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A provisional basinal study of the Waterberg-Karoo, South Africa

by

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ABSTRACT

The formation of the Ellisras basin was influenced by the repeated tectonic instability that is also be noted through the changes in the energy levels of the depositing media of the basin-fill, from the early Carboniferous period, as already indicated by Siepker (1986). This theory is also supported by MacRae (1988) who suggests that the sediment accumulation in certain sections of the Ellisras Basin was indicative of periods of palaeoslope rejuvenation resulting in sandstones, grits and minor conglomerates, alternating with periods of stasis when extensive coal seam deposition occurred.

Studies completed in this thesis indicate the influence of basin movement and depositional thickness of the basin’s formations. These depositional patterns are closely related to mobile geological structures such as lineaments or faults of continuously active geological structures. Bumby and van der Merwe (2004) and Bordy (2000) indicate the possible influence of the Limpopo Mobile Belt as well as the failed East African Rift System on the formation of neighbouring basins. Geological structures also present in the Ellisras Basin can also be observed in these neighbouring bodies such as the Tuli, Tshipise and the Soutpansberg basins.

Observations within the region of the Ellisras Basin, made in neighbouring Botswana by Arnott and Williams (2007) describe the Soutpansberg trough as the main influence in the formation of the Ellisras, Mmamabula and Mopane coalfields. These observations are in line with the findings of this thesis which indicates the consistent presence of continuously active geological structures within this region such as the greater intracratonic Soutpansberg trough which indicated re-activation during late Permian to early Triassic times.

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CHAPTER 1

1. INTRODUCTION

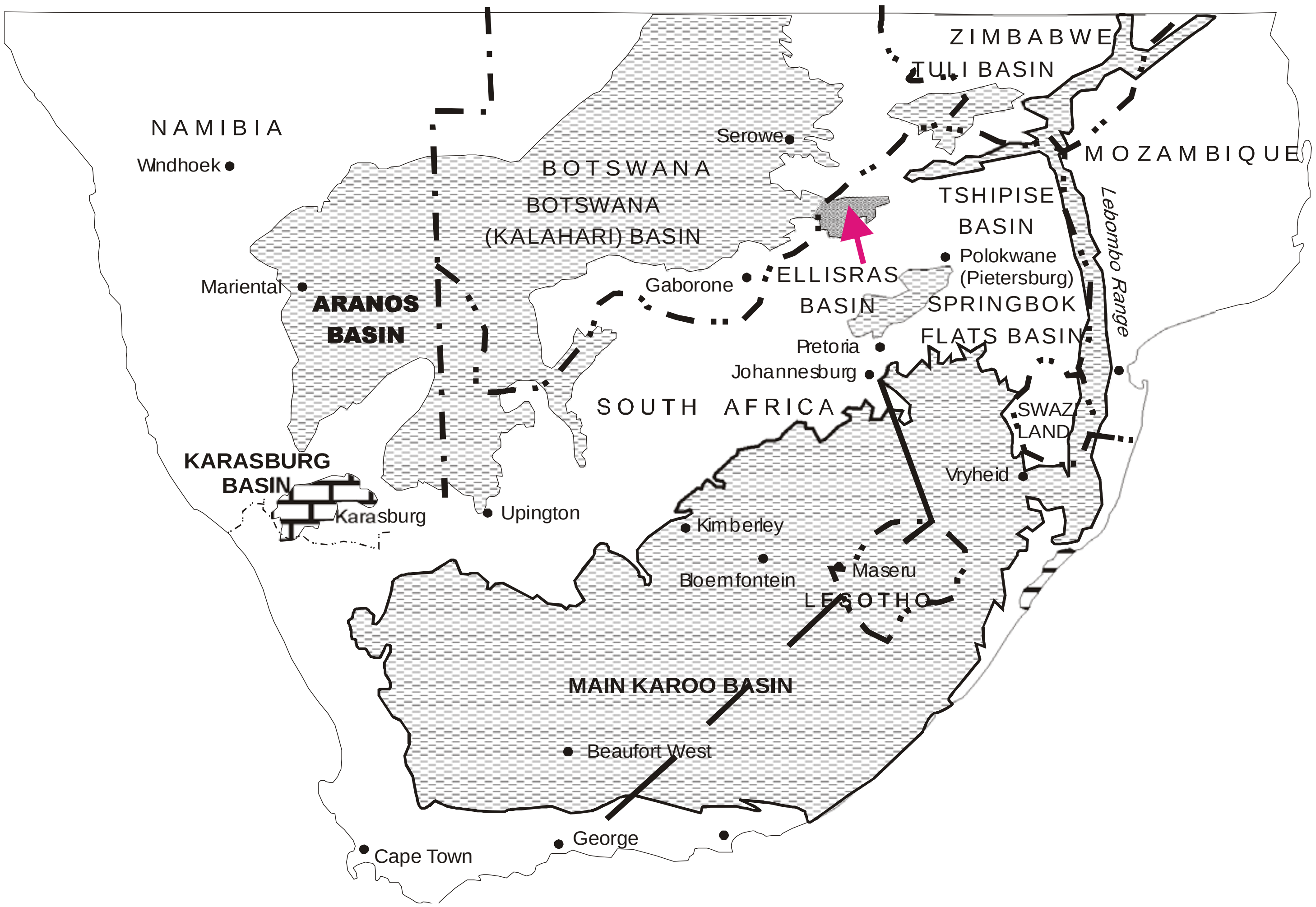
1.1. Aim of Study

The aim of this study is to compare and relate the formation of the Ellisras Basin to the synsedimentary basin evolution patterns. These patterns can answer the question of whether the tectonic instability within this basin influenced the deposition of the coal seams. In addition, the collected geometrical data in this thesis is compared to inferred depositional environments, in order to make a cohesive contribution to concepts of the basin evolutionary history of the Ellisras (otherwise known as the Waterberg-Karoo) basin. This study is a pilot basin analysis rather than a definitive and final answer to a complex problem.

1.2. Location of the Basin

The Ellisras Basin is situated in the northern part of the Waterberg District, located in the Limpopo Province, South Africa (Fig. 1.1). A larger portion of the Basin extends to the west into Botswana where it is referred to as the Kalahari Basin, whilst the eastern part stops short of the Lephalala River. Another river, the Mokolo, flows in a northerly direction into the Limpopo River and is located near the centre and towards the east of the South African part of the Basin. The preserved Basin lies between the latitudes 27 E and 28E, a total distance of approximately 90 kilometres from east to west, covering an area estimated to be 2700 km^2 within South Africa.

Figure 1.1: The Ellisras Basin in Relation to other Karoo basins in Southern Africa (Adapted from Johnson et al., 2006, their Fig. 1, Chapter 22)



The rainfall is erratic, mainly occurring during summer and ranges from 350mm to 500mm per year. Average daily maximum temperatures vary between -5°C in and 40°C , with an average of 21 °C (Bredenkamp et al., 1996).

The soil is mostly deep and greyish in colour overlying granite, quartzite or sandstone (Bredenkamp et al., 1996). The vegetation is described as being short and shrubby. Sandy areas are dominated by trees such as: Silver Clusterleaf *Terminalia sericea,* Yellow Pomegranate *Rhigozum obovatum,* Wild Raisin *Grewia flava* and *Acacia tortilis.* Here the herbaceous layer is often dominated by grasses such as Broom Grass *Eragrostis pallens,* Kalahari Sand Quick *Schmidtia pappophoroides,* Hairy Love Grass *Eragrostis trichophora, Brachiaria nigropedata, Loudetia simplex, Aristida strata* and other *Aristida* species. On shallower and drier soils, Common Corkwood *Commiphora pyracanthoides,* Wild Raisin *Grewia flava,* Shepherd's Tree *Boscia albitrunca* and *Combretum apiculatum* are more prominent, and dense, nearly impenetrable thickets of Blue Thorn *Acacia erubescens,* Black Thorn *A. mellifera* and Sicklebush *Dichrostachys cinerea* are often encountered. Grasses including Guinea Grass *Panicum maximum,* Small Panicum *P coloratum,* Blue Buffalo grass *Cenchrus ciliaris, Anthephora pubescens, Enneapogon scoparius* and *Urochloa mosambicensis* may be dominant (Bredenkamp et al., 1996). The local economy includes cattle and game farming as well as production of vegetables.

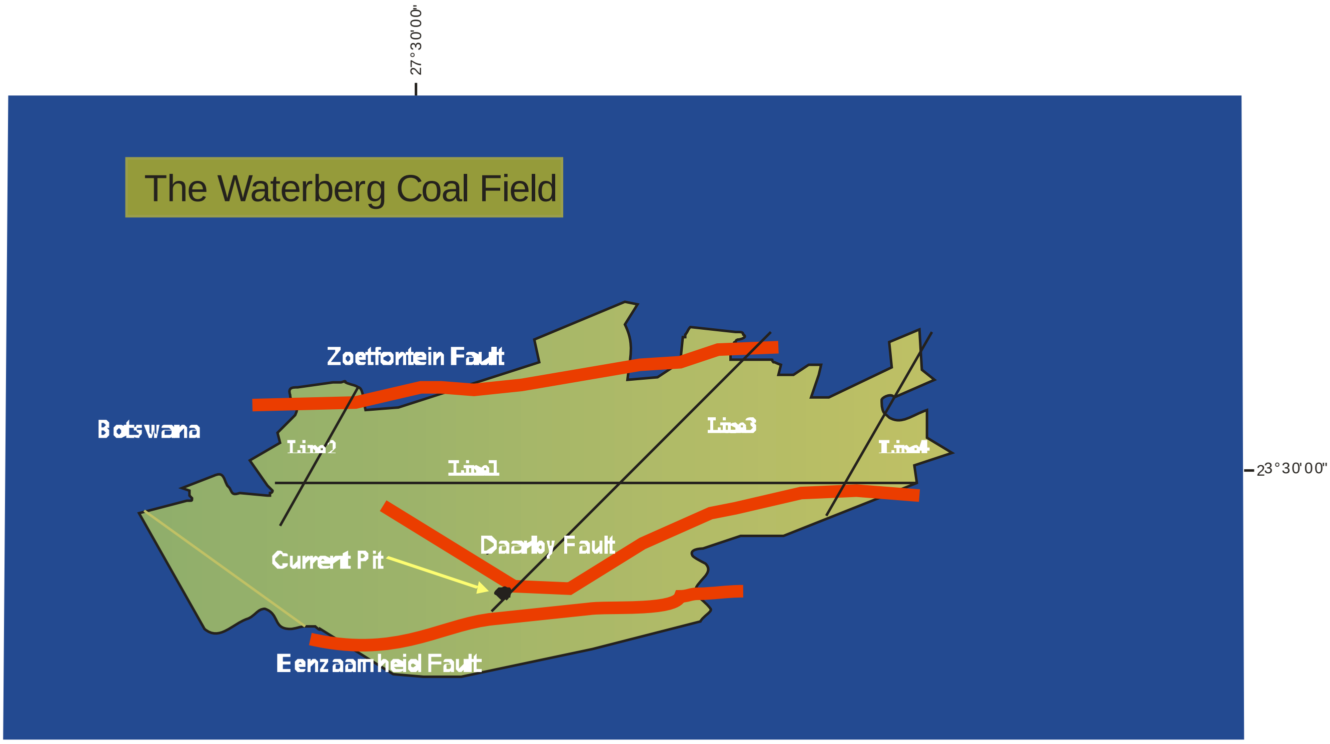
The study area is divided into many different farms, the most notable being Grootegeluk farm that includes the coal mine of similar name. All farm names used in the present study appear on the 1:250000 Ellisras (2326) Council for Geoscience map published in the year 1993.

1.3. Methodology

Fieldwork in the Basin was limited due to the lack of outcrops within the region, and this study thus relied mainly on borehole logs provided by the Council for Geoscience. The latter organisation kindly supplied approximately 830 borehole logs located within the Ellisras Basin. The majority of the borehole logs were found to lack stratigraphic information and only a limited proportion of the holes could thus be usefully applied to basin analysis purposes.

An electronic filing system was set up ("Datamaster") to encompass these data and allow graphic analysis of the thicknesses of coal and non-coal deposits; this system will be discussed in more detail at a later stage of this thesis. In order to reduce the vast number of borehole logs to a manageable proportion, four lines of boreholes across the preserved basin were selected (Fig. 1.2), on the basis of available borehole data and providing a spread across the axis of the preserved basin: the first line runs along the medial long axis of the basin in an approximately E-W direction, the other three lines are across the short axes of the basin, one each in the W, centre and E, and orientated at about 120 degrees (NNE-SSW) to the first line.

Figure1.2: Map Displaying the Lines Drawn on Basin



For each of these lines, profiles have been constructed, showing the preserved stratigraphy and structure of this basin. In most cases only a few of the stratigraphic units can readily be shown: mainly the Dwyka (less often), the Vryheid Formation and the Grootegeluk Formation. From these profiles, the basin shape varies from one line to another - generally these lines reflect a preserved basin shape, sometimes with subordinate sub-basins, and in one case, a half-graben type of geometry. The influence of major faults such as the Daarby Fault, are immediately obvious on these profile lines.

However, it is extremely important to emphasize that preserved basin geometry and geometry of the basin-fill sub-units at the time of deposition are, in most depositories, very different. In order to better understand basin evolution, it is essential to try and reconstruct synsedimentary basin-fill geometry. This is done with isopach maps, illustrating the thickness of chosen stratigraphic units - which are only an approximation of synsedimentary basin-fill geometry, as compaction and sedimentary loading effects are not taken into account in such isopach plots. Furthermore, percentage maps were also prepared, showing things such as proportion of coal and proportion of shale within a carboniferous shale/coal unit such as the Grootegeluk Formation. In contrast to isopach plots, these rather reflect an estimation of sedimentation and tectonics at the time of deposition of specific units.

All of these plots are applied to thickness data from the Grootegeluk and Goedgedacht Formations, which were extracted from the 1986 MSc thesis of Eugene Siepker, which is the accepted standard reference source on the general geology of the Waterberg Basin. Siepker (op. cit.) did not plot much of his data in this way, and the great advantage of his data compared to that from the Council for Gesocience, is that full stratigraphic information is available in Siepker's work. Plots for the individual coal and non-coal layers within the Grootegeluk and Vryheid formations were extracted from the data supplied by the Council of Geosciences, as Siepker’s work could not be used for this purpose as it did not differentiate the coal from the mudstone or sandstone layers in the formations at a scale from which suitable data could be extracted.

1.4. General Geology of the Ellisras Basin Area

The Ellisras basin is a fault-bounded basin, with the Zoetfontein fault in the north, and the Eenzaamheid fault in the south (Fig. 1.2). The basin was created in an area known to have structural lineaments that were cyclically re-activated over time, such as the Melinda fault (Jansen, 1982), Zoetfontein fault (Brandl, 1996) as well as the Sunnyside Shear Zone (Brandl, 1996). These lineaments were most probably influenced by the tectonic instability caused by the intrusion of the Bushveld Complex, which is considered to have been active during early Waterberg deposition (Jansen, 1982; Barker et al., 2006).

Arnott and Williams (2007) find that the coalfields of the Ellisras, Mmamabula and Mopane coalfields (Fig. 1.3) developed within the greater intracratonic Soutpansberg trough, which was re-activated during late Permian to early Triassic times; this viewpoint correlates with the work of Siepker (1986) who discusses continuous tectonic activity occurring within the mentioned timeframe, as further outlined in text below. The findings of this thesis support this view of continuous tectonic activity during most of the Ellisras basin-fill.

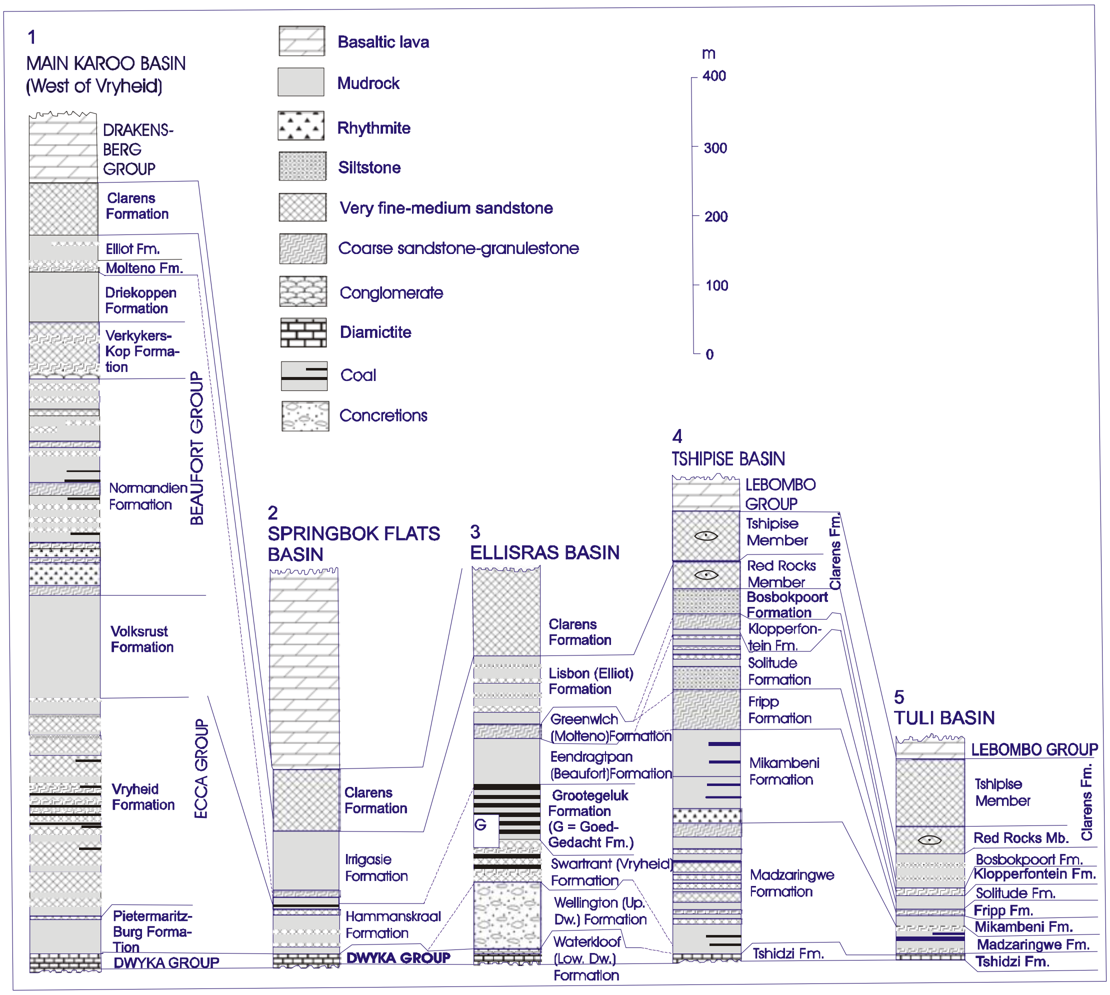
Movement along the Limpopo Mobile belt, as tectonic re-activation due to continuous tension in the Karoo era in the Soutpansberg and Limpopo fault zones occurred, controlled the formation of the Karoo sediments and finally acted as conduits for the extrusion of basalts which terminated the Karoo era (Barker, 1983). Studies have indicated that east-northeast - trending fractures have been rejuvenated in post-Karoo times (Barker, 1983). The Zoetfontein Fault is situated between the Central and Southern Marginal Zones with a large portion of the Ellisras Basin situated on the Southern Marginal Zone (Fig. 1.4).

Such tectonic instability occurring during the evolution of the Ellisras Basin likely contributed towards the structural development of the depository. Being essentially a fault-bounded basin (MacRae, 1988),(Fig. 1.2) an increase in sediment loading – related subsidence due to deposited material may have also contributed towards the re-activation of these faults. The cyclical tectonic instability can also be noted through the changes in energy levels of the depositing media of the Ellisras basin-fill, from the early Carboniferous period, as already indicated by Siepker (1986).

The major coal-bearing horizons are the Grootegeluk and the Vryheid formations and both are found in the Ecca Group (approx 280 Ma) of the Karoo Supergroup together with the Goedgedacht Formation, Fig. 1.3 provides an overview of the stratigraphy of the Ellisras coalfield in relation to other coalfields within the region. Immediately above the coal-bearing formations are the Molteno, Elliot and Clarens (approx. 230

Ma) formations see- Table 1.1 and all are capped by the Drakensberg (approx. 160 Ma) Group basaltic lavas (Siepker, 1986).

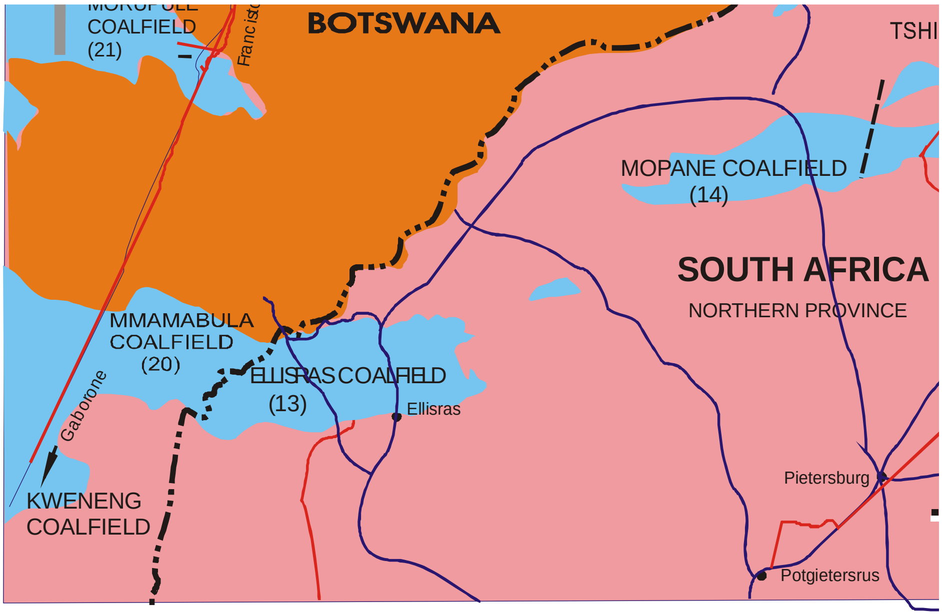
Table 1.1: Stratigraphy and Correlation of Karoo Supergroup Strata (modified after Johnson et al., 1996)



The Grootegeluk Formation is generally carbonaceous, comprising intercalated carbonaceous shales and coal. Vitrinite content increases upward from around 90%, at the base of the Grootegeluk Formation, with a concomitant decrease in inertite (Faure et al., 1996). The Vryheid Formation's coal seams are composed of predominantly dull coal (Faure et al., 1996), with minor carbonaceous mudstone intercalations. The Grootegeluk Formation's coal is classified as a thick interbedded seam deposit type (Faure et al., 1996), and the Vryheid Formation as a multiple seam deposit type.

It has been inferred that the coal and coarse clastic sediment accumulation was indicative of periods of palaeoslope rejuvenation, resulting in sandstone, gritstones and minor conglomerates, alternating with periods of stasis when extensive coal seam formation (peat accumulation) occurred (Siepker, 1986). Ryan (1966) concluded that the sandstones were deposited under shallow-water fluviatile conditions with an average transport direction towards the west (Ryan, 1966; Macrae, 1988).

