction (pen used for scale is 11cm long)

2.2.3 Fossil data collection

Systematic collection of fossils was done in the study area in order to determine faunal biodiversity changes through time. This was done with the help from colleagues from The Bernard Price Institute for Palaeontological Research (BPI); National Museum, Bloemfontein; Albany Museum, Grahamstown; Oxford University, England and The Field Museum, Chicago. Identifiable fossils were collected, their geographic position recorded by

means of a Garmin Global Positioning System (GPS) and placed on the base map. Fossils and lithological units (for facies and architectural elements) were photographed using an 8.3 mega-pixel Kodak Digital camera. Fossils collected during this study were used in conjunction with those from the Beaufort Group GIS fossil database (Nicolas, 2007). However, some of the database fossils are recorded from farm centroids and some farms in the study area are underlain by more than one lithological unit making it difficult to stratigraphically place such fossils and such fossils were ignored for the purposes of this study. The stratigraphic position of fossils was documented on stratigraphic sections and the collected fossils were brought to the BPI for further preparation and curation. After preparation, identification and description was done with the aid of relevant literature and comparison with specimens in the collections of the BPI.

CHAPTER THREE: GEOLOGY

The purpose of this chapter is to provide a lithologic description of the sedimentary rocks of the Abrahamskraal Formation in the study area which comprise a repetitive succession of yellow and grey sandstone units alternating with maroon and green mudstone units.

3.1 Lithology

Although, no Lower Beaufort lithological units are continuous (Rossouw & De Villiers, 1953) in the study area, it was possible, based on their lithology, to recognize several prominent arenaceous and argillaceous stratigraphic units which extend across the entire study area (Figure 3.1a&b). These marker units are coded from A to U depending on their position in the stratigraphic succession, with A being the basal unit (Figure 3.1a). Because certain lithofacies are restricted to particular units, the units will be described first and followed by the facies descriptions in section 3.2.

Arenaceous unit A

Unit A is a thick arenaceous package (2074m thick) comprising of sandstone, siltstone and mudstone inter-beds. Since this unit is predominantly sandy it is thus treated as a sandstone unit. Sedimentary structures include horizontal bedding (facies Sh: see subsection 3.2 on facies description), ripple cross lamination (facies Sr) and in some places, bedding is obscured and the unit ends up appearing as massive (facies Sm). Sandstone colors range from grayish olive green (5GY3/2) to dark yellowish brown (10YR4/2). The lowermost maroon mudrock of the Beaufort Group is present in this unit. This can be seen on the western bank of Vlakkraalrivier, south-west of Tuinkraal farm house, and occurs about 606m above the Ecca-Beaufort contact (Figure 3.1a, Appendix A) as mapped on the 1:250 000 Geological map of Ladismith, Sheet 3320 which itself is about 1km south of the farm house. This first maroon mudrock is a useful marker horizon. Throughout unit A, there is secondary pyrite mineralization in the sandstones as evidenced by pyrite crystals as well as a reddish brown hue (10R3/4) on the rocks (Figure 3.2).

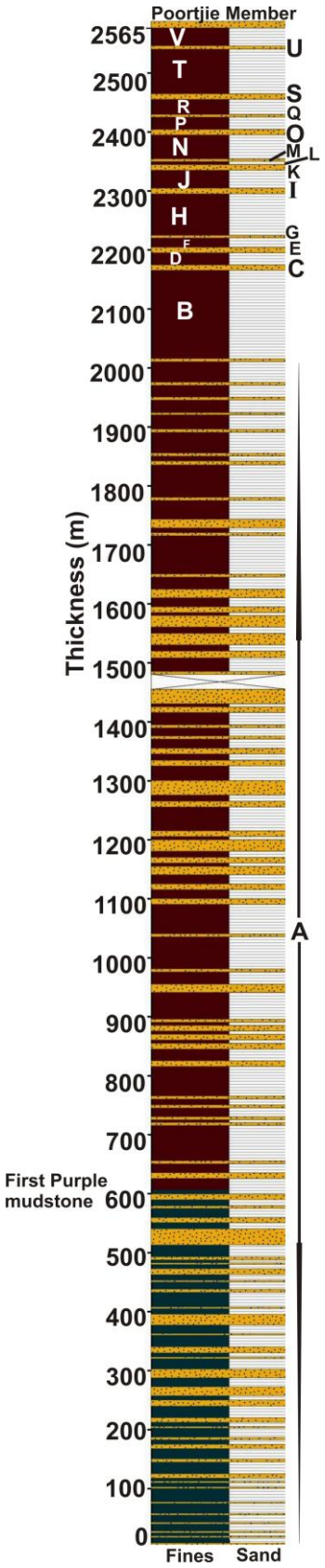


Figure 3.1a: Simplified stratigraphic section of the Abrahamskraal Formation in the study area showing different lithological units coded A-U. See Appendix A for a comprehensive stratigraphic section.

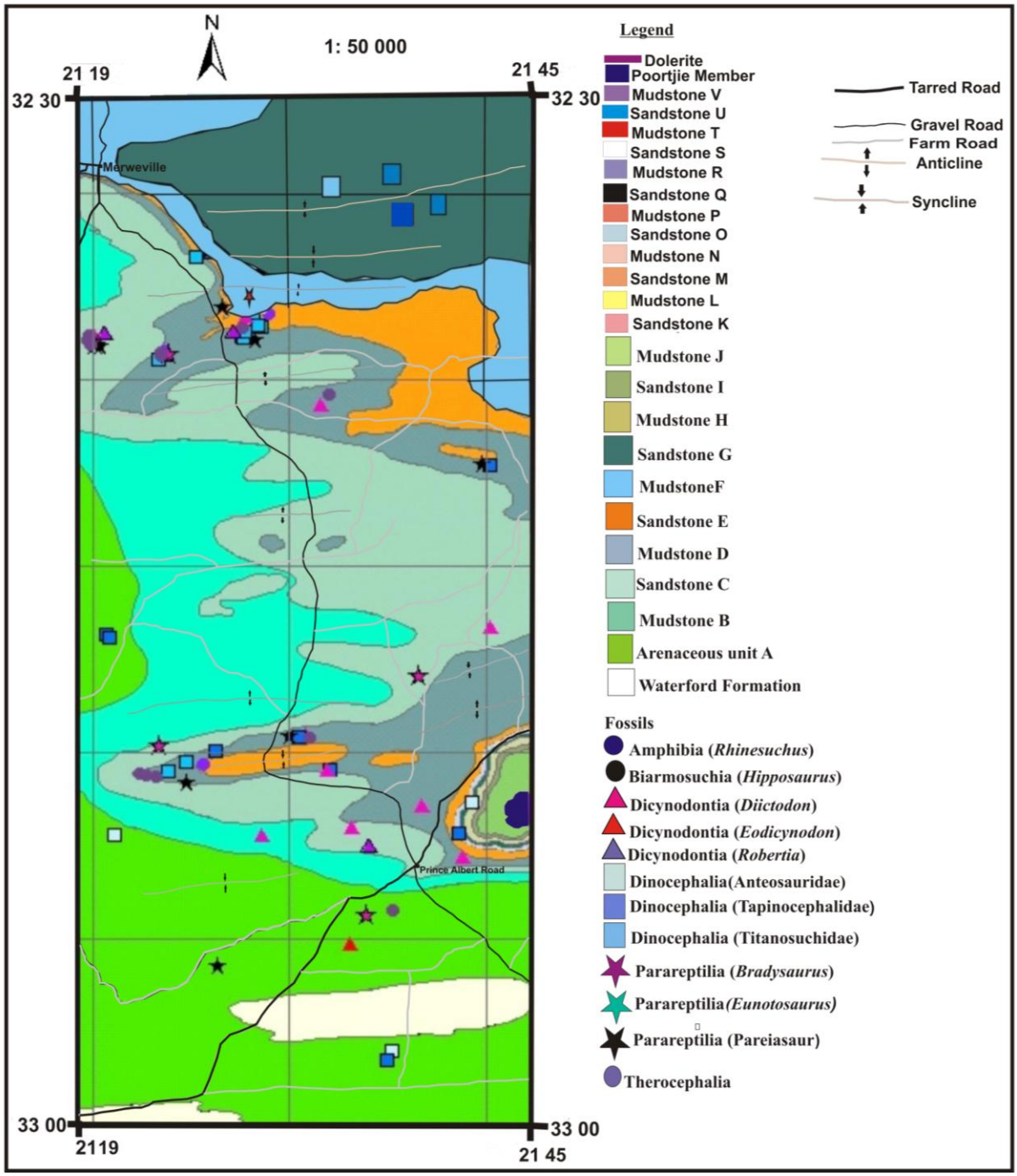


Figure 3.1b: Lithological map from the Ecca – Beaufort contact near Prince Albert Road till sandstone G at Merweville. The map also shows the distribution of different fossil taxa. (Scale 1: 50 000)

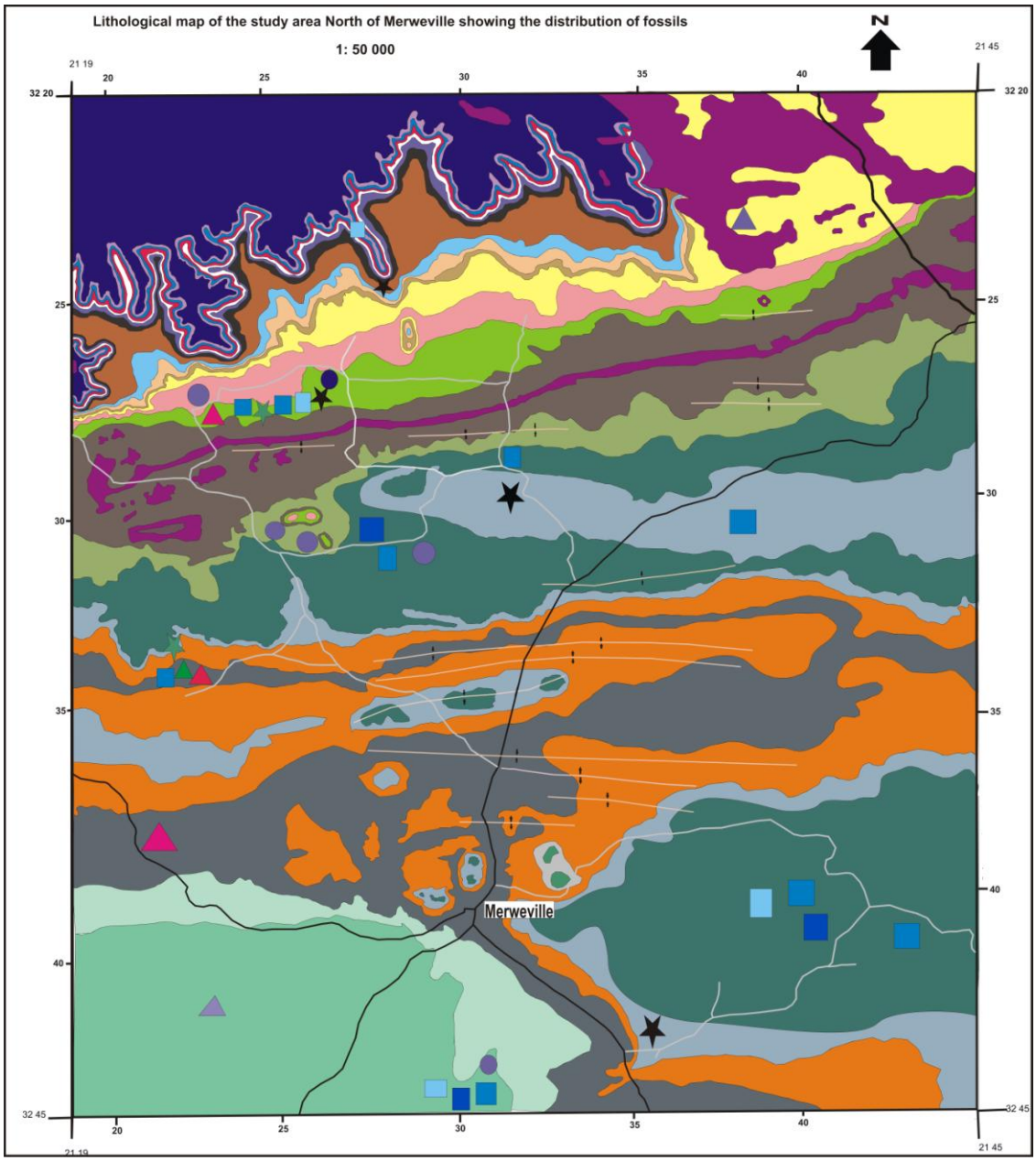


Figure 3.1c: Lithological map of the study area from Merweville up to the base of the Poortjie Member at the Escarpment. Fossil localities are also included.Legend on Figure 3.1b.

Silty-Mudstone B

This is a fine-grained blue (5B6/2) and purple (5P4/2) silty mudstone unit with a mean grain size of approximately 1/32mm. It contains horizons of light reddish brown (10R5/4) calcareous nodules as well as sandstone and siltstone intercalations which display both horizontal bedding and ripple cross lamination. This unit is 96m thick in the southern part of the study area (Figure 3.1a) and is well exposed on the farm Goeimoed (Rietkraal) south of Prince Albert

Road and also on the farm Moordenaas Kraal along the Prince Albert to Merweville road where it is 50m thick (Figure 3.3).



Figure 3.2: Pyrite crystals in a medium-grained sandston (arenaceous unit A)

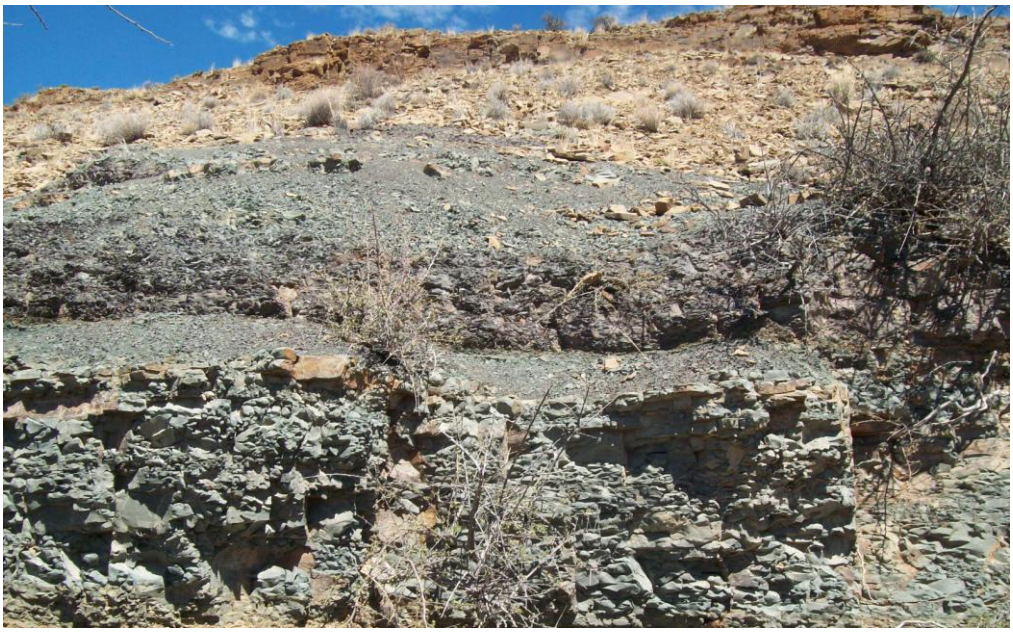


Figure 3.3: Blue and Purple mudstone layer B on the farm Moordenaas Kraal near the Elandskop off ramp on the road from Prince Albert Road to Merweville. The sandstone ontop is unit C.

Sandstone C

This relatively thin unit is 8m thick and comprises medium-grained olive grey (5Y5/2) sandstone which weathers dark yellowish brown (10YR4/2) and has abundant secondary pyrite crystals and heavy minerals. Sedimentary structures include both horizontal bedding and faint lamination (almost massive). Unit C has an abrupt basal contact with the argillaceous unit B. Good exposures of this unit are found on the same locality as mudstone B (Figure 3.4) as well as in road cuttings just after the turn-off to Koedoesfontein farm along the Prince Albert Road to Merweville road.

Silty-Mudstone D

Unit D is a green (10G8/2) and purple (5P6/2) fine-grained unit (grain size: 1/8mm). It is 40m thick in the south and thins to 25m in the northern part of the study area (Figure 3.5). Pseudomorphosed gypsum rosettes, some exceeding 150mm in diameter, occur in specific beds throughout this argillaceous horizon as well as pink weathering silicified siltstone (chert). This unit is host to many vertebrate fossils notably dinocephalians and the dicynodonts *Eosimops*, *Robertia* and *Diictodon* (see Chapter 4)



Figue 3.4: Sandstone layer C which overlies the blue and purple mudstone B. This is on the same locality as Figure. 3.3. This unit is a horizontally bedded grey sandstone which weathers yellowish brown.



Figure 3.5: Silty Mudstone layer D on the Farm Waterval near Koedoesfontein off ramp. The base of the hill marks the beginning of layer D. Towards the top there is a splay sandstone then the hill is capped by sandstone E. Unit C appears thicker on the photograph but this is because it is on flat ground.

Sandstone E

A medium-grained pale yellowish green (10GY7/2) sandstone which weathers pale yellowish orange (10YR8/6) (Figure 3.6) and has an erosive lower contact on unit D is designated sandstone E. This lithological unit could be easily mapped out over a large area throughout the study area. Unit E is 3m thick in the south of the study area but thickens up to10m in the north on the farm Elandsfontein. Petrographically, this sandstone comprises mainly ill-sorted quartz and feldspar and accessory minerals are biotite, chlorite, muscovite, zircon and calcite. Several fragmentary dinocephalian cranial and postcranial elements were found in pebble lag deposits at the base of this unit, especially on the farm Rietfontein.



Figure 3.6: Sandstone layer E on the farm Reitfontein 269. Morphology of this sandstone indicates channeling as well as lateral accretion. The base of this unit is characterized by pebble lags which contain dinocephalian remains. The man at the edge of the picture is used for scale.

Mudstone F

Unit F comprises a fine-grained (facies Fm) blue (5B8/2) and purple (5P6/2) mudstone 18m thick which breaks into small irregular fragments on weathering. This unit contains carbonate nodules, 15m into the unit, and sandstone intercalations and there are no visible sedimentary structures.

Sandstone G

This arenaceous unit is a grey (N7), medium-grained sandstone which weathers yellowish grey (5Y8/1). It is 3m thick and has a basal pebble lag containing abundant dinocephalian fossils. Sandstone G is both massive (Sm) and horizontally bedded (Sh), and has parting lineations on bedding surfaces (Figure 3.7). On the farm Elandsfontein this sandstone also exhibits facies St and Sp.

Mudstone H

Mudstone H is a 40m thick unit comprising a fine-grained grayish green (10GY5/2) mudstone with no visible sedimentary structures. Siltstone interbeds have horizontal bedding at the base overlain by ripple cross lamination. Palaeocurrent directions taken from one of these siltstone interbeds are due north-east (70°). Also present in this unit just like in most argillacous units in the study area is a palaeosol (carbonate nodules) (Figure 3.8).



Figure 3.7: Parting lineations on upper surface of sandstone unit G on the farm Elandsfontein. These parting lineations are a result of weathering along the horizontal laminations and provide a palaeocurrent trend.



Figure 3.8: A palaeosol (coalesced carbonated concretions) in mudstone unit F on the farm Reitfontein 269. These paleosols are a common feature in most argillaceous units in the study area.

Sandstone I

Overlying mudstone H with an erosive contact is medium-grained grey (N7) sandstone, weathering yellowish grey (5Y8/1). This arenaceous sequence is 8m thick in the south and thins to 1.8m in the northern part of the study area. The thickness of the unit varies along strike. It has platy weathering (horizontal bedding) at the base and the upper part of the unit comprises very fine ripple cross lamination which indicates a mean palaeocurrent direction of 62.8° (north-east). On the farms Elandsfontein and Rooifontein this unit has been highly metamorphosed as a result of a dolerite intrusion.

Mudstone J

This fine-grained purple (5P4/2) mudstone unit is 35m thick and is designated facies Fm. No visible sedimentary structures are visible. In the southern part of the study area in the vicinity of Prince Albert Road, this unit is the uppermost unit of the Abrahamskraal Formation and is overlain by the Poortjie Sandstone Member of the overlying Teekloof Formation.

Sandstone K

This is an upward fining moderate blue green (5BG4/6) arenaceous unit, which starts off as a coarse-grained sandstone at the base, and grain size decreases towards the top. This sandstone

has an erosive base with the underlying mudstone J. The predominant sedimentary structure is parallel bedding which is present at the base and is responsible for its blocky weathering. Ripple cross-lamination is present at the top of the unit. The mean palaeocurrent direction for this unit is 29.6° (north-east). On the southern bank of the Wilgebos Rivier, on the farmBullekraal 251, this sandstone unit attains a thickness of 15m (Figure 3.9), though the average thickness is 4.5m.

Mudstone L

This unit is 8.6m thick and is an argillaceous pale purple (5P6/2) unit which could be mapped out over a large area near the escarpment and it has a palaeosol layer as well as siltstone splay deposits. These splay deposits manifest both horizontal bedding and ripple cross-lamination.



Figure 3.9: Sandstone unit K on the southern bank of the Wilgebos Rivier on the farm Bullekraal 257. This is a multistorey sandstone punctuated by pebble-lags (Ss) and thin mudstone layers (M) throughout the stratigraphic extent of the outcrop.

Sandstone M

This blue grey (5B7/1) unit which weathers dark yellowish brown (10YR4/2) is 8m thick, has a 20cm thick pebble lag deposit at the base (facies Ss) with mudclasts with an average diameter of about 25mm. Sandstone M is predominantly a flat bedded unit (facies Sh), though ripple cross laminations (facies Sr) are present but less abundant. The mudclasts of the pebble lag are rounded, suggestive of transportation before deposition.

Mudstone N

Mudstone N is a 38m thick argillaceous unit comprising a basal blue to blue-green (5BG4/6) siltstone fining upwards to purple (5P6/2) mudstone on top. Sedimentary structures are not visible except in a sandstone intercalation which has both horizontal and ripple cross laminations.

Sandstone O

This is a blue-grey (5B7/1), 5m thick sandstone which forms a shelf at the base of the escarpment. The sandstone weathers yellowish grey (5Y8/1) and has a prominent 40cm thick pebble lag at the base comprising mainly mud clasts with an average diameter of 20-50mm. This sandstone unit has horizontal lamination at the base (facies Sh), trough cross-bedding (facies St) midway up the unit and ripple cross bedding (facies Sr) at the top as well as heavy mineral banding towards the top (Figure 3.10).

Mudstone P

This argillaceous unit, with a thickness of 22m, comprises facies Fm and has no visible sedimentary structures. It is very pale blue (5B8/2) at the base and pale purple (5P6/2) near the top. Several carbonate concretionary layers are present with an average diameter of about 200mm and a well defined sandstone intercalation with horizontal bedding at the base and ripple cross bedding at the top was probably deposited in a crevasse splay environment (Stear, 1980).



Figure 3.10: Heavy mineral banding on sandstone unit O on the farm Klipbankskraal/Springfontein. The heavy mineral bands follow the primary bedding (horizontal lamination) of the rock unit (pen used for scale is 15.5cm long).

Sandstone Q

Sandstone Q is a 3.5m thick pale blue (5B8/2) sandstone weathering pale yellowish orange (10YR8/6) (Figure 3.11) with a pebble lag at 500mm intervals throughout the height of the unit. Sedimentary structures include horizontal lamination at the base and ripple cross lamination at the top (facies Sh - Sr).



Figure 3.11: Sandstone unit Q on the farm Klipbankskraal/Springfontein. As in sandstone K this unit has a 30cm thick pebble lag at the base with other smaller lags and mudstone layers up its height.

Mudstone R

This is a fine grained very pale green (10G8/2) mudrock, 39.20m thick and includes a series of thin sandstone intercalations (facies Fl). These intercalations show both horizontal and ripple cross bedding. A prominent palaeosol (carbonate concretions) is present within this mudstone unit and has an average thickness of 250mm.

Sandstone S

Overlying mudstone R is 4.5m thick pale blue (5PB7/2) sandstone which has an erosive base with the underlying unit. This lithological unit is traceable over a large area across the study area along the escarpment. The primary sedimentary structure is parallel bedding (facies Sh) but towards the top, there is no visible bedding and one is tempted to assume that it is massive (facies Sm).

Mudstone T

This is a crumbly fine grained mudstone with siltstone intercalations (facies Fl). It is greyish blue green (5BG5/2) and 85m thick. This mudrock has two palaeosols: the lower one is 5m above the base of the unit and the second one, which is near the top, is about 13m below the top of the unit.

Sandstone U

Above mudstone T is a 2.5m thick pale green (10G6/2) sandstone unit with a pebble lag at the base and with mud clasts averaging 20mm in diameter (Figure 3.12). Sedimentary structures include horizontal bedding at the base and ripple cross lamination at the top. An anteosaurid dinocephalian skull (BP/I/7071) was found in the pebble lag at the base of this unit.

Mudstone V

The topmost unit of the Abrahamskraal Formation is mudstone V which has no visible sedimentary structures and is largely covered by scree and alluvium. It is an 18.5m thick pale purple (5P6/2) argillaceous unit which is overlain by the arenaceous Poortjie Member of the Teekloof Formation.

The base of the Poortjie Member is characterized by a prominent pebble lag and the total thickness of the entire succession from the Ecca-Beaufort contact to the base of the Poortjie

sandstone at Elandsberg near Prince Albert road is 2325m, and is 2565m when measured to the Nuweveld Escarpment.



Figure 3.12: Pebble lag at the base of sandstone unit U (indicated by an arrow in the middle of the picture) on the farm Rondon247/Springfontein.

3.2 Facies Description

In order to describe the lithology in each of the units described in section 3.1, the concept of lithofacies, used by Reading (1984), was applied. A sedimentary facies is a body of sedimentary rock with specific characteristics and is defined on the basis of lithology, color, bedding composition, texture, grain size, sedimentary structures, palaeocurrent pattern as well as fossil content (Reading, 1996; Miall, 2000; Boggs, 2001).

Following the scheme of Miall (1977, 1996) nine lithofacies were identified in the study area and consist of six sandstone facies (Ss, Sm, Sh, Sl, St & Sr), two fine grained facies (Fl & Fm) and one nonclastic facies (P) (Table II). The only course grained rocks in the study area are intra-formational mud-pebble conglomerates imbedded in the sandstone matrix of facies Ss. All facies encountered in the study area are described below and their stratigraphic occurences shown in Appendix A.

Facies Code	Description
Ss	Scour filled sandstone (mud pebble-conglomerate)
Sm	Massive or faint laminated sandstone
Sh	Horizontally laminated sandstone
Sl	Low-angle cross-stratified sandstone
St	Trough cross-stratified sandstone
Sp	Planar cross-bedded sandstone
Sr	Ripple cross-laminated sandstone
Fm	Massive mudrock
Fl	Laminated sandstone, siltstone and mudrock
P	Pedogenic carbonate

Table III. Lithofacies of the study area (after Miall, 1996).

3.2.1 Sandstone facies

The sandstone bodies in most places overlie the mudrock with a low-relief erosive contact, but erosional cutbacks up to 3m deep can be present (Cole *et al.*, 1990; Stear, 1980b). A thin (<1m thick) mud pebble-conglomerate lithofacies is present at most places on this erosive contact as well as on internal erosion surfaces that form floors of storeys within the sandstone body. This lithofacies has been interpreted as a channel lag deposit (Kübler, 1977; Turner, 1978; Cole, 1980a; Stear. 1980a, 1985; Jordaan, 1990) with the mudstone clasts having been derived from collapse and disaggregation of the muddy bank material (Smith, 1987a).