Figure 1.3: Ellisras Coalfield in Relation to Neighbouring Coalfields (adapted from Williams, 2006)



1.4.1 The Karoo Supergroup

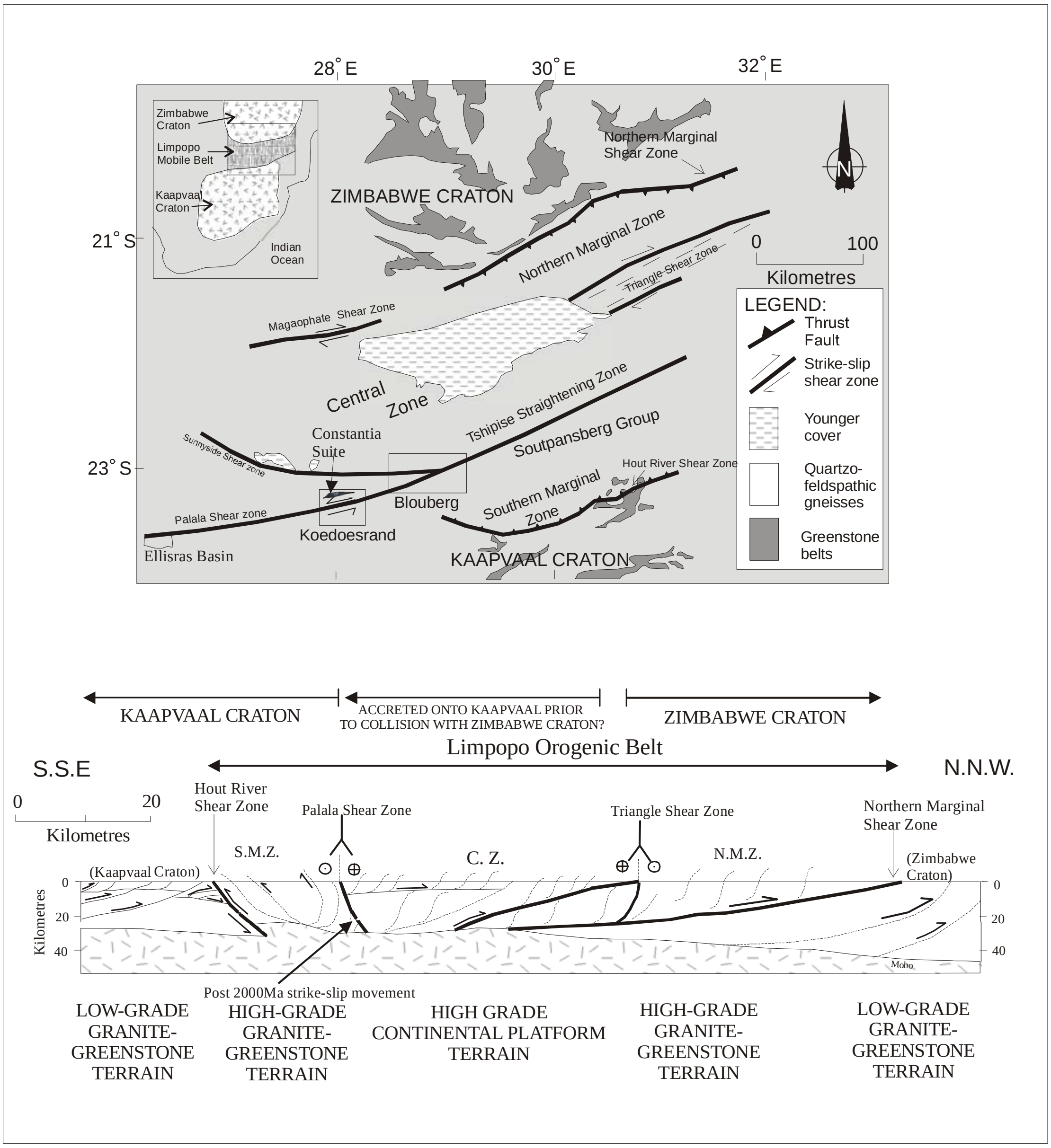
The Karoo Supergroup is preserved in over 50 basins across Africa (Catuneanu et al., 2005) with two major depositories in southern Africa, the Main Karoo and Kalahari basins, as well as a number of subsidiary basins including the Ellisras Basin (Fig. 1.1). The Supergroup ranges in age from the Late Carboniferous to the Early Jurassic (Johnson et al., 1996). The vast majority of coal beds in South Africa occur in the Ecca Group (Faure et al., 1996). According to Rust (1975, p544) the coalfield located in the Ellisras Basin forms an embayment of the much larger "Botswana" (cf. Kalahari, Fig. 1.1) Basin. Faure et al. (1996) refer to this coalfield as the Waterberg Coalfield and describe it as containing approximately 44% of South Africa's in situ reserves of bituminous coal. Johnson et al. (1996) describe the deposition of the entire Karoo succession in its type basin (Main Basin) as normally commencing with diamictites and other glacigene rock types, as seen with the Dwyka Group. This is followed by an interval of shallow basinal (partly marine) to fluviodeltaic mudrocks and sandstones, in which coal seams are commonly present towards the north and NE, the Ecca Group, which also includes the Vryheid and Grootegeluk formations of the Ellisras Basin. Red and greenish mudrocks become common in the higher strata of the overlying Beaufort Group, reflecting essentially subaerial deposition under oxidising, alluvial conditions. Tectonic uplift produced the Molteno Formation sandstones with localised, thin coal beds. Increased aridity is reflected in the semi-arid red beds of the succeeding Elliot Formation, and the aeolian sandstones found in the overlying Clarens Formation (Johnson et al., 1996). Thick basaltic lavas of the Drakensberg Group complete the type succession in the Main Basin.

Understanding the geological and tectonic history of the Karoo Supergroup can give an indication of how the Ellisras Basin was formed. In addition to discussing the influence of climate, Catuneanu (2001; Catuneanu et al., 2005) also considers the influence of tectonic movements on the accumulation of the sedimentary fill in the Karoo basins of southern Africa. According to Catuneanu the tectonic regimes were dominantly flexural in the south, in relation to processes of subduction, accretion and mountain building along the Panthalassan (palaeo-Pacific) margin of Gondwana. This resulted in the formation of a retroarc foreland system, partitioned into foredeep, forebulge and back-bulge (Catuneanu, 2004). This flexural tectonic regime affecting the Main Basin later gave way to dynamic subsidence, which created additional accommodation across the entire foreland system. These tectonic stresses contributed to the formation of different basin types across southern Africa (Catuneanu et al., 2005) and shall be further explored in more detail in a later chapter within this thesis.

1.4.2. The Limpopo Mobile Belt

On the Northern part of the Ellisras Basin is the Palala shear zone (see Fig. 1.4) of the Limpopo Mobile Belt.

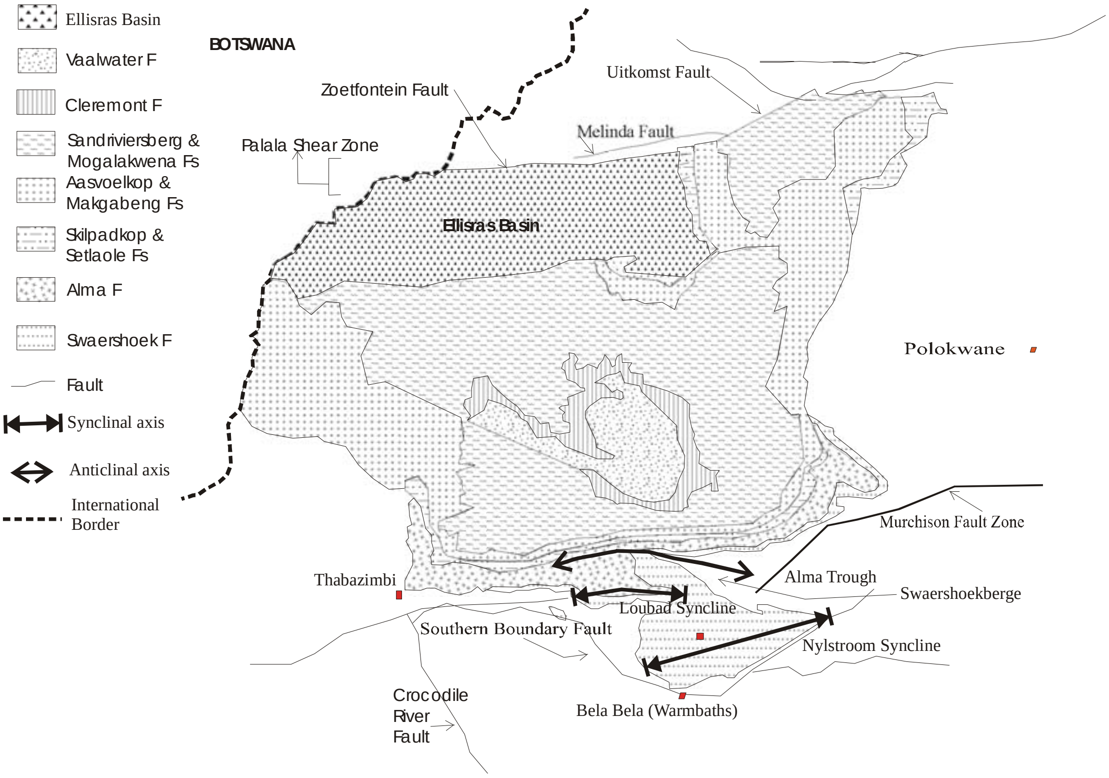
Figure 1.4: Overview of the Limpopo Mobile Belt Structure (Adapted from Bumby and van der Merwe, 2004)



According to Bumby and van der Merwe (2004), the ENE-trending Limpopo belt of southern Africa, a granulite-grade metamorphic belt believed to represent one of the earliest (age subject to debate: Neoarchaean – Palaeoproterozoic) preserved examples of a continent-continent collisional orogeny, has a length of c. 550 km and is c. 250 km wide. The orogenic event reflects a collision between the northern edge of the Kaapvaal craton and the southern edge of the Zimbabwe craton, with the involvement of a third exotic terrane, which has become sandwiched between the two cratons. After collision, the Kaapvaal and Zimbabwe cratons formed the Kalahari craton (Bumby and van der Merwe, 2004).

The Limpopo belt is divided into three sub-parallel ENE-trending zones known as the Southern Marginal Zone, the Central Zone and the Northern Marginal Zone (see Fig. 1.4). The Southern Marginal Zone (SMZ) is considered as part of the greenschist- to amphibolite-grade northern Kaapvaal craton, though it is generally at a higher metamorphic grade and appears to have been exhumed from deeper levels. The southern edge of the SMZ, where it borders the Kaapvaal craton, is marked by the southwards-vergent Hout River Shear zone. The SMZ is separated from the Central Zone by the Palala Shear Zone (PSZ), which consists of a c. 15 km wide mylonitic zone, the type area being the Koedoesrand window (Bumby and van der Merwe, 2004). The Palala Shear zone (and its WSW extension, the Melinda fault zone; Fig. 1.5) generally has a sinistral sense of shear, though it has been re-activated locally in an opposite sense. This shear zone is possibly an intracratonic transpression zone (crustal convergence whereby rocks can be faulted upward to form a positive flower structure) caused by oblique SMZ/Kaapvaal Craton-CZ convergence (Brandl, 1996). Within the Palala Shear Zone is the Zoetfontein Fault (see Fig. 1.5), which seems most likely to have been influenced by the movements along the Central and Southern Zones of the Limpopo Mobile Belt.

Figure 1.5: Overview of the Waterberg Group Formations (adapted from Johnson et al., 2007)



Eastwards, the PSZ becomes covered by younger Proterozoic sedimentary rocks; in the Blouberg area outcrops beneath the younger rocks show that the PSZ is occupied by migmatitic gneiss, presumably reflecting deeper crustal levels of the shear zone (Bumby and van der Merwe, 2004).

The above-mentioned structures are associated with an event that most likely influenced the formation of the Ellisras Basin, namely through the re-activation of the Soutpansberg Group basin (seen in Fig. 1.4). Re-activated during late Permian to early Triassic times (Arnott and Williams, 2007) the Soutpansberg, an intracratonic trough, influenced the formation of the Ellisras, Mmamabula and Mopane coalfields (Fig. 1.3) (Arnott and Williams, 2007). The dominant fault pattern of the Tshipise, Nuanetsi and Tuli Basins (Fig. 1.1) is regarded as being a modified southward extension of the East African Rift system (within a failed triple junction) whose extensions also trend ENE and WSW in the Limpopo area (Bordy, 2000) and was probably developed in a narrow ENE-WSW (Limpopo parallel) trending trough (Jansen, 1975a) after re-activation occurred between the Central and Southern Marginal Zones (Jansen, 1975b).

1.5 Literature Survey

The general geology of the Ellisras basin is covered in detail by Brandl (1996). The geographical location and geological outline is given in the explanation of Sheet 2326, 1:250 000, published by the Council for Geosciences. Information relating to the total thickness and surficial occurrence of the Grootegeluk, Goedegedacht and Vryheid formations is available in Siepker’s (1986) MSc thesis, which also provides a view of the depositional history of the Ellisras basin.

Discussions relating to the climatic and tectonic influences on Karoo Basin evolution were sourced from Catuneanu (1998, 2004 and 2005), Rust (1975) and Johnson et al. (1996). Further information relating to the formation of coal beds, mudstones and sandstones of the region can be viewed in work written by Faure (1996) and MacRae (1988).

CHAPTER 2

STRUCTURAL GEOLOGY OF THE ELLISRAS BASIN

2.1 Introduction

This chapter aims to investigate the structural setting of the Ellisras Basin. Topics such as the influence of the tectonic instability within mainly the northern sector of the Main Karoo Basin and its influence on the formation of the Ellisras basin will thus be addressed. In addition, more fundamental geological features of the northern Kaapvaal craton such as the Limpopo Mobile Belt, the Waterberg Group (and its geodynamic setting) together with other Karoo-aged basins located close to the Ellisras depository (such as the Kalahari, Tuli and Tshipise Basins) are discussed with the aim of further understanding the formation of this particular Basin- see Figs. 1.1, 1.4, 2.1 and 2.2 and 2.3.

Figure 2.1: Simplified Model Outlining the Tectonic Evolution of the Limpopo Area and the Lebombo Monocline (Modified from Bordy, 2000)

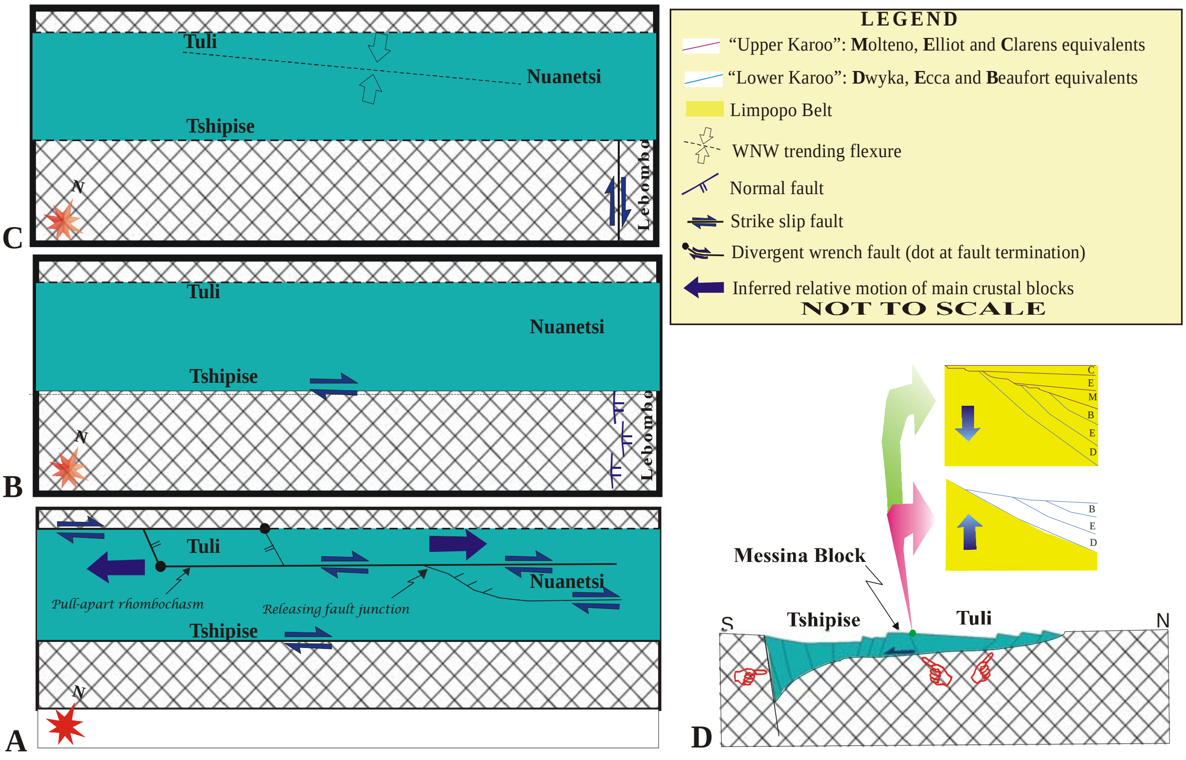
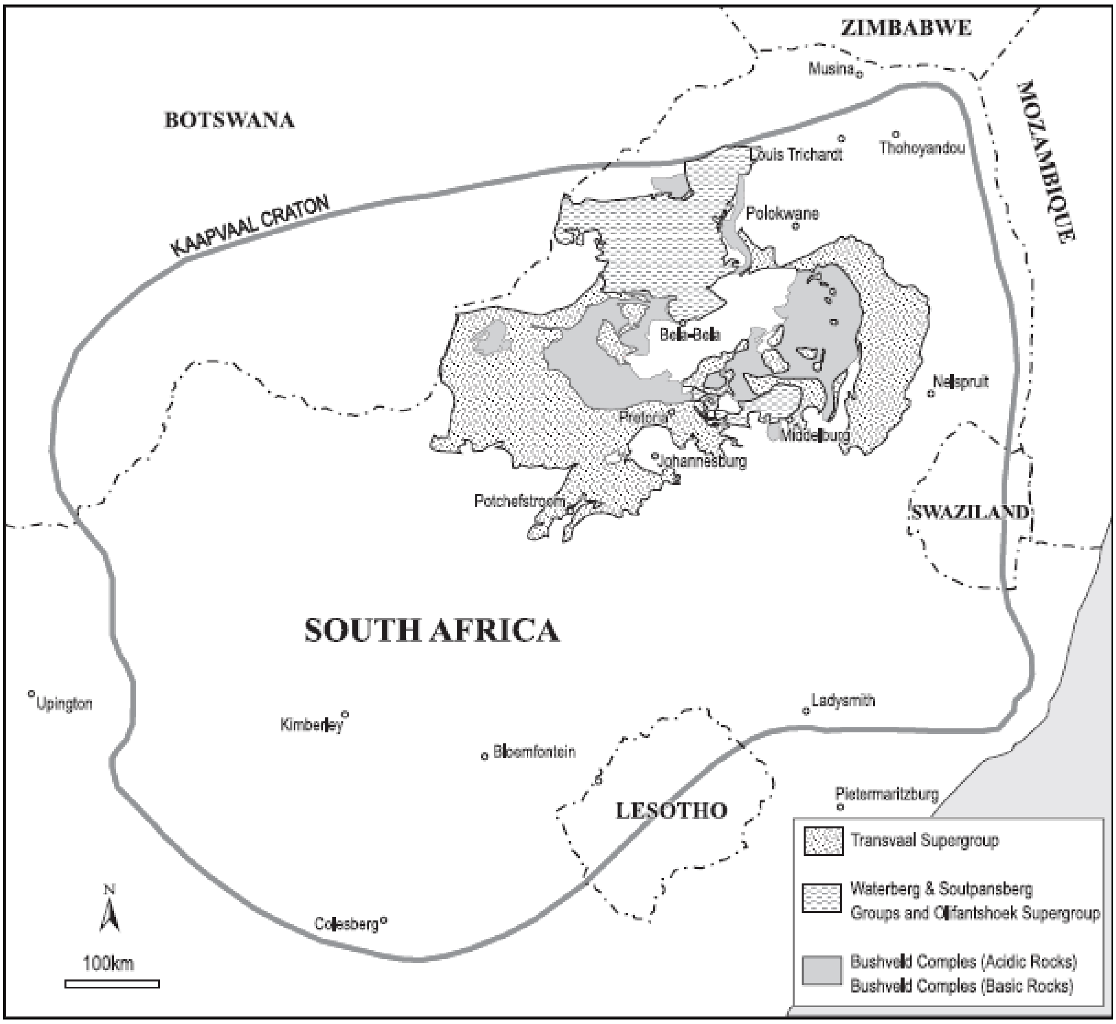


Figure 2.2: Regional Setting of Waterberg-aged units within the Ellisras Basin Vicinity (modified from Johnson et al., 2006)

Fig. 2.3 shows the Waterberg Group in relation to the Transvaal Supergroup and Bushveld Complex as well as the Kaapvaal Craton.

Figure 2.3: Waterberg Group within its Regional Setting of the Kaapvaal Craton,c. 2.6-2.1 Ga Transvaal Supergroup andc. 2050 Ma Bushveld Complex.



2.2. Limpopo Mobile Belt

The Limpopo Mobile Belt (Fig. 1.4) is divided into three zones- the Northern Marginal, Central and Southern Marginal zones. It is 250 km wide and is thought to represent a Himalayan-style collisional event between the Kaapvaal Craton in the South and the Zimbabwean Craton in the north. The Central Zone (CZ) contains rocks dating back to the Archaean (pre-3000 Ma) suggesting that the Zone may be a piece of crust unrelated to the material in the marginal zones of the Limpopo Belt (Barton, 1983). The Central zone consists of high-grade (up to granulite grade) metamorphosed epi-cratonic supracrustal rocks (Beitbridge Complex) with the marginal zones consisting of re-worked granite-greenstone successions of the adjacent cratons (Barton, 1983; Bumby, 2000). The Southern Marginal Zone (SMZ) is composed of granite-greenstone material from the Kaapvaal Craton and is separated from the Kaapvaal Craton by a northward-dipping shear zone (Bumby, 2000). Rocks of the c. 2.6-2.1 Ga Transvaal Supergroup, c. 2.0-1.8 Ga Waterberg Group and c. 2050 Ma Bushveld complex cover large parts of the Southern Marginal Zone (Barton, 1983). Separating the SMZ from the CZ is the Palala Shear Zone, which is composed of mylonitised CZ and Bushveld complex rocks (Bumby, 2000). The contact between the CZ and the Northern Marginal Zone (NMZ) is marked by the Triangle and Magogaphate shear zones (Bumby and van der Merwe, 2004). The NMZ is composed high-grade re-worked granite-greenstone material of the Zimbabwe Craton and is locally intruded by charnockites and enderbites. In the east, the Limpopo Mobile Belt terminates against the Pan-African aged Mozambique mobile belt whilst to the west it terminates against the Kalahari line, which marks the western boundaries of the Zimbabwe and Kaapvaal cratons (Barton, 1983).

2.3. Overview of models of Limpopo Belt evolution

Certain tectonic models explaining the possible evolution of the Limpopo Belt have been postulated. They include the:
Barton and Key (1981) model that was later expanded to include the formation of the Zimbabwe and Kaapvaal cratons.
Fripp (1982) model.
Light (1982) model.
Barker (1983)
McCourt and Vearncombe (1987, 1992)
van Reenen et al. (1987)
De Wit et al. (1992)
Roering et al. (1992)
Kamber et al. (1995)
Holtzer et al. (1998)

This plethora of models for the Limpopo Belt can be quite confusing, especially when compared to more recent findings, as detailed below in some examples from the literature. The formation of the Limpopo Mobile belt according to Barker (1983) provides such an example. In the time period of 2 690 ± 60 Ma, folding created an intense metamorphism which affected the Beit Bridge and Limpopo Groups of supracrustal rocks, along with the intrusion of the Bulai granite-gneiss (Barker, 1983). Discussions in Bumby and van der Merwe (2004) similarly place typical ages from granitic gneisses in the CZ between 2570 and 2664 Ma. However, in contrast, Holtzer et al. (1998) argue that whilst the Bulai Gneiss cross-cuts high grade metamorphic fabrics in the Beitbridge Complex, the peak granulite (Beitbridge Complex event) event post-dates the Bulai Gneiss and has an age of 2.01 Ga. This suggests an early Proterozoic age for the timing of the Limpopo collision (Bumby and van der Merwe, 2004). Several studies have been done on the age of the Limpopo Mobile Belt and others also find the collision event to have occurred at c. 2.0 Ga, with the earliest metamorphism within the belt believed to have occurred between 3.2 and 3.1 Ga (Bumby and van der Merwe, 2004). The alternative viewpoint suggests that regional granulite-facies metamorphism, recorded in the SMZ, CZ and NMZ is believed to have occurred in the time period between 2.65 and 2.52 Ga (Bumby and van der Merwe, 2004); postulate that the granulite-grade event was at 3.15 Ga rather than at 2.6 Ga. Bumby and van der Merwe (2004) question the proposed c. 2.0 Ga Limpopo collision tectonics by highlighting the presence of unmetamorphosed sedimentary strata deposited above the Palala Shear Zone in the Blouberg area. Above this shear zone, lie the Blouberg Formation and Waterberg Group before being capped by the c. 1.85 Ga Soutpansberg Group. Bumby and van der Merwe found it difficult to reconcile the short deposition time (from 2.0 Ga to 1.85 Ga) of the non-metamorphosed sediments prior to the Soutpansberg volcanism, which would usually require much more deposition time. Also puzzling was the fact that the sediments were non-deformed despite being deposited on an area of supposed high tectonic activity (Palala Shear Zone) which would have been active at c. 2.0 Ga in either model, as even in the older collision model (at c. 2.6 - 2.7 Ga) there is reactivation of the Limpopo Belt envisioned at c. 2.0 Ga. In the Barker (1983) model, the following steps are postulated:

- The development of the plutonic bodies in the Central Zone resulted in a period of regional uplift caused possibly by crustal thinning.
- During the period of ±2 300-2 200 the Zimbabwe and Kaapvaal cratons were in a process of moving apart along the Central Zone resulting in fractures and

crustal thinning, consequently producing isostatic uplift (and rotation) that made the region vulnerable to erosion. The Barker (1983) model further suggests that within the period of 2 100 - 2 000 Ma, partial melting of the mantle commenced, resulting in eruptions that flowed into the developing Soutpansberg basin.

Up to this present time period the uplift of the Central zone and Limpopo Mobile belt continue (Barker, 1983).

The Fripp (1982) and Light (1982) models involve the formation of the Limpopo belt along an accreting continental margin, together with the destruction of oceanic crust. Fripp's model considers the Belt as being a remnant of a back-arc - magmatic arc - subduction zone system, whilst that of Light views the Belt as a product of continent-to-continent collision between the Kaapvaal and Zimbabwe cratons and also includes a subduction zone dipping under the Kaapvaal plate.

The Barton and Key (1981/1982) model regards the two cratons (Kaapvaal and Zimbabwe) as being younger than the original proto-craton and that they reflect an amalgamation of microplates brought together by different mechanisms. The Fripp and Light models view this point differently and see each of the cratons as being very old, with unitary features formed at or before 3 800 Ma and the Belt formed by the interaction between these cratons.

2.3.1 More recent models of Limpopo belt evolution

More recent models are summarised by Bumby et al. (2004) and include the authors mentioned below.

McCourt and Vearncombe (1987, 1992), proposed that the CZ had been emplaced westwards/south-westwards as a giant nappe over the previously accreted Kaapvaal and Zimbabwe Cratons around 2.7 Ga. The Palala and Magogaphate-Triangle shear zones are considered to have acted as lateral ramps in this model.

Van Reenen et al. (1987) proposed that all three terraines (NMZ, CZ and SMZ) collided together at about 2.7 Ga. The Palala and Triangle/Magogaphate shear zones are considered to have then been caused later by post-Bushveld Complex (< c. 2050 Ma) lateral shearing within the Limpopo and not as tectonic sutures.

De Wit et al. (1992) consider the Limpopo (Mobile) Belt to have been formed by tectonic juxtaposition during two late-Archean episodes. In the first episode, the CZ was thrust northwards onto the Zimbabwe Craton at the same time the Kaapvaal Craton thrust northwards. The second episode was followed by a movement of southwards directed thrusting with east-west transcurrent faulting accompanying "pop-up" type tectonics. Roering et al. (1992) similarly proposed that the belt was formed as a result of a Himalayan-style continental collision leading to the occurrence of a regional-scale pop-up accommodate along the various Limpopo shear zones.

Rollison (1993) considers the formation of the belt as having been through the gradual accretion of terranes onto the Kaapvaal Craton, thus leading to the sequential joining of the SMZ, CZ, NMZ and Zimbabwe Craton. Kamber et al. (1995) and Holtzer et al. (1998) propose that the belt was formed as a result of dextral transpression.

2.4 The Waterberg Group

The Waterberg Group (Fig. 1.5) occupies more than 20 000 km2 in the northwestern part of the Kaapvaal craton of South Africa (which is generally termed the Main Basin), from where it extends as a thin platform-like cover into southeastern Botswana, and is also represented by a single formation, the Wilgerivier Formation, in the Cullinan-Middleburg Basin. The group is covered by portions of the 1:250 000 topocadastral sheets- 2326 Ellisras, 2328 Pietersburg, 2426 Thabazimbi, 2428 Nylstroom (Jansen, 1982).

The Main Waterberg Basin evolved as a continental fault-bounded basin (Callaghan, 1987). It is is filled by two sequential, yet apparently overlapping successions, termed by (Jansen, 1982) as the "early and late Waterberg Basins", respectively. The former may have spread across the Springbok flats from the location of the Main Basin, to the Cullinan-Middleburg area, and comprises also the Nylstroom protobasin and Alma trough along the southern preserved margin of the Main Basin (Jansen, 1982). Also in the south of the Waterberg Basin is the Thabazimbi Murchinson Lineament which is interpreted as a long lived, fundamental, strike-slip fault system which shows evidence of predominantly left lateral movement, since the deposition of the Alma Formation (Callaghan (1987). It is transtensile forces along the Murchinson Lineament fault system that is believed to have led to the development of the Alma Trough (Callaghan (1987).

More recent work done by Bumby (2000) describes the Waterberg Group as being preserved in two basins, the Middleburg Basin as well as the Warmbaths Basin. Bumby also continues to note that Jansen (1982) refers to the Warmbaths basin as being made up of the Main basin as well as the Nylstroom protobasin.

In age, the Waterberg Group is tentatively placed by Jansen (1982) at between 1 920 and 1 300 Ma with the middle portion of the succession at approximately 1 700 Ma. This is based on indirect evidence, the upper limit being derived from the fact that the group unconformably overlies the Limpopo Belt and the Bushveld Complex, and the lower limit on the basis of diabase intrusions (Jansen, 1982). Recent zircon dating has indicated that the age of the Waterberg Group within South Africa is approximately from Bushveld age (2054 Ma) to about 1,8 Ga (Mapeo et al., 2004).

2.5 Early models of Waterberg basin development: Rust (1975) and Crockett and Jones (1974)

2.5.1 The Kalahari and Ellisras Basins (Rust, 1975)

The Kalahari (Botswana) (Karoo) Basin is mostly covered by Kalahari sand and seems to be essentially a stratigraphic equivalent, although of smaller extent, of the Main Karoo Basin but without the Beaufort succession - the basin also merges north-eastwards into the Ellisras Basin (Figs 1.1 and 2.1). The Ellisras Basin may thus be considered an embayment of the much larger Kalahari Basin (Fig1.1).

Within this region of the Ellisras Basin, the middle Ecca was deposited under shallow water fluvial conditions with an average sediment transport direction westwards. The coal seams tend to be poorer in quality and quantity towards the deeper parts of the Kalahari Basin, which may suggest that some differential tectonic movements affected the Kalahari Basin during coal formation (Rust, 1975). The Ecca sediments of the Kalahari Basin are mainly fine-grained clastics and the major sediment sources were probably to the east, near the Ellisras embayment and to the north.

Both the Palapye and Notwani sectors of the Kalahari Basin (Fig. 2.4) show evidence of post-Waterberg Group structural disturbance along the margins of the regions underlain by these Waterberg rocks. Both the northeastern and southwestern flanks of the Palapye Sector are bounded by northwest or west-northwest trending fault zones (Crocket and Jones, 1974). There is evidence that the line of the major east-northeast trending Zoetfontein Fault coincides with the northern boundary of Waterberg Group occurrence in the Notwani Sector. Brandl (1996) describes the Zoetfontein fault

Figure 2.4: The Botswana Waterberg System

(together with the Melinda fault) as features situated along the northern margin of the Ellisras basin and having been re-activated along a common structure which was active during the pre-Karoo times but not during deposition of the Karoo strata. Both faults have a moderate vertical displacement, the Zoetfontein fault having a downthrow to the north and the Melinda fault, one to the south.

The southern boundary in the Notwani Sector is bounded by an east-northeast - trending lineament whose surface expression may be in the form of shear zones but more often is a pronounced zone of monoclinical flexuring in the rocks of the Waterberg Group (Crocket and Jones, 1974). The latter authors note that evidence exists that some of these boundary zones of structural disturbance were initiated in pre-Waterberg times and may have been active features while the Waterberg rocks themselves were being laid down. The two authors continue to note that along the northern boundary of the Notwani Sector, rocks of the Waterberg Group do not appear to transgress along the line of the Zoetfontein fault. North of this fault, exposures in the Limpopo valley show that the Karoo strata rest directly upon pre-Waterberg metamorphic rocks. In addition, it was also found that a few kilometres to the south and just across the line of the fault, the Karoo strata rest upon a thick succession of rocks of the Waterberg Group. From the above information, Crocket and Jones (1974) concluded that although the most conspicuous effect of movement along the Zoetfontein fault is of a post-Karoo age, there is a strong suggestion of post-Waterberg, Pre-Karoo movement on this fault and a possibility even exists that a fault scarp was present during Waterberg time itself.

Crocket and Jones (1974) found that the Palapye Sector (Fig. 2.4) has the nature of a fault-bounded graben or trough trending northwest and the Notwani Sector appears to be a somewhat similar graben, trending east-northeast. These authors make mention of increasing evidence for major vertical movements of portions of the crust during middle and later Precambrian time in southern and eastern Botswana, as well as in adjacent areas.

2.5.2 Jansen's (1982) model of Waterberg basin evolution: the "Early" and "Late" Waterberg basins

The Waterberg Group in the Main Basin is considered to have been deposited within a continental fault-bounded basin located in the north of the Kaapvaal Craton as well as in the southern edge of the Limpopo Mobile Belt (Bumby, 2000). According to Jansen (1982), the structural pattern of the Main Waterberg Basin developed in several phases. The formation of the Nylstroom syncline (Fig. 2.3) or protobasin and complementary structures is attributed to late-Bushveld magmatic activity that led to subsidence and updoming of the c. 2.050 Ma Rooiberg lavas, which form the roof to this major intrusive complex. Contemporaneous block faulting and erosion of the Bushveld granite initiated deposition of coarse immature sediments of the Alma Formation, with the faults having dominantly northeasterly trends. Subsequent gentle warping may have accentuated the early structures and given rise to local unconformities such as between the Alma and Skilpadkop Formations in the Loubad syncline (Jansen, 1982).

Important faults which seem to have controlled location of the edge of the Main basin include the Murchison Fault Zone in the south and the Melinda Fault Zone in the north (Bumby, 2000). Following the Jansen (1982) model, the late Waterberg Basin was only subjected to local tensional faulting, except near Blouberg in the NE of the Main basin, where intense block faulting occurred and led to the deposition of the arkosic Blouberg beds. Post-Waterberg deformation attained maximum intensity along the southern margin of the Alma trough (which lies just north of the Nylstroom proto-basin, parallel to the Thabazimbi-Murchison lineament; see Fig 2.3) and was largely superimposed on pre-existing trends, transforming the structures into their present outline (Jansen, 1982). The beds were frequently tilted and locally overturned. Between Thabazimbi and Warmbad (Fig. 1.5), beds of the Transvaal Supergroup and Bushveld Complex granite overrode the Waterberg along the Gatkop and Droogekloof thrusts. The intensity of deformation decreased rapidly both east and west of the Alma trough (Jansen, 1982).

The late-Waterberg basin developed on a relatively stable portion of the crust and there was little or no deformation within it along its rims, with the exception of the

Blouberg and Villa Nora areas (northern part of Main basin) and the area north of the Swaershoekberge (south of Main basin) (Fig. 1.5). The unstable portions of the crust underlying or bounding the Waterberg basins were along the Alma trough and the Blouberg area and were determined by fundamental zones of weakness (Jansen, 1982).

The prominent structure of the **Nylstroom protobasin** is the Nylstroom syncline, which developed during and after the formation of the protobasin. On the west, the syncline is bounded by the Loubad and Zwartkloof anticlines, on the north of the Swaerhoekberge anticlinorium and on the southeast by a monoclinal or anticlinal structure in the Rooiberg lavas. A low tectonic saddle in the Swaerhoek beds separates the Loubad and Nylstroom synclines (Jansen, 1982).

Deformation of the Waterberg sequence attained its maximum intensity along the southern margin of the Alma trough (Fig 1.5). It is characterised by block faulting, thrusting and steep tilting of the Waterberg beds and Rooiberg Lavas. (Jansen, 1982).

*Table 2.1: **S**tructures inferred to have affected Waterberg basin evolution*

WATERBERG AGE (Jansen, 1982)	**STRUCTURAL DEVELOPMENTS**
Structures of the Late Waterberg Basin	• Central portion subjected to tensional faulting along the Vaalwater fault zone • Villa Nora area, the Setlaole and Makgabeng Formations are locally faulted and moderately to steeply tilted, partly by drag along the Uitkomst fault (Fig 1.5). • Basin is also bounded on the north by post-Karoo faults
Structures of the Pre-Waterberg	• Post-Rooiberg faults, not intersecting the upper portion of the Swaershoek Formation along the southern margin of the Alma trough. • The Donkerpoort fault, probably active during erosion of the Rooiberg lavas prior to deposition of the Swaershoek beds. • Post-Waterberg compressional pattern in the area

WATERBERG AGE (Jansen, 1982)	**STRUCTURAL DEVELOPMENTS**
	between Thabazimbi and Loubad
	• Fault intersecting southern limb of the Loubad anticline during the deposition of the Swaershoek Formation. • Parallelism in the Loubad and Zwartkloof anticlines between the granite-Rooiberg contact, the Rooiberg-Waterberg contact and the intercalations in the Rooiberg lavas that form the basal beds of the Schrikkloof Formation of the Rooiberg. • Little or no erosion of the Rooiberg lavas prior to deposition of the basal Swaershoek beds. • Extrusions of ignimbrite on the Rooiberg-Waterberg contact and of quartz porphyry in the lowermost Swaershoek beds.
Structures of middle and late-Waterberg Age	• Feldspathic members of the Blouberg Formation were subjected to block faulting, steep tilting and overturning prior to the deposition of the Sesalong Conglomerate (Mogalakwena Formation) • Compressional stresses acted on the north-eastern rim of the basin as seen by the overturning of the successions of the Blouberg block-fault zone
Structures of post-Waterberg Age	• Intense deformation along the Alma trough • Post-Sandriviersberg Formation deformation is present north of the Swaershoekberge anticlinorium through the tilting of the Skilpadkop, Aasvoelkop and Sandriviersberg Formation beds. • The early Waterberg anticlinal and synclinal structures evolved from their embryonic structures into their current shapes, at times resulting in the steep tilting of the

WATERBERG AGE (Jansen, 1982)	**STRUCTURAL DEVELOPMENTS**
	Rooiberg, Glentig (early Waterberg equivalent rocks) and Waterberg successions. The compressional post-Waterberg phase also resulted in fault blocks in the Bushveld granite. • The post-Waterberg phase of deformation ended with tensional faulting and the emplacement of diabase intrusions.
Structures of Post-Karoo Age	• Post-Karoo faults are present in the north of the late Waterberg basin, in the Botswana and probably Blouberg areas, as well as on the southern rims of the Nylstroom proto-basin and Alma trough. • The post-Karoo Melinda and Welgevonden faults are considered to be re-activated Waterberg or post-Waterberg faults

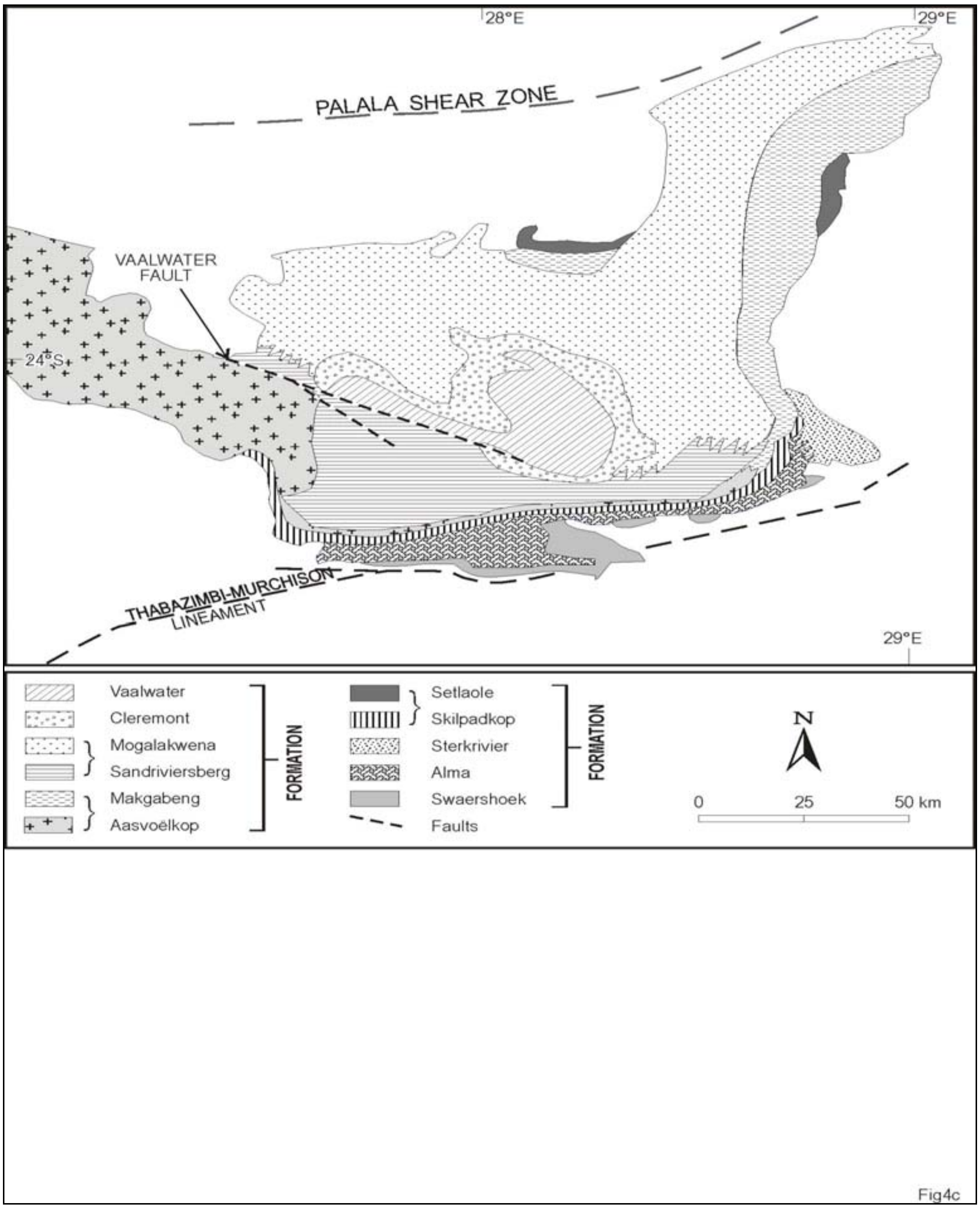


Figure 2.5: Bumby's (2000) work on the evolution of the Waterberg basin

In the time period of the deposition of the Makgabeng Formation, the presence of an elevated palaeotopography to the north, near the southern strand of the Melinda Fault, created an erosional rather than depositional environment. The creation of such a high relief northwards of the southern strand of the Melinda Fault may have been due to syn-Blouberg Basin inversion. Reverse faulting activity occurred to the North of the Blouberg Formation indicating that faulting activity was already established below the Mogalakwena rocks. The study of veins and dyke swarms cutting the Waterberg Group suggest that syn-Blouberg reverse faults may have re-activated during syn-Sibasa (part of the Soutpansberg Group) times. Bumby's (2000) findings indicate that the southern strand of the Melinda fault appears to include northward dipping faults which were active as reverse faults in the syn-Blouberg time period and as normal faults in post Mogalakwena (syn-Sibasa) times, Table 2.1.