Scour filled Sandstone (Ss)

This represents the coarsest sedimentary rock in the study area and is made up of medium-grained sandstone with mudstone and siltstone clasts and occasional fossil bone fragments. Facies Ss is massive and shows no grading or sedimentary structure. The size of the clasts

(measured along the long axis), vary from 5-10mm with an average size of 30mm (Figure 3.13).



Figure 3.13: Facies **Ss** with average mud clast size of 30mm. The pebble lags throughout the study area are matrix supported conglomerates and most contain poorly preserved vertebrate bones (Geological hammer used for scale).

The basal contacts are erosional, abrupt and gradual, the most abundant being erosional contacts. The upper contacts are abrupt. Facies Se of Rust (1978) is similar to this facies Ss. Rust equated his facies Se with the scour surface facies (SS) of Cant and Walker (1976). Miall (1978) included facies Se in his facies code but he then (1996) discarded it because it is now grouped within facies Ss.

Facies Ss is not a dominant facies in the study area in terms of the total thickness but it occurs in many places in association with facies Sm, Sh, Sl, St and Sr, and its thickness varies from 20mm up to 500mm. A number of fossils were collected in this facies a notable one being an anteosaurid dinocephalian skull (BP/I/7071) found in a pebble lag at the base of Sandstone U on the farm Springfontein. The sand grains and clay pebbles in this facies were deposited simultaneously as poorly sorted, coarse bed-load (Rust, 1978; Miall, 1996). Where facies Ss is preceded by an erosional contact, erosion and deposition were probably two separate events (Miall, 1978).

Massive or faint laminated sandstone (Sm)

Sandstone beds in outcrop may appear massive if weathering obliterates lamination. However, true massive sandstones do exist in the study area (Figure 3.14). This facies is made up of gray (N7), light gray or grayish green (10GY5/2) but commonly yellowish gray (5Y8/1) fine to medium-grained sandstone. Facies Sm is associated with facies Ss and Sh and characterized by an abrupt or gradational contact with the underlying or overlying facies. Facies Sm was most probably deposited by sediment laden currents under transitional or upper flow regime conditions (Miall, 1996). A characteristic occurrence of this facies is in small channels resulting from bank collapse Miall, 1996). Conaghan & Jones (1975) attribute the formation of this facies to deposition from highly concentrated, sediment laden currents under transitional or upper flow regime conditions at peak flood. Lack of sedimentary structure may be brought about by the liquefaction of unconsolidated sand (Reddering & Rust, 1994).

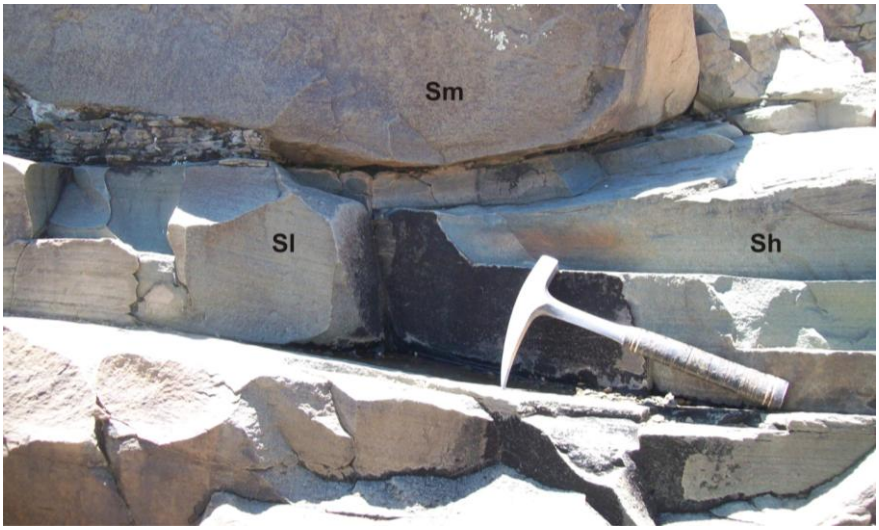


Figure 3.14: Facies **Sm** overlying facies **Sl/Sh** within arenaceous unit A on the farm Tuinkraal. This might imply a sudden surge in depositional energy. (erosive base of facies Sm into Sh/Sl).

Horizontally Stratified Sandstone (Sh)

Facies Sh consists of fine grained grayish blue green (5BG5/2) sandstone and is the dominant sandstone facies in the study area. It occurs as solitary units 1m – 1.5m thick and sometimes grouped together with other sandstone facies (eg. lithofacies Sm and Sr) in thick sandstone packages. Basal contacts of this facies tend to be abrupt although erosional and gradational contacts are also found though rare. This facies is distinguished by flat, parallel lamination (Figure 3.15) with parting lineation (Figure 3.7) occurring on bedding planes which was used to determine palaeocurrent trends. The orientation of the lineation is parallel to flow, but does

not indicate which one of the two opposing directions is the correct palaeocurrent direction (Miall, 1996). According to McBride & Yeakel (1963), parting lineation is due to the orientation of the long axis of the individual grains such that the lineation is orientated in the same direction as the original depositing current hence its usefulness as a palaeocurrent trend indicator. In the study area, facies Sh is found in association with facies Ss, Sl, St, Sr and rarely Sp & Sm. Contacts with facies Ss is gradational while with other facies they are abrupt.



Figure 3.15: Facies **Sh** is the most abundant lithofacies in the study area (Geological hammer used for scale is 32cm long).

Low-angle cross-stratified sandstone (Sl)

This was first described by Cant & Walker (1976) and was subsequently included in lithofacies schemes of Miall (1977) and Rust (1978). Grain size and bedding characteristics of lithofacies Sl are similar to that of lithofacies Sh, with which it is commonly associated and it is often difficult to distinguish between the two (Miall, 1996). The main distinguishing characteristic is the presence of low-angle cross-bedding (Figure 3.16), dipping at 15° and normally 10° (Miall, 1996). In the study area, facies Sl consists of fine grained greenish gray (5GY6/1) sandstone which weathers light yellowish brown (10YR4/6) and occurs above gradational contacts with lithofacies Sm, Sp and Sh. Facies Sl is deposited by shallow, high velocity flow that fills low relief scours (Rust, 1978b) or also as wash-out and humpback dunes that are formed at the transition between subcritical and supercritical flow (Miall, 1996).

Trough cross-stratified sandstone (St)

Just like facies Sl, in the study area facies St occurs as fine grained greenish gray (5GY6/1) sandstone weathering light yellowish brown (10YR4/6). This facies consists of elongated scours filled with scoop-shaped laminae that plunge at a small angle in a downcurrent direction (Harms *et al*., 1975). This facies (Figure 3.17) is found within the thicker sandstone units in association with facies Sh/Sl with basal contacts typically sharp. Trough cross-stratification is an excellent palaeocurrent indicator since the long axes of the elliptical troughs are parallel to palaeoflow (Harms *et al*., 1975). Facies St is generally thought to be formed by three dimensional dune migration in the upper part of the lower flow regime (Harms & Fahnestock, 1965; Miall, 1966) where water depth exceeds 30cm (Hancox, 1998). A number of different sedimentary environments are responsible for the formation of trough cross beds including meandering rivers (Nanson, 1980), flash ephemeral streams (Stear, 1985), and braided rivers (Bristow, 1993).



Figure 3.16: Facies **Sl** in multi-storey sandstone K. This facies is oftenly difficult to differentiate from facies **Sh.**

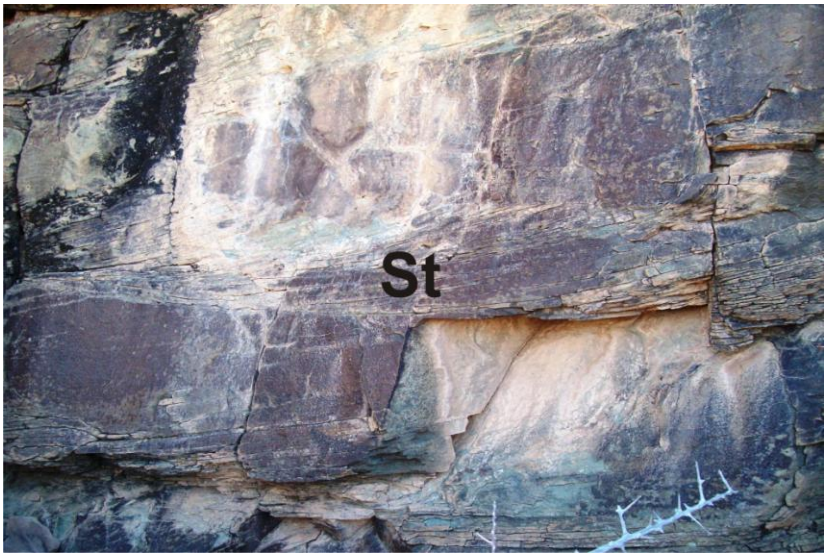


Figure 3.17: Facies **St** on sandstone unit S on the farm Klipbankskraal.

Planar cross-stratified sandstone (Sp)

This facies is less common in the study area than the facies already described. In the few places that it was encountered it occurs as solitary sets in fine grained sandstone (Figure 3.18) and was found in association with facies Sh, Sl and St. Foreset dips ranging between 10-20°. Planar cross-stratification is the internal structure to transverse bars (Smith, 1971, 1972, 1977), linguoid and laterally accreted point bars and large sandwaves (Harms *et al*., 1975). Smith (1972) suggested two other possible ways of forming planar cross bedding; the building of solitary deltas and banks by sediment transported into deeper quiet waters, and by deposition of sediments on the slopes of point bars in meandering channels.



Figure 3.18: This outcrop (sandstone G on the farm Elandsfontein) shows Facies **Sp** below the hammer head. Facies **Sl**/**Sh** is present above the hammer (hammer used for scale is 32cm long).

Ripple cross-laminated sandstone (Sr)

This is the second most ubundant sandstone facies in the study area after facies Sh. Ripple laminated sandstone (Figure 3.19) is found within and on top of sandstone sequences as well as in the form of intercalations in mudstone dominated sequences with both the lower and upper contacts being either abrupt or gradational. Facies Sr occurs as solitary units of about 1.5m-5.0m thick. Grain size of this facies is fine - medium grained and the color is grey (N7), light grey, light greenish grey (10GY5/2) or light olive grey 5GY3/2), but is commonly bleached or limonite stained.



Figure 3.19: Facies **Sr** is the second most abundant facies in thestudy area after **Sh.** In plan view rib and furrow structures are a good palaeocurrent indicator.

Ripples develop at very low flow speeds (<1m/s) and are very sensitive to changes in flow conditions (Miall, 1996). Facies Sr is considered to represent migration and simultaneous upward growth of ripples (Reineck & Singh, 1973). The stratigraphic positioning of facies Sr relative to other facies suggests that they are predominantly formed as bar top deposits due to changes in flow regime during shallowing, or during periods of high water level where previously exposed bar tops become temporarily submerged (Hancox, 1998). Some of these ripples were used to obtain palaeocurrent measurements.

3.2.2 Fine grained facies

Laminated sandstone, siltstone and mudrock/ laminated siltstone and mudrock (Fl)

Lithofacies Fl is common in the study area (Figure 3.20) and consists of interbedded layers of mudrock, siltstone and sandstone with siltstone and sandstone representing splay deposits. Sandstone layers of this facies are fine to medium grained with faint laminations whereas the siltstone is very fine to fine grained with both horizontal and ripple cross laminations. The mudstone is massive with no visible sedimentary structures due to its very fine texture. Both the sandstone and siltstone are light bluish gray (5B7/1) and greenish gray (5G8/1) in color while on the other hand the mudrock is pale yellowish green (10GY7/2), greenish gray (5G8/1)

and maroon (purple mudrock [5P6/2]). This lithofacies is associated with facies Sm, Sh, and Sr and has erosional contacts with overlying sandstone lithofacies. In many places this facies occurs as fining upward sequences with the sandstone showing facies Sh at the base grading upwards into facies Sr then onto a ripple cross-bedded siltstone grading onto mudstone. The sandstone component represents deposition by traction currents while the silt and mud were deposited from suspension (Miall, 1996).

Massive mudrock (Fm)

This consists of massive light yellowish green (10GY7/2), greenish gray (5G8/1) and maroon mudrock (5P6/2). Facies Fm has no primary sedimentary structures and weathers into tiny splinters (Figure 3.21). Both facies Fl and Fm are thick and reach 80- 90m in thickness, from 2075m above the Ecca-Beaufort contact till the base of the Poortjie Member of the Teekloof Formation where they form the muddy/argillaceous interval of the Abrahamskraal Formation (Figure 3.1a). Mud drapes occur on upper surfaces of some sandstone as well as within stacked/multistory sandstones and these mud drapes range from 10-20cm in thickness pinching out laterally. This facies represents the lowest energy sedimentary environment (most distal from the main fluvial channel) Miall, 1996).



Figure 3.20: Facies **Fl** on mudstone unit F on the farm Elandsfontein. Although mudstones seldom show primary sedimentary structures, faint bedding is visible on this mudstone as well as the siltstone interbeds.



Figure 3.21: Facies **Fm** is the most common mudstone facies in the study area. No sedimentary structures are visible.

3.2.3 Nonclastic facies

Pedogenic Carbonates (P)

Facies P occurs in association with facies Fl and Fm and is common throughout the study area. This facies comprises horizons of weak red (5R/4/2) calcareous nodules (Figure 3.8). Rain infiltration leaches dissolvable ions downward, whereas evaporation and capillary groundwater flow during arid periods concentrate these same ions near the surface. The result is the gradual development of carbonate cements that coalesce into nodules and these in turn, into more or less continuous carbonate substrates with a blocky fracturing pattern (Miall, 1996). The nodules vary in size from 10mm to 500mm and are ovoid in shape with long axes of the nodules parallel to the bedding plane of the sediments containing these nodules. Modern calcitic soils are referred to as caliche or calcrete and these terms have been adopted by sedimentologists for palaeosols (Miall, 1996). Most of the fossils have been discovered in these carbonate nodules since they are hard and more resistant to weathering, thus preserving the fossils.

3.3 Architectural Elements Analysis

The concept of architectural analysis was introduced as a tool for the interpretation of fluvial depositional environments (Miall,1985) as reliance on vertical sequences alone can be misleading as vertical sequences can be deposited by different processes (Reading, 1984). Vertical profiles are not sufficiently diagnostic for facies analysis because they cannot adequately represent three-dimensional variations in composition and geometry (Miall, 1985).

Lateral profiling relies to a large extent on the recognition of large-scale depositional features termed macroforms which according to Jackson (1975) are a result of the cumulative effect of sedimentation over long periods of time. Lateral profiling also addresses the shape and internal geometry of fluvial sand and mudstone bodies (Allen, 1983; Haszeldine, 1983; Miall, 1988). Bounding surfaces are surfaces of non-deposition or erosion representing time periods of a few minutes to hundreds of thousands of years (Miall, 1988) and macroforms are bounded by fourth-order surfaces but when an element rests on the floor of a channel, its base is defined by the base of the channel which is a surface of fifth-order rank or higher (Miall, 1996). Some elements are commonly truncated by overlying channels, in which case their upper bounding surface is the fifth-order surface at the base of that channel and it is for this reason that fourth-order surfaces are rarely preserved (Miall, 1996). However, where they are preserved, they may be recognized by their convex up shape, which in part, parallels stratification in the underlying beds, and indicates that they are surfaces of accretion (Miall, 1996).

Descriptions and definitions of architectural elements should include the following parameters summarized by Miall (1985) as:

-Nature of lower and upper bounding surfaces: erosional or gradational; planar, irregular, curved (concave or convex)

-External geometry: sheets, lens, wedge, scoop, U shaped fill

-Scale: thickness, lateral extent parallel and perpendicular to flow direction

-Internal geometry: lithofacies assemblage, vertical sequence, presence of secondary erosion surfaces and their orientation, bedform palaeoflow directions, relationship of internal bedding to bounding surfaces (parallel, onlap, downlap).

Dominant lithofacies present in the sandstone units of the study area are Ss, Sh and Sr with subordinate Sm, Sp and Sl. Stear (1980), Friend (1983), Pizzuto (1987), Smith (1989), Miall (1996), Hancox (1998), Neveling (2002) all distinguished between the sedimentary deposits

formed within channels (channel deposits), and those of the overbank environment (overbank fines) and the architectural elements encountered in the study area are also grouped into channel and over-bank deposits. Allen (1983) recognized eight kinds of depositional features/architectural elements in a study of a Devonian sandy braided stream deposit of the Welsh borders area. Ramos and Sopena (1983) defined five types of gravel and sandy body in a Permo-Triassic unit in Spain. Miall (1985) distinguished eight basic architectural elements which he later (1996) increased to eight channel elements and eight overbank elements.

A number of architectural elements have been recognized within sandstones of the Abrahamskraal Formation in the study area including channel fills (CH), laminated sand sheets (LS) and lateral accretion (LA) deposits (Table IV). Individual channel sandstones in the study area range in thickness from 2-3m up to 14m. It appears that both large (width of 100m or more) and smaller (width of 15-20m) channels are represented in the study area (Rubidge *et al*., 2000). Larger channels carried the main discharge and are interpreted to have been active for a comparatively long time, whereas the smaller channels were abandoned after a few flood events (Rubidge *et al*., 2000).

Element	**Symbol**	**Principal lithofacies assemblage**	**Geometry & Relationships**
Channels	CH	Any combination	Finger, lens or sheet. Concave-up erosional base and shape highly variable; internal concave-up secondary erosional surfaces common.
Lateral Accretion	LA	St, Sp, Sh, Sl, Sr, Ss	Wedge, sheet, lobe, characterized by lateral accretion surfaces
Laminated sandsheets	LS	Sh, Sl, less St, Sr	Sheet, blanket
Overbank fines	OF	Fm, Fl	Thin to thick blankets; commonly interbedded with LS and may fill abandoned channels
Crevasse splays	CS	Sh,Sr,Fl	Lens up to hundreds of meters laterally. From crevasse channel into floodplain. Less than 1.5m thick.

Table III. Architectural elements encountered in the study area (after Miall, 1996).

3.3.1 Channel deposits

In the stratigraphic succession of the Abrahamskraal Formation channel deposits are more abundant from the Ecca-Beaufort contact at the base up to about 2075m. From this stratigraphic level upwards to the base of the Poortjie Member, overbank deposits become more abundant. Channel deposits are a result of high energy deposition and they provide important information on the fluvial systems and vary in size forming tabular and lenticular deposits (Neveling, 2002).The larger sandstone bodies in the study area are multistory sandstones of which each storey is considered to be the remnant of a single palaeo-channel (Stear, 1980b). The grouping of several of these remnants in multistory sandstones represents a sequence of fluvial events in which various palaeo-channels shared the same general course (Rubidge *et al*., 2000).

Channels may be classified into fixed (ribbon-shaped) geometry, mobile (broad and shallow with complex fill geometry) or sheet-like (essentially unchannelized), (Friend *et al*., 1979; Friend, 1983; Blakey & Gubitosa, 1984). Fixed channels are narrow, with width/depth ratios of less than 15. Mobile channels are filled by a process of channel migration or switching within a single major channel sour with a width/depth ratio greater than 15. Where the width/depth ration exceeds 100, the channel is said to be sheet-like (Miall, 1985).These variations in channel margins are reflective of bank stability, slope and discharge. Channels cut into mud dominated fines, especially where the banks are stabilized by a dense root network, offer a considerable resistance to erosion (Smith, 1976) and tend to be steep. By contrast those that cut into unconsolidated sand and gravel are easily eroded and may retreat rapidly, resulting in lower channel margin slopes or stepped margins with steep cutbank sections alternating with flat terraces formed by bar complexes and partly filled minor channels (Miall, 1985).

3.3.1.1 Channel fills (Element CH)

The largest identifiable autocyclic element in any fluvial system is CH which is only observed if the concave-up channel scour surface (Figure 3.22) can be identified (Miall, 1985). Sloping channel margins (<10°- 45°) are also useful for identification of element CH. Floors of channels always comprise lithofacies Ss which is about 50cm thick and is sometimes laterally extensive.

Element CH was erected for channels in the order of 10-100m in width that cannot be broken down into components such as DA and LA (Miall 1985, 1996). These channels include major channels bounded by fifth-order bounding surfaces as well as minor channels bounded by fourth-order bounding surfaces (Miall, 1996). Channel fills consist of stacked and fining upwards packages with sandstone at the base grading into siltstone and mudstone towards the top.

For example, on the farm Elandsfontein at S32°31.399'/E21°24.497', sandstone unit E exhibits a minor channel fill occurring as a sandstone lens overlying a concave-up erosional surface (third order macroform) (Figure 3.22). Here the channel is about 40m wide and 2m thick giving a width/depth ratio of 20 (fixed channel). The channel slope is 19° and this internal fill is structured by ripple cross lamination (facies Sr) indicating a mean palaeocurrent direction of 69°.

3.3.1.2 Lateral accretion deposits (Element LA)

These are characterized by large scale third order bounding surfaces dipping at (<10°) angles and off-lapping at their upper and lower terminations (Miall, 1996).
Where the main flow of the channel is directed away from the bank (inside of a meander) this leads to a helical overturn pattern and the return flow passes obliquely up the bed of the inner bank. As a result, significant sedimentation takes places, and the bank accretes laterally at a high angle to the principal flow direction (Miall, 1996). A distinctive architectural element then develops characterized by large scale, gently dipping third order bounding surfaces that correspond to the successive increments of lateral growth (Miall, 1996). These surfaces have traditionally been termed epsilon cross bedding (Allen, 1963a). The upper terminations are off-lapped and the lower terminations downlap onto the channel floor (Miall, 1996).
This architectural element is well exposed on sandstone unit E on the farm Elandsfontein (S32°31.502¹/E21°24.433¹). There is a pebble lag (facies Ss) at the base followed by weak horizontal bedding in the middle (facies Sl), and overlain by horizontal bedding (facies Sh) right through to the top of the outcrop. The strike of the outcrop is north - south and accretion is due south from the north (Figure 3.23). This element (LA) is also observed in Figure 3.22.

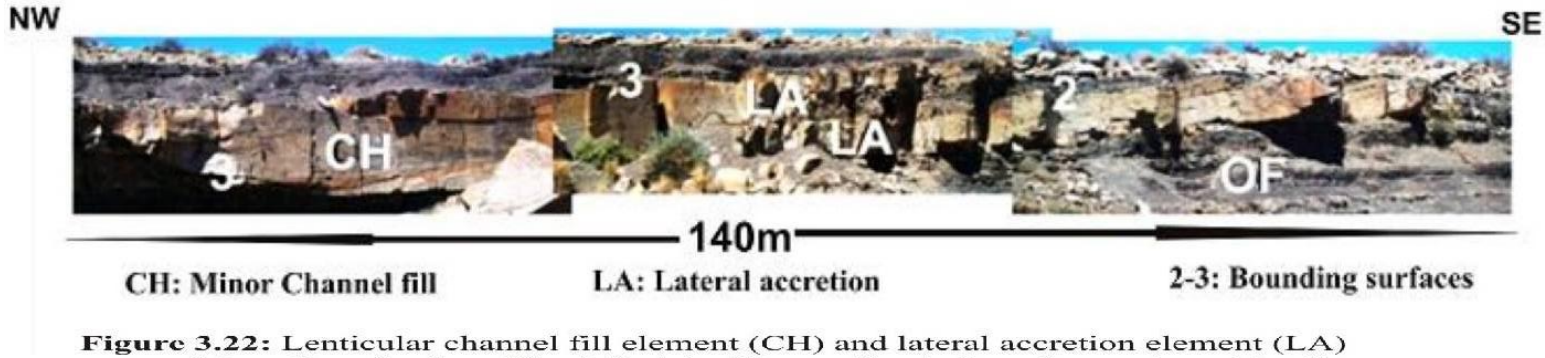


Figure 3.22: Lenticular channel fill element (CH) and lateral accretion element (LA) on sandstone E on the farm Elandsfontein. Observation is from the western side of the outcrop. Palaeocurrent direction is 69 degrees (perpendicular relative to this view.

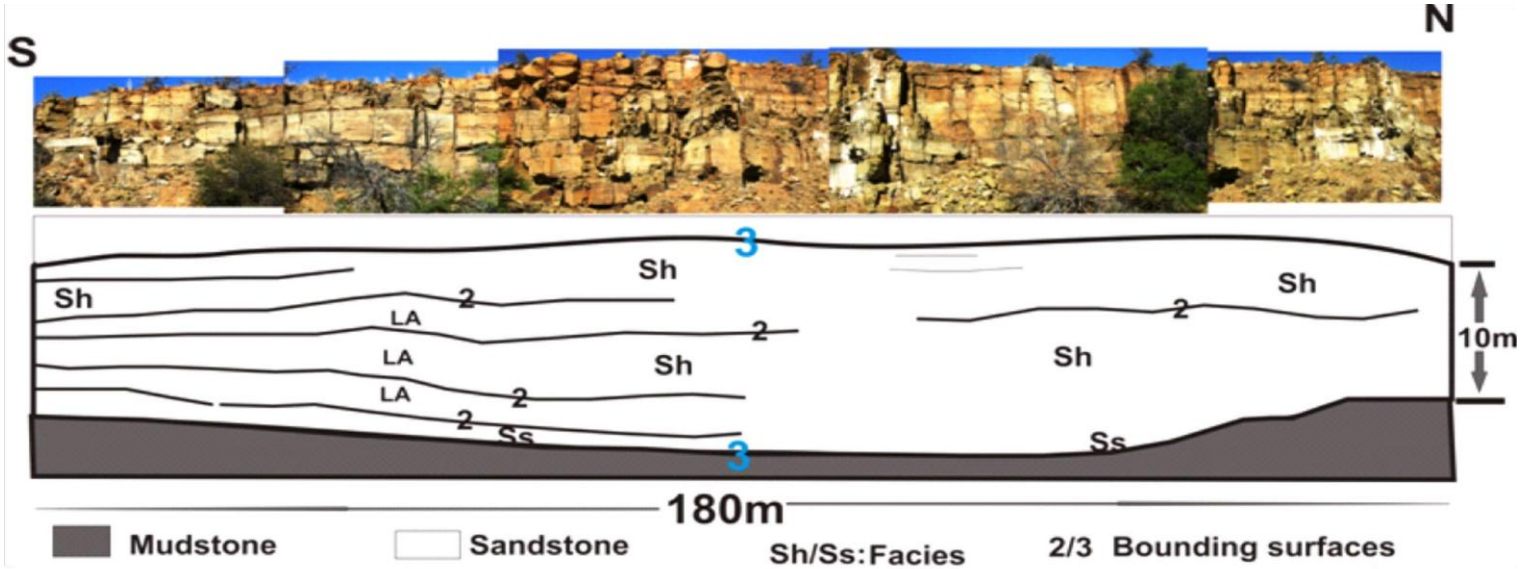


Figure 3.23: Profile of lateral accretion deposits (element LA) on sandstone E on the farm Elandsfontein. Observation made from the eastern side of the outcrop and the palaeochannel was accreting from north to south.

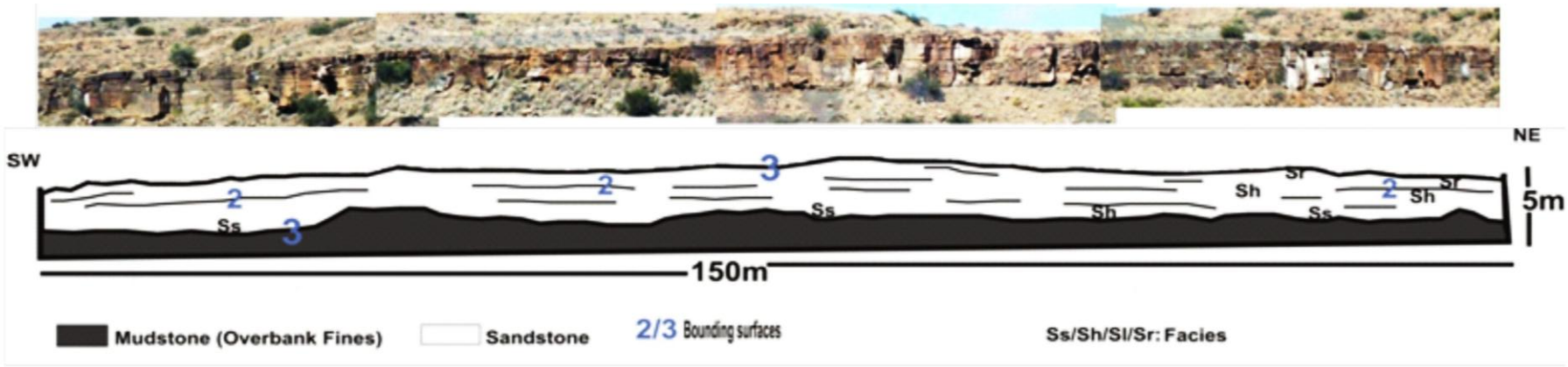


Figure 3.24: Lateral profile of laminated sandsheet (element LS) for sandstone I on the farm Rooifontein. Observation was from the eastern side of the outcrop. Palaeocurrent direction measured ontop of the outcrop is 70 degrees.

SSW NNE

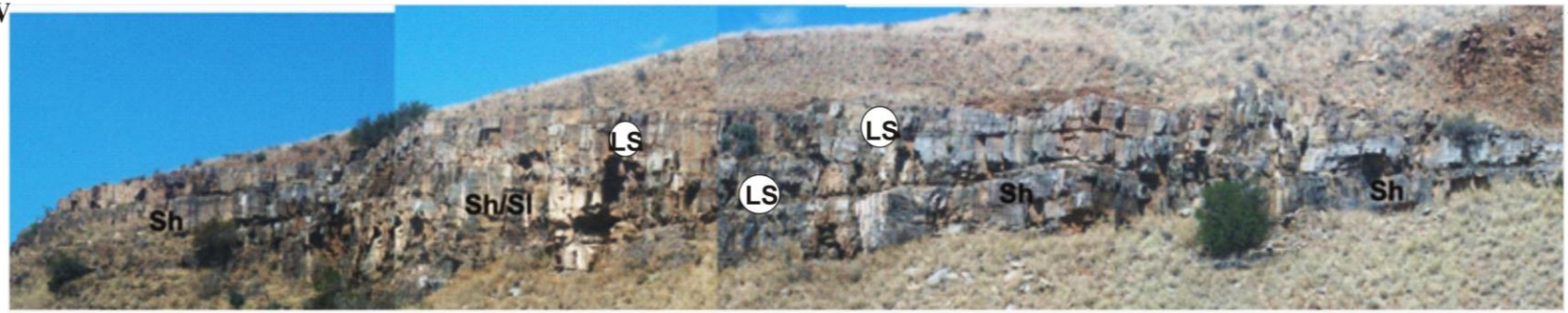


Figure 3.25: Lateral profile of sandstone O on the farm Klipbankskraal showing element LS.Observation made from the southeastern side of the 120m wide outcrop. No sedimentary structures on outcrop to determine palaeocurrent direction.

3.3.1.3 Laminated sand sheets (Element LS)

Several workers have described this element for modern environments e.g. Turnbridge (1981) and Stear (1985) and from the rock record e.g. McKee *et al.*, (1967).

At numerous localities in the study area, large scale deposits consist of tabular sandstones 1.8m to 15m thick which are laterally extensive for hundreds of meters, some even going for a couple of kilometers. These tabular channel sandstones consist of stacked horizontal sandstone sheets separated by erosional or abrupt first to third order bounding surfaces. Facies Sh and Sr predominate with subordinate Ss and Sl. Trends representing upward decrease in flow energy are often manifested by lithofacies sequences Ss-Sh-Sl-St-Sr-Fm; Sh-Sr-Fm. Element LS has been interpreted as the product of flash floods depositing sand under upper flow regime plane bed conditions (Miall, 1977, 1984b; Turnbridge, 1981,1984; Sneh, 1983).

Sandstone unit I on the farm Rooifontein exhibits element LS (Figure 3.24). At the base of the outcrop, there is both low angle cross beds (Sl) and horizontal bedding (Sh). The laminae of facies Sh/Sl are subparallel to the gently dipping bounding surfaces. The topmost sand sheet has ripple cross laminations. The individual sand sheets get thinner towards the top.

Sandstone unit O on the farm Klipbankskraal/Springfontein at S32° 24.445¹/E21° 25.727¹ displays element LS with an erosive base with a 40cm thick pebble lag (Ss), overlain by Sh/Sl with thin lags throughout the outcrop which taper laterally. Some of the sandstone beds manifest element LA (Figure 3.25). Overall, for this element in the study area, the individual sand sheets are 0.5 – 2.0m thick, rest on flat to slightly scoured erosion surfaces, and are capped by St or Sr which are indicative of waning flow conditions at the end of a flood event (Miall, 1985). The individual sand sheets can be traced laterally for more than a kilometre in some places, and at the edges, they thin and split into thinner units dominated by lithofacies Sr and eventually peter out laterally to interfinger with over-bank fines.

The palaeocurrents in this architectural element are generally northeast and north-northeast although local divergence occurs. Flood deposits of Bijou Creek, Colorado are usually given as the modern analogue for element LS (McKee *et al.*, 1967). Ephemeral streams of the Lake Eyre Basin in Australia also contain local accumulations of this element (Williams, 1971).

3.3.2 Elements of the Overbank environment

Despite the fact that the Beaufort Group is dominated by fine grained deposits (Stear, 1980; Rubidge, 1988; Smith, 1989; Hancox, 1998), the overbank deposits have historically not received as much attention as channel deposits (Miall, 1996). This is primarily because of the paucity of distinguishing criteria such as sedimentary structures and bounding surfaces in fine grained rocks (Stear, 1980). However despite these challenges, several authors (Allen, 1965; Coleman, 1969; Reineck & Singh, 1973; Stear, 1980; Fielding, 1986; Rubidge, 1988; Smith, 1989; Groenewald, 1996; Miall, 1996; Hancox, 1998) have described different interchannel environments. In the study area, floodplain deposits are represented by crevasse splays as well as massive floodbasin mudstones.

3.3.2.1 Overbank Fines (Element OF)

In the study area, element OF is characterized by lithofacies Fl, consisting of mud or silt with thin lenses of silt to fine sand, commonly showing ripple cross lamination (Figure 3.26). Additional facies include calcrete (Allen, 1974; Leeder, 1975) and crevasse splay sand sheets (Horne *et al*., 1978; Smith, 1983; Bridge, 1984). Most of the OF deposits in the study area have a sheet-like geometry, reflecting their origin by vertical aggradation (Miall, 1985). Near active channels these deposits are split by crevasse splays, display low depositional dips of leeves, and are truncated by channel cutbanks.

Overbank fines are fine grained sedimentary rocks that were deposited in the interchannel areas. In the study area these form the bulk of the sedimentary succession from 2075m above the Ecca-Beaufort contact till the base of the Poortjie Member of the Teekloof Formation. These deposits represent fine grained suspension setting from floodwaters that accumulated in the low-lying basins between channels after channel avulsion, overbank flooding or crevassing (Allen, 1965,; Reineck & Singh, 1973). Deposits of considerable thickness e.g. mudstone unit B (96m thick) consist of massive mudstone (facies Fm) in some places interbedded with siltstone and sandstone layers (facies Fl). Crumbly weathering obscures sedimentary structures such that the mudstones/siltstones appear massive. Calcareous nodular layers (facies P) occur in these floodbasin deposits.

These fine-grained rocks were transported as sediment in suspension from the confines of the channel into the surrounding overbank environment during flood events. Friend (1983)

pointed out that there are many factors which control the geometry and thickness of overbank sequences and their relative importance in a fluvial succession. These include sediment supply, channel pattern, subsidence rate and channel migration/avulsion behaviour.



Fig. 3.26: Overbank fines (Element OF) for mudstone F on the farm Elandsfontein. Observation made from the western side of the outcrop. Mudstone F is capped by a laminated sandsheet (sandstone G).

3.3.2.2 Crevasse splays (CS)

These are thin tabular sandstones/siltstones with sharp lower and upper surfaces and occur as interbeds in fine grained facies (Fl). Crevasse splays are formed when flood water in the main channel spills into the adjacent floodplain during high stage events. Local breaches in the levees known as crevasse splays funnel the flow of water from the channel and provide conduits for suspended and bed load sediment from the channel into near channel portions of the floodbasin (Galloway & Hobday, 1983). By this means, coarser channel sediment may be introduced into the flood plain (Collison, 1998b). Flood waters often erode strata close to the main channel thereby forming crevasse channels filled by fine-grained sediments when the flood subsides and distributary channels have been abandoned (Allen, 1965; Coleman, 1969).

Crevasse splays may be small, consisting of lenticular sandstones (< 1.5m thick) which pinch out distally (Figure 3.27). Proximal splay deposits are characterized by sharp basal contacts, channelling and a variety of cross-bedding types (Rubidge, 1988). Since these splay sandstones are less than 1.5m thick, they are not shown in the stratigraphic section (Figure

3.1a, Appendix A). Their lenticular geometry helps to distinguish them from sheet flow deposits formed during large scale overbank floods (Neveling, 2002). The basal bounding surfaces are flat and abrupt whereas the upper surfaces are slightly convex. Siltstones and mudstones overlie these splay sandstones to form upward fining cycles. Facies Sr is prevalent in this macroform. Prevalence of facies Sh at the base suggests upper flow regime conditions while the presence of overlying Sr represents deposition of sediments during waning flow.



Fig. 3.27: Crevasse splay sandstones [CS] (bordered by dotted lines) in overbank fines (mudstone H) and at the top is a laminated sandsheet [LS] (Ss I: Sandstone I). Lower splay is 50cm thick while the upper one is 1.0m thick.

The vertical transition from horizontal bedding to ripple cross lamination within a flood event is indicative of deposition of suspended sediment from a decelerating flow on a flat bed and the transition from laminar to turbulent boundary conditions (Jopling & Walker, 1968). Crevasse splay deposits thus consist of interbedded fine grained sandstones, siltstones and mudstones on which palaeosols may be developed (Krans, 1987). Ripple, climbing ripple, wavy and medium scale trough cross lamination, mud drapes, graded beds and local scour and fill structures are common sedimentary structures in these crevasse splay deposits (Rubidge, 1988). In some rare instances, the splay sandstones are preceded and overlain by light green siltstone which is indicative of a gradual increase in the velocity of overbank deposition rather than a sudden, catastrophic flood event (Neveling, 2002).

3.3 Palaeocurrent analysis

A total of 190 bedforms were measured at 19 data points in the study area covering the whole stratigraphic interval from the Ecca-Beaufort contact till the base of the Poortjie Member. The results of these measurements are presented in Appendix A and manifest a predominantly NE palaeocurrent direction.

Sedimentary structures which supply the most consistent palaeocurrent data in the study area are the symmetrical wave ripples (rib & furrow structures) and ripple drift cross laminations and these sedimentary structures in the study area give a palaeocurrent direction towards the north-east for most of the sandstones except sandstone C whose palaeoflow direction is due east (Table III).

Theron (1975) obtained slightly divergent palaeocurrent directions in the sub-aerially deposited Beaufort rocks of the southwestern corner of the Karoo Basin.

Kübler (1977) undertook a regional palaeocurrent analysis of the Beaufort West- Merweville-Fraserburg area and the results of his study showed that the overall bimodal distribution of palaeocurrents in the area he investigated is similar to the pattern of certain reaches in the modern meandering Mississippi River. This led to him concluding that the Lower Beaufort channels were meandering and they flowed in a northerly to northeasterly direction, with a provenance area to the southwest. This trend was also observed by Stear (1980) who postulated an overall easterly to northeasterly palaeoflow direction for the sandstones of the Moordenaarskaroo.

Le Roux *et al*, (1994) conducted a palaeoenvironmental study in the Moordenaarskraal, north of Laingsburg and their results showed that the regional palaeoslope in this part of the Karoo Basin was northeastward. The northeasterly directed palaeocurrents i.e northeasterly fluvial transport system noted in this and previous studies implie a provenance coinciding with the Cape Fold Belt (Cole & Wipplinger, 2001).
As is evident from table III and Appendix A, the overall palaeocurrent direction for the entire sucession in the study area is northeast and this corroborates work by previous workers in different parts of the southwestern corner of the Karoo Basin.

Lithological unit	Grid coordinates	Mean Palaeocurrent reading (°)
Arenaceous unit **A** (Tuinkraal) Point a	S33° 01.316[1]/E21° 40.372[1]	88.4
Point b	S33° 01.308[1]/E21° 40.960[1]	42.2
Point c	S33° 01.196[1]/E21° 40.933[1]	70.6
Point d	S33°01.096[1]/E21° 40.881[1]	38.2
Point e	S33° 00.958[1]/E21° 40.902[1]	84.6
Point f	S33° 00.120[1]/E21° 41.010[1]	85.0
Sandstone **C** (Moordenaas kraal) Point a	S32° 51.443[1]/E21° 37.448[1]	90.0
Point b	S32° 51.448[1]/E21° 37.360[1]	92.2
Sandstone **E** Point a (Rietfontein)	S32° 51.421[1]/E21° 37.378[1]	97.0
Point b (Elandsfontein)	S32° 43.762[1]/E21° 36.502[1]	77.0
Point c (Elandsfontein)	S32 °43.957[1]/E21° 36.270[1]	69.0
Sandstone **G** (Elandsfontein) Point a	S32° 31.101[1]/E21° 25.653[1]	62.0
Point b	S32° 29.255[1]/E21° 26.072[1]	76.6
Sandstone **I** (Elandsfontein)	S32° 30.401[1]/E21° 25.648[1]	62.8
Sandstone **K** (Elandsfontein) Point a	S32° 30.306[1]/E21° 25.822[1]	53.6
Point b	S32° 27.535[1]/E21° 26.397[1]	29.4
Sandstone **M** (Klipbankskraal) Point a	S32° 22.542[1]/E21° 27.202[1]	75.5
Point b	S32° 22.156[1]/E21° 27.248[1]	42.6
Sandstone **U** (Springfontein)	S32°22.271[1]/E21°27.362[1]	66.0

Table IV. Palaeocurrent data for the sandstones in the study area (measured from rib & furrow structures.

CHAPTER FOUR: PALAEONTOLOGY

During the course of fieldwork for this study, many fossils were collected in the study area (Appendix B). In addition because of the compilation of the GIS based database of fossils from the Beaufort Group (Nicolas, 2007) this study has also utilized all fossils previously collected from the study area (Appendix C) which are housed in South African museum collections. In Appenddix B, dicynodonts were identified by Kenneth Angielczyk and Bruce Rubidge, dinocephalians by Bruce Rubidge, therocephalians by Fernando Abdala.

4.1 Amphibia

Only two rhinesuchid amphibians (identified by Bruce Rubidge) were collected during this study, BP/I/6885 from sandstone E on the farm Rietfontein 269 (S32°43.786'/E21°36.496') and BP/I/7038 (Figure 4.1) from mudstone J on the farm Rooifontein 258 (S32°27.797'E21°23.653'). Using the data from the database of Nicolas (2007) the stratigraphic range of *Rhinesuchus* is thus extrapolated from the base of the *Tapinocephalus* Assemblage Zone upwards into the Poortjie Member (Figure 4.2).



Figure 4.1: Dorsal view of rhinesuchid amphibian skull recovered from mudstone J on the farm Rooifontein 258, Merweville. Scale in cm.

4.2 Parareptiles

The parareptiles found in the study area are pareiasaurs and *Eunotosaurus*.

4.2.1 Pareiasaurs

Two pareiasaurid genera were recovered in the study area namely *Bradysaurus* and *Embrithosaurus. Bradysaurus* is the most basal pareiasaur which first occurs in arenaceous unit A in the *Tapinocephalus* Assemblage Zone on the farm Badsfontein. About 25 *Bradysaurus* specimens have been recovered from the study area. *Embrithosaurus* is more derived than *Bradysaurus* (Lee, 1997) and only a single specimen is recorded in the study area for this genus (SAM-PK-008034) from sandstone E on the farm Hogeveld. The stratigraphic range of pareiasaurs extends upwards from arenaceous unit A and the highest occurrence of this taxon in the study area is a pareiasaur indet from mudstone P (BP/I/7082) on the farm Springfontein/ Rondom 247. However, pareiasaurians are known to occur throughout the *Tapinocephalus* Assemblage Zone into the overlying *Pristerognathus* Assemblage Zone (Smith & Keyser, 1995) but refinement of their taxonomy is essential before they can be useful for biostratigraphic research.

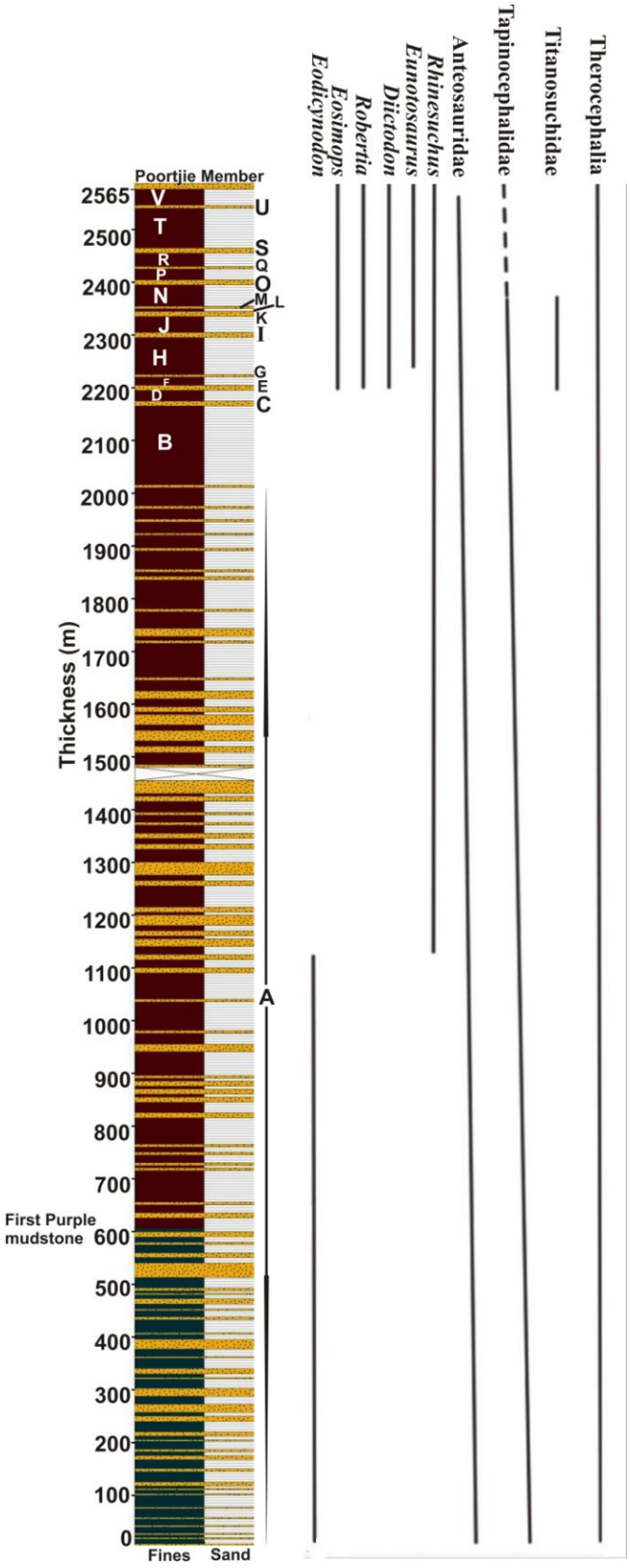


Figure 4.2: Stratigraphic section showing stratigraphic ranges of different fossil taxa in the study area. A-U represents the lithologicl units. Red colour denotes areas in the stratigraphic column where maroon mudrocks may occur, the green shows the portion of the stratigraphic column where no maroon mudrocks are present.

4.2.2 *Eunotosaurus*

The parareptile *Eunotosaurus*, easily recognized in the field by its anteroposteriorly elongate dorsal vertebra that articulate with anteroposteriorly expanded ribs (Figure 4.3). The stratigraphically lowermost occurrence of *Eunotosaurus* is from mudstone F, about 7.0m below sandstone G (specimen 2011/267 from the farm Eselsfontein). Three more specimens were found in mudstone J on the farm Rooifontein (BP/I/7024, BP/I/7027 & BP/I/7121). Our collecting reveals that the stratigraphic range of *Eunotosaurus* in the study area therefore extends from mudstone F (2210m above the base of the Abrahamskraal Formation) into the overlying Poortjie Member of the Teekloof Formation (Figure 4.2).



Figure 4.3: *Eunotosaurus* postcranial fragment showing the antero-posteriorly expanded ribs.

4.3 Therapsids

4.3.1 Biarmosuchia

In the study area, only a single biarmosuchian, the skull of *Hipposaurus* (BP/I/6879), identified by Bruce Rubidge, (Figure 4.4) was recovered from mudstone unit F on the farm Reitfontein 269 about 360m below the Poortjie Member of the Teekloof Formation.

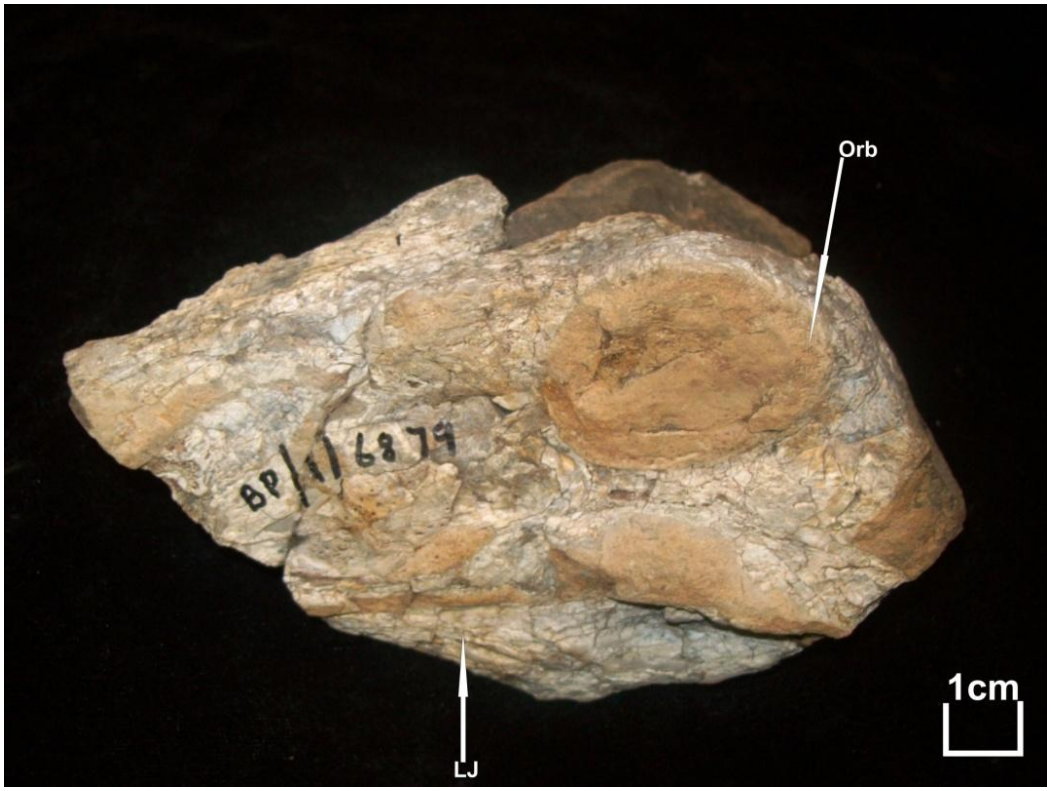


Figure 4.4: Lateral view of the skull of *Hipposaurus* (BP/I/6879) recovered from mudstone unit F on the farm Rietfontein 269. The snout is missing and the skull is facing to the left. **Orb** represents the eye orbit and **LJ** is the lower jaw.

4.3.2 Dicynodontia

Dicynodont therapsids were cosmopolitan members of the Middle and Late Permian terrestrial ecosystems (Angielczyk & Sullivan, 2008). As is the case with all biozones of the Beaufort Group, dicynodonts are the most abundant tetrapods in the *Eodicynodon* and *Tapinocephalus* Assemblage Zones. In the study area, dicynodonts found include *Eodicynodon*, *Eosimops*, *Robertia* and *Diictodon*.

4.3.2.1 *Eodicynodon*

This is the stratigraphically lowermost dicynodont in the Abrahamskraal Formation (Rubidge, 1990b, 1995). *Eodicynodon* specimens were not found during this study but from my stratigraphic measurements as well as the stratigraphic position of specimen BP/I/6230 (Jinnah & Rubidge, 2007) it is apparent that the range of the genus extends from the base of the Beaufort Group up to 1104m. This stratigraphic interval is covered entirely by arenaceous layer A and 1104m thus coincides with the upper limit of the *Eodicynodon* Assemblage Zone (Figure 4.2). Until the discovery of specimen BP/I/6230 all the *Eodicynodon* specimens were from below the first purple mudrock.

4.3.2.2 *Eosimops*

This dicynodont genus, previously known from only the poorly preserved holotype, is now known from a number of specimens from the *Tapinocephalus* & *Pristerognathus* assemblage zones (Angielczyk & Rubidge, 2012). *Eosimops* is distinguished by the following characteristics: posterior median palatal ridge that forms a flattened Y-shaped platform surrounding the anterior median palatal ridges, parietals widely exposed on the skull roof, small number of postcanine teeth on the maxilla and a widened postorbital bar (Angielczyk & Rubidge, 2012).

Only two *Eosimops* specimens (BP/I/7039 & BP/I/7041) (Figure 4.5) were recovered in the study area, both from a pedogenic horizon in mudstone D about 5.0m below sandstone E on the farm Eselsfontein.

4.3.2.3 *Robertia*

This pylaecephalid dicynodont is characterized by a wide intertemporal region, exposing the parietals in the midline. the presence of a moderately wide skull roof, a few small teeth placed irregularly on the maxilla (King & Rubidge, 1993) and the palatine bone in the roof of its mouth was not as reduced as in *Diictodon*, a notch immediately in front of the tusk-like canines on the upper jaw, wide vomer and a tall crista oesophagea (Angielczyk, *pers obs*) (Figure 4.6).

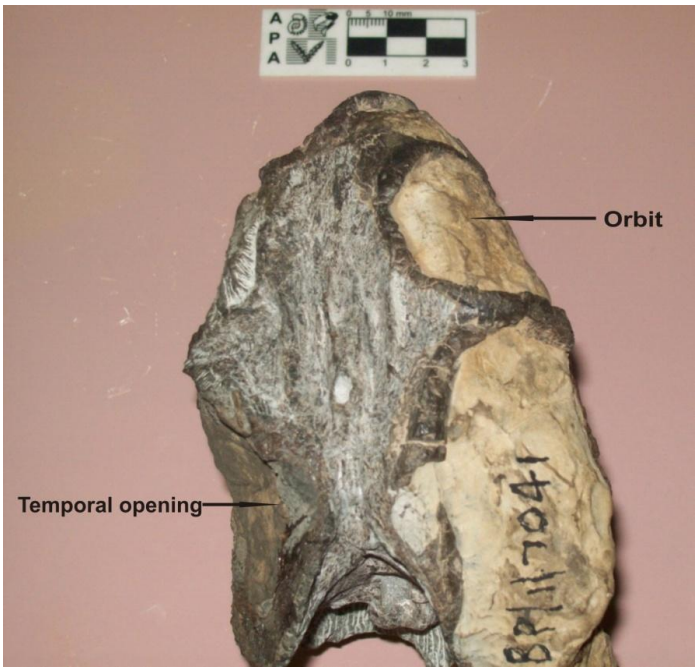


Figure 4.5: Dorsal view of *Eosimops* skull recovered from mudstone D on the farm Eselsfontein.