2.6 Recent models for Karoo Basin evolution relevant to the Ellisras Basin: Brandl (1996), Catuneanu (1998, 2005) and Bordy (2000)

2.6.1 Brandl's (1996) model

Brandl (1996) has also written on the structural geology of the Ellisras Basin and briefly discusses the following structures:

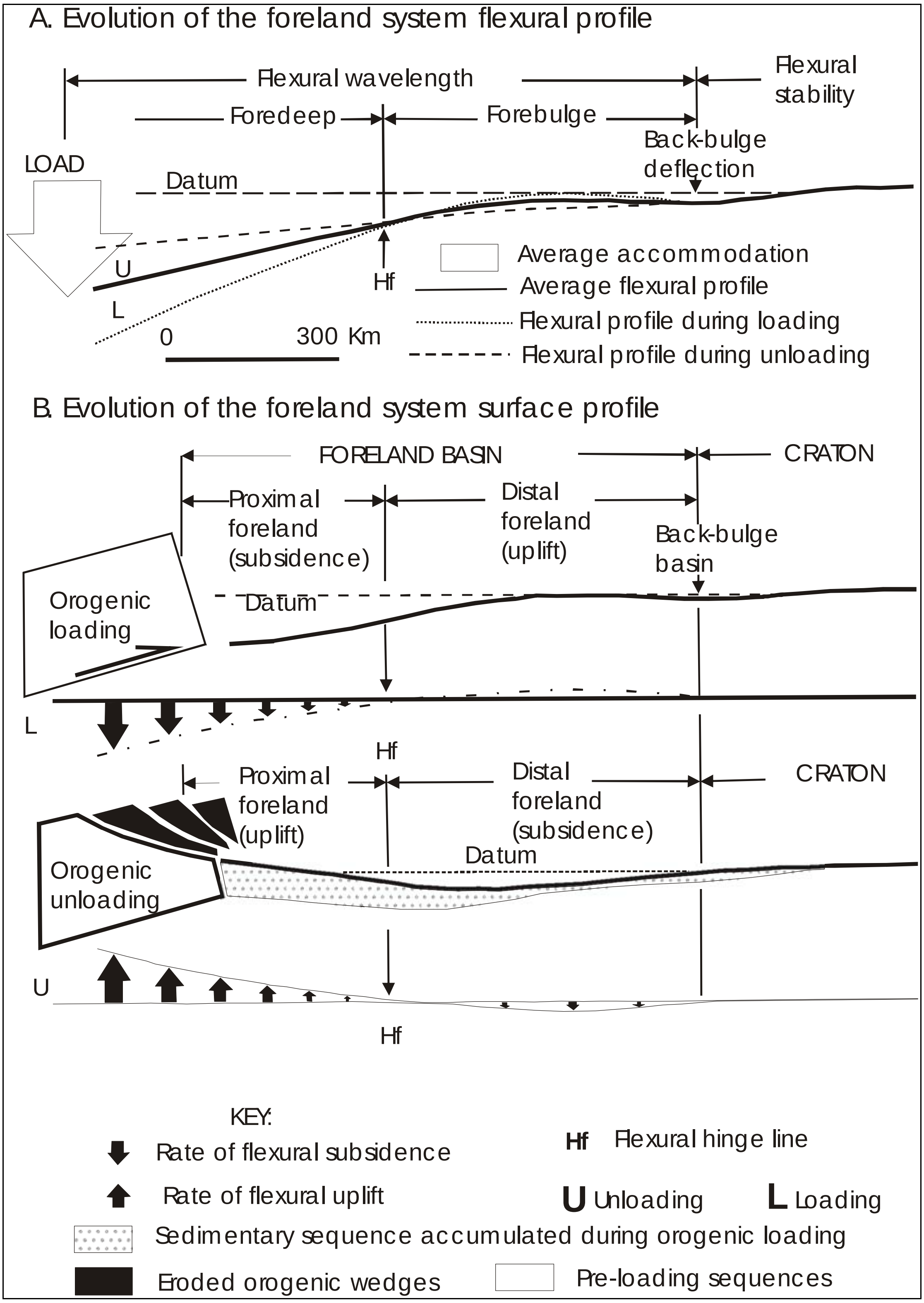
1. The Eenzaamheid Fault (Fig. 2.1) which bounds the northern margin of the Waterberg rocks east of the Ellisras basin, and has a downthrow to the north and a vertical displacement of up to 250 m in certain areas.
2. The Daarby Fault (Fig. 2.1) that connects the Eenzaamheid and Zoetfontein faults (Fig. 2.1), with a maximum throw of about 300m near the Grootegeluk Coal Mine. It consists of a western north-northwest trending branch and an eastern east-northeast - striking branch.
3. The Waterberg Group strata (east of the Ellisras basin), Fig. 1.5, tilt towards the south or southwest and are transected by a few minor northwest-trending brittle faults such as the Boleleme Fault that forms a well-exposed breccia zone on Cumberland 9 LQ.
4. The Palala Shear Belt (Figs. 1.4 and 1.5) is thought to represent an intracratonic transpression zone caused by the oblique convergence of the Central Zone (Limpopo Mobile Belt) with the Kaapvaal Craton/Southern Marginal Zone. The result was a shortening across the shear belt accompanied by left lateral transcurrent shear movement. It extends 1000 km from central Botswana to the Soutpansberg in South Africa (Schaller et al., 1999). Low grade post-orogenic transcurrent faulting in the Palala Shear Zone at c. 1.9 Ga may be associated with the transtensional opening of the Soutpansberg and Palapye grabens. This shear zone is interpreted as a Protorezoic suture zone, along which the Archaean Kaapvaal and Zimbabwe Provinces were juxtaposed (Schaller et al., 1999). Late stage re-activation of the Palala Shear Zone is represented by the northern strand of the Melinda Fault, a dextral strike-slip fault with up to 17km of total displacement (Bumby, 2000).

5. The Beaufort Shear Zone that has a left lateral overall shear sense with displacement being in the order of a few kilometres.
6. The Abbottspoort Shear Zone is a 20m wide ductile zone and is thought to have a similar sense of movement as the Beaufort Shear Zone. It is believed that both shear zones have been re-activated in pre-and post-Karoo times, as brittle faults displaying a prominent vertical component.
7. The Sunnyside Shear (Fig 1.4) is exposed in the bed of the Limpopo River (west of the Ellisras basin) and is characterised by planar mylonitic fabric parallel to the strike of the shearing. It is more developed further west in Botswana and is interpreted to have a left-lateral sense of movement. As with the Abbotspoort and Beaufort Shear Zones, it was re-activated in pre-Karoo and possibly also post-Karoo times as a normal fault.
8. The Constantia Suite (Fig. 1.4) gneisses were deformed into open to isoclinal south-verging folds along generally east-west trending axes. This deformation occurred during a major phase (approx. 2.6 Ga) of compression or possibly transpression along the suite. The axial planes of these folds vary in strike from 80 degrees to 100 degrees and dip 30 to 80 degrees towards the north.

2.6.2 Catuneanu's model of Karoo Basin evolution in southern Africa

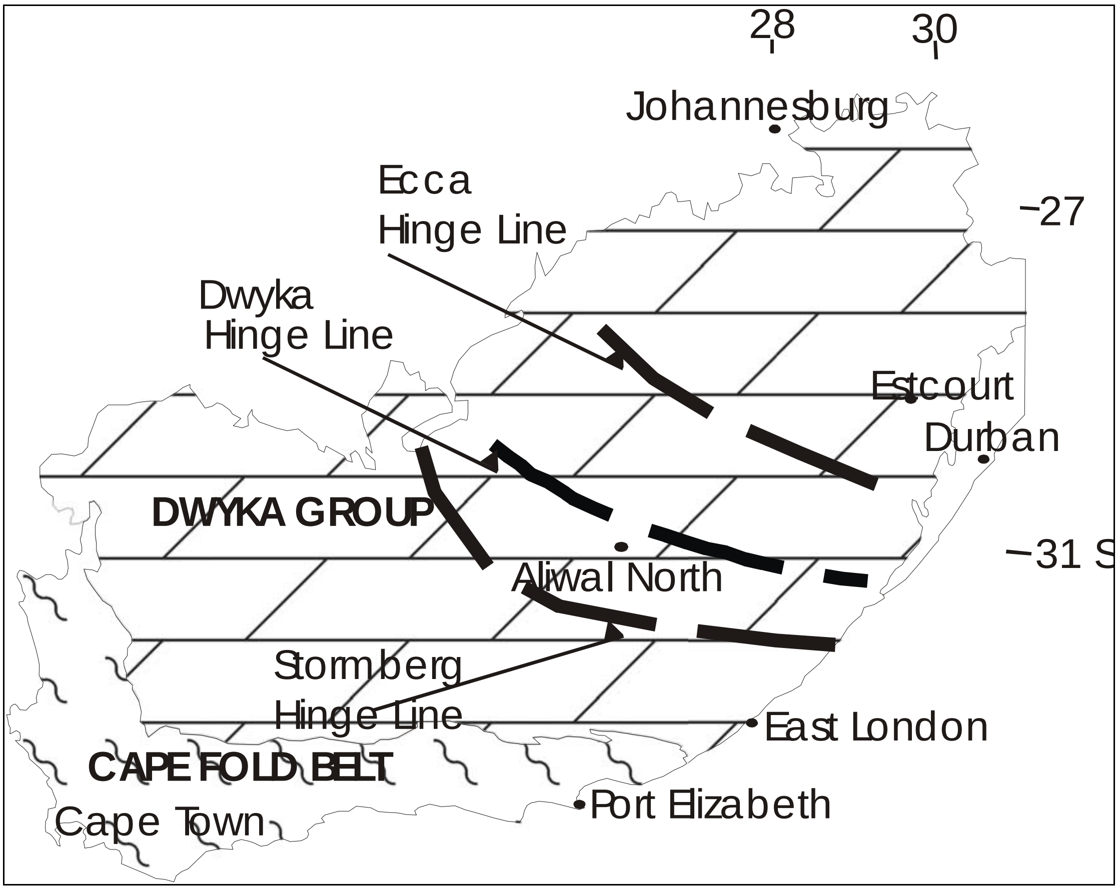
Catuneanu (2005) discusses flexural tectonics relevant to the Main Karoo Basin that later gave way to dynamic subsidence which created additional accommodation across the entire foreland system. Catuneanu believed that these tectonic stresses contributed to the formation of different basin types across Africa. According to Tarbuck and Lutgens (1992) grabens occur in areas of plate divergence and tensional stresses and tend to be bounded by normal faults. This may be part of a link between the two approaches of Catuneanu (2005) and Crocket and Jones (1974). In Fig. 2.6 (A), the flexural foredeep and the forebulge undergo an out-of-phase subsidence and upliftin response to orogenic loading and unloading (Catuneanu, Hancox and Rubidge, 1998). In these stages surface processes, such as sedimentation and erosion, tend to bring the foreland topography to the elevation of the adjacent craton (datum). In (B), the proximal foreland illustrates the depositional foredeep (loading case) and a topographic slope dipping away from the orogenic load (unloading case). The distal foreland represents the topographic forebulge (loading case) and the depositional foresag (unloading case).

Figure 2.6: Evolution of the (A) foreland system and (B) surface profile (adapted from Catuneanu, 1998). Not to vertical scale.



Catuneanu (1998) describes a possible basin development model for the main Karoo Basin (in South Africa) that may have partly influenced the structural geology of the Ellisras Basin.

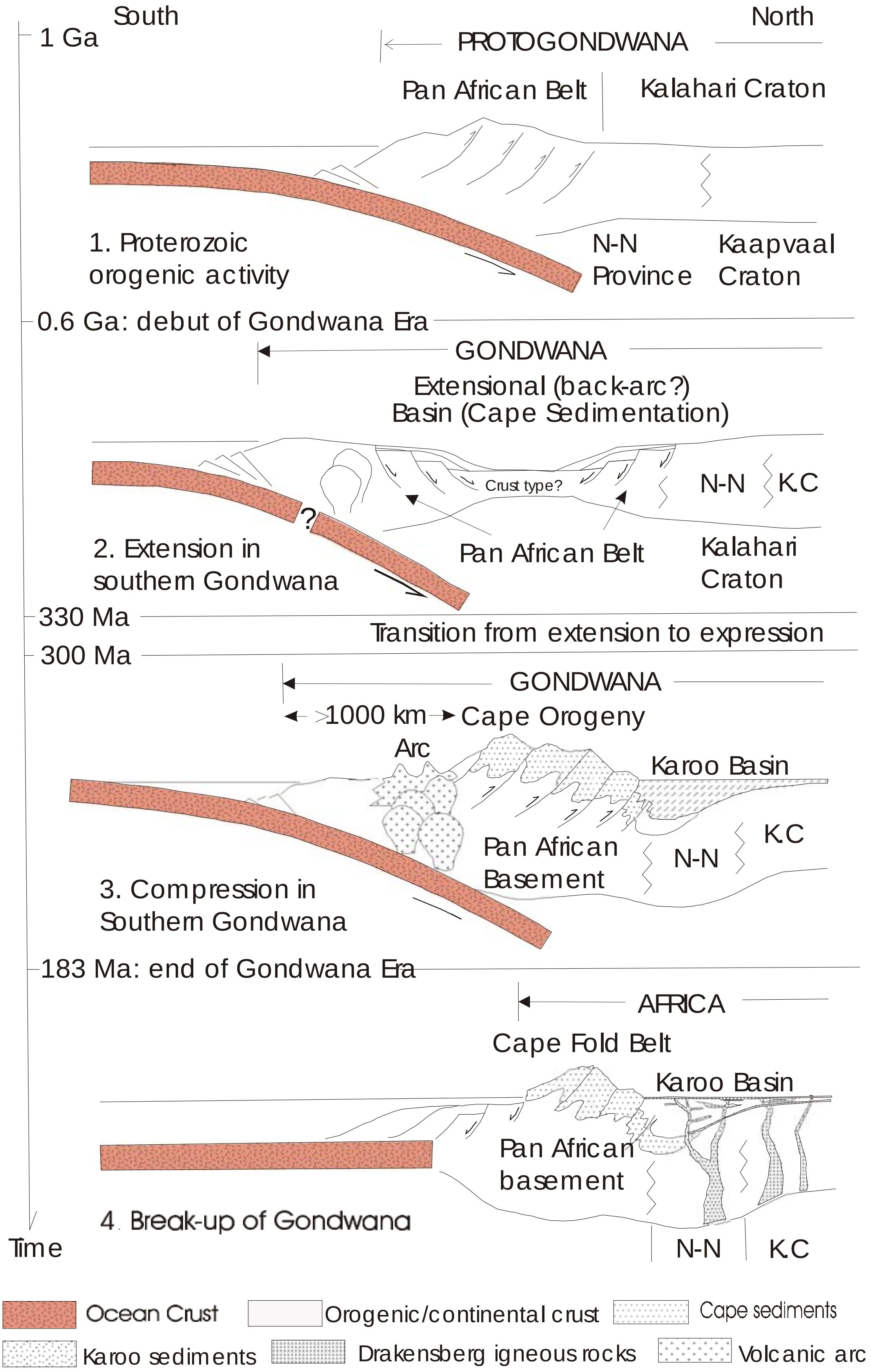
Figure 2.7: Pattern of hinge line migration for the Dwyka, Ecca and Stormberg Groups (adapted from Catuneanu, 1998).



Catuneanu (1998), following many earlier workers relates the Cape Fold Belt to the subduction of the paleo-Pacific plate underneath the Gondwana plate and the subsequent development of a foreland system. According to this model, and as seen in that represented by Fig. 2.6, the flexural foredeep and forebulge underwent an out-of-phase subsidence and uplift in response to orogenic loading and unloading through the ages of the Late Carboniferous to the Middle Triassic (figs 2.6 and 2.8). The loading and unloading of stress in these regions seems likely to have affected the tectonic setting of the distal foreland, which is inclusive of the Ellisras Basin (Catuneanu, 1998). This model points towards a complex geodynamic evolution of the main Karoo Basin. This is represented by simultaneous base level rise and fall cycles within the

Main Karoo Basin settings. The main cause of this coeval subsidence and uplift may have been due to a hinge line whose migration was caused by the redistribution of the orogenic load (Catuneanu, 1998) (Fig 2.7). This migration may have resulted in the generation of contrasting facies and stratigraphic patterns between the proximal and distal regions of the foreland system. This migration pattern can be viewed across the Dwyka, Ecca and Stormberg groups through Fig. 2.7 (Catuneanu, Hancox and Rubidge, 1998).

Figure 2.8: Crustal Evolution of southern Africa (adapted from Catuneanu, 1998). N-N=Namaqualand-Natal, K.C= Kaapvaal Craton.



2.6.3 Tectonic Model for the Limpopo area and Limpopo Monocline, syn-Karoo period (Bordy, 2000)

Bordy (2000) postulates a model within this region in which the first of two right-lateral strike-slip faults was responsible for the generation of the Tuli, Nuanetsi and Tshipise Basins (Figs. 1.1 and 2.1). This tectonic displacement occurred along pre-existing ENE and NE trending faults during the sedimentation of the lower part of the Karoo Supergroup. The model describes the Tuli Basin as being a pull-apart rhombochasm due to a releasing overstep whilst the Nuanetsi was due to a releasing fault junction (Fig. 2.1). The model continues, with mention of the rotative offlap of strata most likely found in the lower sequence of the Karoo Supergroup (Dwyka, Ecca and Beaufort equivalents) during the Tshipise basin extension, with the rotative onlap of the upper Karoo (Molteno, Elliot and Clarens equivalents) occurring during a period of convergent right-lateral strike-slip movement. Next to follow was asthenospheric upwelling and intracratonic rifting which initiated the Lebombo Monocline. The dominant fault pattern of the Tshipise, Nuanetsi and Tuli Basins is regarded as being a modified southward extension of the East African Rift system, within a failed rift triple junction (Fig. 2.1). Extensional structures associated with the system trend N-S, ESE and ENE in the Lebombo Monocline as well as ENE and WNW in the Limpopo area (Figs. 1.4 and 2.1). They also trend NNE in the Save Basin.

The second right-lateral strike slip system occurred in the mid-Jurassic time period and is considered to be related to the southward migration of Madagascar. Bordy (2000) also considers a different tectonic development for the Tuli Basin.

The Tshipise Basin is orientated towards the ENE-WSW and is situated south of the Limpopo River and north of the Soutpansberg in South Africa. It further extends into Zimbabwe where it is called the Bubye Coalfield. Karoo rocks in this basin dip northwards and have E-W strikes, which terminate against faults towards the north (Fig. 2.1). Post-Karoo and post-Waterberg faults occur and have an ENE trend with a throw down to the south. Syndepositional tectonism during the deposition of the Karoo Supergroup included many periods of either non-deposition or sediment removal at different levels of the basin-fill. Narrow or half-grabens are believed to have been formed during the deposition of the Dwyka Group beds.

The E-W trending Nuanetsi Basin is located along the northeastern border area of the Limpopo River in South Africa and in the southeast of Zimbabwe, numerous ESE and north trending faults modified its deposition.

2.6.4 Tectonic Development of Karoo basins (Tuli Basin) (Bordy, 2000)

The Tuli Basin lies around the conjunction of the borders of Zimbabwe, Botswana and South Africa (Fig. 1.1). An ENE trending fault located in the northern boundary of the Karoo rocks can be traced to the Archaean basement and is believed to have been active also in post-Karoo times. The basin has a graben structure due to faults which form part of the late to post-Karoo fracture system, which broadly follows the axis of the Limpopo Belt. The Karoo rocks of the basin are considered to be flexurally downwarped along an ESE axis and subsequently downfaulted by a combination of NE and ENE trending fractures.

The formation of the Karoo Supergroup occurred through an initial compressive system before commencing to an extensive regime, which could be related to the break-up of Gondwana.

2.7 Possible Scenarios for the formation of the Ellisras Basin

Arnott and Williams (2007) find that the coalfields of the Ellisras, Mmamabula and Mopane coalfields (Fig. 1.3) developed within the greater intracratonic Soutpansberg trough, which was re-activated during late Permean to early Triassic times; this viewpoint correlates with the work of Siepker (1986) who discusses continuous tectonic activity occurring within the mentioned timeframe.

Figure 2.9: Location of the Mmamabula Energy Project in relation to the Ellisras Basin and International borders (adapted from Williams (2006), his Fig. 4.1)

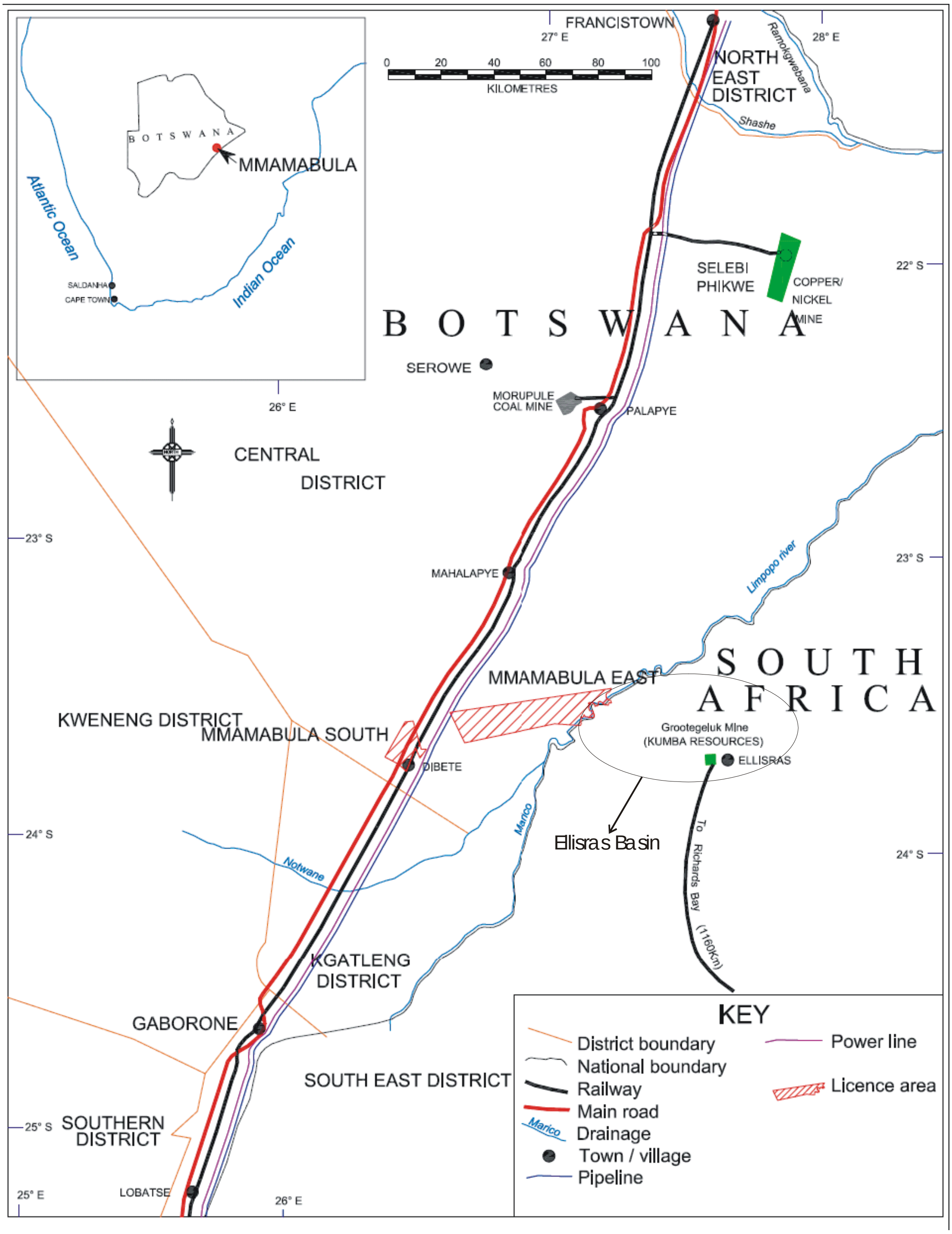


Figure 2.9 displays the study area (which extends from the Ellisras Basin and into the Kalahari Basin) for Arnott and Williams (2007), located in Botswana's Mmamabula East area. Fig. 2.10 displays the structural set up of the Mmamabula East project area

and similarities in terms of faults it shares with the Ellisras Basin are made visible (the Zoetfontein and Southern Boundary faults).

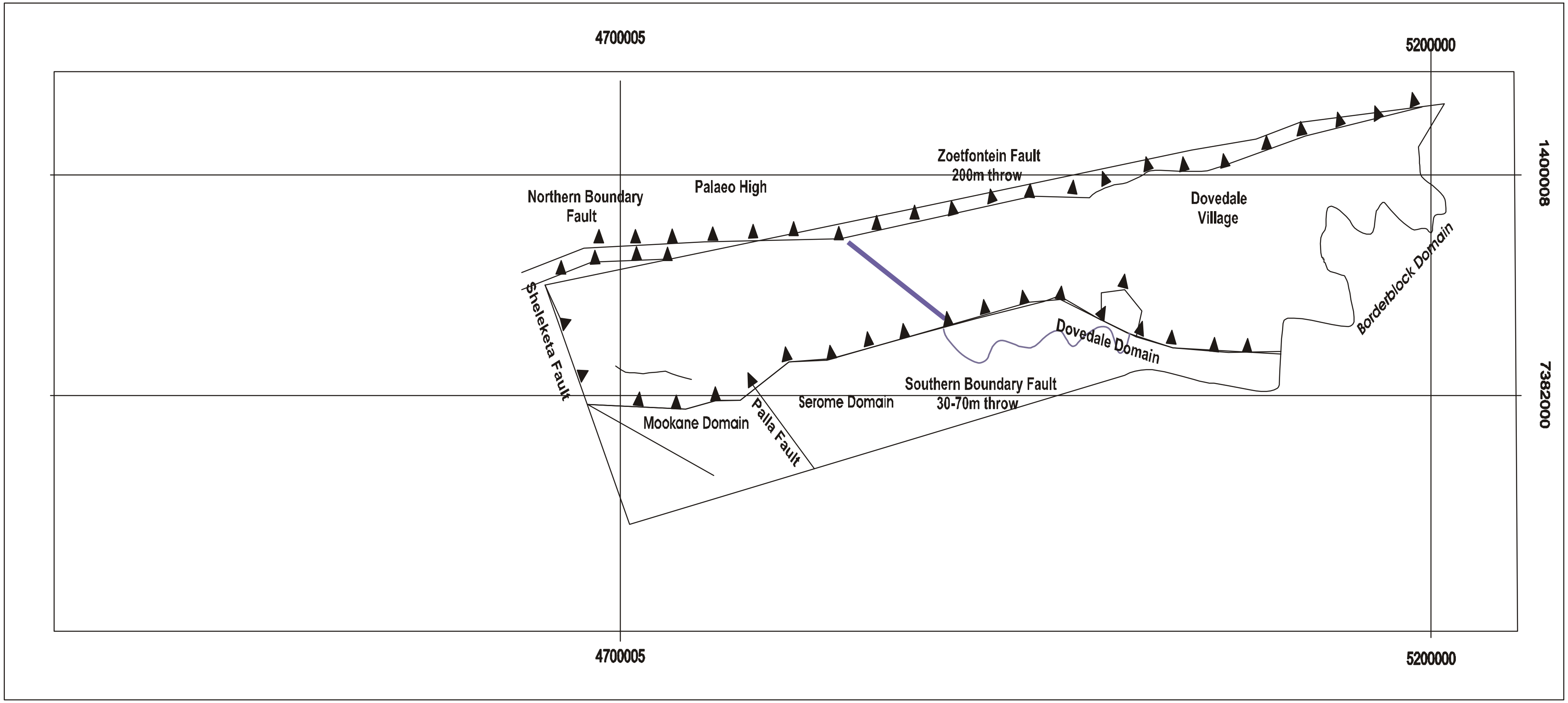
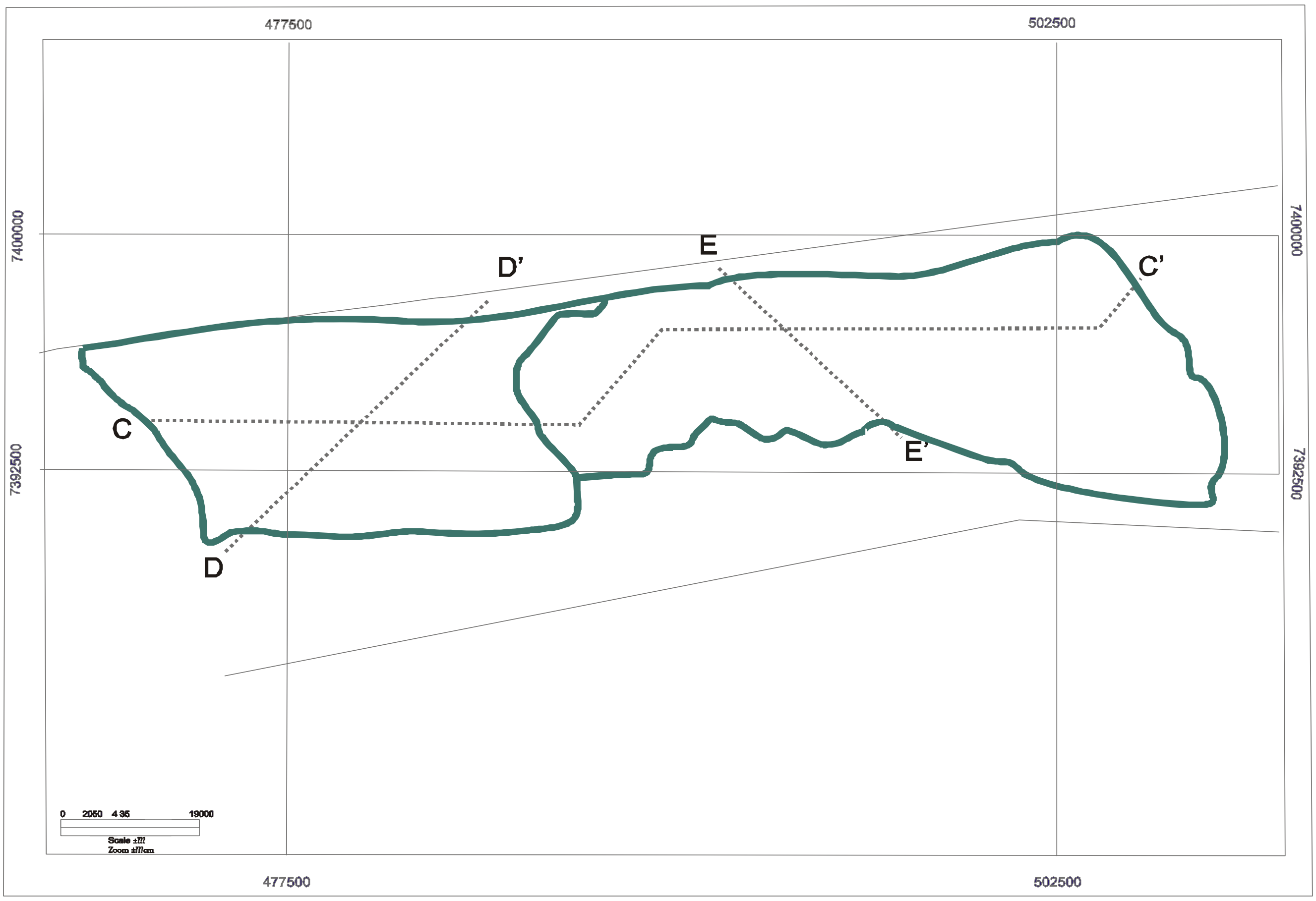


Figure 2.10: Structural domains and fault areas of the Mmamabula East project area, Botswana (adapted from Arnott and Williams (2007), their Fig. 7.8)

Arnott and Williams (2007), continue to analyse their project area by drawing cross-sections along their project area as depicted by Fig. 2.11.

Figure 2.11: Locations of geological cross-sections of Mmamabula East (adapted from Arnott and Williams (2007), their Fig. 9.4)



The profiles (no depth readings given, please see Table 3.4) display uneven and at times graben-like structures similar to that of the Ellisras Basin as seen in Fig.s 2.12 to 2.14 (not to scale). More discussions on the geology of this area as well as on the M2 and D1 seams is found in Chapter 3, Stratigraphy, of this thesis (also see Table 3.4).

Figure 2.12: C-C' geological cross-section (adapted from Arnott and Williams (2007), their Fig. 9.5. Not up to Scale; please see Table 3.4 for seam thickness estimate.

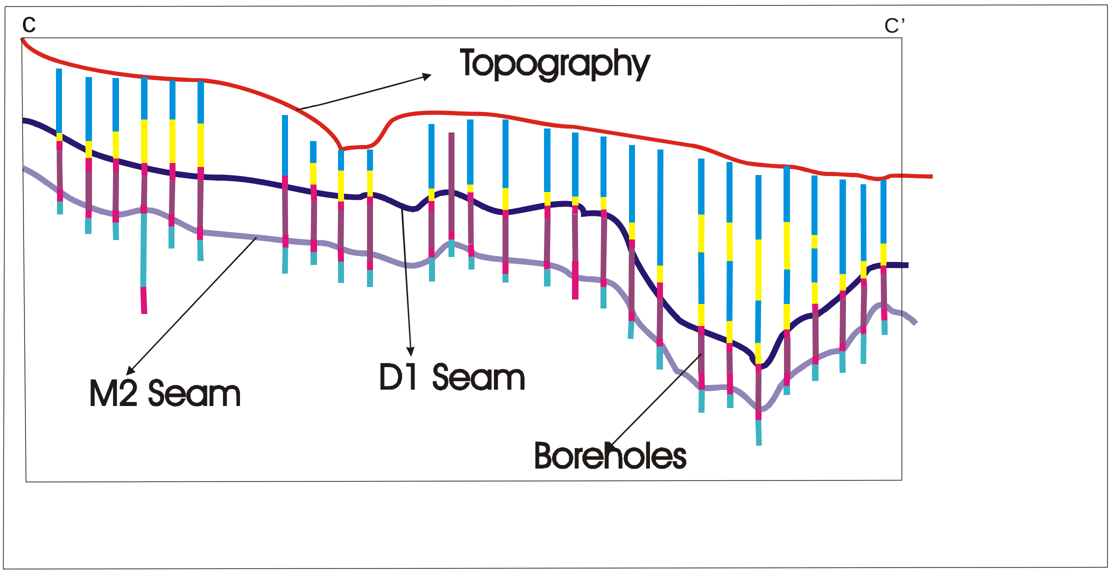
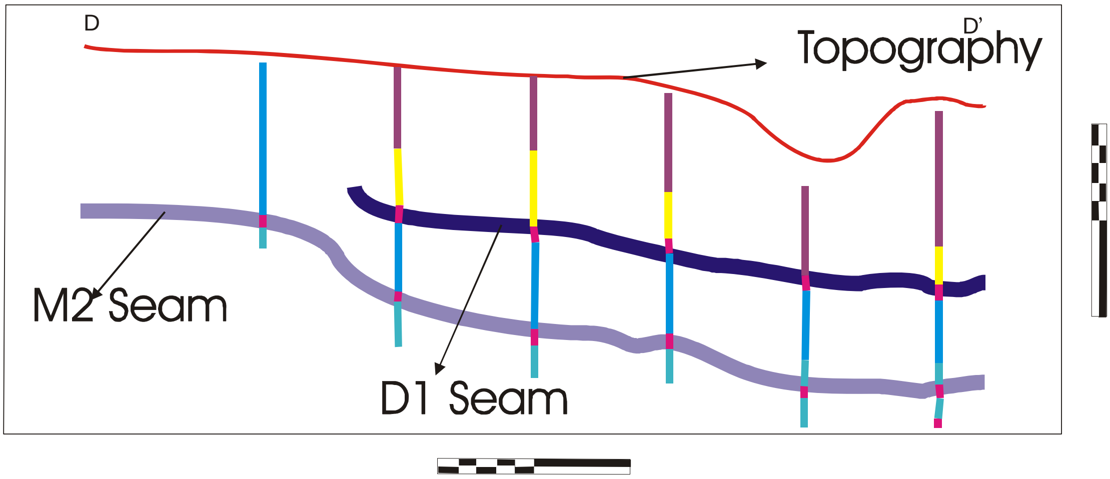


Figure 2.13: D-D' geological cross-section (adapted from Arnott and Williams (2007), their Fig. 9.6.). Not up to Scale; please see Table 3.4 for thickness estimate.



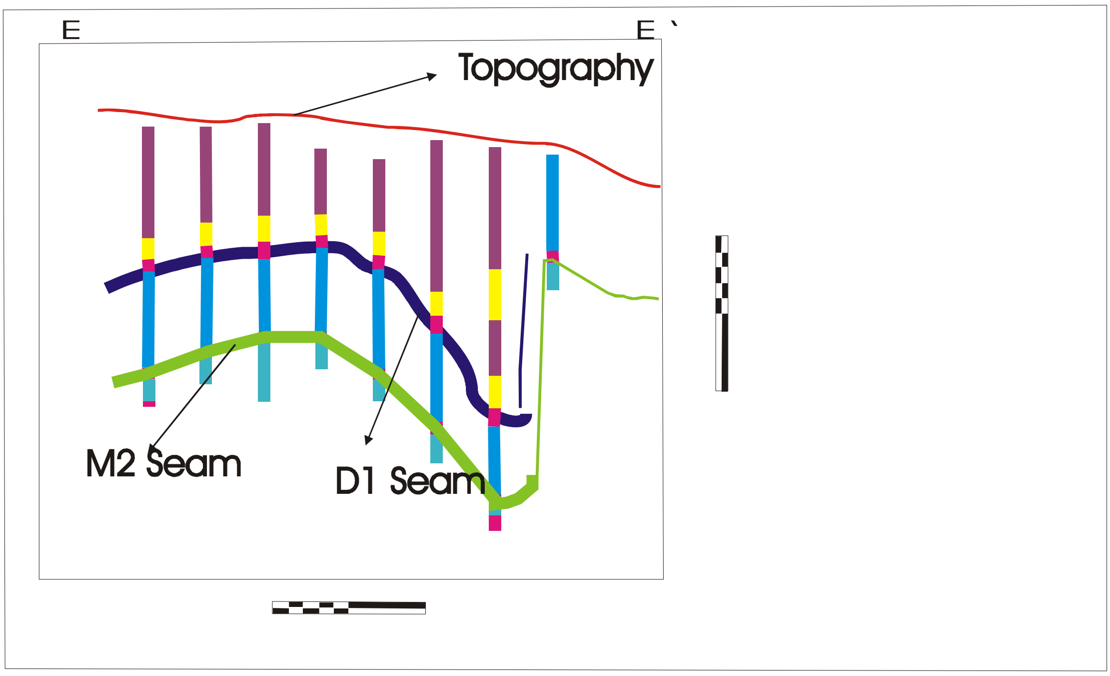


Figure 2.14: E-E' geological cross-section (adapted from Arnott and Williams (2007), their Fig. 9.7. Not up to Scale; please see Table 3.4 for seam thickness estimate.

According to Arnott and Williams (2007), the coal bearing Karoo sediments within the Mmamabula East area are bounded to the north by the major Zoetfontein Fault and the associated Northern Boundary Fault and in the west by the smaller Sheleketa Fault and in the south by two smaller faults, the Southern Boundary Fault and the Palla Fault (refer Fig. 2.7).

Arnott and Williams (2007) continue to observe that within this faulted basin in Mmamabula East, the coal bearing sediments are generally flat lying with minor regional undulations postulated to be associated with similar undulations in the pre-Karoo floor rock.

One such major undulation, termed the palaeo-high, divides the Mookane Block from the rest of the coal bearing area at Mmamabula East. Due to the fact that the coal seams were deposited over this pre-existing basement high, coal seam elevations increase gradually towards this feature, resulting in increased weathering in the area immediately above the palaeo-high (Arnott and Williams, 2007) .

The natural break in coal resource limits which occurs over the palaeo-high as a result of weathering (and erosion), has been used to define the limit of the Mookane Block coal resource. All coal resources occurring on the other side of the palaeohigh are therefore separated from the Mookane Block coal by this palaeo-high which causes a complete break in the D1 seam resource and a partial break in the M2 seam resource due to weathering and erosion.

Faulting at Mmamabula South (area seen in Fig. 2.6) is much more pronounced than in the East with northwest-southeast and east-west orientated sets of faults present (Arnott and Williams, 2007).

These faults have divided the Mmamabula South project area into eleven separate faulted blocks with throws of up to 50 m between faulted blocks.
Observable is a significant strike slip component in the northwest-southeast orientated fault sets (Arnott and Williams, 2007).

Siepker's (1986) view of the formation of the Ellisras Basin assumes that this depository represents part of a pre-Karoo glacial valley infilled by Karoo strata. The northern part of the basin, underlain by ultramafic rocks of the Limpopo mobile belt, with granites, gabbros and norites of the Bushveld Igneous Complex to the east, represents an inferred palaeohigh (Siepker, 1986). The quartzites and conglomerates of the Waterberg Group underlying the Karoo succession to the south represent a palaeolow area within this model.

Based on Siepker's (1986) model, the following outline of sequential geological events can be made of the Basin's possible history:

1. Sedimentation within most Karoo-aged basins throughout southern and eastern Africa began during the Late Carboniferous (Bumby and Guiraud, 2005). The base of the Karoo succession of the Ellisras basin (Dwyka Group) consists of diamictite in the northern part of the basin and muddy rhythmite towards the south. This may support Siepker's assumption that this was once a pre-glacial valley, but does not really support any specific mode of early basin formation.
2. During the Phanerozoic, Africa (and Gondwana) migrated from the South Pole northwards towards its present latitude and the fill of preserved basins reflects a concomitant change in palaeoclimate (e.g., Bumby and Guirard, 2005 and many previous workers). The formation of a swamp environment

contributed towards the deposition of No.1 Coal seam in the Ellisras basin. One may also assume that there was little tectonic activity during this period as coal requires a stable environment to form. The trending of fluvial channels, represented by sandstone units within the No.1 Coal seam was east-west. This concurs with Bordy's (2000) description of depositional environments and palaeo-drainage patterns which trend towards the E and NE to WSW within the Ellisras Basin's Ecca Group. This coal seam deposition was followed by probable tectonic activity (or, alternatively, climate change) as indicated by a thin laterally extensive coarse grained sandstone unit. One condition necessary for the increase in transporting current strength is a change in slope possibly caused by tectonic uplift or downthrow of terrain (e.g, faults). This deposition was followed by that of mudstone which was overlain by coarse-grained sandstone and finally capped by the No.2 Coal seam (Siepker, 1986).

3. As with the first coal seam, the second was also related to east-west trending fluvial channels within this seam (Siepker, 1986).
4. Deposition of the Grootegeluk Formation is considered to have occurred in a period of basin infilling and poor drainage resulting in the deposition of a 100m thick interlayered coal and mudstone succession. The mud was most likely introduced into the basin from an external source, in cyclicity with the deposition of coal as a result of cyclic basin subsidence and/or periodic mud input (Siepker, 1986).
5. The Molteno Formation consists mainly of sandstone and indicates a steeper palaeoslope with accompanying high energy levels due to renewed uplift (Siepker, 1986).
6. The Elliot Formation indicates a gentler palaeoslope with a decrease in energy levels. This is shown by the presence of fining-upward sandstone units with mudstone or siltstone at the top (Siepker, 1986).
7. Volcanism of the Drakensberg Formation terminated deposition in the basin. The Daarby Fault was active after the deposition of the volcanic material, as in the east, one section of the fault has left the basalts intact (Siepker, 1986).

Bumby and Guiraud (2005) discuss the formation of African basins during the Phanerozoic period. Two models by Catuneanu et al. (1998) and Turner (1999) are discussed which refer to the possible formation of the main Karoo Basin. As discussed in the previous sections of this thesis, Catuneanu et al. (1998) recognised a direct relationship between episodic uplift in the Cape fold belt and the progradation of sediments onto the craton. After collision, the weaker pan-African basement of the Cape Fold Belt shortened more in comparison to the more rigid crust of the Precambrian Kaapvaal craton (Bumby and Guiraud, 2005). This resulted in more localized orogenic loading on the southern edge of Gondwana and formation of the Main Karoo Basin and related smaller basins further to the north, such as the Ellisras. The resulting flexural tectonics and dynamic subsidence within the main Karoo Basin led to the formation of a retroarc foreland system plus related intracratonic basins to the north (Catuneanu et al., 2005). Turner (1999) has challenged this application of the retro-arc foreland basin model and chooses to relate age data, stratigraphic and stacking patterns as well as small amounts of volcanic detritus within the upper Karoo formations to mantle plume-linked thermal uplift and the onset of early rifting, to the southeast of the preserved basin, close to the later Agulhas Falkland fracture zone (Catuneanu et al., 2005). Thus, according to Turner (1999), the upper Karoo in the Main Basin is related to extension associated with Gondwana break-up rather than purely orogenic unloading in the Cape Fold Belt (Bumby and Guiraud, 2005).

The Ellisras basin was created in an area known to have structural lineaments that were cyclically re-activated over time, such as the Melinda fault (Jansen, 1982), Zoetfontein fault (Brandl, 1996) as well as the Sunnyside Shear Zone (Brandl, 1996). These lineaments were most probably influenced by the tectonic instability caused by the intrusion of the Bushveld Complex, which is considered to have been active during early Waterberg deposition (Jansen, 1982; Barker et al., 2006). Movement along the Limpopo Mobile belt, as tectonic re-activation due to continuous tension in the Karoo era in the Soutpansberg and Limpopo fault zones occurred, controlled the formation of the Karoo sediments and finally acted as conduits for the extrusion of basalts which terminated the Karoo era (Barker, 1983). Studies have indicated that east-northeast - trending fractures have been rejuvenated in post-Karoo times (Barker, 1983). The Zoetfontein Fault is situated between the Central and Southern Marginal

Zones with a large portion of the Ellisras Basin situated on the Southern Marginal Zone (Fig. 1.4).

Such tectonic instability occurring during the evolution of the Ellisras Basin likely contributed towards the structural development of the depository. Being essentially a fault-bounded basin (MacRae, 1988),(Fig. 1.2) an increase in sediment loading – related subsidence due to deposited material may have also contributed towards the re-activation of these faults. The cyclical tectonic instability can also be noted through the changes in energy levels of the depositing media of the Ellisras basin-fill, from the early Carboniferous period, as already indicated by Siepker (1986). MacRae (1988) suggests that the coal/sandstone accumulation in certain sections of the Ellisras Basin was indicative of periods of palaeoslope rejuvenation resulting in sandstones, grits and minor conglomerates, alternating with periods of stasis when extensive coal seam deposition occurred. MacRae continues to discuss the possibility of basin subsidence creating a wet environment conducive to the formation of marshy areas, and once subsidence slowed, coal seams were formed.

CHAPTER 3

THE STRATIGRAPHY OF THE ELLISRAS BASIN-FILL

3.1 Introduction to the Main Karoo Basin Stratigraphy (based largely on Johnson et al., 1996) and southern African subsidiary Karoo basins

The Karoo Supergroup in southern Africa occurs in the areally extensive Main Karoo (fig 3.1) and Kalahari basins as well as in a number of subsidiary basins (fig 1.1) in South Africa, Namibia, Botswana, Zimbabwe and Mozambique. A written summary of stratigraphic subdivisions for the basins shown in Fig. 1.1 is given in the table below.