Figure 4.6: Palatal view of *Robertia* skull showing (C) canines (tusks)and (P) post-canine teeth.

In the study area seven *Robertia* specimens were recovered, four from mudstone D (BP/I/7042, BP/I/7100, BP/I/7103 & 01/D11/11) two from mudstone J (BP/I/7095, BP/I/7102) and the uppermost one from mudstone L (BP/I/5385). Accordingly the stratigraphic range of *Robertia* extends from the last occurrence of *Eodicynodon* (2180m from the Ecca-Beaufort contact in mudstone D into the Poortjie Member (Figure 4.2). The uppermost range is based on Rubidge & Angielczyk (2008) who reported that *Robertia* first appears in the *Tapinocephalus* Assemblage Zone after the last occurrence of *Eodicynodon* and continues into the strata assigned to the *Pristerognathus* Assemblage Zone (Poortjie Member).

4.3.2.4 *Diictodon*

Diictodon is easily recognized by its relatively narrow inter-temporal region in which the post-orbitals extensively overlap the parietals, absence of post-canine teeth in the maxilla, long inter-pterygoid vacuity and a low ridge-like crista oesophagea (Angielczyk, *pers comm*) (Figure 4.7).

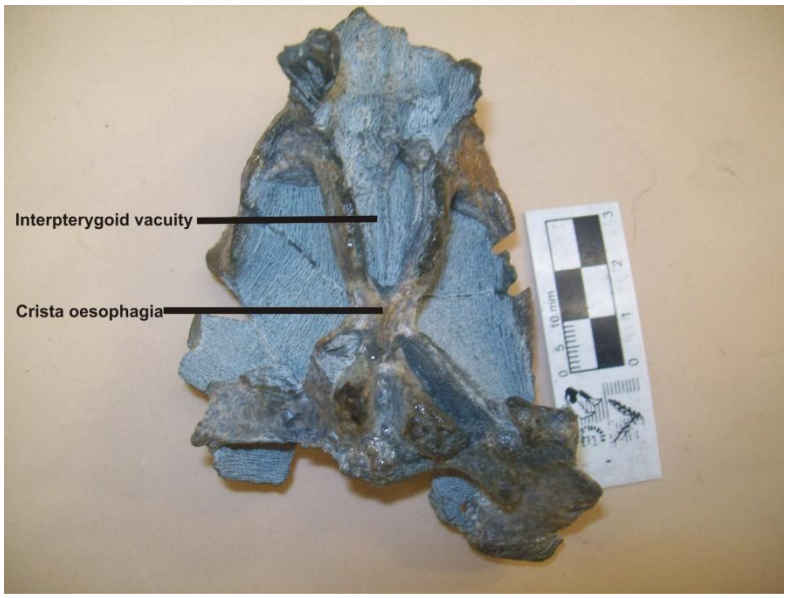


Figure 4.7: Ventral view of a *Diictodon* skull showing the long interpterygoid vacuity and low ridge-like crista oesophagia. Scale is in cm.

Stratigraphically, *Diictodon* first appears in mudstone unit D at 2180m above the Ecca-Beaufort contact (Figure 4.2) and extends up to the end of the *Dicynodon* Assemblage Zone (Kitching, 1995).

4.4 Dinocephalia

Dinocephalian remains are relatively abundant in the study area and in this report are considered under the families Anteosauridae, Titanosuchidae and Tapinocephalidae.

4.4.1 Anteosauridae

Anteosaurs were not recognized as a separate group of dinocephalians until the work by Boonstra (1954a), who separated Anteosauridae from Titanosuchidae. King (1988) considered dinocephalians with a small heel on the incisor, a slight tendency towards pachyostosis, and the jaw articulation shifted slightly forwards to belong to Antiosauridae. Anteosaurs represent a monophyletic group of dinocephalians supported by the following characteristics: upward canted maxilla, vomers with raised, elongated ridges, jugal lacrimal ridge and a strongly anteroventrally curved post-orbital bar (Kammerer, 2010).

The most basal anteosaur in the study area is *Australosyodon nyaphuli* [NMQR 3152] (Rubidge, 1991). This specimen was discovered at the base of the Beaufort Group on the farm Tuinkraal near Prince Albert Road on arenaceous unit A about 450m above the Ecca-Beaufort contact. It is distinguished from other anteosaurs except *Syodon* and *Notosyodon* on the basis of a frontal contribution to the pineal boss and a contact between the frontal and the attachment site of the jaw adductor musculature (Kammerer, 2010).

In the study area the lowest occurrence of *Anteosaurus* is in mudstone unit B on the farm Buffels Valley 268 (SAM-PK-011302), then sandstone unit G (SAM-PK- K00275) on the farm Padderfontein 272, BP/I/7074 from mudstone L on the farm Bullekraal 257, and the uppermost occurrence is from a pebble lag just below sandstone U on the farm Rondon 247 (BP/I/7071) [Figure 4.8], 21m below the Poortjie Sandstone Member of the Teekloof Formation.

4.4.2 Titanosuchidae

These are herbivorous dinocephalians in which the canine has been retained, the very strong incisors have a piercing talon and a crushing heel and the long series of postcanines have serrated spatulate crowns (Boonstra, 1969). The titanosuchids are abundant in the study area, represented by the short-legged *Jonkeria* and the long-legged *Titanosuchus* (Boonstra, 1969;

King, 1988), and as they are difficult to differentiate in unprepared specimens in this study they are grouped together as titanosuchid dinocephalians. The lowermost occurrence of titanosuchids is in sandstone unit C, on the farm Buffels valley 268 (SAM-PK-011462). Higher up in the succession *Jonkeria* was found in mudstone J on the farm Bullekraal 251/Klipbankskraal (SAM-PK- K08669). The stratigraphic range of titanosuchidae in the study area is thus from sandstone C up to Mudstone J (from 2130m above the Ecca-Beaufort contact up to 2290m [Figure 4.2]).

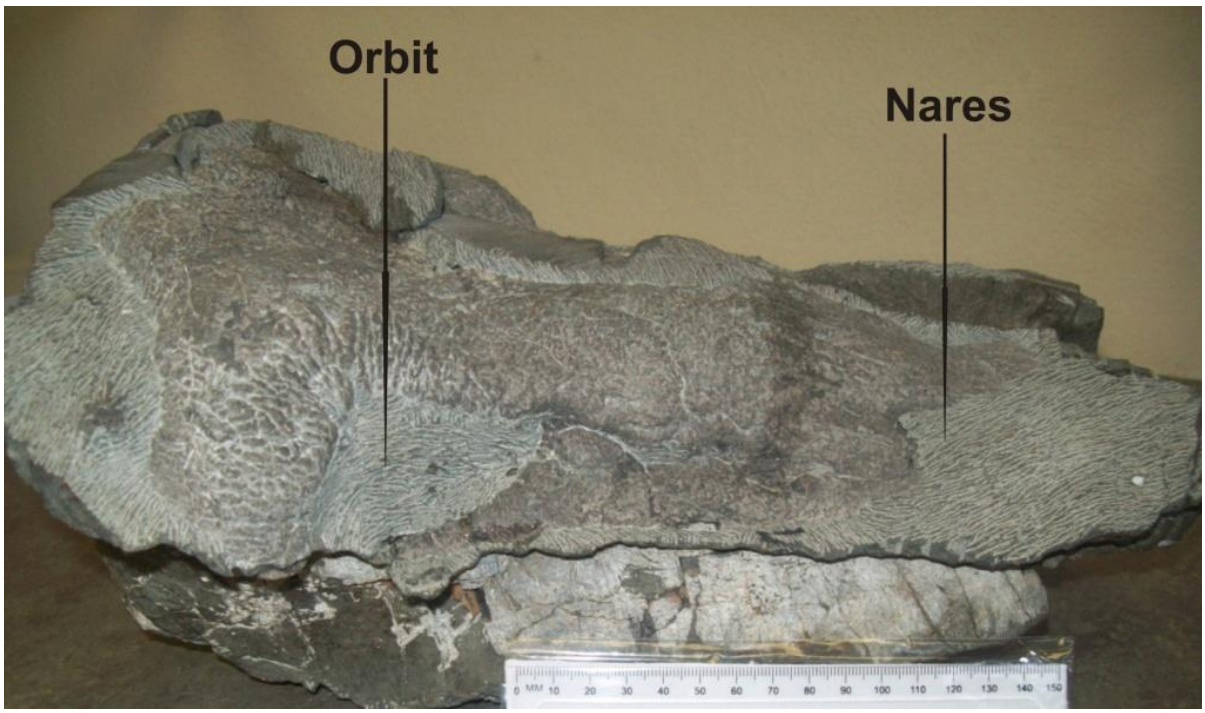


Figure 4.8: Dorsolateral view of *Anteosaurus* skull (BP/I/7071) recovered in a pebble lag below sandstone U on the farm Rondon 247 showing the typical pachyostosis of the skull roof which facilitated head butting behavior. 15cm ruler used for scale.

4.4.3 Tapinocephalidae

The taxonomy of the Tapinocephalids is in a state of confusion and is being revised by Güven who will be proposing several taxonomic modifications. Accordingly the data presented here is tentative pending the outcome of the taxonomic revision of Güven.

These were herbivorous dinocephalians distinguished by the following characteristics: thick cranial bone, thick postorbital bars, heavily pachyostosed skull elements (Modesto *et al.*,

2001), and leaf shaped and serrated postcanine teeth (Rubidge, 1991). The skulls are massive and either long snouted (such as *Struthiocephalus*) or high and short (such as *Moschops*).

Stratigraphically the range of tapinocephalids extends from the *Eodicynodon* Assemblage Zone (arenaceous unit A) represented by *Tapinocaninus pamelae* (NMQR 2987) from the farm Modderdrift in the Prince Albert district, about 230m above the Ecca-Beaufort contact (Rubidge, 1988). This specimen has moderate pachyostosis with broad postorbital bar, incisor teeth with crushing heel and several palatal teeth on the palatine boss (Rubidge, 1991). In mudstone B on the farm Buffels Valley 268, the family tapinocephalidae is represented by *Keratocephalus* (SAM-PK-011937), *Moschops* (SAM-PK-011581) and *Struthiocephalus* (SAM-PK-011580). The highest occurrence is in sandstone unit G for *Struthiocephalus* [SAM-PK-K00272] on the farm Padderfontein 272 as well as SAM-PK-005006 on the farm Wilgebosch Drift. *Moschops* was also found in mudstone J on the farm Rooifontein (S32°27.804'/E021°23.670'). Some *Criocephalosaurus,* characterized by a broad intertemporal region overhanging the greatly reduced temporal fossa as well as cranial roof thickened by pachyostosis making an enormous parietal canal (Boonstra, 1969) are recorded on the farm Ongeluksfontein/Jakkalsfontein in mudstone D (SAM-PK-K00270) and on Bontjes Akker 275 (SAM-PK-K00319 & SAM-PK-K00318) but these latter two specimens are recorded from farm centroids without definite GPS coordinates and these could be from mudstone F, sandstone G or mudstone H since these are the lithological units that outcrop on this farm.

In the study area, the stratigraphic range of tapinocephalids extends from arenaceous unit A to mudstone J at 2290m (Figure 4.2). Outside the study area, there is a record of *Criocephalosaurus* in the *Pristerognathus* Assemblage Zone in the Beaufort West area thereby extending the stratigraphic range of this genus from the *Tapinocephalus* Assemblage Zone into the Poortjie Member of the Teekloof Formation (Güven *et al*., 2012).

4.5 Therocephalia

The stratigraphically lowermost therocephalians in the Abrahamskraal Formation are the two scylacosaurids distinguished by a long and comparatively narrow snout and unusual saber-like canine teeth (Figure 4.9), from the *Eodicynodon* Assemblage Zone (*Glanosuchus*

macrops [NM QR2908] and *Ictidosaurus angusticeps* [NM QR2910]). These both came from below the first purple mudrock of the Abrahamskraal Formation on the farm Modderdrift (Abdala *et al*., 2008; Rubidge *et. al*, 1983). *Glanosuchus* occurs in the *Eodicynodon* and *Tapinocephalus* Assemblage Zones, *Scylacosaurus* only in the *Tapinocephalus* Assemblage Zone and *Pristerognathus* occurs throughout the *Tapinocaphalus* Assemblage Zone (Appendix B & C) into the overlying *Pristerognathus* Assemblage Zone (Abdala *et al*., 2008).



Figure 4.9: Lateral view of the scylacosaurid therocephalian (*Glanosuchus*).

CHAPTER FIVE: DISCUSSION

5.1. STRATIGRAPHY

5.1.1. Lithostratigraphy

This study has, for the first time, recognized 22 distinctive arenaceous and argillaceous stratigraphic units (named A-V) which make up the Abrahamskraal Formation, have a large geographical distribution and have been mapped throughout the study area. The entire thickness of the Formation is 2565m, with unit A comprising 2075m and B-V being 490m. This lithostratigraphic scheme corroborates Jordaan's (1990) mega-sequence A from his section measured on the farm Combrinkskraal, south of Leeu Gamka which is situated southeast of my study area. Jordaan's mega-sequence A attains a maximum hickness of 2454m on the farms Combrinkskraal and Blaaukranse on the banks of Gamka River. His mega-sequence A comprises a 1916m thick arenaceous Combrinkskraal member at the base of the Abrahamskraal Formation and is the equivalent of arenaceous unit A which is 2075m thick in the study area. West of the study area on the farm Wilgerbosfontein in the Laingsburg district, the Combrinkskraal member thins to only 700m thick (Jordaan, 1990).

Jordaan (1990) considers that the basal Combrinkskraal member grades upwards into the argillaceous Leeu Gamka member (about 600m thick), which outcrops on the banks of Gamka River on the farms Blaukranse and Kweekkraal and thins in the north to only 60m thick on the farm Droogvoetsfontein near Fraserburg. The Leeu Gamka member of Jordaan correlates with lithological units B up to V (490m thick succession) in the study area (Figure 5.1).

According to Jordaan (1990) the Poortjie Member forms part of an arenaceous interval (Koup Member) which is up to several hundred meters thick but in which individual sandstones can be traced for no more than a few kilometers along strike. Jordaan's Koup member grades laterally into the Middleton Formation in the Eastern Cape Province (Visser & Dukas, 1979).

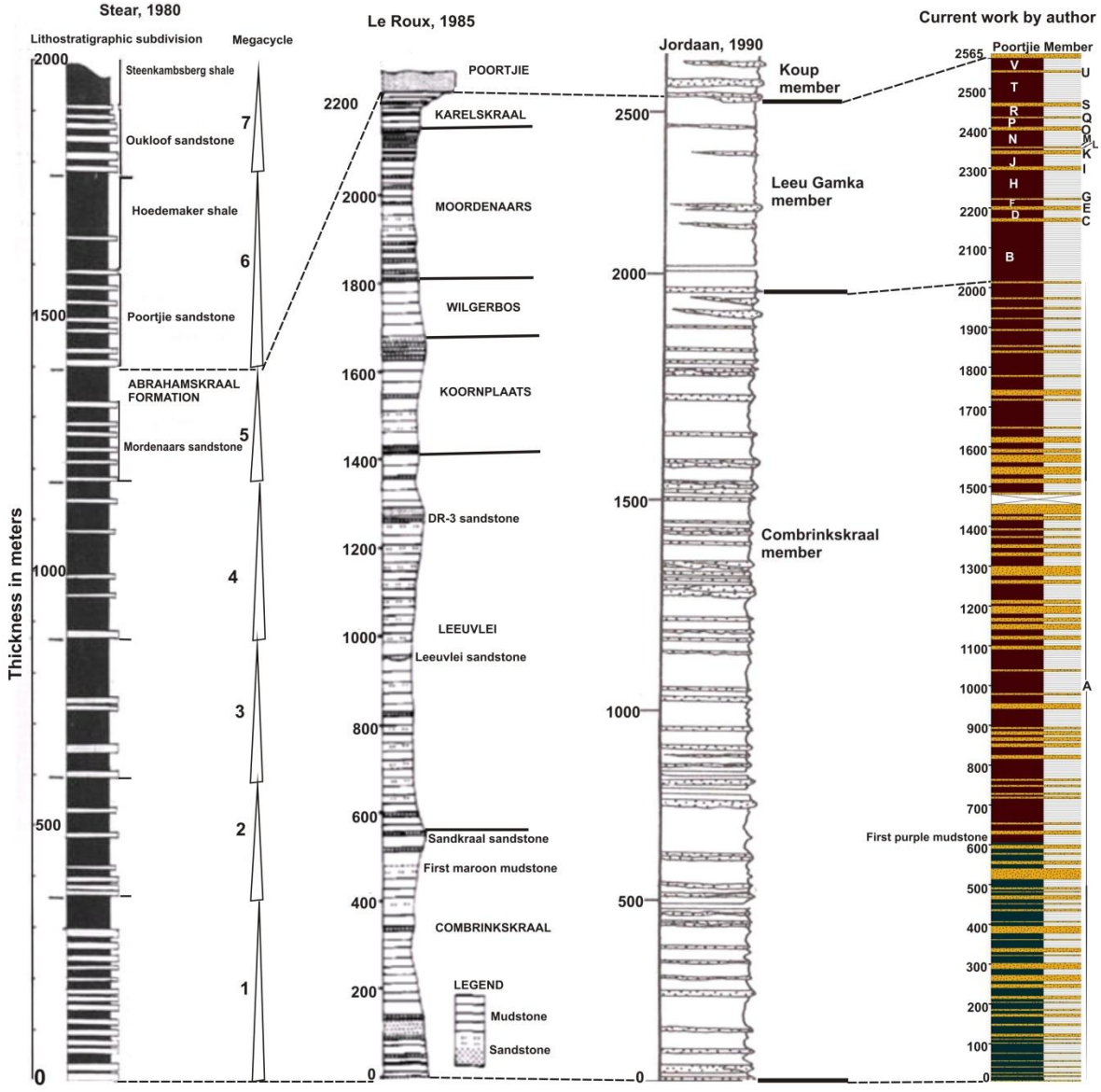


Figure 5.1: Comparison of Stear (1980), Le Roux, 1985, Jordaan (1990) and current work by author.

Rocks of the study area conform to Rubidge's (1988) lithofacies association 3 which consists of upward fining fluvial type sequences with erosively based sandstone at the bottom often with a pebble lag at the base and grading upwards into siltstone and mudstone (Appendix A). Large scale upward fining sequences marked by arenaceous basal intervals and grading

upwards into predominantly argillaceous intervals are evident throughout the western Karoo Basin (Jordaan, 1990). Several orders of upward fining cycles are evident in the study area, each cycle consisting of intra-formational conglomerate overlying an erosive base, grading upwards into sandstone and ultimately mudstones or siltstones on-top. This constitutes a single cyclothem which is representative of a single sedimentary cycle. (Duff *et al.*,1967).

Sandstone constitutes about 30% (745m out of 2565m) of the total lithology in the study area. This figure compares with Johnson (1976) who considered the Koonap Formation (lateral equivalent of the Abrahamskraal Formation) to comprise 20-30% sandstone.

5.1.2. Depositional environment

Allen (1983) and Miall (1985, 1988) spearheaded a new approach that addresses three dimensional complexes in fluvial deposits. This has greatly improved the understanding as well as the interpretation of fluvial lithology (Neveling, 2002).
The sedimentary structures in the study area reflect an upward decrease in palaeoflow velocities within a single cyclothem from upper-flow regime, horizontally laminated sandstones with intraformational clay pebble conglomerate (Ss) at the base of most of these sandstones onto medium-scale trough cross bedding (St) and ripple cross bedding (Sr) at the top grading into overbank fines (Fm/Fl).

The fluvially generated deposits in the study area are subdivided into sandstone rich channel facies associations (arenaceous unit A with element LS, and rarely LA, internally structured by facies Ss, Sh, Sm and Sr) and fines dominated floodplain associations (units B-V with elements LS, LA, CS and predominantly OF). Arenaceous unit A conforms to facies association 3 (of Rubidge *et. al*., 2000). The most abundant facies in the study area is horizontal laminated sandstone (Sh) (Appendix A) though massive sandstone (Sm) is more abundant in arenaceous unit A. Horizontal bedding forms at stream-flow velocities too high for rough bedforms such as ripples, dunes and waves to remain stable. It is formed under upper flow regime conditions that exist at the transition between subcritical and supercritical flow (Reineck & Singh, 1973). This occurs in fine to very fine grained sands at velocities of approximately 1m/s and at water depths of 0.25m- 0.5m (Harms *et al.*, 1975; Miall, 1996) where units up to several meters thick can be deposited during a single event such as a flash flood (McKee *et al*., 1967; Sneh, 1983; Miall, 1996). According to Miall (1996) the

predominance of facies Sh is one of the key indicators of flashy ephemeral flow. A high percentage of facies Sh in a system is often used as evidence for non-perennial rather than perennial flow (Stear, 1983). Miall (1977), Rust (1978), Turnbridge (1981) and Stear (1983, 1985) also list a high percentage of facies Sh as a critical element of the facies model for ancient ephemeral streams. Modern perennial rivers subject to strongly fluctuating discharge also show similar high percentage of Sh for example at Bijou creek (Mckee *et al*., 1967).

Throughout the study area, most sandstones and siltstones show a vertical transition from horizontal bedding to low angle cross bedding then ripple cross lamination at the top (Sh- Sl-Sr). This probably represents a low energy bar top and waning flood deposits (Stear, 1980). According to Boggs (1995) the succession Ss-Sh-Sr is indicative of a decrease in energy conditions. The sandstones and siltstones of arenaceous unit A with horizontal bedding and ripple cross lamination and abrupt lower and upper contacts may have been deposited under relatively high energy conditions resembling an overbank splay or natural levee environment (Coleman & Prior, 1982). The fining upward trend of the channel sequence results either from lateral migration of the channel or more commonly from channel abandonment, where the upper fine member represents infilling of the channel by diminishing flow or even later by overbank flooding from an adjacent active channel (Coleman & Prior, 1982). Flood dominated sedimentation is also evidenced in the relatively large proportion of facies Sh and St in the lateral accretion units. These structures reflect upper flow regime conditions typical of flood stage sedimentation (Allen, 1963).

Turner (1978) considered that the Lower Beaufort succession in the southern Karoo can be divided according to the changing sandstone/mudstone ratio where this ratio shows a systematic upward decrease in the sandstone fraction from the Ecca-Beaufort contact to the base of the Poortjie Member. He envisaged that the lower part of the Abrahamskraal Formation was deposited in low sinuosity channel environment, the middle part to have been the result of high sinuosity channels, and the upper portion to be a floodbasin environment facies. This work corroborates Turner's observations. The overall sandstone/mudstone ratio for the entire succession is 1:2.3 and compares with Turners's (1978) ratio of 1:2 or 1:3 determined for the Abrahamskraal Formation as opposed to a sandstone/mudstone ratio of 1.4 or 1.6 for the overlying Teelkoof Formation (Keyser and Smith, 1978).

From the Ecca-Beaufort contact to the top of arenaceous unit A, the low proportion of overbank fines is consistent with the 'bed-load' character of low sinuosity fluvial systems as suggested by Turner (1978), their presumed inability to create thick overbank sequences as well as their extreme channel instability (Allen, 1978). This stratigraphic interval is dominated by the channel element and overbank deposits are reduced to a minimum with a sandtone: mudstone ratio of 1: 3.4. This can possibly be ascribed to the ease with which anabranches of the stream can move across the floodplain (Allen, 1978), and are some of the diagnostic features of a braided depositional environment. Friend (1983) cautions that the overall proportion of fine grained sediment in a sequence must not by itself be used as an index of channel pattern since levees, crevasse splays and fans can locally introduce coarse grained sediment into an area that is otherwise characterized by fine grained sedimentation.

Argillaceous units (overbank fines) higher up in the stratigraphic succession (2075m- 2565m) make up the bulk of the lithology in this stratigraphic interval (Figure 3.1a, Appendix A) and have abrupt contacts with interbedded sandstone units. The overall sandstone: mudstone ratio in this stratigraphic interval (mudstone B- mudstone V) is 1:9.6 and this suggests that low energy conditions prevailed during the deposition of these fine grained units, occasionally interrupted by higher energy pulses of deposition during which sand was transported in and deposited. The overbank fines were deposited mainly from suspension in open standing bodies of water. The interbedded sandstones and siltstones were formed during flooding events when bedload spilled from channels onto the floodplains through crevasse splays in natural levees (Jordaan, 1990). Deposits of considerable thickness (up to 90m thick) resulted, consisting of massive mudstone and siltstones (facies Fm) and in some places interbedded with thin siltstone and sandstone intercalations (facies Fl). The thin sandstone and siltstone layers in these thick mudstone units are interpreted as small channels on the floodbasin and represent deposition from both saltation and suspension load (Miall, 1996) and are interpreted here as crevasse splays.

"Chert" beds are also present in the argillaceous units particularly mudstones D & H. These "cherts" were interpreted by Smith (1989) as marginal lacustrine carbonates that accumulated in the seasonally exposed surface muds around playa-type lakes and onto which a rain of volcanic ash fell. The diagenetic solution of the glass shards would have released silica and could subsequently have replaced the surrounding carbonate to form a preferentially silicified chert layer (Smith, 1989).

Sandstone bodies in the study area, especially in the argillaceous section of the succession (from 2075- 2565m), can be classified as sheet sandstones. Stear (1980, 1983) recognized two main morphological types of sandstone bodies in the Abrahamskraal Formation namely composite sheet sandstones (tabular) versus ribbon sandstones (elongate). Flat based sheet sandstones with steep channel margins and epsilon type cross bedding (Allen, 1965b) are attributed to deposition by high sinuosity meandering streams (Stear, 1980). Stacked channel complexes especially from sandstone unit I till unit U at the escarpment(low sinuosity stacked channel facies association) are a product of vertical accretion within a relatively stable channel under conditions of rapid basinal subsidence (Miall, 1985). Also the multistoreyed sandstones are considered to be the product of a single palaeochannel (Stear, 1980) and the grouping of several of these multistoreyed sandstones represents a sequence of fluvial events in which various palaeochannels shared the same general course (Rubidge, 1988). Pulses of high regime sheet-flooding were the dominant forms of discharge as evidenced by the prevalence of horizontally bedded deposits filling large erosional troughs in multistory sandstone sequences (Stear, 1980). Some sandstone units in the argillaceous zones occur as splay bodies isolated in overbank deposits (Figure 3.27) and these are referred to as crevasse splays.

The combination of architectural elements (CH, LA, LS and OF) in the study area, points to the presence of a fine grained meandering river system (Miall, 1985, 1996). The dominance of floodplain fines especially from mudstone unit B till the base of the Poortjie Sandstone Member is characteristic of fine grained meandering streams (Miall, 1985) especially the floodplains of delta-plain environments such as the late Quaternary Granges- Brahmaputra delta (Goodbred & Kuehl, 2000). Thick and thin, lenticular bedload and mixed load dominated channel fill elements, lateral accretion element (LA) with facies Sh, St and Sr (Figure 3.25), presence of thick suspended load floodplain deposits are all indicative of a mixed load, high sinuosity meandering fluvial system with frequent periods of overbank flooding and levee breach (Allen, 1965a, b; Jackson, 1976; Lewin, 1978; Bridge, 1985).

The conglomeritic lags (matrix supported conglomerates) at the base of sandstone layers in arenaceous unit A at 625m, 861m, 1427m, 1450m and at the base of sandstone units G,M,O,Q & U (Appendix A) which are made up of fine grained angular clasts are probably

derived from the proximal floodplain environment (Rubidge, 1988). Collapse of cutbanks in high sinuosity rivers commonly produces matrix supported conglomerates with angular clasts (Allen, 1970; Reineck & Singh, 1973; Miall, 1988).

Various authors have put forward different theories about the formation of intraformational conglomerates. Allen (1964a) considered cohesive levee and backswamp silts (muds) as the main source of intraclasts, formed by erosion and collapse of channel banks. Smith (1972) demonstrated experimentally that dried mud fragments underwent rapid attrition during transportation and that they were negligible sources of intraclasts. Rust (1984) concluded that desiccation cracking and bank collapse could be a significant source of intraclasts only if the mud clasts were large enough to remain moist inside, thereby retaining a cohesive core for the duration of the transportation process (Jordaan, 1990).

It is thus possible that the mudrock intraclasts in the study area were formed by channel erosion of more competent, argillaceous alluvial plain deposits which formed banks of fluvial channels (Jordaan, 1990). Presence of facies Ss at the base of stacked sandstones and prevalence of facies Sh is indicative of a high energy depositional environment. On the farm Bullekraal 251 on sandstone unit K, the uneven scour surfaces on which lateral accretion units accumulated are evidence of rapid increase in flow velocities, prior to sedimentation during rising and peak flood events (Friend *et al*., 1979; Shepherd, 1987).

Moody-Stuart (1966) used cross-sectional shape to distinguish between two types of fluvial sandstone bodies in a Devonian sequence in Spitsbergen; concave-upwards lenticular channel sandstone bodies which are interpreted as products of low sinuosity streams (sandstones of arenaceous unit A); and the flat-based tabular or sheet-like sandstone bodies (which form the bulk of sandstones in the study area especially in the upper 490m of the Abrahamskraal Formation)) characterized by steep channel margins and epsilon cross bedding (sandstone units E & K) (Allen, 1965b) and are attributed to deposition by high sinuosity streams.

Local thickening of sandstones (arenaceous unit A and sandstones K, M, O, Q, S, U) is as a result of sheet sandstones superimposed one upon the other in a stacked fashion, attaining a local thickness of 15m or more (high sinuosity stacked channel facies association), for

example on the southern bank of Wilgebosrivier, on the farm Bullekraal 251 at S32° 27.579'/E21°26.353', sandstone unit K attains a thickness of 15m (Figure 3.9).

These composite sandstone sheets were apparently formed by the amalgamation of stacked channel point-bars and sheet flood deposits. The channel sandstones of arenaceous unit A occur as laterally persistent multistoreyed deposits 10-12m thick (low sinuosity stacked channel facies association) (Appendix A). These are exposed on the Vlakraalrivier banks and river bed as well as sticking out as prominent ridges on the farm Tuinkraal. These sandstones are internally structured by horizontal bedding at the base and ripple cross lamination at the top. These are braided stream deposits comparable to the Bijou Creek-type (Miall, 1977) where the distal braided streams and alluvial plain are characterized by distinctive second order fining upwards cycles that contain an abundance of erosional scours (facies Ss), trough cross bedding (facies St), horizontal bedding (facies Sh) and significant mud content (facies Fl/Fm).

Puidgefabregas & Van Vliet (1978) interpreted composite multistory sandstone sheets (element LS) as valley-fill deposits of superimposed meanderbelts. Composite sheets are interpreted as valley-fill deposits as opposed to ribbon sandstone bodies which would be interpreted as channel fill deposits. Some of the composite/stacked sandstone sheets are separated by shale and intraformational conglomerate beds (Figure 3.9) and this stacking of erosively bounded sheet deposits in lateral and vertical profile suggests a series of accretion and scouring events took place under highly fluctuating hydrological conditions in a multichannel system characterized by episodic sheet flooding (Stear, 1980).

The sandstone bodies represent fluvial channel deposits, whereas the interbedded siltstone and mudstone as well as thick sequences of mudrock between the sandstone packages represent overbank and floodplain deposits (Smith 1980; 1989). The coarse grained members of the cycles may represent periods of maximum aggradation in response to uplift and thrust loading in the source area, coupled with subsidence in the depositional area (Stear, 1980).The tectono-sedimentary setting of the southwestern Beaufort Group is analogous to that of the present day Himalayan Molasse Basin of Northern India, where rapid subsidence of the Indo-Gangetic Plain is taking place simultaneously with inferred thrust-fault uplift along the outer Himalayan chain (Johnson & Vondra, 1972). The fine grained members (Figure 3.1a,

Appendix A), characterized by a greater proportion of overbank to channel deposits, were deposited during periods of quiescence between major thrust events (Stear, 1980).

The predominance of 'skull only' preservation of dicynodont remains suggests extended periods of subaerial exposure followed by flooding which removed the post-cranial material (Smith, 1981). Majority of the fossils were found in overbank fines and very few in sandstone units. Maybe it might be due to the fact that the floodbasin environment provided the better conditions for the preservation of fossils.

5.1.3. Biostratigraphy

As is evident from Chapter 4, a large number of fossil tatrapod taxa are known from the *Tapinocephalus* Assemblage Zone, but the stratigraphic ranges of individual genera are currently not well understood and are addressed in this section.

Most of the fossils in the Beaufort Group GIS fossil database (Nicolas, 2007) have their localities recorded only as farm names (farm centroides) but most of the farms are extensive so that the stratigraphic position of a fossil may vary considerably from one corner/end of the farm to the other. For example, on the farm Vindragersfontein, lithological units D, E, F & G are present, and on Bontjes Akker 275 units F, G & H outcrop. Accordingly, fossils recorded by farm centroids, could not be incorporated into the biostratigraphic scheme.
Therefore, only those database fossils with definite GPS coordinates as well as those from farms underlain by only one lithological unit were used for the purposes of this study.

Amphibia:

Temnospondyl fossils are scarce in the study area and are represented only by the family Rhinesuchidae, whose stratigraphic range spans the entire *Tapinocephalus* Assemblage Zone. Rhinesuchids appear to be endemic to Gondwana and have been recorded in Permian rocks of Brazil, India, Malawi and South Africa (Barbarena *et al*., 1985; Damiani & Rubidge, 2003).

Parareptilia:

Eunotosaurus occurs in the upper third of the *Tapinocephalus* Assemblage Zone in the study area with its first appearance in mudstone F, at 2210m above the Ecca-Beaufort boundary

(Figure 4.2) and its stratigraphic range spans from this level into and throughout the overlying Poortjie Member of the Teekloof Formation. This corresponds with the situation outside the study area, where the stratigraphically lowermost known *Eunotosaurus* specimens occur between 2150-2210m above the Ecca-Beaufort boundary with the highest occurrences recorded in the Poortjie Member (Day *et. al*., 2013).

Biarmosuchia:

Only one *Hipposaurus* specimen (BP/I/6879) was recovered in the study area in mudstone unit F (350m below the Poortjie Member). Currently five specimens of the genus are known [BP/I/6879, SAM-PK-8950, SAM-PK-9081, SAM-PK-K252 & NMQR 3006] (Nicolas, 2007). All appear to occur higher up in the *Tapinocephalus* Assemblage zone reflecting a range from between 350 -50m below the Poortjie Member of the Teekloof Formation. Smith & Keyser (1995) consider the range of *Hipposaurus* to extend from the base of the *Tapinocephalus* Assemblage Zone into the overlying *Pristerognathus* Assemblage Zone but all of the specimens recorded appear to come from high in the Abrahamskraal Formation, and not to be present in the Poortjie Member.

Dicynodontia:

The number of recognized dicynodont genera from the *Eodicynodon* and *Tapinocephalus* Assemblage zones has been reduced to only *Colobodectes*, *Lanthanostegus*, *Robertia*, *Pristerodon*, *Chelydontops*, *Diictodon* and *Eosimops* through the relatively recent work of several workers such as Cluver & Hutton (1981), Cluver & King (1983), King (1988), King & Rubidge (1993), Keyser (1993), Modesto *et al* (2002, 2003) and Rubidge & Angielczyk (2012). However, in the study area, only *Eodicynodon Eosimops*, *Robertia* and *Diictodon* were recognized and appear to have distinctive stratigraphic ranges.

The results of this research corroborate the biostratigraphic scheme proposed by Rubidge and Angielczyk (2008). *Eodicynodon* is the lowermost and oldest dicynodont in this part of the Karoo Basin, with a stratigraphic range extending from the Ecca-Beaufort boundary up to 1104m (Figure 4.2).

However, due to paucity of fossils in mudstone B and sandstone C, *Robertia*, *Eosimops* and *Diictodon* all start at the same horizon after the disappearance of *Eodicynodon* from mudstone D (2180m above the Ecca-Beaufort contact). *Robertia* ranges from mudstone unit

D and continues upwards till mudstone L (about 200m below the Poortjie Member) though according to Rubidge & Angielczyk (2008) it continues into the *Pristerognathus* Assemblage Zone (Poortjie Member).

The range of *Eosimops* in the study area extends from mudstone layer D and because of the paucity of *Eosimops* specimens in the study area (only two specimens have been recovered, both from mudstone unit D) the upper range of the genus has not been determined but from occurrences in other parts of the basin it is evident that the upper range of the genus is the Poortjie Member (Angielczyk & Rubidge, 2012).

The stratigraphic range of *Diictodon* is the longest of any amniote genus occurring in the Beaufort Group. *Diictodon* ranges from 2180m above the Ecca-Beaufort boundary and becomes extinct close to the Permo-Triassic boundary in the upper *Dicynodon* Assemblage Zone (Rubidge, 1995; Smith and Ward, 2001; Ward *et al*., 2005; Smith and Botha, 2005; Botha and Smith, 2006). In the study area *Diictodon* is more abundant than *Robertia* (14 *Diictodon* compared to 7 *Robertia*) in their overlap interval from mudstone unit D till the upper limit of the Abrahamskraal Formation (from 2173m-2565m).

Most of the dicynodonts were recovered in argillaceous units with most of the skulls found in association with or enveloped by calcareous nodular material. Only a few skulls came from arenaceous units e.g. BP/I/6862 & BP/I/6863 which are *Diictodon* skulls recovered from sandstone unit E on the farm Reitfontein 269. Carbonate concretions in mudstone D contain best preserved dicynodont skulls. The bone serves as a nucleus for the formation of carbonate concretions.

Dinocephalia:

Apart from dicynodonts, dinocephalians are the most abundant tetrapod taxon from the Abrahamskraal Formation in the study area.

The dinocephalian subfamily Tapinocephalidae was the dominant and most successful herbivorous therapsid group of the Middle to early Late Permian (Atayman *et al*., 2009) and are most abundantly known from the *Eodicynodon* and *Tapinocephalus* Assemblage Zones, with eight valid genera currently recognized (Atayman *et al*., 2009). Tapinocephalids are represented in the *Eodicynodon* Assemblage Zone by *Tapinocaninus pamelae* which was

however recovered outside the study area but in the same district (Prince Albert). In the *Tapinocephalus* Assemblage Zone in the study area, tapinocephalids are represented by *Criocephalosaurus*, *Keratocephalus*, *Moschops* and *Struthiocephalus*.

The stratigraphic range of this dinocephalian subfamily extends from arenaceous unit A (*Eodicynodon* biozone) up to mudstone unit J (2290m above the Ecca-Beaufort boundary). However, the recently discovered tapinocephalid dinocephalian *Criocephalosaurus* (SAMPK-K10888) from the Poortjie Member of the Teekloof Formation in the Beaufort West area in South Africa becomes the first tapinocephalid from the Poortjie Member (Güven *et. al,* 2012). Before this discovery all South African tapinocephalids apart from *Tapinocaninus* were known from only the Abraamskraal Formation (*Tapinocephalus* Assemblage Zone). This now extends the stratigraphic range of tapinocephalids, shown as a dotted line extension on Figure 4.2 (as well as the dinocephalian clade as a whole) from the Ecca-Beaufort contact (Unit A of the Abrahamskraal Formation) to the lower Poortjie Member of the Teekloof Formation. Because of the taxonomic confusion which exists in the tapinocephalidae it will become possible to determine the ranges of individual tapinocephalid genera only when the current taxonomic research of Güven is completed (Güven *et. al*., 2012). Currently it is evident that the stratigraphic range of tapinocaninus is from 230-450m and is is restricted to Arenaceous unit A.

Anteosaurids which are less abundant than the herbivorous tapinocephalids also have an extensive stratigraphic distribution in the study area starting from the base in unit A by *Australosyodon nyaphuli* then followed by *Anteosaurus* from mudstone B till the base of sandstone U (Figure 4.2). Titanosuchids have a shorter range in the study area represented only in the interval from sandstone C till mudstone J [2130m-2290m] (Figure 4.2).

On the farm Rooifontein in mudstone unit J there is a fairly abundant occurrence of dinocephalian fossil remains comprising *Anteosaurus* and various tapinocephalid and titanosuchid cranial and post-cranial fragments which litter a sizeable area (approximately fifty square meters) both in-situ and scattered loosely on the ground. This could represent a local catastrophe. It appears that above unit J, dinocephalian remains become fewer as one ascends the stratigraphic succession.

Therocephalia:

Therocephalia are a paraphyletic group and the oldest record of this taxon, are two scylacosaurids *Glanosuchus* and *Ictidosaurus* from the *Eodicynodon* Assemblage Zone to the east of the study area. The only therocephalian families from the *Tapinocephalus* Assemblage Zone are the Lycosuchidae and Scylacosauridae, and it is within this biozone that the first major pulse of therocephalian diversification occurred (Abdala *et al*., 2008). In the study area only scylacosaurid therocephalians have been found (Appendix B & C). Therocephalian diversity is abruptly reduced in the *Pristerognathus* Assemblage Zone in what seems to be a transitional fauna for therocephalians (Abdala *et al*., 2008).

The upper limit of the *Eodicynodon* range defines the top of the *Eodicynodon* Assemblage Zone, and thus the base of the *Tapinocephalus* Assemblage Zone, which is 1104m above the Ecca-Beaufort contact in the study area. The upper limit of the *Tapinocephalus* Assemblage Zone in the study area (characterized by the last occurrence of dinocephalians) is the base of sandstone U which is 21m below the Poortjie sandstone (Jirah, 2012). This is contrary to Keyser & Smith's (1979) proposition that the upper limit of dinocephalians is about 120m below the Poortjie Member of the Teekloof Formation. The total thickness of the *Tapinocephalus* Assemblage Zone in the study area is therefore 1440m and the base of the *Pristerognathus* Assemblage Zone is 21m below the Poortjie sandstone.

The stratigraphic interval from 1104m to 2165m from the base of the Abrahamskraal Formation is biostratigraphically poorly resolved because of the paucity of fossils. As a result the lower range of limits of the pylaecephalids *Eosimops, Robertia* & *Diictodon* cannot be delimited with confidence in the study area. However, Rubidge & Angielczyk, (2008), Marpmann *et al*., (2009) and Day (pers comm.) who have worked over a large area of the Abrahamskraal Formation consider that Robertia first appears in the stratigraphic record jus above the range of *Eodicynodon*.

5.1.4 Biostratigraphic Correlation

Recent dates from ash beds in the lower Beaufort Group place the *Eodicynodon* and *Tapinocephalus* Biozones in the Middle Permian (Rubidge *et al*., 2013) and it is thus now possible to assign a more precise age to Pangean successions which correlate with these Beaufort Biozones.

Eunotosaurus, scylacosaurid and lycosuchid therocephalians and all the basal dicynodonts from the *Eodicynodon* and *Tapinocephalus* Assemblage Zones, apart from *Diictodon*, are endemic to the Karoo Basin and have not yet been recorded in other Middle Permian continental deposits. Since *Diictodon* has a long stratigraphic range from the Middle Permian to the end of the late Permian, it is not of use in refined biostratigraphic correlation. This leaves only dinocephalians, basal anomodonts and pareiasaurs which are of potential use. The pareiasaurs *Bradysaurus*, *Embrithosaurus* and *Nochelosaurus* which occur in the *Tapinocephalus* Assemblage Zone are the most basal pareiasaurs (Lee, 1994) and are not known outside of the Karoo Basin suggesting that pareiasaurians diversified originally in southern Africa and later invaded Laurasian Pangea (Modesto & Rybczynski, 2000). Accordingly dinocephalians, which have a relatively short stratigraphic range, are the best taxon to use for Pangean wide biostratigraphic correlation. Anteosaurid dinocephalians were the dominant terrestrial predators during the Middle Permian period (~270-260Ma), with a cosmopolitan distribution. Anteosaurs are known from Southern Africa, Russia, China and Brazil (Kammerer, 2010), represented in the *Eodicynodon-Tapinocephalus* assemblage Zones of South Africa, Ocher and Ischeevo complexes of Russia (Kammerer, 2011), Xidagou Formation in China (Cheng & Li, 1996, 1997) and Rio da Rasto Formation in Brazil (Langer, 2000).

In South Africa the fauna of the *Eodicynodon* Assemblage Zone (268-265.8Ma), comprises the most basal and also the earliest dicynodont, *Eodicynodon* (Barry, 1974; Cluver & King, 1983; Rubidge, 1990a, b), dinocephalians *Australosyodon* and *Tapinocaninus* (Rubidge, 1991, 1994) and scylacopsaurid therocephalians (*Glanosuchus* and *Ictidosaurus*) (Abdala *et al*., 2008). In other parts of the world, Wordian faunas are known also from the Xidagou Formation in Gansu, northern China (Li & Cheng, 1995; Cheng & Li, 1996; Li et al., 1996) and the *Estemenosuchus* fauna of Ocher complex in Russia (Modesto & Rybczynski, 2000 as well as in the Morro Pelado Member of the Rio da Rosto Formation, Brazil (Langer, 2000).

The assemblage from the *Eodicynodon* Assemblage Zone in the South African Karoo Basin, is thought to be of Kazanian (Wordian) age, and older than the Russian Zone I assemblage (Rubidge & Hopson 1990; Lucas 2004; Rubidge 2005).

The fauna of the South African *Tapinocephalus* Assemblage Zone comprises the anteosaurid dinocephalian *Anteosaurus*, tapinocephalids *Criocephalosaurus, Keratocephalus, Struthiocephalus, Moschops and Tapinocephalus.* Zimbabwe and South Africa have in common, anteosaurid and tapinocephalid (*Criocephalosaurus*) dinocephalians (Boonstra, 1946; Lepper *et al*., 2000; Munyikwa, 2001). The *Tapinocephalus* Biozone has scylacosaurid therocephalians (*Pristerognathus* and *Scylacosaurus*) and these correlate with *Porosteognathus* from the Russian Isheevo Assemblage (Boonstra, 1969; Battail, 2000; Battail & Surkov, 2000; Modesto & Rybczynski, 2000). Zone II (Isheevo) of the Russian Permian (Ivakhnenko *et al.* , 1997) has long been correlated to the South African *Tapinocephalus* Assemblage Zone based on shared evolutionary counterparts in biarmosuchians, anteosaurid and tapinocephalid dinocephalians and anomodonts. Basal anomodonts from the *Tapinocephalus* Assemblage Zone are *Anomocephalus* and *Galeops* from South Africa (Rubidge & Hopson, 1990, 1996; Modesto *et al*., 1999, 2000), *Otsheria* from Ocher ,Russia (Modesto & Rybczynski, 2000) and *Besiridens* from China (Jun *et al*., 2011; Battail, 2000). Isheevo Assemblage fauna also shares with South Africa biarmosuchians *Hipposaurus* from South Africa and *Biarmosuchus* from Russia (Rubidge & Kitching, 2003; Rubidge & Sidor, 2001, 2002). Also the presence of tapinocephalids in the Ruhuhu Formation in Tanzania implies a partial correlation with the Abrahamskraal Formation (Simon *et al*., 2010). The discovery of *Criocephalosaurus* in the Poortjie Member of the Teekloof Formation extends the occurrence of dinocephalians from the Capitanian into the Wuchiapingian [260.5Ma] (Güven *et al*., 2012).

The Brazilian Posto Queimado fauna which comprises of pareiasaurids coexisting with dinocephalians (Anteosauroidea and Titanosuchidae) correlates with both the *Eodicynodon* and *Tapinocephalus* assemblage zones of South Africa (Langer, 2000) and Russia's Isheevo Assemblage (Cisneros *et al*, 2005). This implies a Late Kazanian to Early Tatarian age for the Posto Queimado fauna, Isheevo Assemblage fauna and the *Eodicynodon - Tapinocephalus* Assemblage Zone fauna (Keyser & Smith, 1995; Battail, 2000; Langer, 2000).

5.2. PALAEOENVIRONMENTAL ANALYSIS

This study has shown the lower Abrahamskraal Formation (up to 2075m from the Ecca-Beaufort contact) to be largely arenaceous and above this stratigraphic level the rest of the formation comprises alternating sandstone and mudstone successions which can be mapped across the whole study area. This change in lithology indicates two very different depositional environments.

Turner (1978) recognized low sinuosity channels in the lowermost part of the Adelaide Subgroup in the western Karoo region overlain by high sinuosity channels in the middle part. Jordaan (1990) on the other hand recognized braided and both low and high sinuosity meandering channels in the lower Beaufort group sandstones of the western Karoo Basin and suggested that the braided palaeorivers changed downstream to meandering rivers. Vertical and lateral superposition of palaeochannels represents the repeated scouring and accretion by rivers that were localized within one area of the floodplain for a certain period of time. It is highly likely that the position of each new channel was influenced by the geometry of its predecessor and may, therefore, indicate the periodic localization of stream systems in a meander-belt or braid-belt (Stear, 1983).

The multistory channel sandstones of arenaceous unit A are products of a braided depositional environment (Figure 5.2). Such multistory sandstones were interpreted by Stear (1985) as products of a single major flood event, and do not represent numerous separate flood sequences. The inter-storey scours reflecting separate erosive pulses, accompanying various flood peaks or surges during the same flood episode. The morphology of arenaceous unit A sandstones is also analogous to portions of the Intracratonic Lake Eyre Basin of Central Australia (Bonython & Mason, 1953) where the catastrophic flash-floods in the Lake Eyre region transport and deposit masses of sediment by means of ephemeral braided streams. Sandy braided streams produce lenticular and multistory cross bedded sandstones with few mudrock interbeds (Tucker, 2011).

Horizontally laminated sandstones dominate arenaceous unit A palaeochannel sequences. This depositional sequence is similar to the sediments of the 1981 Laingsburg (Buffels Valley) flood (Stear, 1985) and also similar in many respects to the flash-flood deposits recorded by McKee *et al* (1967) from Bijou Creek, Colorado cited by Miall (1977) as the type example and facies model for sandy ephemeral braided stream deposits .

A meandering depositional model with abundant avulsion and crevassing is suggested here for the interval from 2075m till the base of the Poortjie sandstone (Figure 5.3) characterized by a higher percentage of overbank fines relative to channel sandstone deposits with architectural elements LA and LS, CS in overbank fines (element OF). This designates a lower energy fluvial system with confined high-sinuosity single channels (Miall, 1996). The lithology in this stratigraphic interval is dominated by fine grained overbank deposits (facies OF). Element LA (sandstones E & O) is a common occurrence in laterally accreted units deposited in the more distal, downstream areas on point bars where channel sinuosities were higher. This is reflective of a more uniform and less vigorous discharge conditions during the waning stage of floods on point bars and in proximal overbank areas (Stear, 1983). However, lateral accretion bedding in some of the individual palaeo-channels of composite sandstone sheets does not necessarily imply that the entire channel system was highly sinuous. Lateral bedding can occur in any river channel that progressively shifts its course (Jackson, 1978). Though lateral accretion is normally associated with high sinuosity meandering streams, it can be equally common in low sinuosity streams particularly in the sandy types of braided streams (Rust, 1978b).
Meandering streams produce fining upward cross bedded sandstone units up to several meters thick with lateral accretion surfaces, interbedded with mudrocks, which may contain calcretes and thin persistent sandstones deposited by crevasse splays and floods (Tucker, 2011).

Comprehensive sedimentological analyses of the volumetrically dominant interchannel facies association (Stear, 1978, 1980b; Smith, 1979, 1980; McPherson & Germs, 1979) have shown that the thick argillaceous floodplain sequences (from 2075m till 2065m [Figure 3.1a, Appendix A]) are products of seasonal deposition in semi arid, low relief flood plains that consisted of a continuously shifting pattern of ephemeral rivers and temporal lakes fringed by vast subaerially exposed mudflats. The mixed-load ephemeral channels deposited the multistory sandstone bodies by a process of both vertical and lateral accretion (Stear, 1985). The horizontally laminated lithofacies in the channel sandstones commonly alternates with ripple laminated units in a similar fashion to that observed by Stear (1985) in the lower finer-grained unit of the Laingsburg (1981) flood deposits.

The depositional model for the Abrahamskraal Formation in the study area concurs with Catuneanu *et al*., (1998) who concluded that the Koonap Formation (the lateral equivalent of

the Abrahamskraal Formation) is dominated by greenish silty mudstones and sandstones organized in fining upward cycles deposited in high energy (braided river) systems grading upwards into lower energy (meandering) systems .

Deposition of the Abrahamskraal Formation occurred under semi-arid conditions as evidenced by pedogenic carbonate horizons and gypsum desert-rose evaporates (Keyser, 1966). The increase in ferric oxide, as reflected through the increasing occurrence of red mudstone and siltstone, is evidence of deposition of the sediments in a warmer highland with periodic rainfall (Rossouw & De Villiers, 1953). From the Ecca-Beaufort contact till 606m (Figure 3.1a), the lack of red mudstone in the interchannel deposits suggests that there may have been no prolonged periods of exposure and resultant oxidation (Rubidge, 1988).

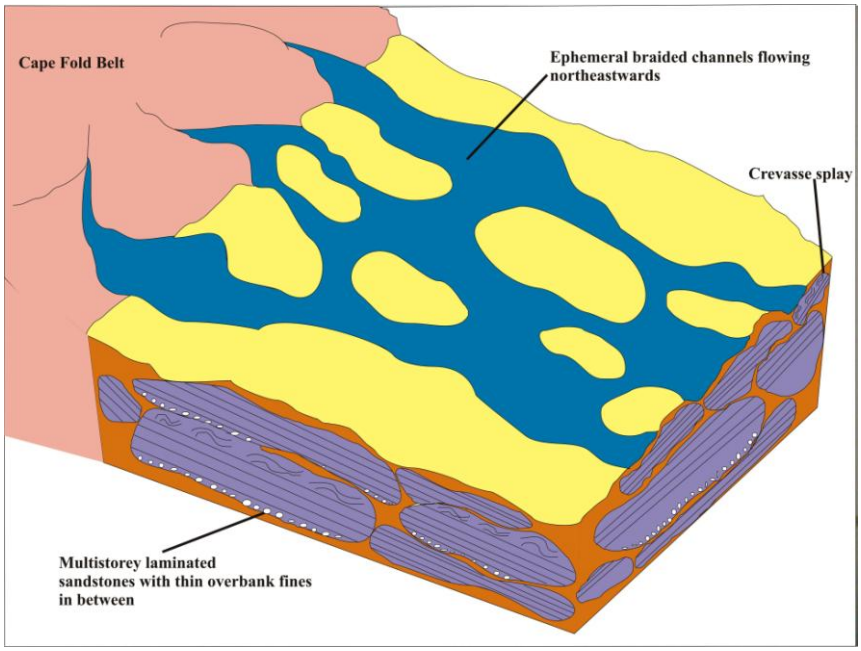


Figure 5.2: Palaeoenvironmental reconstruction of the Abrahamskraal Formation from the Ecca-Beaufort contact to the top of arenaceous unit A (0-2075m). Braided palaeoenvironment affected by the Cape Orogeny resulting in a high energy depositional environment leading to the formation of thick sandstoe beds with less mudstone interbeds (drawing modified from Tucker, 2011).