Table 3.1: Nomenclature and Tentative Correlation of the stratigraphy in the Main Karoo Basin and in the Springbok Flats, Ellisras, Tshipise and Tuli basins (summarised from Fig. 1.1)

Main Karoo Basin (for eastern part of basin only, in Kwazulu-Natal-Mpumpalanga)		**Springbok Flats Basin**	**Ellisras Basin**	**Tshipise Basin**	**Tuli Basin**
Drakensberg Group		Drakensberg Group	Drakensberg lavas	Lebombo Group	Lebombo Group
Stormberg Group	Clarens Formation	Clarens Formation	Clarens Formation	Tshipise Member	Tshipise Member
				Red Rocks Member	Red Rocks Member
	Elliot Formation	Irrigasie Formation?	Lisbon Formation	Bosbokpoort Formation	Bosbokpoort Formation
				Klopperfontein Formation	Klopperfontein Formation
				Solitude Formation	Solitude Formation
	Molteno Formation		Greenwich Formation	Fripp Formation?	Fripp Formation
Beaufort Group	Driekopen Formation		Eendragtpan Formation	Mikambeni Formation	Mikambeni Formation
	Verkykerskop Formation				
	Normandien Formation				
	Volksrust Formation				

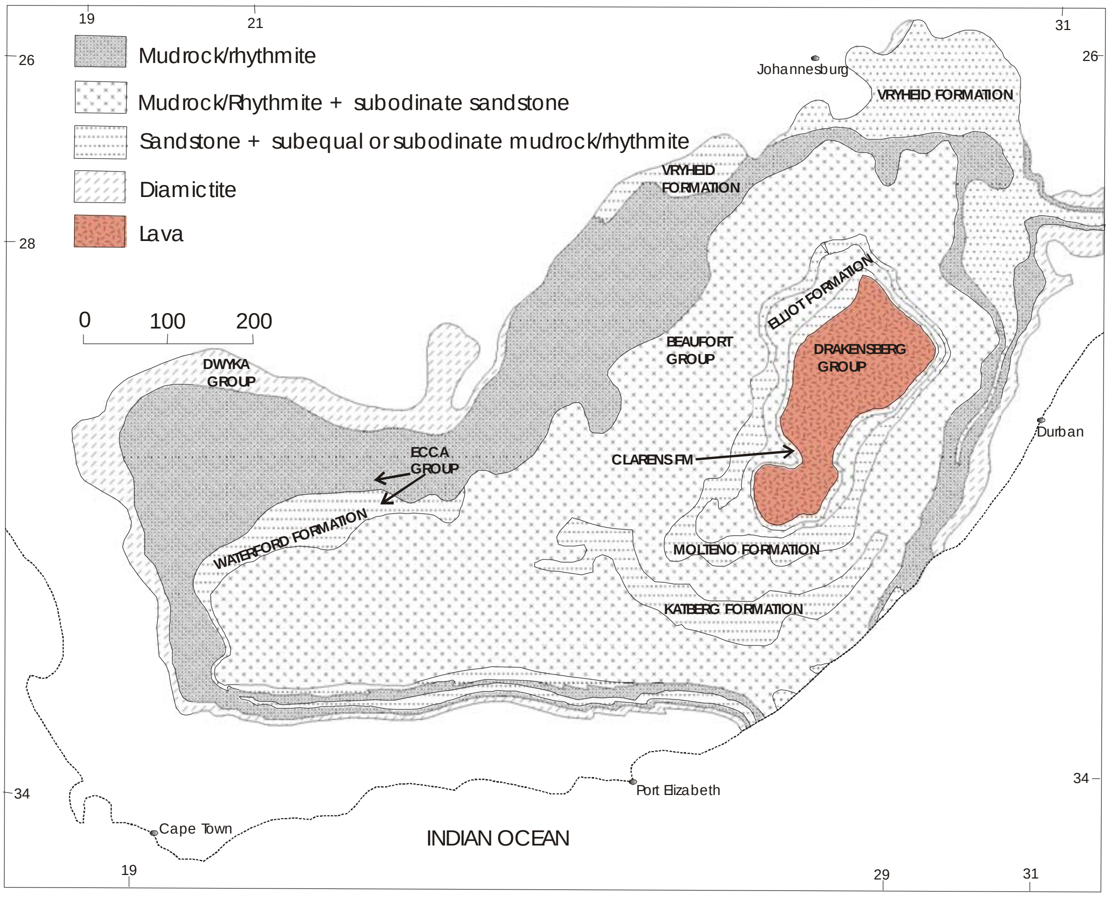
Main Karoo Basin (for eastern part of basin only, in Kwazulu-Natal-Mpumpalanga)		**Springbok Flats Basin**	**Ellisras Basin**	**Tshipise Basin**	**Tuli Basin**
Ecca Group	Vryheid Formation	Hammanskraal Formation	Grootegeluk/ Goedgedacht Formation?		
				Madzaringwe Formation?	Madzaringwe Formation
	Pietermaritzburg Formation		Swartrant Formation		
Dwyka Group	Dwyka Group	Wellington Formation?	Tshidzi Formation?	Tshidzi Formation	Tshidzi Formation
		Waterkloof Formation			

The Main Karoo Basin of South Africa, which serves as the type basin overall, is interpreted as a flexural retro-arc foreland basin, while the rest are seen as intracratonic sag basins or rift basins (Catuneanu et al., 2005). Although the southern African basins containing the Karoo Supergroup strata appear in different tectonic settings, the overall climatic overprinting resulted in similar vertical lithological profiles (e.g., Johnson et al., 1996; Bordy et al., 2002). The progressive climatic shift from glacial to cool, moist conditions, then to warm, semi-arid and finally to hot, arid conditions is attributed to Africa's (and Gondwana's, of which it formed a part) latitudinal drift from cold/glacial to desert climatic belts (e.g., Bordy et al., 2002).

The Karoo Supergroup ranges in age from Late Carboniferous to Early Jurassic. The strata were deposited in glacial, deep marine (including turbidite), shallow marine, deltaic, fluvial, lacustrine and aeolian environments. Correlations are made between various formations belonging to respective basins as seen in Fig. 1.1 and Table 3.1.
Some of the present "basins" could be preserved by the products of later tectonic movements rather than exclusively reflecting pre- and syndepositional subsidence.
The nomenclature used to identify various basins can become confusing. The Ellisras Basin has been referred to as the Waterberg (Karoo) Basin- which could be confused with the basin in which the Proterozoic Waterberg Group was deposited. This is further confused by the existence of a Waterberg Karoo Basin in Namibia. The Tshipise Basin is alternatively referred to as the Soutpansberg Basin- which also denotes the depositional basin of the Proterozoic Soutpansberg Group. The Mazunga

Basin in Zimbabwe constitutes the eastern part of the Tuli Basin in Botswana but the latter name is at times used for the whole basin. The Save (Sabi) Basin has, together with the Tuli Basin, been referred to as the Sabi (Save)-Limpopo Basin or simply regarded as two basins (Sabi and Sabi-Lundi). In some sources, the Waterberg Basin in Namibia is referred to as the Etjo Basin whilst the Aranos Basin has been used to describe the part of the extensive Kalahari Basin that occurs in Namibia.

Figure 3.1: Schematic Distribution of the major lithostratigraphic units of the Main Karoo Basin (Adapted from Johnson et al., 2006)



The **Dwyka Group** is up to 800m thick in the Main Basin in which it includes a northern Mbizane Formation and a southern Elandsvlei Formation. The rocks found in these two groups display glacial or glacially-related features and include diamictites, conglomerates, fluvioglacial pebbly sandstone and rhythmite. In the Kalahari Basin in Botswana the Dwyka Group is thickest in the southwest. The Dwyka in the Main Karoo Basin rests on Precambrian bedrock surfaces along the northern basin margin, in the south it overlies the Cape Supergroup unconformably or paraconformably, while in the east it unconformably overlies the Phanerozoic Natal Group and Msikaba Formation (Johnson et al., 2006).

A number of lithofacies, discussed in Johnson et al. (2006), have been identified in the Dwyka Group and include:

- Massive diamictite facies
- Stratified diamictite
- Massive carbonate-rich diamictite facies
- Conglomerate facies
- Sandstone facies
- Mudrock with dropstone facies and
- Mudrock facies.

The glacigene rocks found at the commencement of the Karoo depositional cycle in most of the basins represent ground moraine left by retreating glaciers and the melt-out products of ice-sheets. Fluvial outwash material and seasonal varvites resulted from suspension settling under quiet water conditions, forming a subordinate Dwyka component.

In the southern half of the Main Karoo Basin and in the Karasburg Basin of Namibia, the glacial episode was followed by the deposition of a thick mudrock succession (Prince Albert, Whitehill, Tierberg and Aussenkjer Formations) representing suspension settling in relatively deep water.

The Prince Albert (south of Main basin) and Pietermaritzburg (NE of Main basin) Formations are situated above the Dwyka Group and make up part of the overlying Permian **Ecca Group**, which has up to 16 formations (Johnson et al., 1996, 2006). The Whitehill Formation in turn overlies the Prince Albert, and also consists of black (white-weathering) carbonaceous shale. The formation loses this distinctive weathering character towards the northeast and can be correlated with the coal-bearing strata in the Vryheid Formation (fig. 3.1).

Along the “foredeep” (Fig 2.6) part of the Main Karoo Basin are the sandstones of the Ripon, Laingsburg and Skoorsteenberg Formations, representing turbidites deposited as submarine fan complexes at the foot of advancing delta slopes. The mudrocks and rhythmites of the Fort Brown Formation and the upper parts of the Kookfontein and Tierberg Formations (underlying the Waterford Formation) constitute delta slope deposits which grade upwards via coarsening-upward cycles into the sandstone-rich delta front-related Waterford Formation.

Exploitation of coal in the Karoo basins, although mainly in the northeastern part of the Main Karoo Basin (MKB), also includes:

- Swartrant, Grootegeluk and Vryheid Formations (Ellisras Basin)
- Morupule Formation (Eastern Kalahari Basin)
- Otshe, Boritse, Mmamabula, Mosomane, Serowe, Morupule and Tlapana Formations (main part of Kalahari Basin)
- Hammanskraal Formation (Springbok Flats Basin)
- Madzaringwe and Mikambeni Formations (Tshipise Basin)
- Fulton’s Drift Mudstones (Tuli Basin)
- Lundi Coal Measures (Save Basin).

Identified coalfields situated near the Ellisras Basin are seen in the Fig. 1.3.

The Vryheid Formation comprises both coarsening-upward deltaic cycles and fining-upward fluvial cycles. It is sandwiched between mudrocks of the Pietermaritzburg and Volksrust Formations within the NE of the Main basin, which represent transgressive “shelf”-like sediments.

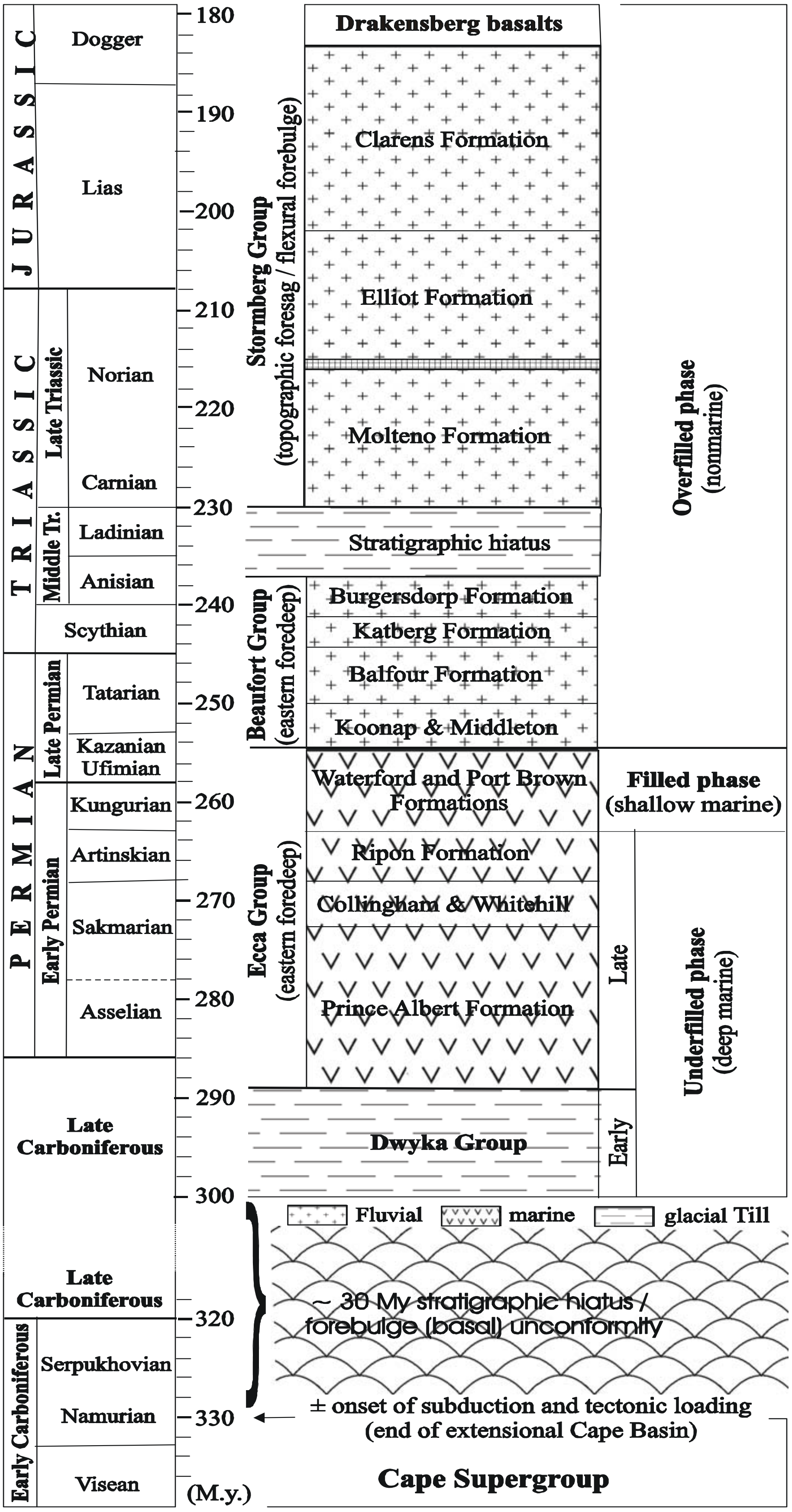
The change in depositional environments seen in the Ellisras Basin (Siepker, 1986; Catuneanu , 2005) is discussed with relation to other basins in southern Africa by Johnson et al. (1996). He discusses two zones within the Ellisras basin-fill, known as the lower and upper intervals. Commonly found in the lower interval are dark-coloured shales with interspersed siltstones and sandstones as well as occasional coal seams, formed within environments considered to have been marine, lacustrine, deltaic and fluvial. This interval is represented by the Ecca Group, as well as part of the lowermost Beaufort Group in some places. The upper interval genetic conditions are considered by Johnson et al. (1996) to have been somewhat different in comparison to the lower interval. They represent overbank fluvial deposits, subaerially deposited under oxidizing conditions. This interval is mostly located in the Beaufort Group as well as the equivalents of the overlying Molteno, Elliot and Clarens Formations in the Main Basin (with total cumulative thickness there of up to 7000m). These three units can together be considered as the Stormberg Group (e.g., Catuneanu et al., 2005) in the Main Basin.

The Beaufort Group together with the Molteno and Elliot Formations in the Main Basin consist almost entirely of fining-upward fluvial sediments. The rivers were mostly meandering types with extensive flood plain muds predominating over lenticular channel sands. However, the sandstone-rich Katberg and Molteno Formations appear to have been deposited by braided low sinuosity rivers (Johnson et al., 1996).

Capping the Karoo sedimentary column in the Main and most other Karoo basins is a largely aeolian sandstone unit termed the Clarens Formation (with massive, loess-type deposits as well as cross-bedded palaeo-dunes), known as the Ntane and Nkalatlou Formations in Botswana. Fluvial and playa lake environments have also been identified, reflecting wetter desert palaeoclimatic conditions. On top of the Clarens are the basaltic lavas of the Drakensberg Group (MKB) and its equivalents elsewhere.
Along the western border of Mozambique is the Lebombo Group consisting mainly of basic and acid lavas, capping a narrow belt of Karoo rocks (Lebombo Karoo Basin) within that region (located along the Lebombo Range as seen in Fig. 1.1).

The chronostratigraphy of the components of the Karoo Supergroup in the Main Karoo Basin is summarised below in Fig. 3.2 (Catuneanu et al., 2005, their Fig. 2):

Figure 3.2: Lithostratigraphic Subdivisions of the Karoo Supergroup in the Main Karoo Basin (adapted from Catuneanu et al., 2005)



The chronostratigraphy of the components of the Karoo Supergroup in the subsidiary basins north of the Main Karoo Basin is as follows:

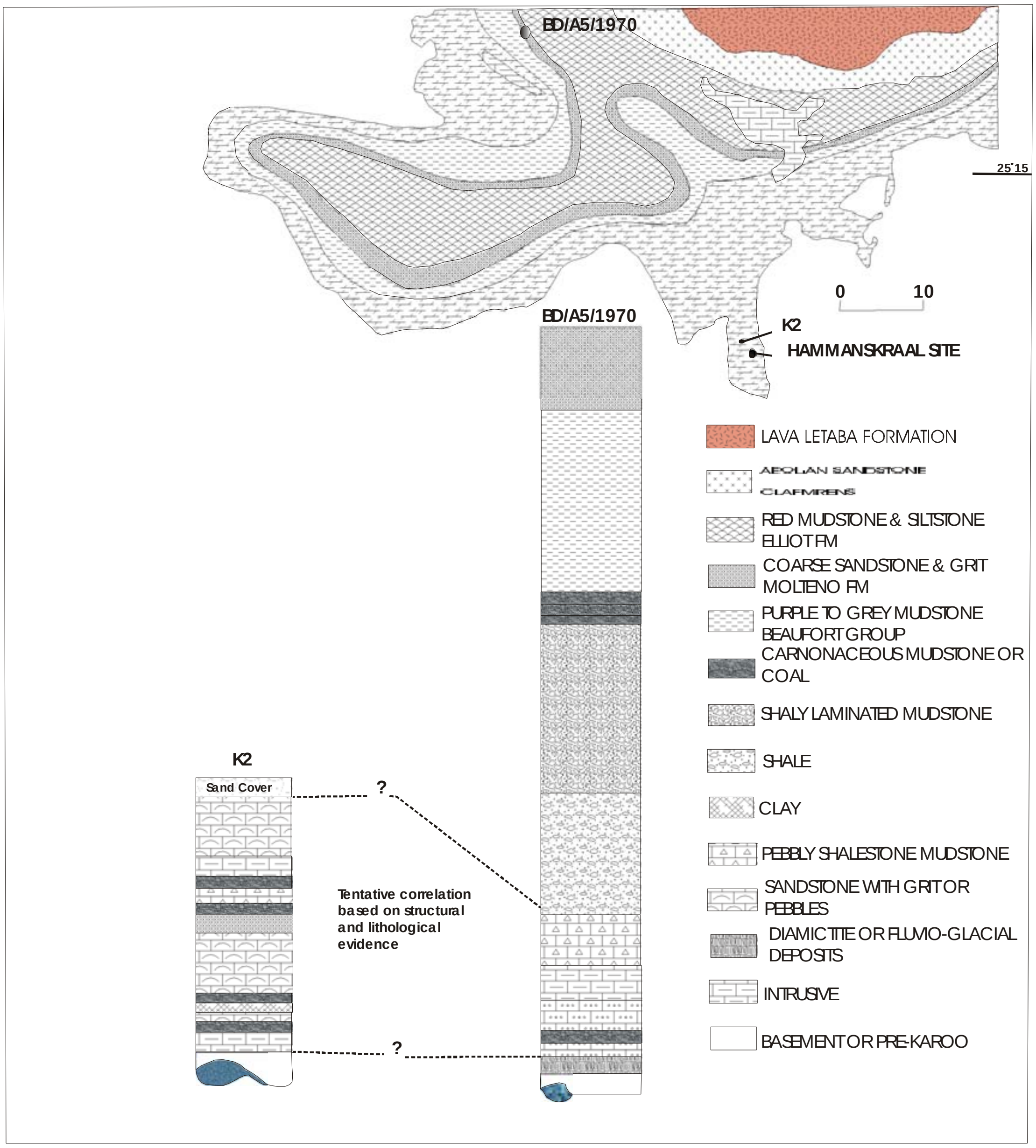
- The Dwyka and Ecca strata in the southwest of the Kalahari Basin have no significant time gap between them. The Dwyka extends from the late Carboniferous to the early Permian.
- The Permian-Triassic boundary within the northern basins is a narrow interval between the uppermost coal seams and the strata correlated with the Molteno and other younger ("Stormberg") main-basin-equivalent formations. These strata include the lenticular sandstone bodies of the Irrigasie Formation in the Springbok Flats Basin, the Greenwich Formation in the Ellisras Basin and the Fripp (Klopperfontein) Formation in the Tshipise Basin as well as the Lebung Group in Botswana.

Further details on the above formations can be found in work compiled and edited by Johnson et al. (2006).

3.2. The Springbok Flats Basin

The Springbok Flats area (fig 1.1), lying to the north of Pretoria, is a double basin with east-northeasterly directed longer axes formed from a single basin by post-Karoo folding, and bounded on the northwestern side by post-Karoo faulting (Haughton, 1969). MacRae (1988) records the geology of the southern part of the Springbok Flats Basin, as seen in Fig. 3.3 below.

Figure 3.3: Detailed lithostratigraphy of the southern part of the Springbok Flats (adopted (– doesn't mean the same as "adapted") from Fig. 3.7 of MacRae, 1988). Note also borehole in northern part of map and log thereof next to legend.



The floor of the basin lies at least 2000 feet (656m) below its rim and shows a considerable amount of unevenness (Haughton, 1969). Haughton (1969) notes that there is no direct continuity between the Karoo beds of the basin and its outliers as well as with Karoo rocks lying to the south of the Witwatersrand ridge (ie. In the Main Basin). The Dwyka Group within the Springbok Flats basin seldom exceeds a few metres in thickness but can be up to 40m in local basement depressions (Johnson et al., 2006). These rocks consist of mudrock, diamictite and conglomerate with occasional coal seams (Johnson et al., 2006). The diamictites and polymictic conglomerates, and mudrocks bearing dropstones and boulder-size clasts in this unit, suggest glaciogenesis (Johnson et al., 2006). The conglomerates may represent outwash gravels and the mudrocks could be glaciomarine or lacustrine deposits. The coal seams indicate deposition during warmer climatic conditions (perhaps even in short-lived interglacials) when plant growth flourished (Johnson et al., 2006).

Only from a few scattered points has the presence of basal glacial conglomerate been recorded; usually it is one or other members of the Ecca Group that rests on the pre-Karoo floor (Haughton, 1969). This Group was divided by Haughton (op. cit.) into Lower Ecca Shale stage, Middle Ecca Coal Measures stage and Upper Ecca Shale stage. The Lower Ecca exists only in hollows in the floor and is overlapped by the Coal Measures. The maximum thickness of the former is 220ft (72m), while the sandstones and coal seams of the latter have a range of thickness from 30 to 200ft (10 to 66m). The upper shales have a more consistent thickness between 250 and 300ft (80 to 98m); their basal portion is generally black in colour, but gray or blue shales lie in the upper part (Haughton, 1969). Other work, such as that of MacRae (1988) has referred to the three Ecca stages as simply the Ecca Group. Further work, seen in Fig. 3.8 of MacRae (1988) has also linked the Lower Ecca Shale stage to the Pietermaritzburg Formation in the Main Basin, and the shaly sandstone containing laminae of shale and siltstone below the main coal zone, with the Vryheid Formation of the Main Basin (Table 3.1).