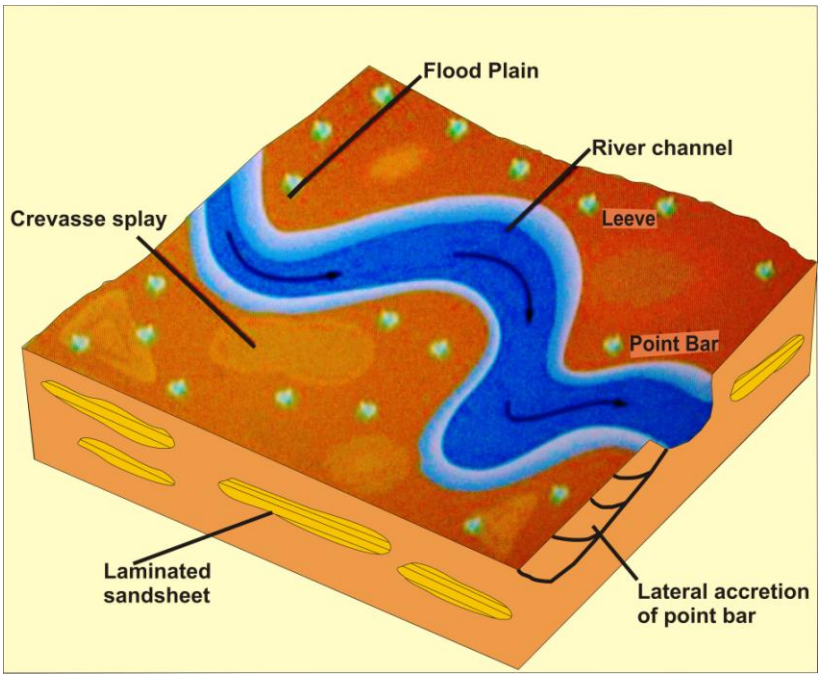


Figure 5.3: Palaeoenvironmental reconstruction of the stratigraphic succession from mudstone B till the base of the Poortjie Sandstone (2075m- 2565m). This was a meandering fluvial environment with thicker overbank fines relative to sandstone units. (drawing modified from Tucker, 2011).

Due to the complex nature of variables involved in fluvial systems, it is least probable that a single parameter can be used on its own as incontrovertible criteria for recognizing ancient channel type and lack of knowledge about the preservation potential of fluvial bedforms limits the application of lithofacies criteria in ancient alluvial sequences to generalizations (Stear, 1980). Lateral accretion bedding in some of the individual palaeo-channels of composite sandstone sheets does not necessarily imply that the entire channel system was highly sinuous. According to Rust (1978b) and Cant (1978), although lateral accretion is normally associated with high sinuosity meandering streams, it can be equally as common in low sinuosity streams, particularly in the sandy types of braided streams. Theoretically, sandy braided rivers are able to migrate freely across their floodplains than meandering rivers contained within confining channel banks (Stear, 1980). Therefore, in view of the overall unidirectional flow pattern of the palaeochannels of the Abrahamskraal Formation, the sandstone sheets especially from sandstone C till sandstone U could also be interpreted in terms of randomly migrating low sinuosity braided stream systems. Campbell (1976) described the Composite sandstone sheet of Westwater Canyon Member of the Jurassic Morrison Formation in New Mexico and suggested that this represents a composite

arrangement of low sinuosity channels within a sandy braided complex comparably with the modern braided alluvial fan of the sandy Kosi River (Gole & Chitale, 1966).

5.3 TECTONIC SEDIMENTATION MODEL

Rust (1962) pointed out that there was a relationship between the orogenic processes in the Cape Fold Belt and deposition in the Karoo Basin. Successive tectonic events in the source area gave rise to a series of rapid but sporadic uplifts, degradation and deposition, resulting in the formation of a stacked sequence of depofacies (megacycles) in a fairly stable basin (Stear, 1980, (Hälbich, 1983; Cole, 1992; Catuneanu *et al*., 1998).

Orogenic loading (thrusting) results in differential foredeep subsidence, with increasing rates towards the thrust belt and as a consequence, the gradient of the topographic profile decreases with time, allowing the transition from higher energy sand-bed braided systems (arenaceous unit A) at the base to lower energy sand-bed, fine grained meandering (mudstone B till base of Poortjie Member) fluvial systems (Catuneanu and Bowker, 2001). Subsidence and fluvial aggradation during times of orogenic loading had a strong influence on the third order depositional sequences (fining upwards sequences). These fining upwards trends of the third order cyclotherms might be associated with the gradual decrease in topography gradients during stages of orogenic loading.

Catuneanu *et al.*, (1998) applied the reciprocal flexural profile model to the Karoo Basin and according to this model, overthrust loading in the Cape Fold Belt created subsidence in the proximal part of the foreland basin (foredeep). This load created an upward deflection (forebulge) distally. Even though the forebulge may not have formed a topographic high, it would have influenced deposition of the sedimentary strata overlying it. During orogenic unloading, the foredeep is uplifted while the forebulge undergoes subsidence (Catuneanu *et al.*, 1998). The tectonic uplift of the Cape Fold Belt provided a large amount of sedimentary detritus to the basin, such that sediment supply exceeded the rate of generation of accommodation space causing a normal regressionary sequence (Rubidge *et al*., 2000). Sediment supply was from the south, causing shoreline progradation northwards through time (Rubidge *et al*., 1999). This reciprocal flexural profile model predicts contrasting stratigraphies for the proximal and distal sectors of the basin and as such, the sedimentary

strata from the same stratigraphic interval in different parts of the basin do not necessarily represent rocks of the same age (Neveling, 2002). The study area is restricted to only the proximal sector and is considered to have built out because of a prograding shoreline.

However, Tankard *et al*., (2009) refute the flexural foreland model and proposed subsidence due to lithospheric deflection as a result of mantle flow coupled to distant subduction (Pysklwec & Mitrovica, 1999). The Karoo sedimentary fill is interpreted by Tankard *et al*., (2009) as a product of crustal uplift, fault controlled subsidence and long periods of regional subsidence during which faulting was subordinate. Subsidence of the early Karoo Basin is envisaged as occurring mainly by vertical displacement of rigid basement blocks decoupled along crustal-scale boundary faults (Tankard *et al*., 2009). In the southern Karoo, Beaufort seismic reflections at the loading edge of the Cape Fold Belt have gentle northward dips, parallel to the roof thrust of a tectonic wedge and this is interpreted as demonstrating that deformation occurred in late Beaufort times. As a result Tankard *et al*., (2009) argue that the subsidence of the Permian lower Karoo Basin predated the Cape orogeny which is interpreted as Triassic in age while the lower Beaufort is inferred to be a deltaic basin-filling phase. The Tankard *et al*., (2009) model does not address the contrasting stratigraphies for the proximal and distal sectors of the basin and this aspect is unambiguously addressed by the Catuneanu *et al*., (1998) reciprocal flexural model.

McLean & Jerzykiewicz (1978) ascribe the formation of megacycles in a 3600m thick alluvial sequence of Cretaceous-Tertiary age (Brazeau Formation in the Central Alberta foothills, western Canada) to sporadic loading and subsidence by isostatic compensation in the foredeep of an encroaching thrust belt. Coarse grained members of the megacycles (analogous to arenaceous unit A) representing periods of maximum aggradation in response to uplift and thrust loading in the source area while fine grained members which are characterized by a greater proportion of overbank to channel deposits (analogous to stratigraphic interval from 2075m till 2565m above the Ecca-Beaufort contact in the study area), were deposited during periods of quiescence between major thrusts (Stear, 1980). The McLean & Jerzykiewicz tectonic scheme is similar to the tectonic and sedimentary framework of the Lower Beaufort in the western Karoo hence it is more likely that the deposition of the Abrahamskraal Formation might have been controlled by similar allocyclic mechanisms.

CHAPTER SIX: CONCLUSION

Despite several published attempts, lithostratigraphic subdivision of the Abrahamskraal Formation has been problematic because of the lack of lateral continuity of the lithological units. This study has for the first time, identified lithostratigraphic units which are easily recognizable and have been mapped. Stratigraphic logging revealed that the Abrahamskraal Formation is 2565m thick in this part of the basin. Through this study and utilizing previously published work on the Abrahamskraal Formation it has been possible to draw up a stratigraphic section which for the first time provides an accurate lithostratigraphy and thickness of the Abrahamskraal Formation in this part of the Karoo Basin. The basal 2075m is largely arenaceous, and above this level argillaceous units become progressively thicker while sandy units become thinner.

Extensive stratigraphic fossil collecting and the utilization of the Beaufort Group GIS fossil database (Nicolas, 2007) enabled the recognition of which tetrapod taxa occur at different stratigraphic levels thereby making it possible to come up with refined biostratigraphic ranges of taxa for the Abrahamskraal Formation in this southwestern corner of the basin.

This study confirmed that there is paucity of fossils in the lower levels of the Abrahamskraal Formation especially from the Ecca-Beaufort contact up to 2165m (top of mudstone B) from the base of the Beaufort Group. This can partially be attributed to the steep dip of the beds in this stratigraphic interval with lithological units dipping in excess of 60-70° making prospecting for fossils more difficult, but also the fact that the lower part of the Abrahamskraal Formation is largely arenaceous compared with the upper part of the succession possibly provided poorer conditions for the preservation of fossils. From this stratigraphic level up to the Poortjie Member, the structural dip is less steep, in places almost horizontal, and this might be the reason it is easier to find vertebrate fossil remains in this higher stratigraphic interval. Collecting from this project showed that the *Tapinocephalus* Assemblage Zone in the study area extends up to 20m below the Poortjie Member. This is slightly higher than the 120m below the Pootjie Member suggested by Keyser & Smith (1979).

This study confirmed that *Eodicynodon* is restricted to the basal 1104m of the Abrahamskraal Formation, and is succeeded by *Robertia*, *Eosimops* and *Diictodon* which occur upwards of 2180m. Dinocephalians have been shown by this study, to range from the base of the Abrahamskraal Formation (*Australosyodon)* from below the first purple mudrock of the Abrahamskraal Formation up to just 20m below the Poortjie Member. The only tapinocephalid from unit A (*Eodicynodon* Assemblage Zone) is *Tapinocaninus*, and this is succeeded by more derived tapinocephalids in the *Tapinocephalus* Assemblage Zone. *Eunotosaurus* has been confirmed from this study to be confined to the upper third of the Abrahamskraal Formation, its stratigraphic range starting from 2210m above the Ecca-Beaufort contact and continuing into the *Pristerognathus* Assemblage Zone.

The presence of fossils which have been demonstrated to occur in upper third of the *Tapinocephalus* Assemblage zone (*Eunotosaurus* and dinocephalians) and more derived dicynodonts than *Eodicynodon* such as *Colobodectes* and *Lanthanostegus* close to the Ecca-Beaufort contact in the northwestern and southeastern parts of the basin implies that the Ecca-Beaufort boundary youngs towards the northwest and southeast and is reflective of a northeasterly prograding shoreline in response to basin tectonic development, as previously documented for the basin (Rubidge *et al*, 2000; Rubidge, 2005).

The interval from 1104m- 2170m (the upper half of arenaceous unit A and mudstone unit B) is very poor in fossils and future studies should target this strratigraphic level so as to refine the dicynodont biostratigraphic scheme with respect to *Robertia*, *Eosimops*, & *Diictodon.* This study also contributes to the determination of the upper stratigraphic limit of dinocephalians since for the first time in this part of the Karoo Basin, the last occurrence of dinocephalians is seen to be higher than that previously envisaged by Keyser and Smith (1979). This together with the recent discovery of a tapinocephalid dinocephalian in the lower Poortjie Member near Beaufort West (Güven, 2012) gives a new insight into the extinction of dinocephalians as to whether it was a sudden catastrophe or if it was a gradual process which is older than 261.275 Ma (Rubidge *et al* 2013).

Lithofacies studies and architectural element analysis have led to refined palaeoenvironmental interpretation. Architectural element analysis revealed laminated sandsheets, lateral accretion, and overbank fines for the lower arenaceous part of the

stratigraphic succession. Fluvial deposits displaying these elements are deposited by low sinuosity systems with a high braiding parameter (Miall 1985). From the Ecca-Beaufort con tact until a stratigraphic horizon 2075m higher (arenaceous unit A) this interval was deposited by low to high sinuosity with a high braiding parameter characterized by more sandstone units and less fines with elements CH, LA, LS and OF.The results of this research showed that sandstones of the Lower Abrahamskraal Formation were deposited by shallow, sandy, low sinuosity channels.

In contrast sandstone units of the upper Abrahamskraal Formation from 2075m till the base of the Poortjie sandstone (2565m) this was a high sinuosity depositional environment with a low braiding parameter, with less sandstones and more mudstones which show elements LA, LS and OF were deposited by a high energy, high sinuosity depositional environment as is evidenced by the presence of elements LA and LS, internally structured by predominantly facies Sh/Sl. The floodplain deposits from 2075m- 2565m comprize mainly argillaceous units interpreted as having formed by sheet flow of sediment over the banks of minor distributary channels during periods of flood stage (Fielding, 1986). Argillaceous zones in the study area consist predominantly of siltstone and mudstone with only minor amounts of sandstone which occur as single channel and splay bodies isolated in over-bank deposits (Stear, 1983).

In view of the lack of restricting valley walls in the Lower Beaufort and an overall unidirectional flow pattern of most palaeo-channels, the composite sandstone sheets could be interpreted in terms of randomly migrating low sinuosity stream systems which contained both braided and meandering channels (Turner, 1978). The formation of laterally persistent composite sheets in the Abrahamskraal Formation was favored, therefore, by a lack of restricting valley walls, resulting in the ability of channel complexes to migrate randomly across their flood plains.

Lower Beaufort sedimentation in the study area was initiated in the Middle Permian by uplift in the Gondwanide mountainlands (Hälbich, 1983; Cole, 1992; Veevers *et al*., 1994c; Rubidge, 2005). This resulted in foredeep deposition of a 2565m thick upward fining succession of sandstones and blue and purple mudstones containing numerous thin chert bands (volcanic ash) and rich tetrapod faunas of the Abrahamskraal Formation. This succession was deposited initially by overbank flooding of braided rivers then later by meandering rivers of variable sinuosity higher up in the succession, draining an extensive

alluvial plain sloping gently towards the northeast in the direction of the receding Ecca shoreline (Turner, 1978). The preferential preservation of upper flow regime plane beds (facies Sh) and lower flow regime ripple cross lamination (facies Sr) is reflective of a seasonally fluctuating discharge regime of the main rivers. The overall fining upwards Abrahamskraal Formation (Visser and Dukas, 1979; Stear, 1980) is interpreted as a product of decreasing foredeep slope, channel gradients and sediment supply. Second order cycles (local large scale units, tens of metres thick) that comprise the regular alternations between channel sandstones and overbank shales are a common feature in the study area. The channel sandstones representing periods of maximum aggradation in response to uplift and thrust loading in the source area coupled with the subsidence in the depositional area (Stear, 1980) and fine grained members deposited during periods of quiescence between major thrust events (Stear, 1980). Under relatively constant discharge conditions, changes in fluvial style from braided to meandering may be directly related to a decrease in the slope gradient of the paleotopographic profile (Schumm, 1985) suggesting a tectonic control on accommodation and sedimentation regimes for the arenaceous unit A and mudstone B up to mudstone V sequences.

Orogenic unloading (thrusting) resulted in differential foredeep subsidence, with increasing rates towards the thrust-fold belt and as a result, the gradient of the topographic profile decreased with time, allowing the transition from higher to lower energy fluvial systems (Catuneanu & Bowker, 2001). This decrease in the topographic gradients during stages of subsidence and sediment accumulation induced changes with time from high energy sand-bed braided systems at the base (lower 2074m of the succession) and fine grained meandering systems at the top.

The current view is that the palaeogeography of the entire Adelaide time (Lower Beaufort) was generally represented by wet floodplains with high water tables (Smith et al., 1998).

This study has also contributed the global correlation of Middle Permian terrestrial tatrapod faunas where the *Eodicynodon* Assemblage Zone fauna correlates with fauna from Russia Zone Ocher and Ischeevo complexes (Fröbisch & Reisz, 2011), Xidagou Formation in China (Liu & Rubidge, 2010) and Rio da Rasto Formation fauna, Brazil (Cisneros *et al.*, 2011). The *Tapinocephalus* Assemblage Zone fauna correlates with fauna from Mezen and Ischeevo in Russia (Modesto & Rybczynski, 2011), Posto Queimado fauna from Brazil (Langer, 2000),

and the fauna from the Madumabisa mudstone strata of Zimbabwe (Boonstra, 1946; Bond, 1973; Leeper *et al*., 2000; Munyikwa, 2001).

The multidisciplinary approach applied in this study (sedimentology, lithostratigraphy and biostratigraphy) helped solve problems which each discipline in isolation could not have achieved. With continued fossil collection around the basin coupled with a taxonomic revision of the existing fossil collections, new biostratigraphic trends will continue to emerge which will enable refinement of the existing basin development models as well as facilitating both intra and interbasinal correlations.

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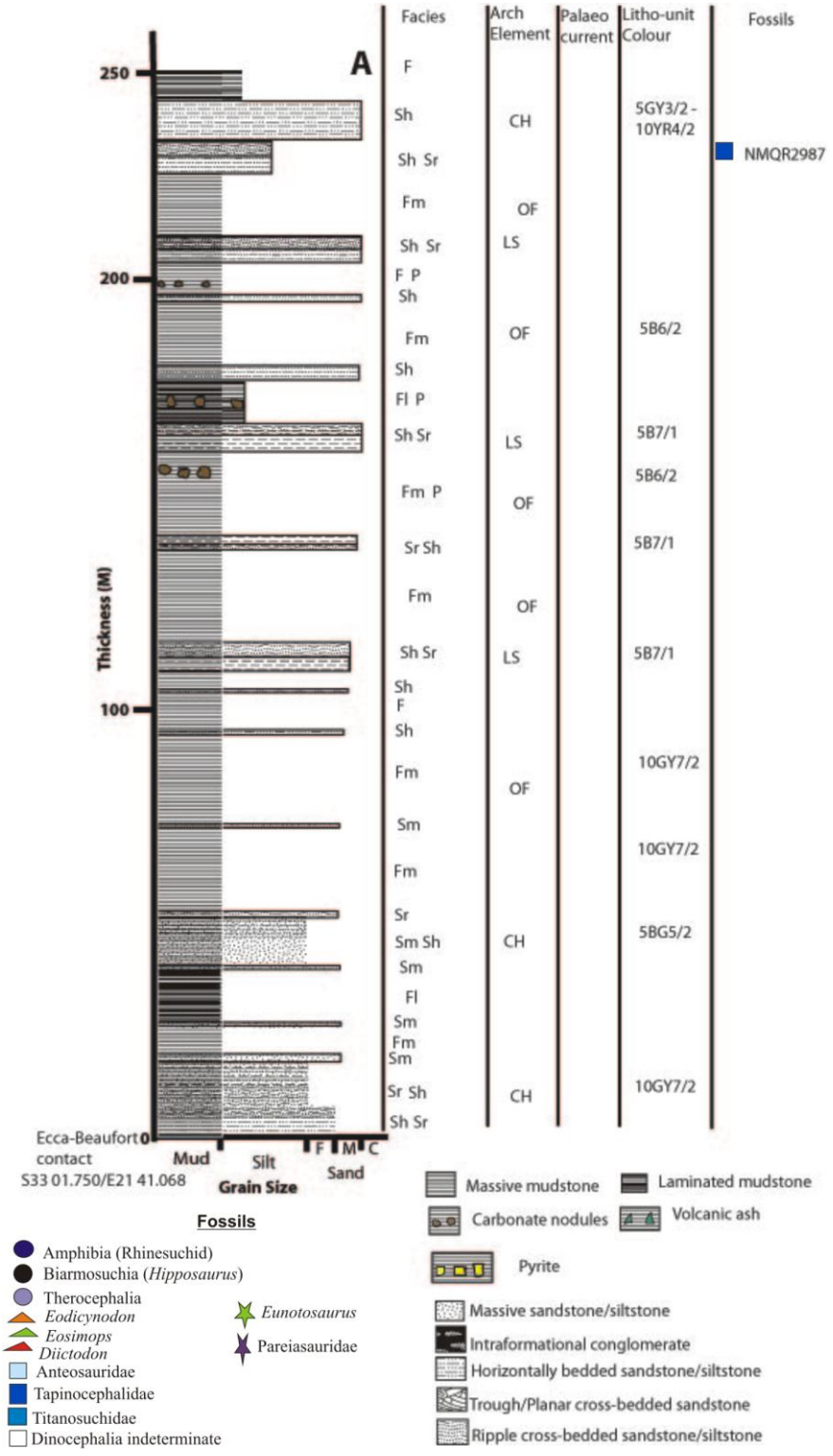
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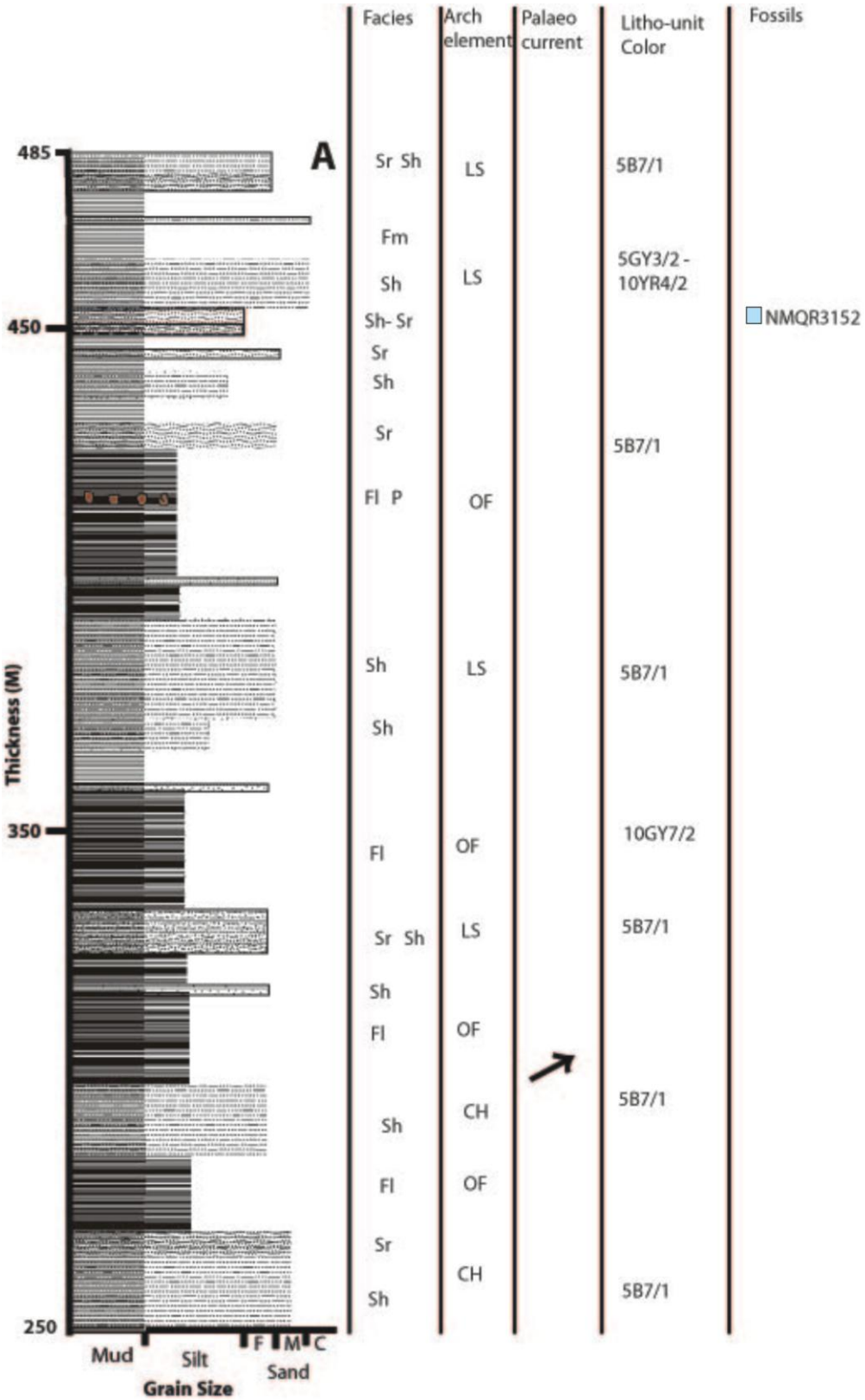
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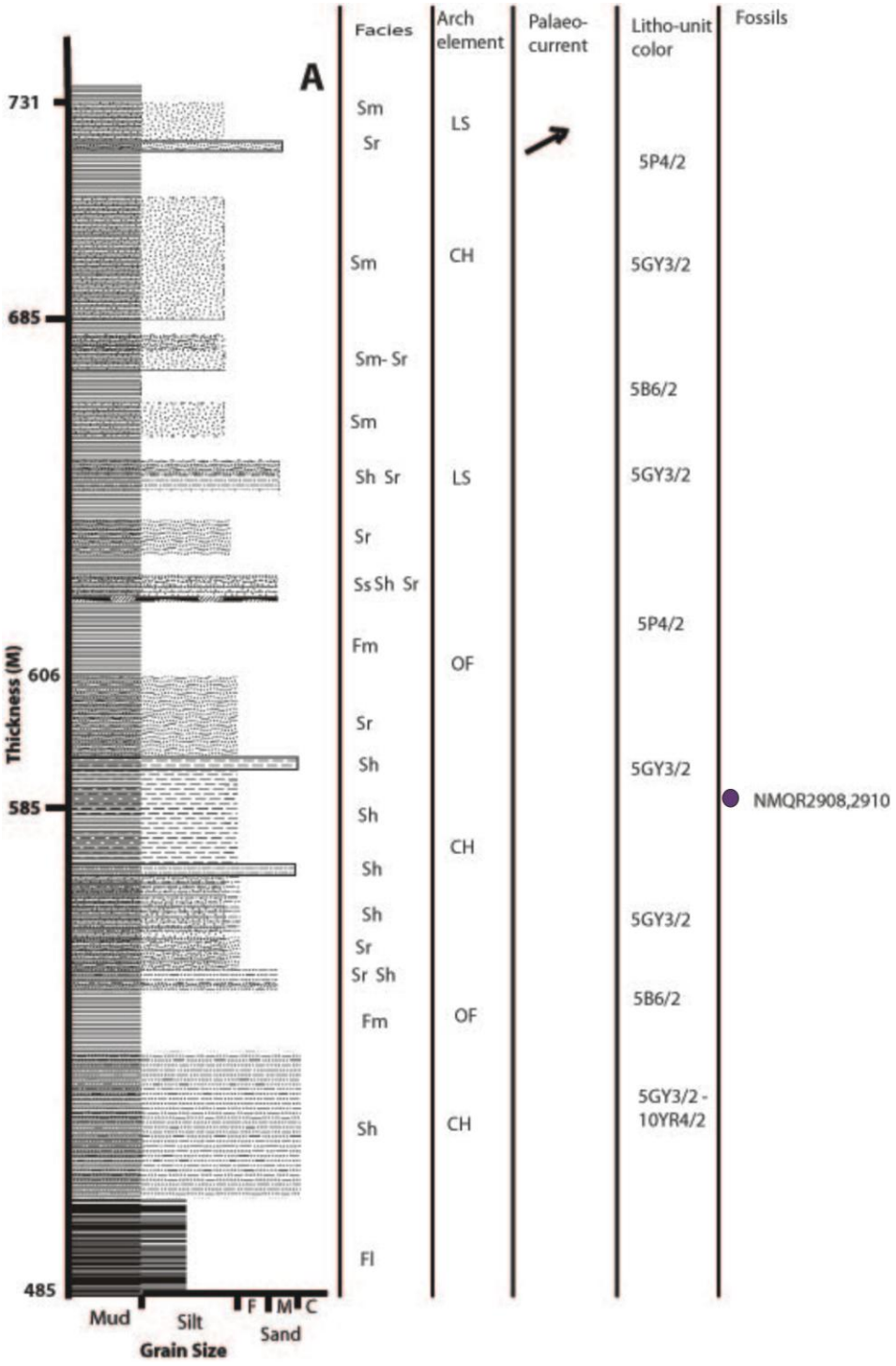
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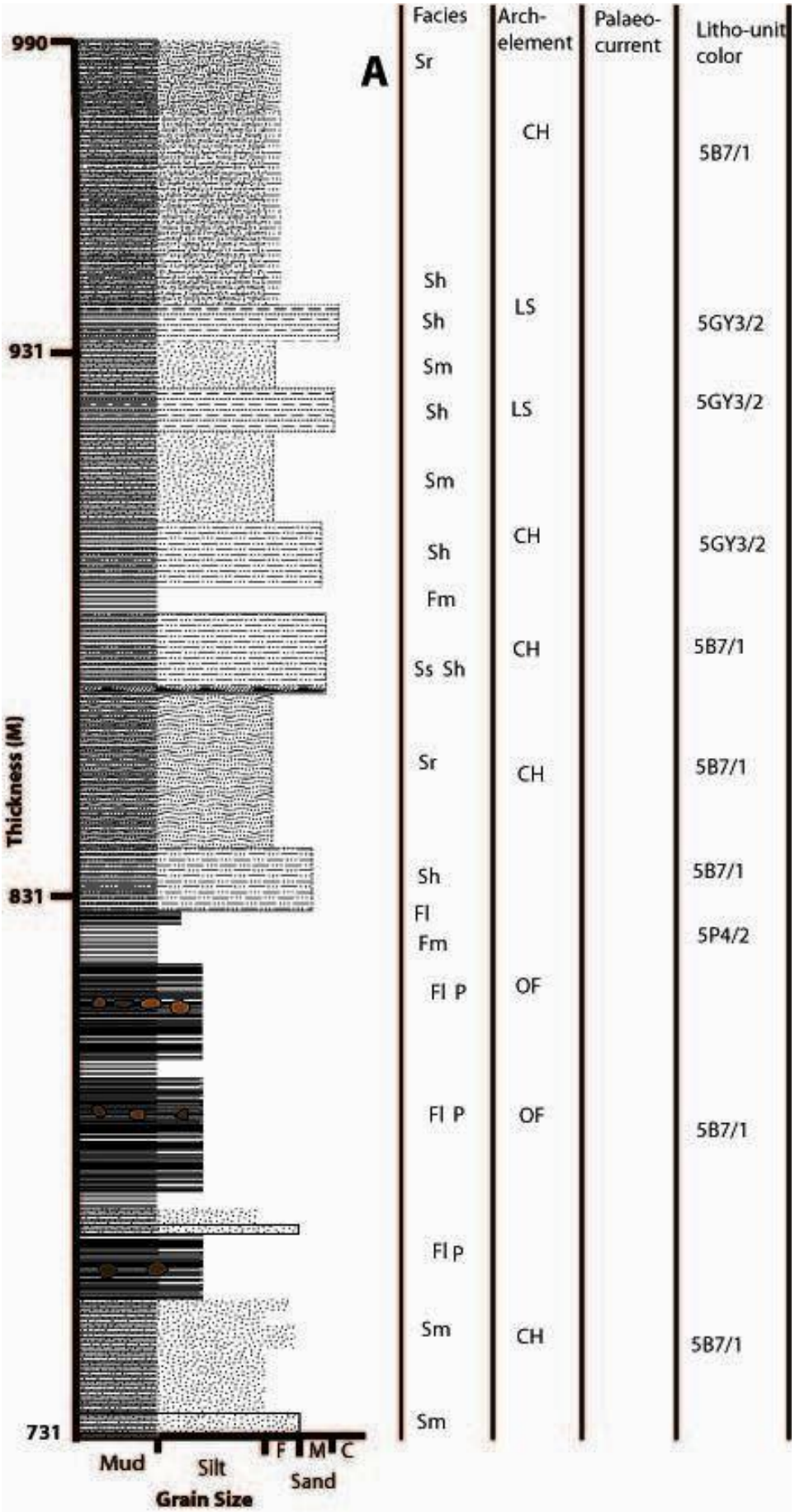
APPENDICES