Table 3.2: Summary of various lithostratigraphic nomenclatures for the Springbok Flats basin (adapted from Fig. 3.7 of MacRae, 1988)

Historical (Du Toit, 1954; Haughton, 1969)		S.A.C.S., 1980	De Jager, 1983, fig 2(a). Referenced from Mc Rae, 1988.
Stormberg Series	Bushveld Amygdaloid	Letaba Formation	Letaba Formation
	Bushveld Sandstone	Clarens Sandstone Formation	Clarens Sandstone Formation
	Bushveld Mudstone	Irrigasie Formation	Elliot Formation
			Molteno Formation
Ecca Series	Upper Ecca Shale Stage	Ecca Group (Formations not named)	Beaufort Group
	Middle Ecca Coal Measures Stage		Vryheid Formation
	Lower Ecca Shale Stage		Pietermaritzburg Shale Formation
Dwyka Series		Not named	Dwyka Group

The single coal zone of bright coal characteristically interlaminated with dark carbonaceous mudstone, in the Upper Ecca stage is correlated with the lower part of the Beaufort Group of the Main Basin (Table 3.1). The Beaufort Group itself is absent in the Springbok Flats Basin, and thus there is a disconformable hiatus between the top of the Upper Ecca Shales and the so-called Bushveld Mudstones (Haughton, 1969). Haughton (1969) describes these Bushveld mudstones, otherwise referred to as the Irrigasie Formation (Table 3.2), or as the Elliot and Molteno Formations (fig 3.8 of MacRae, 1988), as consisting of soft red, purplish or greenish claystones and mudstones with occasional sandy layers.

The overlying Bushveld Sandstone (Haughton, 1969) is otherwise referred to as the Clarens Formation (MacRae, 1988) and is characterised by a pale yellow or sometimes pink coloured fine sandstone assemblage. This succession is followed by amygdaloidal basalts of up to 1200ft (384m) in thickness. Other authors refer to these basalts as the Letaba Formation (MacRae, 1988).

Drilling (MacRae, 1988) of the Springbok Flats Karoo succession to the northeast of Hammanskraal (Fig. 3.3) has revealed two potential zones of coal development - an upper carbonaceous mudstone and bright coal association and a lower succession of fine-grained sandstone, gritty sandstone, shaly sandstone in various combinations which contain laminae of shale, siltstone and in some places thin coal seams (most likely representing the Ecca Series).

Johnson et al. (2006) use different lithological nomenclature to that of Haughton (1969). They describe the formations overlying the Dwyka Group as the Hammanskraal, Irrigasie and Clarens Formations as seen in the following accounts below:

- The Hammanskraal Formation consists of medium- to coarse-grained, immature sandstones, locally interbedded with shaly coal occurring at the base of the succession. The basal succession is overlain by a grey mudrock-dominated interval, which coarsens upwards into micaceous, fine- to medium-grained sandstones. A so called “Coal Zone” lies on top of the formation and is up to 12m thick with 60 to70% alternating carbonaceous mudrock and 30 to 40% bright coal seams. An interpretation of this formation describes the coarse sandstones and mudrocks at the base of the formation as probable products of fluvial activity. The inferior quality of the associated coal could be seen as having formed in a cold, periglacial climate with low water tables causing peat oxidation. The Coal Zone indicates a more humid climate and the marshes were probably drowned during wet conditions, thus giving rise to shale intercalations (Johnson et al., 1996).
- The overlying Irrigasie Formation (in excess of 200m thick) includes brownish-red mudstone with green mottling which changes to purple towards the base with a thin zone of grey mudstone and shale directly overlying the Coal Zone. Also present in variable thickness (up to 45m) is sandstone, within the grey and purple mudrock interval. Erosively-based coarse sandstone and conglomerate grade upwards into siltstone. Thin fining-upward sequences with mud-clast conglomerates at the base also occur in the overlying red mudstone interval. And

bioturbation is also noted to be common in these rocks. An interpretation of the Irrigasie setting is that the fine-grained sediments were most likely transported by sluggish, ephemeral, suspension-load rivers and deposited on floodplains or in lakes occupying low-lying areas. The fining-upward sandstones with erosive bases are thought to represent channel deposits, probably of braided rivers (Johnson et al., 1996).

- The Clarens Formation encompasses fine-grained, well-sorted, massive or cross-bedded quartzose sandstones, pink to cream in colour and frequently mottled. Its sedimentary structures seem compatible with those of aeolian deposition, with interludes of ephemeral streams (Johnson et al., 1996).

3.3. The Tuli Basin

Considerable research has been done by Bordy (2000) on the Tuli and the Tshipise Basins (fig 1.1). Some of her work and data derived from other sources on these basins are contained in this section of the thesis. A summary of Bordy's (2000) and others' stratigraphic subdivisions of the basin-fill are summarised in Table 3.3.

Table 3.3: Nomenclature and Tentative Correlation of the Karoo Supergroup in the Main Karoo and Tuli basins (adapted from Bordy, 2000)

Main Karoo Basin (Johnson, 1994)		Tuli Basin (South Africa) (Bordy, 2000)		Tuli Basin (South Africa) (Chidley, 1985)		Tuli Basin (Zimbabwe) (Thompson, 1975)	Tuli Basin (Botswana) (Smith, 1984)	
Stormberg Group	Clarens Formation	Clarens Formation		Clarens Formation	Tshipise Sandstone Member	Forest Sandstone	Lebung Group	Tsheung Sandstone Formation
	Elliot Formation	Upper Unit			Red Rock Member	Red Beds		Thune Formation
	Molteno Formation		Middle Unit?	Bosbokpoort Formation				Korebo Formation
				Klopperfontein Formation		“Escarpment Grit”		
Beaufort Group		Middle Unit?		Solitude Formation				
Ecca Group		Basal Unit (undifferentiated)		Fripp Formation				
				Basal Beds	Mikambeni Formation	Fulton’s Drift Mudstones	Seswe Formation	
					MadzarIndwe Formation		Mofdiahogolo Formation	
					diamictites	Basal Beds (Undifferentiated)		

The Tuli basin-fill consists of a sedimentary succession (from 450 to 500m thick) (Table 1.1), composed of three main stratigraphic units, namely the informal Basal, Middle and Upper units as described by Bordy and Catuneanu (2002). The preserved Tuli Basin is located in the three countries of Zimbabwe, South Africa and Botswana which explains why it has various Karoo Supergroup nomenclatural descriptions (Bordy et al., 2002), as seen in Table 3.3.

Chidley (1985) and Bordy (2001; 2002) describe the South African part of the basin-fill. Chidley (1985) refers to the lowermost sedimentary rocks as being infrequent, structureless, coarse diamictites composed of angular blocks of basement rocks floating in finer grained (mudstone and shale) material. The angular basement blocks are up to 80cm in size whilst the maximum thickness of the formation is about 2m. Lithologically, the unit may correspond to the Tshidizi Formation described by McCourt and Brandl (1980) in the Tshipise Basin (Bordy, 2000). A possible correlation of Chidley's (1985) diamictites with the Dwyka facies of the Main Karoo may thus be inferred (Bordy, 2002).

The Madzaringwe Formation forms the base of the Ecca Group in South Africa and overlies the diamictites (Chidley, 1985). It begins as a 5 to 6m thick gritty-conglomerate unit overlain by 12 to 15m of grey, laminated and homogeneous shale with plant debris, which develops into a 20m thick coal zone with 6 continuous seams. Ortlepp (1986) describes the coal-bearing series, as being located at depths of less than 50m along the southern margin of the preserved basin, but attaining a depth of over 300m near the Limpopo River. The two major (1.6m and 1.2m thick), flat lying coal seams are overlain by mudstones and minor sandstones as well as being interbedded with mudstone (Ortlepp, 1986; Bordy, 2000). The upper section of the Madzaringwe Formation consists mainly of cross-bedded, feldspathic quartz sandstones. Bordy et al. (2002) describe the coal-bearing fluvio-lacustrine deposits of their Basal Unit as being very similar to the deposits of the fluvial interval in the Vryheid Formation of the Main Karoo Basin. The Mikambeni Formation follows and completes what Chidley (1985) termed the "Basal Beds" of the Tuli Basin-fill (Bordy, 2000) (Table 3.3). It consists of shales and siltstones with occasional coal seamlets (Chidley, 1985).

A further 5 to 10m above this unit are well-sorted, medium- to coarse-grained, planar cross-bedded, arkosic, pinkish sandstones with abundant conglomerate intercalations, which are interpreted as fluvial channel deposits (Bordy, 2000). This is considered to be part of the Fripp Formation, underlying the Beaufort Group's Solitude Formation (Chidley, 1985) (Table 3.3). In addition, sandstones within the eastern part of the basin have been described as being pale to reddish-brown with very coarse sandstones and conglomerates - the dip of these beds is of the order of 10 degrees to the west or southwest (Söhnge et al., 1948).

In Zimbabwe, work done by Thompson (1975), Watkeys (1979), and Cooper (1980), describes the Ecca Group (known as Fulton's Drift Mudstones; see Table 3.3) as consisting of grey to black argillaceous shales, mudstones, coal seams and a few discontinuous, lenticular white to light grey sandstones and pebble beds, the latter being more common near the base. Watkeys (1979) concludes that the formation was probably deposited in a shallow, stagnant basin under tundra conditions.

Smith (1984) continues to describe the Botswana section of the Ecca Group within the Tuli basin-fill as being represented by two formations, the 5.5m thick basal mudstones of the Mofdiahogolo Formation and the 60m thick Seswe Formation. The basal mudstones of the first formation are represented by grey-brown mudstones with sandstone balls and scattered quartz grains. At the base of the unit is an argillaceous sandstone unit with a fining–upward character. Also present is a succession of deposits of inferred post-glacial melt-water lakes, which were at times entered by muddy debris flows. The Seswe Formation comprises a lower carbonaceous mudstone member with thin coals and sandstones (40m thick) as well as an upper member of non-carbonaceous, variegated khaki-coloured mudstones (20m thick) (Smith, 1984).

The Beaufort Group (Table 3.3) in the South African part of the basin is described by Chidley (1985) as being represented by white, pink, green and khaki siltstones and very fine-grained sandstones with grey mudstones, all forming part of the Solitude Formation. The maximum thickness of the formation is 25m and was likely formed in the distal floodplain area of a mature meandering system (Chidley, 1985).

In South Africa (Chidley, 1985; Bordy et al., 2001), the "Stormberg Group" (an informal term) comprises:

- A 10-12m thick, trough cross-bedded, coarse sandstone and conglomerate unit, the Klopperfontein Formation, interpreted as being a proximal bedload-dominated, braided stream deposit, and correlated with the Molteno Formation in the Main Karoo Basin.
- The overlying Bosbokpoort Formation (Table 3.3) occurs as a basin–wide unit and is dominated by red fine-grained strata. The 60m thick brick-red, purplish mudstones and siltstones contain calcareous nodules and concretions, which led Chidley (1985) to suggest an origin as floodplain deposits under semi-arid climatic conditions.
- The following succession is the Clarens Formation, which is divided into the Red Rocks Member and the Tshipise Sandstone Member. The Red Rocks Member is about 60m thick and consists of argillaceous, very fine- to fine-grained pinkish to red sandstones. The beds are considered to have been formed under arid conditions in distal overbank floodplain settings. A calcareous concretionary zone implies a period of non-deposition whilst conglomerates point to the possible presence of wadi-type ephermeral stream systems. The Tshipise Sandstone Member has a 5-140m thick, very fine- to fine-grained, mostly creamy coloured succession, with large scale aeolian dune cross-bedding with palaeo-current directions from west to east.

In Zimbabwe the Stormberg Group is represented by the “Escarpment Grit” Formation (Cooper, 1980), the Red Beds Formation (Smith, 1984) and the “Forest Sandstone” Formation (Bordy, 2000) (Table 3.3):

- The reddish Escarpment Grit consists of coarse- to very coarse-grained, white to pale grey or pink, upward-fining sandstones and is also known as the Gushu Formation in the Zambezi Karoo Basin (Cooper, 1980).
- The lower part of the Main Karoo Basin’s Elliot Formation is correlated to a 300m thick succession (the Red Beds Formation) of red to purple mudstones, fine-grained sandstones and marls, with common scattered, very fine-grained red sandstone pebbles and calcareous nodules (Thompson, 1975; Cooper, 1980). Bedding is rare in the sandstones (Watkeys, 1979).
- A further 80-100m thick formation (“Forest Sandstone”) consisting of pinkish white to brownish, fine- to medium-grained, well-sorted sandstones, calcareous in

their lower part and cross-bedded higher up (Thompson, 1975; Cooper, 1980). Watkeys (1979) noted that due to basalt extrusions, the sandstones were metamorphosed down to a depth of 2m. Watkeys further regarded the cross-bedded sandstones as aeolian dunes deposited under arid climate conditions.

In Botswana, the Korebo Formation is correlated with the Escarpment Grit and Red Beds Formations of Zimbabwe (Smith, 1984) (Table 3.3). Above the Korebo Formation lies the Thune Formation, which is succeeded by the Tsheung Sandstone Formation (Smith, 1984):

- The Korebo Formation, 33m thick in certain boreholes, consists mainly of mudstones, siltstones and fine-grained sandstones. The depositional environment is thought to have been a playa-lake system with ephemeral floods under semi-arid conditions (Smith, 1984).
- The Thune Formation is regarded as a transitional unit between the Korebo and the dune-bedded Tsheung Sandstone Formation (Smith, 1984). This approximately 64m thick formation contains fine-grained sandstones and siltstones with some cross-bedded sandstone intercalations and is considered to be fluvial in origin (Smith, 1984).
- The Tsheung Formation (no thickness data available) is considered to be generally massive, uniform, fine- to medium-grained, well-sorted and occasionally trough cross-bedded (Smith, 1984).

The above successions across the three nationally segregated basin parts are capped by basalt extrusions, as with the Drakensberg basalts (187 Ma) in the Main Karoo Basin. Discussions by Catuneanu et al. (2005) relate the basalts to the break-up of Gondwana during the Late Triassic and early Cretaceous. In the Main Karoo and Springbok Flats Basins these lithologies are tholeiitic lavas, with olivine-rich Batoka basalts (166-105 Ma) occurring in the Zimbabwean basins, and olivine-poor and acid lavas of the Lebombo Group (190 Ma) being found in that basin (Fig. 1.1) (Catuneanu et al., 2005). The Drakensberg–equivalent stratigraphic unit for the Springbok Flats, Tshipise and Tuli Basins is the Letaba Formation (Catuneanu et al., 2005).

3.4. The Tshipise Basin (Bordy, 2000)

Faulting that strikes parallel to the Limpopo Belt (ENE to WSW) controlled the location and shape of the Tshipise Basin (Fig. 1.1) (Johnson et al., 2006). The basal formation consists of larger clasts and fragments in an argillaceous to sandy matrix (Bordy, 2000). Known as the Tshidzi Formation (Table 3.3), it consists of diamictite, with clasts ranging up to 2m in diameter (Johnson et al., 2006). Relatively coarse-grained sandstones are interbedded with diamictite locally, and generally reflect glacial and fluvio-glacial (braided stream) settings (Johnson et al., 2006). The fluvioglacial sediments of the Dwyka group (Tshidzi Formation) were transported in an E-ENE to W-WSW direction (van der Berg, 1980).

The Madzaringwe, Mikhambeni and the Fripp Sandstone Formations represent the Ecca Group, although in certain literature the Mikhameni Formation represents the Beaufort Group and the Fripp Sandstone Formation correlates with the lower part of the Molteno Formation of the Main Basin (van der Berg, 1980), see also Table 3.3 for partially analogous stratigraphy in the Tuli Basin.

According to McCourt and Brandl (1980) as well as Brandl (1981), the Madzaringwe Formation consists of alternating sandstone, siltstone and shale and has a maximum thickness of 200m, with the thickest coal seam being 3.9m. The sandstone is feldspathic, usually micaceous and commonly cross-bedded (Johnson et al., 2006). The basal 25-35m of the formation comprises carbonaceous shale and thin coal seams, with the main coal seam being between 2-3m thick and 85 to 100m above the carbonaceous zone (Johnson et al., 2006). The Madzaringwe Formation seems to have been deposited by meandering rivers flowing from the northwest - the sandstones could represent point bar, levee and crevasse splay deposits (Johnson et al., 2006). The coal seams were most likely formed under cool, reducing environments (Johnson et al., 2006).

The Mikhambeni Formation (120-150m) consists of massive, dark and pale mudstones and black shales, with a few thin laminated sandstone layers toward the base with some scattered, very thin coal layers (McCourt and Brandl, 1980; Brandl, 1981). Three units can be recognised, as described by Johnson et al. (2006):

- A 15-20m thick lower unit comprising of alternating black shale and grey, feldspathic sandstone.
- A middle unit, 50m thick and comprising black, carbonaceous shale with occasional bright coal seams.

- An upper unit, 60 to 70m thick with dark-grey mudstone with plant fragments and occasional seams of bright coal.

The Mikambeni Formation is up to 150m thick and its overall fine-grained character points to deposition on the distal floodplains of meandering rivers (Johnson et al., 2006).

The Fripp Sandstone Formation (up to 110m thick) has white feldspathic, trough cross-bedded, fine- and very coarse-grained sandstones with pebble horizons and occasional thin silty bands (Bordy, 2000). Palaeocurrent measurements indicate transport directions from SE to NW (van der Berg, 1980). The sandstones were probably deposited by braided rivers flowing towards the northwest and west (Johnson et al., 2006). Plant fossils suggest that this formation correlates to the Molteno Formation of the Main Karoo Basin.

The Beaufort Group is equated to the Solitude Formation (Fig. 4 of Johnson, 1996) (Table 1.1) which is up to 170m thick, consisting of alternating purple mudstones, grey shales and some carbonaceous shales (Brandl, 1981). The basal portion of the lower part may consist of black shales with occasional bands of bright coal. The formation probably represents overbank deposits of meandering rivers with extensive floodplains, with the dark shales and associated coals having accumulated in flood basins and marshes under reducing conditions (Johnson et al., 2006).

In the Stormberg Group, the Klopperfontein Formation (Table 3.1) is thought to correlate with the Elliot Formation of the Main Karoo Basin (van der Berg, 1980). The formation consists of medium-grained, white, feldspathic sandstones, which are less quartzitic than those in the Fripp Sandstone Formation. It is up to 20m thick and was probably deposited in a braided stream system (Brandl, 1981).

The Kloppersfontein Formation is followed by the Bosbokspoort Formation which is correlated with the Elliot Formation (Red Beds) of the Main Karoo Basin (Bordy, 2000). It is characterised by red mudstones and very fine sandstones and believed to have a maximum thickness of about 100m (McCourt and Brandl, 1980). Palaeocurrent directions indicate transportation from SSE to NNW. The red colours and abundance of concretions suggest deposition on the floodplains of meandering rivers under dry, oxidising conditions (Johnson et al., 2006).

The following succession is the Clarens Formation, inclusive of the Red Rocks and Tshipise Members (as seen in Fig. 4 of Johnson, 1996). The formation has a cumulative thickness of up to 300m and comprises of very fine- to fine-grained, white- and cream-coloured sandstones (McCourt and Brandl, 1980). A NNE transportation direction is recorded on the large scale cross-bedding (Bordy, 2000). The Red Rocks Member comprises of very fine- and fine-grained, light-red argillaceous sandstone with irregular patches or occasional layers of cream-coloured sandstone (Johnson et al., 2006). The Tshipise Member consists of fine-grained, well-sorted white- or cream-coloured sandstone with large-scale cross-bedding (Johnson et al., 2006). This formation is considered to be aeolian, though inferred water-lain deposits are present in lower parts of the succession (Johnson et al., 2006). As with the Tuli and Springbok Flats Basins, the sedimentary Karoo formations are capped by the volcanic rocks of the Letaba Formation.

3.5. The Kalahari Basin

Clark et al. (1986) identifed and discussed the composition of the Dwyka, Ecca, Lebung and Stormberg Groups as summarised below:

- The Dwyka is regarded as the basal unit of the Karoo in Botswana and consists of diamictites, pebbly mudstones and well-laminated clays or varvites. Alternating with the succession are impersistent sandstones, mudstones and conglomerates. Glaciogenic sediments characterise the rocks of this group.
- The Ecca Group lies disconformably on the Dwyka Group and includes fluvial/coal swamp facies. The lower part of the group consists of medium- to coarse-grained sandstones with finer sandstones, siltstones, mudstones, shale and coal. The upper part of the group is typified by a sequence of carbonaceous clays with coals and in places, sandstones. Important coal-bearing formations are found in this group.

The Lebung Group unconformably overlies the lower Karoo succession. It is characterised by a red bed facies of siltstones and fluvial sandstones, followed

upwards by fine- to medium-grained, well-sorted sandstones of white to reddish-brown colour, which are locally cross-bedded and believed to be aeolian in origin.
The Stormberg Group is composed almost entirely of basaltic lavas formerly equated to the Drakensburg stage (of the Main Karoo Basin).

The coal mineralisation found within the greater Mmamabula coal field, in south-eastern Botswana occurs within the Dibete Formation of the Upper Ecca Subgroup, see Table 3.4, and the Mmamabula Formation of the Middle Ecca Subgroup (Arnott and Williams, 2007**).**

The Ecca Group is developed over most of this south eastern region of Botswana.
The Lower Ecca Subgroup (Mapashalela Formation, KEp Member) consists of mudstones, grading upwards into siltstones interbedded with sandstone horizons.
Progressing upwards into the Middle Ecca Subgroup (or Mmamabula Formation - KEm), five Members comprise interbedded mudstones, siltstones, sandstones and coal seams (Arnott and Williams, 2007**)**.

The overlying basal Dibete Formation (KEb) of the Upper Ecca Subgroup consists of interbedded mudstones and coal seams with intermittent lenses of sandstone in places.
The KEb Coal Member marks the transition between the Middle and Upper Ecca Subgroups (Arnott and Williams, 2007**)**.

The topmost Dibete coal and mudstone sequence is terminated by interbedded sandstones and siltstones belonging to the Serorome Clastic Member (KEds).
Coals and interbedded sandstones and mudstones forming part of the Dovedale Formation, are found above the Serorome Clastic Member, and are overlain by the Korotlo Beds (KEk) which consist of mudstones (Arnott and Williams, 2007**)**.

Table 3.4: Generalised stratigraphy for the Eastern Section of the Kalahari Basin (adapted from Arnott and Williams, 2007, their Table 7.2)

SEAM		Thick (m)	Lithology	Member	Formation	Sub Group	Group	Super Group	Age
	🟨	**5.0**	**Unconsolidated sand**						
	🟦	**15.0**	**Mudstone, grey-brown**	**KEk**	**Dovedale**	**Upper**	**Ecca**	**Karoo**	**Late Carboniferous to Jurassic**
	🟩	**9.0**	**Carbonaceous Mudstone & thin Coal bands**	**KEd1-2**					
	🟧	**8.0**	**Sandstone (Serorome Clastic Member)**	**KEds**					
	🟩	**17.0**	**Carbonaceous Mudstone & thin Coal bands**	**KEb3**	**Dibete**				
	🟧	**7.0**	**Sandstone**	**KEbp**					
	🟩	**11.0**	**Carbonaceous Mudstone & thin Coal bands**	**KEb2**					
D1	🟪	**6.0**	COAL						
	🟧	**20.0**	**Sandstone, Feldspathic**	**KEm5**	**Mmamabula**	**Middle**			
M3	🟪🟪		**Sandstone, Feldspathic**	**KEm4**					
	🟧		**Sandstone with minor Mudstone**	**KEm3**					
M2	🟪	**3.0**	COAL	**KEm2**					
	🟧	**6.0**	**Sandstone**	**KEm1**					
	🟥	**20.0**	**Siltstone with interbedded Sandstone**						
M1	🟪🟪	**1.0**	COAL						
	🟦	**10.0**	**Siltstone**			**Lower**			
	🟥	**25.0**	**Siltstone with interbedded Sandstone**	**KEp**	**Mapashalela**				
	🟦	**50.0**	**Siltstone and Mudstone**						

SEAM		Thick (m)	Lithology	Member	Formation	Sub Group	Group	Super Group	Age
	🟧	**26.0**	**Sandstone (Ked)**	**Ked**		**Dukwi**	**Dwyka**		
	🟦		**Pre-Karoo Quartzite and intrusives**				**Waterberg**		**Early to mid Proterozoic**

The Dwyka Group is then overlain by the Lower, Middle and Upper Subgroups of the Ecca Group. Coal bearing formations developed within these subgroups include the Mmamabula Formation (Middle Ecca subgroup) and Dibete Formation- lower portion of the Upper Ecca subgroup (Arnott and Williams, 2007**)**.