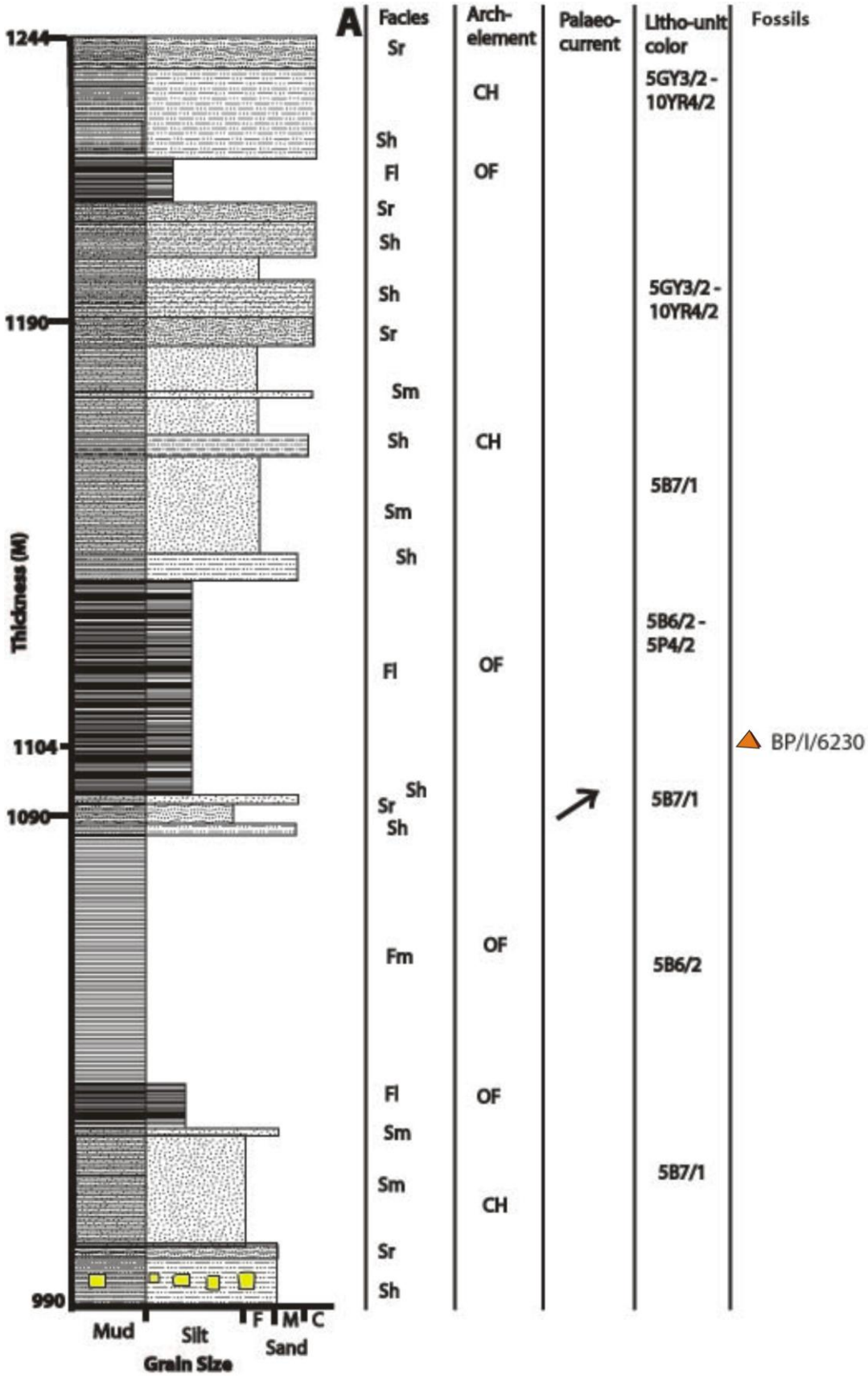
Appendix A: Comprehensive stratigraphic section of the Abrahamskraal Formation in the study area showing litho facies, palaeocurrent directions colours of lithological units, and fossils.

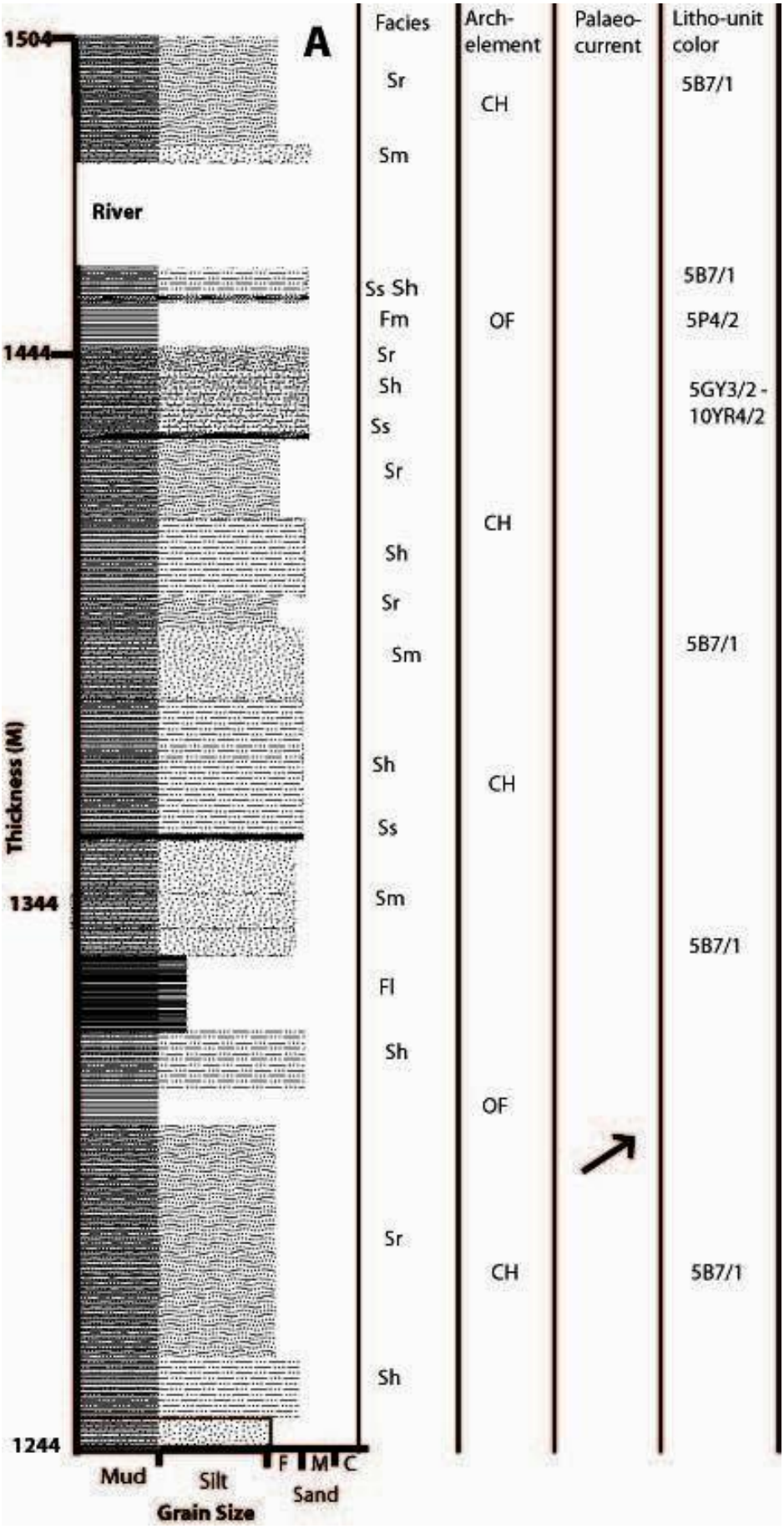


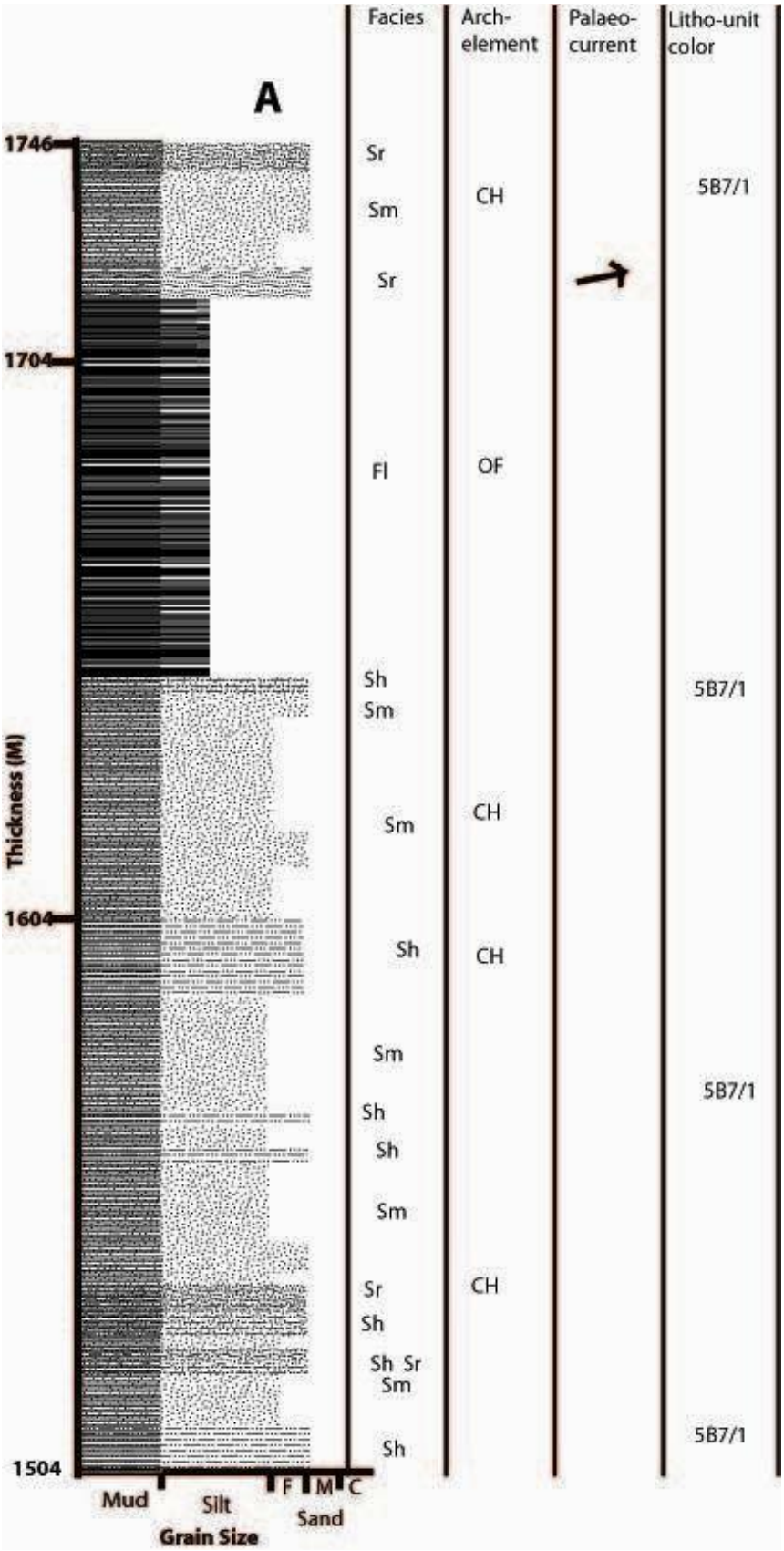

A
485
450
350
250
Thickness (M)
Mud
Silt
F
M
C
Sand
Grain Size
Facies
Arch element
Palaeo current
Litho-unit Color
Fossils
Sr Sh
Fm
Sh
Sh- Sr
Sr
Sh
Sr
Fl P
Sh
Sh
Fl
Sr Sh
Sh
Fl
Sh
Fl
Sr
Sh
LS
LS
OF
LS
OF
LS
OF
CH
OF
CH
5B7/1
5GY3/2 - 10YR4/2
5B7/1
5B7/1
10GY7/2
5B7/1
5B7/1
5B7/1
NMQR3152

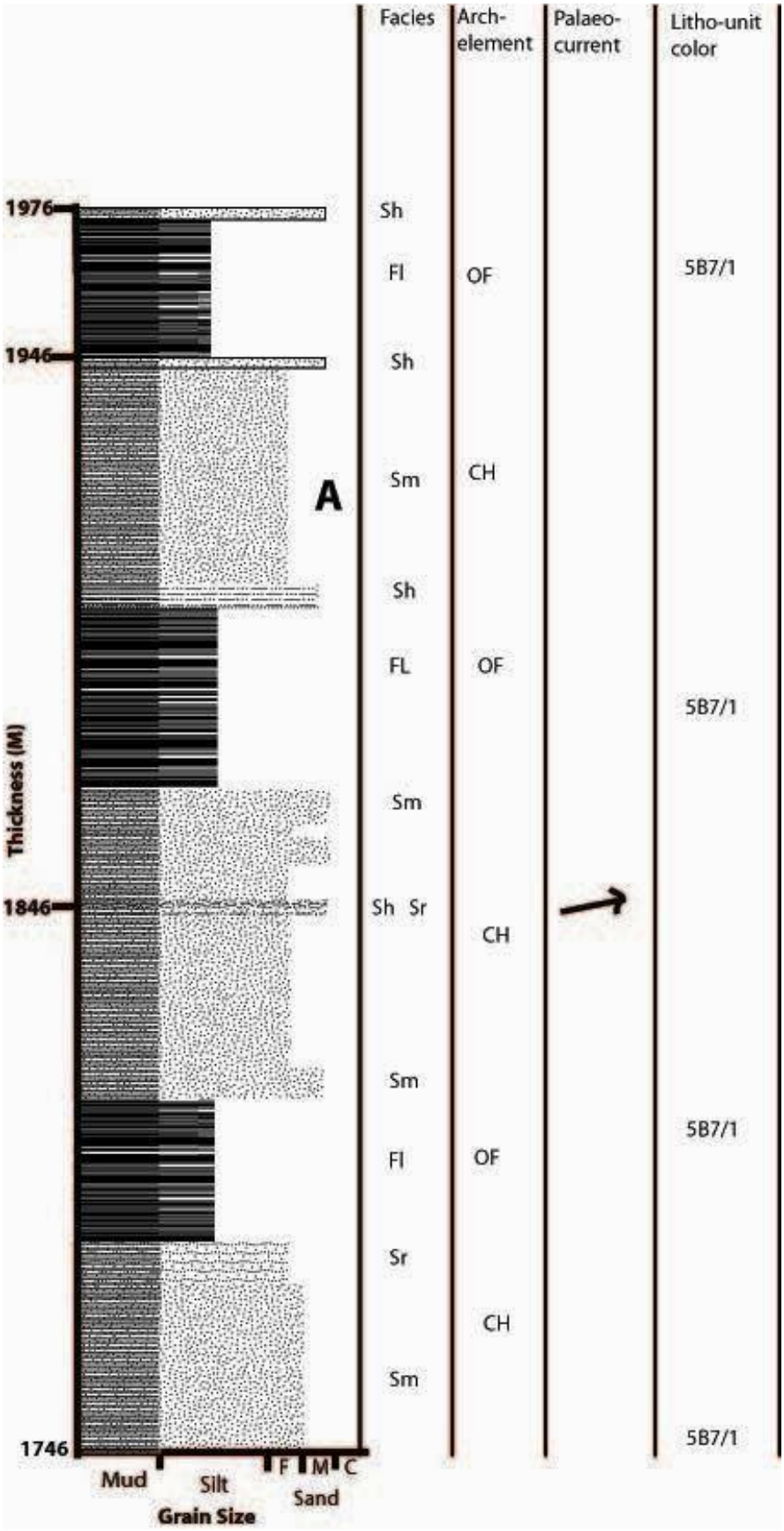

A
731
685
606
585
485
Thickness (M)
Mud
Silt
F
M
C
Sand
Grain Size
Facies
Sm
Sr
Sm
Sm- Sr
Sm
Sh Sr
Sr
Ss Sh Sr
Fm
Sr
Sh
Sh
Sh
Sh
Sr
Sr Sh
Fm
Sh
Fl
Arch element
LS
CH
LS
OF
CH
OF
CH
Palaeo-current
Litho-unit color
5P4/2
5GY3/2
5B6/2
5GY3/2
5P4/2
5GY3/2
5GY3/2
5B6/2
5GY3/2 - 10YR4/2
Fossils
NMQR2908,2910

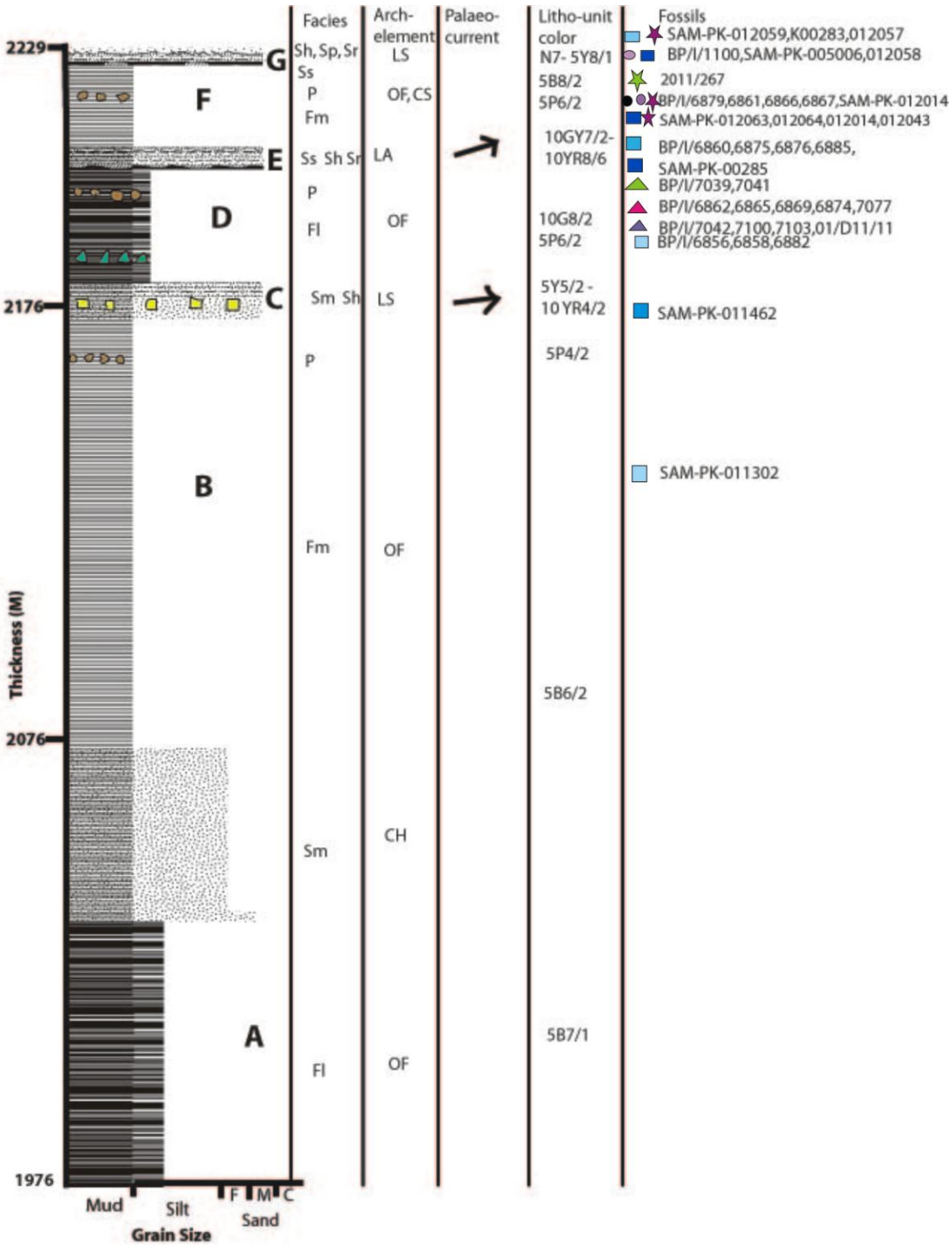

A
990
931
831
731
Thickness (M)
Facies
Arch-element
Palaeo-current
Litho-unit color
Sr
CH
5B7/1
Sh
Sh
LS
5GY3/2
Sm
Sh
LS
5GY3/2
Sm
Sh
CH
5GY3/2
Fm
Ss Sh
CH
5B7/1
Sr
CH
5B7/1
Sh
5B7/1
Fl
Fm
5P4/2
Fl P
OF
Fl P
OF
5B7/1
Fl P
Sm
CH
5B7/1
Sm
Mud
Silt
Sand
F
M
C
Grain Size

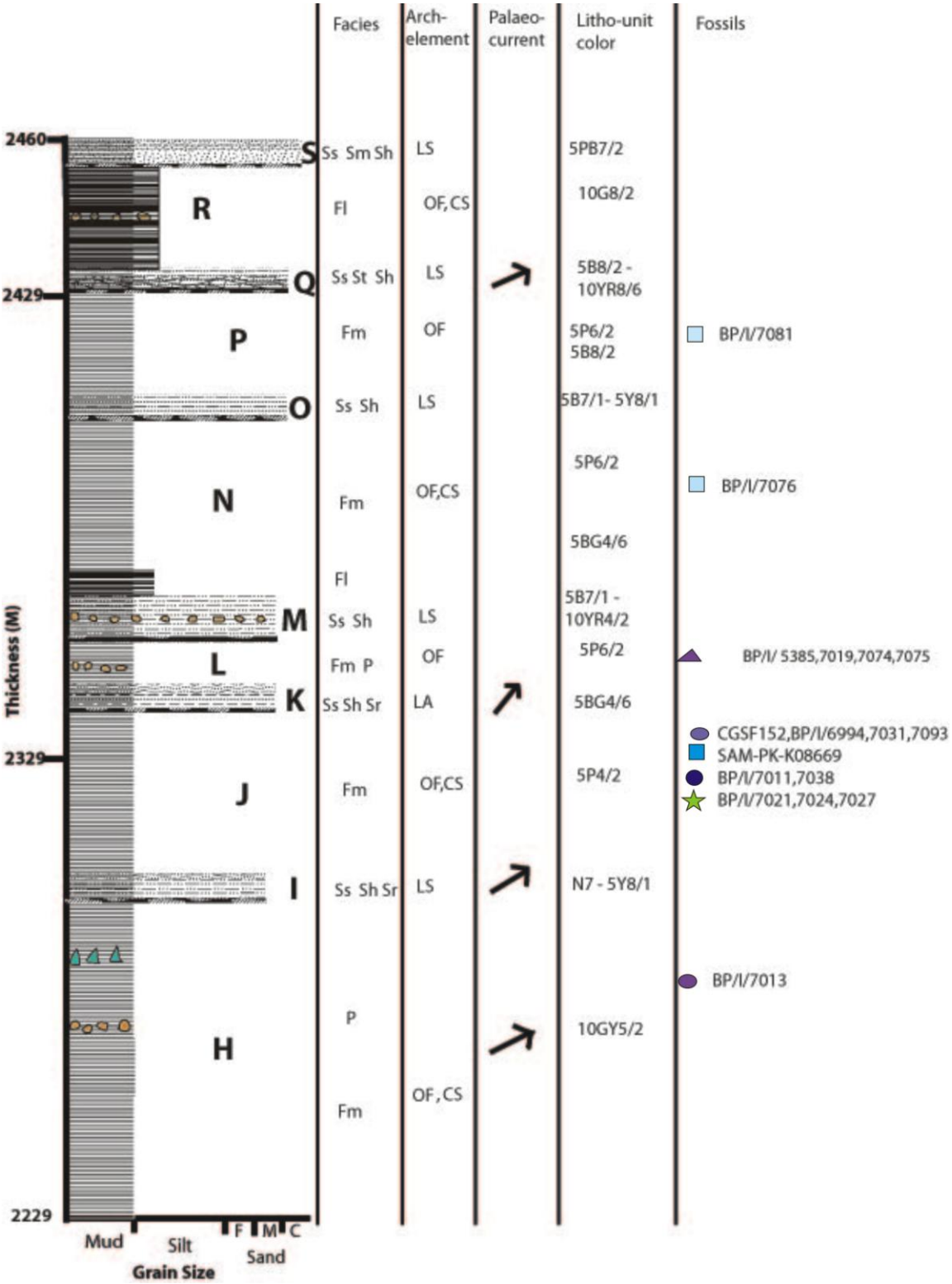

A
Facies
Arch-element
Palaeo-current
Litho-unit color
Fossils
1244
1190
1104
1090
990
Thickness (M)
Sr
Sh
Fl
Sr
Sh
Sh
Sr
Sm
Sh
Sm
Sh
Fl
Sr Sh
Sh
Fm
Fl
Sm
Sm
Sr
Sh
CH
OF
CH
OF
OF
CH
5GY3/2 - 10YR4/2
5GY3/2 - 10YR4/2
5B7/1
5B6/2 - 5P4/2
5B7/1
5B6/2
5B7/1
BP/I/6230
Mud
Silt
F
M
C
Sand
Grain Size

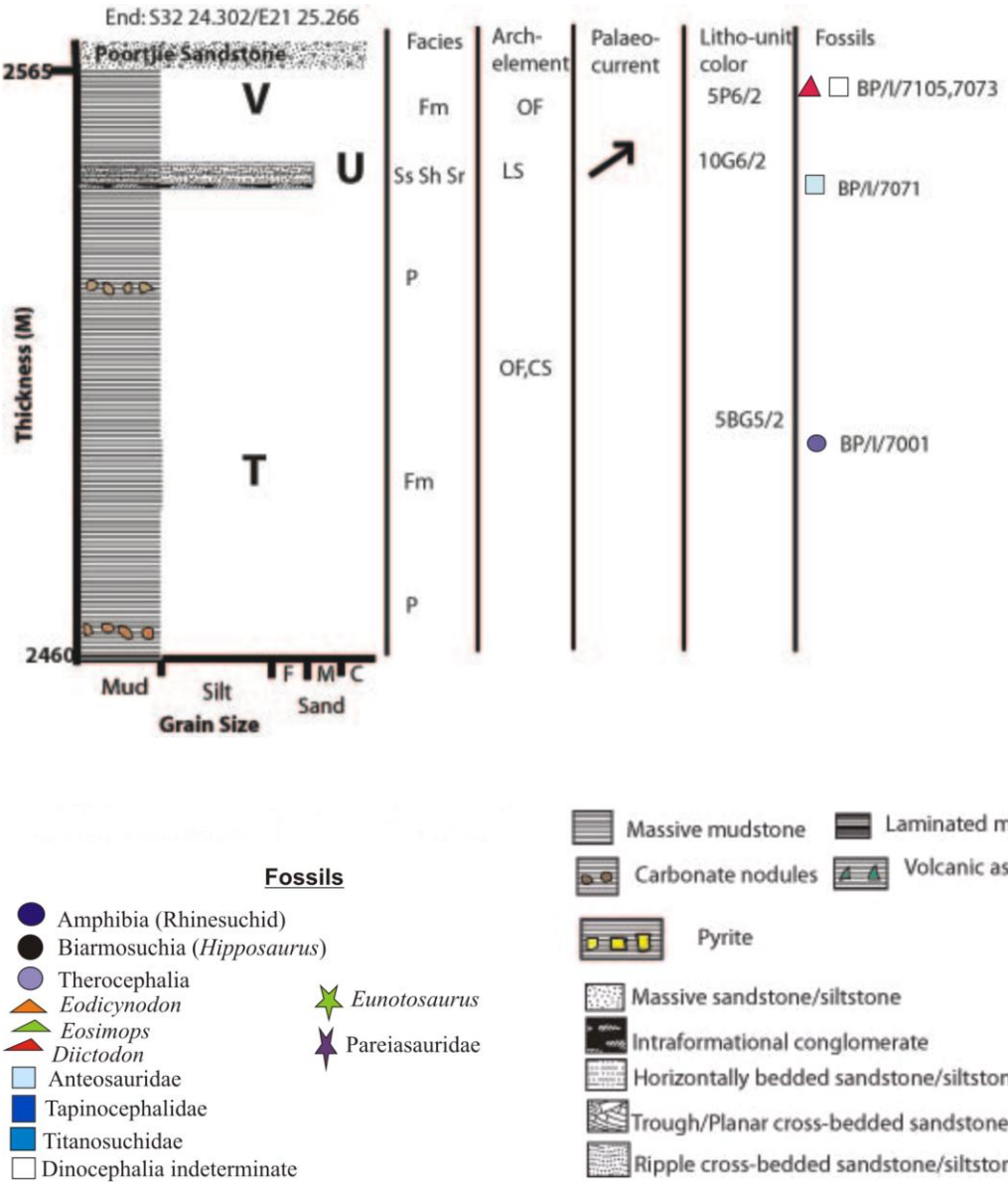

A
1504
1444
1344
1244
Thickness (M)
River
Facies
Arch-element
Palaeo-current
Litho-unit color
Sr
Sm
Ss Sh
Fm
Sr
Sh
Ss
Sr
Sh
Sr
Sm
Sh
Ss
Sm
Fl
Sh
Sr
Sh
CH
OF
CH
CH
OF
CH
5B7/1
5B7/1
5P4/2
5GY3/2 - 10YR4/2
5B7/1
5B7/1
5B7/1
Mud
Silt
F
M
C
Sand
Grain Size


A
Facies
Arch-element
Palaeo-current
Litho-unit color
1746
1704
1604
1504
Thickness (M)
Sr
Sm
Sr
Fl
Sh
Sm
Sm
Sh
Sm
Sh
Sh
Sm
Sr
Sh
Sh Sr
Sm
Sh
CH
OF
CH
CH
CH
5B7/1
5B7/1
5B7/1
5B7/1
Mud
Silt
F
M
C
Sand
Grain Size


Facies
Arch-element
Palaeo-current
Litho-unit color
1976
1946
1846
1746
Thickness (M)
A
Sh
Fl
Sh
Sm
Sh
FL
Sm
Sh Sr
Sm
Fl
Sr
Sm
OF
CH
OF
CH
5B7/1
5B7/1
5B7/1
5B7/1
Mud
Silt
F
M
C
Sand
Grain Size


Facies
Arch-element
Palaeo-current
Litho-unit color
Fossils
2229
2176
2076
1976
Thickness (M)
G
F
E
D
C
B
A
Sh, Sp, Sr
Ss
P
Fm
LS
OF, CS
Ss Sh Sr
LA
Fl
OF
Sm Sh
LS
Sm
CH
N7- 5Y8/1
5B8/2
5P6/2
10GY7/2-
10YR8/6
10G8/2
5P6/2
5Y5/2 -
10 YR4/2
5P4/2
5B6/2
5B7/1
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2011/267
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SAM-PK-012063,012064,012014,012043
BP/I/6860,6875,6876,6885,
SAM-PK-00285
BP/I/7039,7041
BP/I/6862,6865,6869,6874,7077
BP/I/7042,7100,7103,01/D11/11
BP/I/6856,6858,6882
SAM-PK-011462
SAM-PK-011302
Mud
Silt
F M C
Sand
Grain Size


Facies
Arch-element
Palaeo-current
Litho-unit color
Fossils
2460
2429
2329
2229
Thickness (M)
S
R
Q
P
O
N
M
L
K
J
I
H
Ss Sm Sh
Fl
Ss St Sh
Fm
Ss Sh
Fm
Fl
Ss Sh
Fm P
Ss Sh Sr
Fm
Ss Sh Sr
P
Fm
LS
OF, CS
LS
OF
LS
OF,CS
LA
OF,CS
LS
OF , CS
5PB7/2
10G8/2
5B8/2 - 10YR8/6
5P6/2
5B8/2
5B7/1- 5Y8/1
5P6/2
5BG4/6
5B7/1 - 10YR4/2
5P6/2
5BG4/6
5P4/2
N7 - 5Y8/1
10GY5/2
BP/I/7081
BP/I/7076
BP/I/ 5385,7019,7074,7075
CGSF152,BP/I/6994,7031,7093
SAM-PK-K08669
BP/I/7011,7038
BP/I/7021,7024,7027
BP/I/7013
Mud
Silt
F M C
Sand
Grain Size


End: S32 24.302/E21 25.266
Poortjie Sandstone
2565
2460
Thickness (M)
V
U
T
Facies
Fm
Ss Sh Sr
P
Fm
P
Arch-element
OF
LS
OF,CS
Palaeo-current
Litho-unit color
5P6/2
10G6/2
5BG5/2
Fossils
BP/I/7105,7073
BP/I/7071
BP/I/7001
Mud
Silt
F M C
Sand
Grain Size
Fossils
Amphibia (Rhinesuchid)
Biarmosuchia (Hipposaurus)
Therocephalia
Eodicynodon
Eosimops
Diictodon
Anteosauridae
Tapinocephalidae
Titanosuchidae
Dinocephalia indeterminate
Eunotosaurus
Pareiasauridae
Massive mudstone
Laminated mudstone
Carbonate nodules
Volcanic ash
Pyrite
Massive sandstone/siltstone
Intraformational conglomerate
Horizontally bedded sandstone/siltstone
Trough/Planar cross-bedded sandstone
Ripple cross-bedded sandstone/siltstone

Appendix B: Fossils collected during this study

BP/I/Number	Field Number	Taxon Assignment	GPS Coordinates	Lithological unit	Locality
6854	09/01/K7	Dinocephalia	S32º42.437'/E21º35.645'	Sandstone G	Rietfontein 269
6885	09/01/E1	Amphibian *Rhinesuchus*	S32º43.786'/E21º36.496'	Sandstone E	Rietfontein 269
6855	09/01/C5	Dinocephalia	S32º42.621'/E21º35.675'	Mudstone F	Rietfontein 269
6856	09/01/C4	Dinocephalia Tapinocephalidae	S32º56.437′/E21º38.017′	Mudstone D	Ratelfontein 74 alias Jakhalsfontein
6857	09/01/E6	Dinocephalia	S32º43.288'/E21º36.121'	Mudstone D	Rietfontein
6858	09/01/B8	Dinocephalia Tapinocephalidae	S32º43.947'/E21º37.399'	Mudstone D	Reitfontein 269
6859	09/01/K2	Dinocephalia *Titanosuchus*	S32º44.012'/E21º36.273'	Mudstone D	Rietfontein 269
6860	09/01/K1	Dinocephalia *Titanosuchus*	S32º44.058'/E21º36.175'	Sandstone E	Rietfontein 269
6861	09/01/E7	Therocephalia Scylacosauridae	S32º44.124'/E21º36.186'	Mudstone F	Rietfontein 269
6862	09/01/E2	Dicynodontia *Diictodon*	S32º43.729'/E21º36.225'	Mudstone D	Rietfontein 269
6863	09/10/E3	Dicynodontia *Diictodon*	S32º43.729'/E21º36.225'	Sandstone E	Rietfontein 269
6864	09/01/G11	Therocephalia Scylacosauridae	S32º43.730'/E21º36.823'	Mudstone F	Rietfontein 269
6865	09/01/B3 (a+b	Dicynodontia *Diictodon*	S32º43.459'/E21º37.155'	Mudstone D	Rietfontein 269
6866	09/01/B10	Therocephalia *Glanosuchus*	S32º43.459'/E21º37.155'	Mudstone F	Rietfontein 269
6867	09/01/G6	Dinocephalia *Titanosuchus*	S32º42.727'/E21º36.214'	Mudstone F	Rietfontein 269
6868	09/01/E5	Dicynodontia	S32º42.941'/E21º35.838'	Mudstone D	Rietfontein 269
6869	09/01/C11	Dicynodontia *Diictodon*	S32º58.979'/E21º42.292'	Mudstone D	Reitfontein 269
6870	09/01/G12	Pareiasauria	S32º43.225/E21º34.961'	Mudstone D	Rietfontein 269
6871	09/01/G7	Pareiasauria	S32º42.239'/E21º35.386'	Mudstone D	Rietfontein 269
6872	09/01/B4	Coprolite	S32º43.573'/E21º37.018'	Mudstone F	Rietfontein 269
6873	09/01/G9	Dinocephalia	S32º43.530'/E21º38.492'	Mudstone F	Rietfontein 269
6874	09/01/C8	Dicynodontia *Diictodon*	S32º42.925'/E21º37.710'	Mudstone D	Rietfontein 269
6875	09/01/K4	Dinocephalia *Titanosuchus*	S32º43.989'/E21º36.399'	Sandstone E	Rietfontein 269
6876	09/01/K3	Dinocephalia *Titanosuchus*	S32º43.959'/E21º36.344'	Sandstone E	Rietfontein 269
6877	09/01/B6	Therocephalia Scylacosauridae	S32º43.686'/E21º36.869'	Mudstone D	Rietfontein 269
6878	09/01/B3c	Dicynodontia *Diictodon*	S32º43.459'/E21º37.155'	Sandstone E	Rietfontein 269
6879	09/01/G4	Biarmosuchia *Hipposaurus*	S32º43.262'/E21º35.910'	Mudstone F	Rietfontein 269
6880	09/01/C6	Therocephalia	S32º43.724'/E21º36.232'	Mudstone D	Rietfontein 269

6881	09/01/A1	*Broomia*???	S32º43.084'/E21º36.381'	Mudstone F	Reitfontein 269
6882	09/01/G5	Dinocephalia Tapinocephalidae	S32º42.713'/E21º36.214'	Mudstone D	Rietfontein 269
6883	09/01/C7	Dinocephalia *Styracocephalus*?	S32º43.442'/E21º36.224'	Mudstone F	Rietfontein 269
6884	09/01/C3	Dinocephalia *Titanosuchus*	S32º43.825'/E21º35.943'	Mudstone D	Rietfontein 269
	09/01/C10	Dicynodontia *Diictodon*	S32º56.437'/E21º38.017'	Mudstone D	Ratelfontein 74
	09/01/G10	Fish scales *Caruicthys* sp indent	S32˚43.632'/E21˚38.028'	Mudstone F	Rietfontein 269
	09/01/K9	Dicynodontia *Robertia*	S32˚44.351'/E21˚35.893'	Mudstone F	Rietfontein 269
6985	MDSJ/10/17/01	Dinocephalia	S32°29.256¹/E21°26.090¹	Sandstone G	Elandsfontein 257
6986	MDSJ/10/14/04	Dinocephalia	S32°27.836¹/E21°23.134¹	Mudstone J	Rooifontein 258
6987	MDSJ/10/14/05	Dinocephalia	S32 27.840/E21 23.132	Mudstone J	Rooifontein 258
6993	10/01/L9	Dinocephalia	S32 27.808/E21 23.669	Mudstone J	Klipbankskraal
6994	10/01/J5	Therocephalia	S32 28.062/E21 23.008	Mudstone J	Klipbankskraal
6995	10/01/H2	Dinocephalia	S32 33.122/E21 24.990	Mudstone J	Klipbankskraal
6996	10/10/L22	Dicynodontia	S32 32.704/E21 25.375	Mudstone D	Eselsfontein
6997	10/01/G1	Dinocephalia	S32 26.572/E21 26.209	Mudstone J	Bullekraal 251
6998	10/01/M7	Dicynodontia	S32 55.264/E21 37.858	Mudstone D	Jakkalsfontein
6999	10/01/K4	Dinocephalian	S32 27.877/E21 25.150	Mudstone J	Bullekraal 251
7000	10/01/M6	Dicynodontia	S32 55.269/E21 37.738	Mudstone D	Jakkalsfontein
7001	10/01/J17	Therocephalia	S32 24.330/E21 25.257	Mudstone T	Lyshoek 248
7002	10/01/L12	Dinocephalian	S32 27.801/E21 23.636	Mudstone J	Klipbankskraal
7003	10/01/J21	Therocephalian	S32 27.757/E21 23.651	Mudstone J	Klipbankskraal
7004	10/01/D5	Dinocephalian	S32 30.230/E21 26.333	Mudstone H	Elandsfontein 257
7005	10/01/K6	Therocephalian	S32 27.613/E21 25.219	Mudstone J	Bullekraal 251
7006	10/01/M12	Therocephalia	S32 54.438/E21 37.326	Mudstone B	Jakkalsfontein
7007	10/01/L10	Therocephalia	S32 27.806/E21 23.673	Mudstone J	Klipbankskraal
7008	10/01/C2	Dinocephalia	S32 29.288/E21 27.803	Mudstone H	Elandsfontein 257
7009	10/01/J16	Dinocephalia	S32 28.127/E21 23.060	Mudstone J	Klipbankskraal
7010	10/01/C1	Dicynodontia	S32 28.695/E21 26.874	Mudstone F	Elandsfontein 257
7011	10/01/L14	Amphibia Rhinesuchidae	S32 27.796/E21 23.650	Mudstone J	Klipbankskraal
7012	10/01/N1	Dinocephalia	S32 31.268/E21 25.106	Sandstone D	Elandsfontein 257
7013	10/01/D1	Therocephalia	S32 31.626/E21 27.704	Mudstone H	Elandsfontein 257
7014	10/01/M8	Pareiasauria	S32 55.284/E21 36.777	Mudstone D	Jakkalsfontein
7015	10/01/E4	Dinocephalia	S32 31.256/E21 25.108	Mudstone H	Elandsfontein 257
7016	10/01/J13	Dicynodontia	S32 27.868/E21 23.313	Mudstone J	Klipbankskraal

7017	10/01/K7	Dinocephalian	S32 27.782/E21 25.561	Mudstone J	Bullekraal 251
7018	10/01/G3	Dinocephalia	S32 26.548/E21 26.120	Mudstone L	Bullekraal 251
7019	10/01/G4	Pareiasauria	S32 26.656/E21 26.036	Mudstone L	Bullekraal 251
7020	10/01/L7	Dinocephalia	S32 28.054/E21 23.308	Mudstone J	Klipbankskraal
7021	10/01/L17	Dicynodontia	S32 32.664/E21 25.430	Mudstone D	Eselsfontein
7022	10/01/L3	Dinocephalian	S32 28.166/E21 23.321	Mudstone J	Klipbankskraal
7023	10/01/L4	Dinocephalia	S32 28.133/E21 23.308	Mudstone J	Klipbankskraal
7024	10/01/J3	Parareptilia	S32 28.113/E21 23.071	Mudstone J	Klipbankskraal
7025	10/01/K2	Dinocephalian	S32 27.732/E21 25.239	Mudstone J	Bullekraal 251
7026	10/01/J2	Dinocephalian	S32 28.094/E21 22.996	Mudstone J	Klipbankskraal
7027	10/01/J12	Parareptilia	S32 27.868/E21 23.313	Mudstone J	Klipbankskraal
7028	10/01/M3	Dicynodontia	S32 55.179/E21 37.481	Mudstone D	Jakkalsfontein
7029	10/01/D7	Dinocephalian	S32 30.814/E21 24.755	Mudstone H	Elandsfontein
7030	10/01/M4	Dicynodontia	S32 55.295/E21 37.827	Mudstone D	Jakkalsfontein
7031	10/01/J14	Therocephalia	S32 27.868/E21 23.313	Mudstone J	Klipbankskraal
7032	10/01/D4	Dinocephalia	S32 31.249/E21 25.467	Mudstone H	Elandsfontein 257
7033	10/01/K1	Dinocephalia	S32 27.626/.E2125.187	Mudstone J	Bullekraal 251
7034	10/01/J18	Dinocephalia	S32 27.765/E21 23.678	Mudstone J	Klipbankskraal
7035	10/01/B1	Dinocephalian	S32 30.595/E21 26.462	Mudstone J	Elandsfontein 257
7036	10/01/D3	Parareptilia	S32 31.248/E21 25.563	Mudstone H	°Elandsfontein 257
7037	10/01/E3	Parareptilia	S32 31.234/E21 25.437	Sandstone G	Elandsfontein 257
7038	10/01/L14	Amphibia	S32 27.796/E21 23.650	Mudstone J	Klipbankskraal
7071	01/C4/11	Dinocephalia *Anteosaurus*	S32° 23.601[1]/E21°28.137[1]	Sandstone U	Springfontein
7072	01/G4/11	Dinocpehalia *Anteosaurus*	S32° 26.046[1]/E21°26.656[1]	Mudstone L	Bullekraal 251
7073	01/E6/11	Dinocephalia	S32° 24.187[1]/E21° 27.977[1]	Mudstone V	Springfontein
7074	01/G3/11	Dinocephalia *Anteosaurus*	S32° 26.071[1]/E21° 26.654[1]	Mudstone L	Bullekraal 251
7075	01/E2/11	Dinocephalia *Anteosaurus*	S32°26.086[1]/E21°26.699[1]	Mudstone L	Bullekraal 251
7076	01/E3/11	Dincephalia	S32° 23.514[1]/E21°27.623[1]	Mudstone N	Springfontein
7077	01/D3/11	Dicynodontia *Diictodon*	S32° 59.656[1]/E21°43.454[1]	Mudstone D	Goeiemoed 90
7078	01/D4/11	Dicynodontia	S32° 59.656[1]/E21°43.454[1]	Mudstone D	Goeiemoed 90
7079	01/D5/11	Dicynodontia	S32° 59.656[1]/E21°43.454[1]	Mudstone D	Goeiemoed 90
7080	01/D18/11	Dinocephalia	S32° 59.319[1]/E21°43.528[1]	Mudstone F	Goeiemoed 90
7081	01/B4/11	Dinocephalia Anteosauridae	S32° 23.347[1]/E21°26.620[1]	Mudstone P	Springfontein
7082	01/E5/11	Pareiasauria	S32° 24.068[1]/E21°27.855[1]	Mudstone P	Springfontein

7084	01/E1/11	Therocephalia	S32° 26.078[1]/E21°26.660[1]	Mudstone J	Bullekraal 251
7085	01/D20/11	Dinocephalia	S32°59.319[1]/E21°43.528[1]	Mudstone F	Goeiemoed 90
7086	01/C1/11	Dinocephalia	S32° 24.104[1]/E21°28.033[1]	Mudstone L	Springfontein
7091	01/B2/11	Dicynodontia	S32° 23.307[1]/E21°26.469[1]	Mudstone L	Springfontein
7092	01/E8/11	Dicynodontia	S32° 24.005[1]/E21°28.001[1]	Mudstone V	Springfontein
7093	01/D9/11	Therocephalia Scylacosauridae indet.	S32° 59.406[1]/E21°43.994[1]	Mudstone J	Goeiemoed 90
7094	01/D15/11	Dinocephalia	S32° 59.478[1]/E21°43.828[1]	Mudstone F	Goeiemoed 90
7100	01/D16/11	Dicynodontia *Robertia*	S32° 59.057[1]/E21°43.861[1]	Mudstone D	Goeiemoed 90
7103	01/D2/11	Dicynodontia *Robertia or Eosimops*	S32° 59.656[1]/E21°43.454[1]	Mudstone D	Goeiemoed 90
7105	01/E7/11	Dicynodontia *Diictodon*	S32° 24.001[1]/E21°28.001[1]	Mudstone V	Springfontein

Appendix C: Beaufort Group GIS Database fossils (Nicolas, 2007) in study area.

Catalogue Number	Taxon Assignment	Current Identification	Locality Farm name	Lithological unit
SAM-PK-001885	Dicynodontia	Dicynodont	Mechaus Request 242	Mudstone F
SAM-PK-K08669	Dinocephalia	Titanosuchid	Klipbankskraal	Mudstone J
CGS F152	Therocephalia	Pristerognathid	Klipbankskraal	Mudstone J
SAM-PK-012057	Pareiasaurian	*Bradysaurus*	Leeukraal	Sandstone G
SAM-PK-012059	Dinocephalia	*Titanosuchus*	Leeukraal	Sandstone G
SAM-PK-012058	Tapinocephalid dinocephalian	*Struthiocephalus*	Leeukraal	Sandstone G
BP/I/1100	Therocephalian	*Glanosuchus*	Leeukraal	Sandstone G
SAM-PK-005006	Tapinocephalid dinocephalian	*Struthiocephalus*	Welgebosch Drift 253	Sandstone G
SAM-PK-012064	Dinocephalia	Tapinocephalid	Schoenmaker	Mudstone F
SAM-PK-012063	Dinocephalia	Tapinocephalid	Schoenmaker	Mudstone F
SAM-PK-012067	Dinocephalia	Tapinocephalid	Schoenmaker	Mudstone F
SAM-PK-012066	Dinocephalia	Tapinocephalid	Schoenmaker	Mudstone F
SAM-PK-K00259	Dicynodontia	*Diictodon*	Platdorings 262	Mudstone D
SAM-PK-K00270	Tapinocephalid dinocephalian	*Criocephalosaurus*	Jakkalsfontein	Mudstone D
SAM-PK-008034	Pareiasaurian	*Embrithosaurus*	Hogeveld 271	Sandstone E
SAM-PK-008934	Pareiasaurian	*Bradysaurus*	Leeuwfontein273	Mudstone D

SAM-PK-K00284	Dinocephalia	*Anteosaurus*	Leeuwfontein 273	Mudstone F
SAM-PK-K00285	Dinocephalia	Tapinocephalid	Welgemoed	Sandstone E
SAM-PK-001887	Dinocephalia	Anteosaurid	Vindragasfontein 280	Units D,E,F,G on farm
SAM-PK-011886	Titanosuchid dinocephalian	*Jonkeria*	Vindragasfontein 280	Units D,E,F,G on farm
SAM-PK-K05200	Dinocephalia	*Tapinocephalus*	Vindragasfontein 280	Units D,E,F,G on farm
SAM-PK-011888	Therocephalia	Scylacosaurid	Vindragasfontein 280	Sandstone G
SAM-PK-K00275	Dinocephalia	Anteosaurid	Padderfontein 272	Sandstone G
SAM-PK-K00283	Dinocephalia	Titanosuchid	Padderfontein 272	Sandstone G
SAM-PK-K00272	Dinocephalia	Tapinocephalid	Padderfontein 272	Sandstone G
SAM-PK-012014	Pareiasaurian	*Bradysaurus*	Rietfontein 269	Mudstone F
SAM-PK-012043	Pareiasaurian	*Bradysaurus*	Rietfontein 269	Mudstone F
BP/I/346	Dicynodontia	*Diictodon*	Buffels Valley 268	Mudstone D
SAM-PK-K07982	Dicynodontia	*Robertia*	Buffels Valley 268	Mudstone D
SAM-PK-011462	Dinocephalia	Titanosuchid	Buffels Valley 268	Sandstone C
SAM-PK-011302	Dinocephalia	*Anteosaurus*	Buffels Valley 268	Mudstone B

SAM-PK-011460/011456	Therocephalia	*Glanosuchus*	Buffels Valley 268	Mudstone B
BP/I/5385	Dicynodontia	*Robertia*	Die Drift 17	Mudstone L