The Lower Ecca Subgroup (Mapashalela Formation, KEp Member) includes upward grading mudstones, continuing up into siltstones interbedded with sandstone horizons (Arnott and Williams, 2007**)**. The Middle Ecca (or Mmamabula Formation) Subgroup overlies the Lower Ecca Subgroup that comprises five Members (Kem $^{1\text{–}5}$) containing interbedded mudstones, siltstones, sandstones and coal seams (Arnott and Williams, 2007**)**. Within the Mmamabula Formation (KEm Member), three coal seams have been correlated across the southeastern region of Botswana, these being the basal M1 seam, middle M2 seam and uppermost M3 seam. The M1 seam has an erratic thickness, whilst the M2, seam is continuous across the region and the M3 seam is inconsistently developed (Arnott and Williams, 2007**)**.

The basal Dibete Formation (KEb) of the Upper Ecca Subgroup consists of a thick succession of up to 60 m of interbedded mudstones and coal seams with intermittent lenses of sandstone in places. The transition between the Middle and Upper Ecca Subgroups is marked by a coal seam termed the D1 seam (KEb Coal Member) (Arnott and Williams, 2007**)**.

Twenty metres of sandstone, found at the top of the Mmamabula Formation, separate the D1 coal seam from the M2 seam. The coal seams above the D1 seam form part of two interbedded coal and mudstone sequences (KEb2 and KEb3) separated by a predominantly sandstone unit (KEbp), (Arnott and Williams, 2007**)**. Intermittent lenses of mudstone and less common sandstone are found within both the M2 seam and D1 seam.

The topmost Dibete coal and mudstone sequence (KEb3) is terminated by interbedded sandstones and siltstones belonging to the Serorome Clastic Member (KEds) (Arnott and Williams, 2007**)**. Coals and interbedded sandstones and mudstones, which form part of the Dovedale Formation (KEd1 and KEd2), are found above the Serorome Clastic Member, these in turn being overlain by the Korotlo Beds (KEk) which consist of mudstones(Arnott and Williams, 2007**)**.

3.6 The Ellisras (Waterberg) Basin Stratigraphy

The base of the basin-fill is an erosional surface, and Haughton (1969) recorded a glaciated surface of granite visible at farm Tafelberg on the Palala River. As mentioned by Johnson (1996) regarding the typical Karoo depositional cycle, the first sediments encountered above the erosional surface are tillites and fluvioglacial conglomerates which appear to have accumulated in irregular, palaeotopographically low-lying areas of the basin.

Various authors have attempted to create a lithostratigraphic nomenclature to be utilised in describing the various stratigraphic units located in the Ellisras Basin. They include Beukes (1985), Faure et al. (1996), Siepker (1986) and the Council for Geoscience (South Africa). Suggestions by Johnson (1996) indicate that the principal difference between the Main Karoo Basin and the other smaller depositories in South Africa, is the finer non-fluvial sediments in the northern basins reflecting lacustrine rather than open “shelf” conditions. Beukes (1985) (as cited in MacRae, 1988) further argues that all the classic lithostratigraphic units of the Karoo Supergroup in the Main Basin are indeed developed in the Waterberg (Ellisras) Basin (fig 1.1) and that this justifies the use of the nomenclature proposed for the Main Karoo Basin. This argument was challenged by the fact that there is no clear connection between the

Waterberg and Main basins thus resulting in difficulty during correlation of lithologic character and stratigraphic position (MacRae, 1988).

Beukes' (1985) lithostratigraphic nomenclature that subdivides the Ellisras basin-fill into increments (of genetic stratigraphy) is summarised by MacRae (1988) as follows:

- Increment 1: This section includes ground moraine deposits, poorly sorted upward-fining conglomerate and sandstone units, which Beukes considered to represent products of proglacial melt-water and braided fluvial reworking of moraine material. Overlying these lithologies is a unit of sandstones and siltstones. A fairly regular feature in this section is the presence of dropstones most probably from ice-rafted material. The unit may also represent lacustrine turbidites, splays and varves in more distal environments, according to Beukes.
- Increment 2: In this section are grey, brown and black sandy shales, and flaggy micaceous siltstones, most likely representing pro-delta silts with occasional bands of debris rain, which accumulated after a major transgression of the shoreline.

  The next unit is a white feldspathic sandstone, grits, conglomerate lenses alternating with carbonaceous mudstone and coal seams. This coal/sandstone accumulation was indicative of periods of palaeoslope rejuvenation resulting in sandstone, grits and minor conglomerates alternating with periods of stasis allowing for extensive coal-seam formation, in the view of Beukes (1985). The sandstones were likely deposited under shallow-water fluviatile conditions, with an average transport direction to the west. The sandstones, lying below the lowest relatively thick coal seam (coal seam 1), are ripple-cross-laminated sands interpreted as channel distributary and mouth-sandbar deposits. The occasional presence of thin upward-coarsening siltstone to sandstone units was interpreted as reflecting splays filling delta inter-distributary bays.
- Increment 3: Included is the coal/sandstone accumulation commencing from Coal Seam 1 and ending at the top of Coal seam 2, interpreted as delta lobe channel sands, flood-plain splays and swamp accumulations.
- Increment 4: The transgression of the shoreline is considered to have resulted in the thin accumulation of upward-coarsening siltstones followed by Coal Seam 3.

- Increment 5: This is described as a complex unit of matt coal, carbonaceous mudstone, gritty mudstone, siltstone and sandstone. The cause of deposition could have been an intermittent period of proximal flood-plain development with channels, splays and mudflows alternating with fine carbonaceous mud and peat formation (Coal Seam 4).
- Increment 6: Includes a continuous sequence of black shales and mudstones with intercalated thin bright coal seams. This may have been a sedimentary environment distal in relation to the source area. As mentioned by Johnson (1996) and Siepker (1986) such situations tend to indicate areas of basinal subsidence with the deposition of argillaceous sediments followed by slower subsidence - by which coal seams are formed.

3.7 Grootegeluk Coal Mine Lithostratigraphic Nomenclature (Faure et al., 1996)

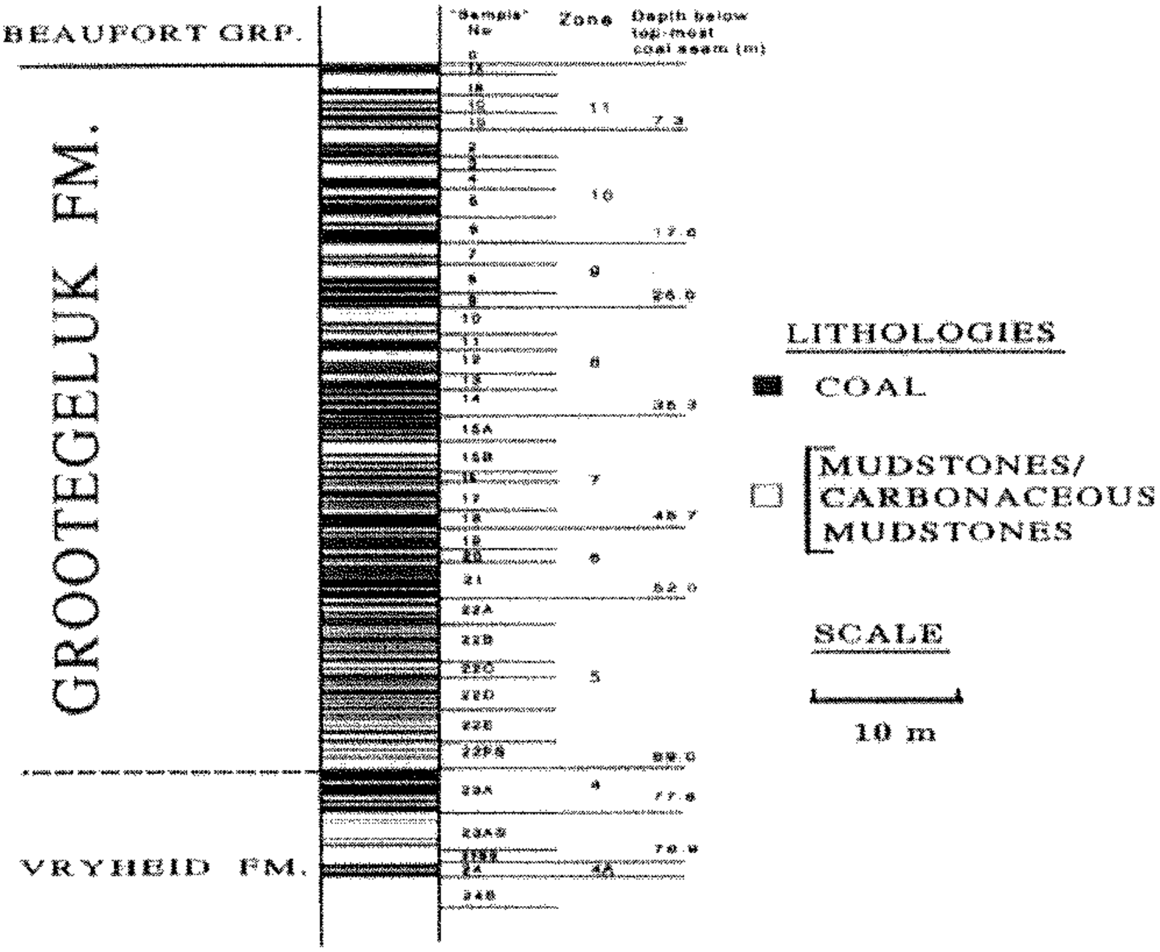
Faure et al. (1996) describe divisions applied to the Ecca Group coals in the Ellisras (Waterberg) Basin by staff of the Grootegeluk Coal Mine. The predominantly dull coal seams (1, 2, 3, 4 and 4A) of the Vryheid Formation retained the original numbering of De Jager. The remaining seams were re-classified by the Grootegeluk Coal mine into zones 5 to 11.

According to Faure et al. (1996), De Jager describes No. 1 seam as being generally thin, but up to 2m thick in certain parts, and as consisting of dull heavy coal with occasional shale partings and generally some bright bands in the lower half. The No. 2 seam has a consistent thickness of 1.0 to 4.5m in the western shallow sector but is generally up to 5.2m in the central deep sector of the basin. He continues to note that both No. 1 and 2 coal seams are often overlain by a thin conglomerate layer, suggesting removal by erosion of the upper parts of the accumulated plant material, and the two seams are separated by up to 5m of coarse-grained, white feldspathic sandstone. No. 3 seam, which is up to 9m thick, is generally separated from No. 2 seam by about 5m of impure fine- and medium-grained, cross-bedded sandstone. In certain areas a thin No. 3A seam can be seen. No. 3 seam consists mainly of dull coal with mixed dull and bright coal in its lower parts. The No. 4 and 4A seams constitute a clear transition phase between middle Ecca and Upper Ecca stages in this field; these seams occur about 4m to 9m, respectively, above No.3.

De Jager continued to describe the Upper Ecca Stage as consisting mostly of bright coal with massive carbonaceous shale. The better composite seams occur in three zones which are mainly No’s. 5A (up to 3.12m thick), 5B (up to 2.44m thick) and 5C (up to 2.03m thick). Other zones De Jager studied include No’s. 6A (up to 1.63m thick), 6B (up to 2.13m thick), 6C (up to 1.17m thick) and 7 (up to 0.81m thick).

Faure et al. (their Fig. 4, 1996) briefly describe the overlying zones (5A to 7), which they numbered from 5 to 11 and which are found in the Grootegeluk Formation (fig. 3.4).

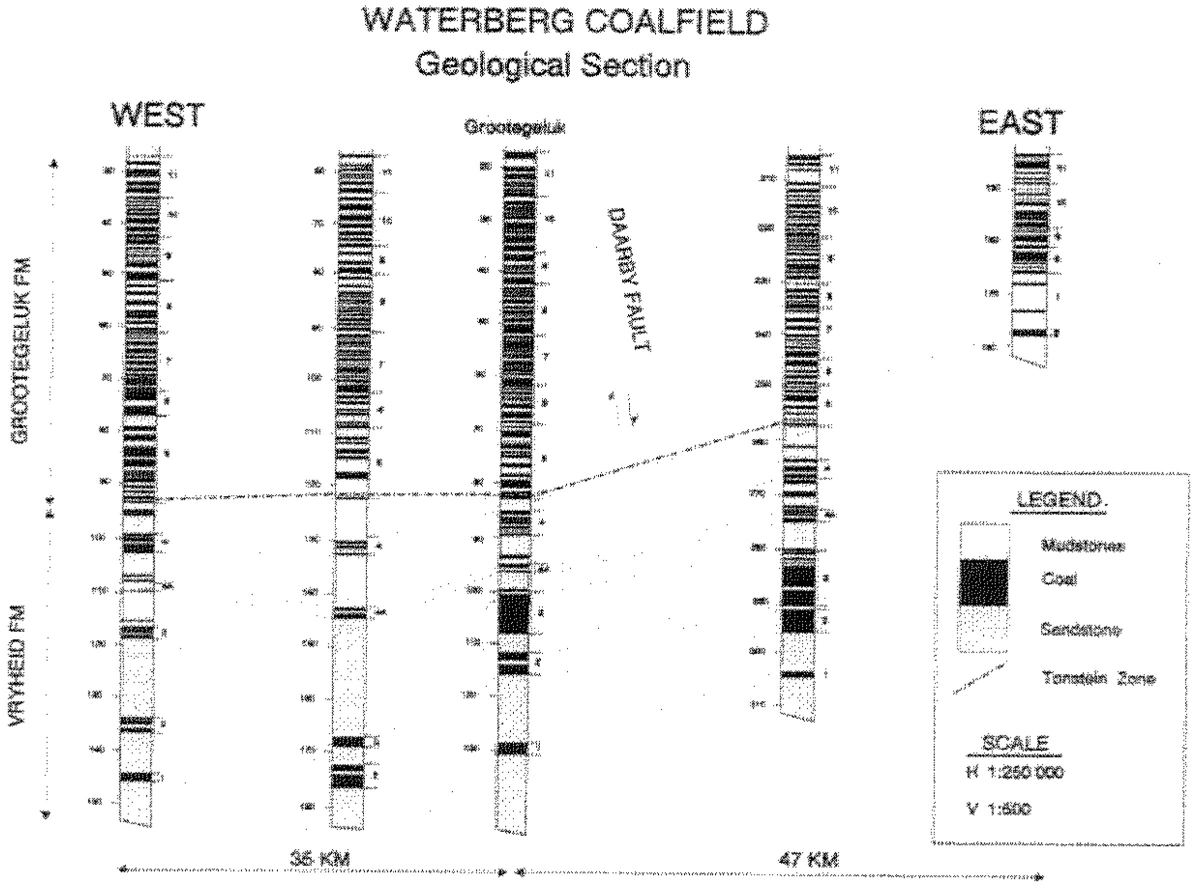
Figure 3.4: Lithological nomenclature for the Grootegeluk Coal Mine (as seen from Faure et al., their Fig. 4, 1996)



The zones are further described as a multitude of intercalated bright coal and mud layers. Not much additional information on the Grootegeluk Coal Mine zoning is available to the public.

Fig. 3 of Faure et al. (1996), as seen below (fig 3.5), gives a west to east cross-profile of the basin, displaying the stratigraphy as well as the influence of the Daarby Fault.

Figure 3.5: West to east cross-section of the Ellisras (Waterberg Basin). Fig. 3 of Faure et al., 1996.



The above nomenclature is similar to that used by the Council for Geoscience, South Africa, in its description of Ellisras Basin boreholes. The Vryheid Formation contains zones 1, 2, 3, 4A, and 4, and comprises mainly sandstone, coal, shale, siltstone and mudstone, grit and at times some Dwyka tillite. Zones 5 to 11 mainly consist of coal interbedded with shale, siltstone and mudstone. A point of caution has to be made regarding the low level of reliability of the Council of Geoscience’s borehole descriptions, as they seem to be lacking in detail at certain depths or are at times apparently inaccurately labelled.

3.8 Siepker's Lithostratigraphic Nomenclature (Siepker, 1986)

Siepker describes 11 genetic stratigraphic units in his unpublished thesis (1986), otherwise termed Genetic Units of Sedimentation (GUS) (Genetiese Eenhede van Sedimentasie (GES) in Afrikaans, as they appear in his thesis).

In addition, Brandl (1996) compiled descriptions of various formations in the Ellisras Basin for the Council for Geoscience, based largely on the work of Siepker (1986). Below is a summary of this work, prepared as part of this thesis, but which also attempts to correlate the various Genetic Units of Sedimentation of Siepker (1986) to the various formations described by Brandl (1996), and also denotes their most likely Main Karoo Basin equivalents:

3.8.1 Clarens Formation (GUS 9)

This formation forms a prominent surficial topography, and has a maximum thickness of approximately 130m. It consists of massive, cream to off-white, well sorted, fine-grained sandstone; locally there are coarser-grained units and even pebbly sandstones. It also includes visible large planar cross-beds (inferred palaeowinds from W-SW) and a gradational lower contact. The formation seems to represent a palaeodesert dominated by dunes with minor wadis feeding sebkhas and playas.

3.8.2 Lisbon Formation (Elliot equivalent) GUS 8

The Lisbon Formation occurs throughout the Karoo outcrop area and has a constant thickness of 100-110m. The lower contact is either sharp or gradational, and is taken at the base of the first thick massive mudrock. The formation comprises a succession of largely red massive mudrocks and minor (lenticular) fine to coarse sandstones with pebble washes. Calcareous concretions are common in the mudrocks, and also present are 5-10 m thick cycles of thin basal sandstone passing up into siltstone or mudstone – with sharp basal contacts for the cycles. Bioturbation by *Skolithos* and *Cruziana* is common. The setting seems to have been one of meandering rivers and floodplains under warm and dry conditions.

3.8.3 Greenwich Formation (Molteno equivalent) GUS 7

Forms a narrow outcrop band in N, E and central parts of the Karoo outcrop of the Ellisras basin, and has a sharp erosive contact with the underlying Eendragtpan Formation. It probably extended well beyond the present Karoo outcrop boundaries. Thickness varies from 7-33 m and it comprises of mainly medium- to coarse-grained purple-red-green-white sandstone (slightly feldspathic; fine sandstones are micaceous). It is commonly cross-bedded, and has grit, with local thin conglomerate lenses and thin laminated mudstones. Upward-fining units are common, mostly capped by thin mudstones. This formation is interpreted as braided stream deposits. The deposition of sandstone is thought to have been preceded by substantial uplift of the hinterland to the N and E.

3.8.4 Eendragtpan Formation (Beaufort equivalent) GUS 6

This formation conformably overlies the Grootegeluk Formation except to the NE, and E of the Mokolo River where it transgresses onto Limpopo gneisses. It is composed entirely of variegated mudstones, becoming silty in the lower third of the succession. The colour varies from grey to blueish grey with purple and red towards the top, with common reduction spots. There are thin beds of yellow-grey mudstone locally with a low level of radioactivity. Sharp boundaries exist between differently coloured beds. The formation’s maximum thickness is 110 m in the central part, decreasing gradually to 40 m towards N and E. It is inferred to be a floodplain or flood basin deposit – with total absence of plant or coaly material.

3.8.5 Grootegeluk Formation (Middle Ecca equivalent) GUS 5

The formation has a thickness of 110m in the S, 40-60m in the NW and N, 50m in the SE and 10-20m in the NE. It conformably overlies the Swartrant Formation in the E and extreme S, while in the central and N areas of the preserved basin, the lower half of the Grootegeluk apparently interfingers with the Goedgedacht Formation. The formation consists of mudstone, carbonaceous shale and coal, all repeated cyclically – cycles have basal coal layer with sharp basal contact, grading up into mudstone. Lenses, concretions and nodules of siderite are common throughout the succession, along with fracture-fillings of calcite and pyrite. Mudrocks vary from a dark very carbon-rich and laminated type, to a light coloured slightly carbonaceous and massive type (thicker beds which overlie the former type gradationally). Generally, the coals and highly carbonaceous shales are prominent in the lower half of the succession. *Glossopteris* imprints are common. Where the succession is complete, it is divided up into 38 zones, each comprising a variable number of cycles. Zones 1-6 at the base comprise dark, highly carbonaceous mudstone and dull coal with minor bright (vitrinite) coal; pollen is common. Zones 7-28 comprise of alternating bright and dull coal, and carbonaceous shale – microcycles ideally consist of alternating laminae (0.2m) of vitrinite, mudstone, exinite (pollen-rich) and detrital material. Zones 29-38 comprise of vitrinite-rich (up to 88%) bright coal and carbonaceous shale. The vitrinite content increases from about 2% at the base to 65% at the top, with inertinite and exinite decreasing sympathetically. The palaeoenvironment seemed to be in a tectonically stable area with delta abandonment and fluctuating water table – muddy material was probably derived from an alluvial fan to the N.

3.8.6 Goedgedacht Formation (no Main Karoo Basin equivalent) GUS 4

According to Siepker (1986) this formation is only present in the N and NW part of the Ellisras basin Karoo outcrops. It supposedly decreases from a maximum thickness of 80 m in the N, towards the S, where it interfingers with the Swartrant Formation (contacts are sharp and marked in places by impure coal beds). In the north, the formation rests nonconformably on Constantia Suite granitoids-gneiss-mafic rocks. The Goedgedacht Formation consists of units of mudstones with graded bedding as well as with angular quartz grains (sand to pebble sizes) in their basal parts, which may be capped by thin impure vitrinite-rich coal. Also present is soft sediment deformation, and intraformational clay pellets and coaly material are common. Upward-coarsening units (coaly mudstone-mudstone-siltstone- medium- to coarse-grained sandstone) only occur locally; upward-fining cycles are rare. The contacts between units are generally sharp but not erosive. A few outcrops are comprised of alternating gritty sandstone and mudstone, or of gritty feldspathic sandstone (all in basal part of formation). Mudstones are massive and are thought to reflect mudflows, with localized sandstones probably reflecting braided streams on a fan surface. The overall inferred palaeoenvironment seems to equate to an alluvial fan in a proglacial setting with stagnant or retreating glaciers to the N, and progradation of the fan to the

S. Scattered grains of quartz (not of feldspar) in mudstones decrease from N to S, with southern-most mudstones having none.

3.8.7 Swartrant Formation (Lower Ecca equivalent) GUS 1-3

This formation underlies most of the area of Karoo outcrop except in the NW. Maximum thickness ranges from 2-75 m in the N, to 7-50 m in the E and about 130 m in the centre. It further comprises of lower, middle and upper zones. The lower zone largely consists of sandstones, some finer material, No. 1 coal seam (dull coal) – with flaser structures, ripple cross-laminations and cross-bedding; plant root imprints are also quite common. The model of formation is likely to have included a delta-front which, in time, became a delta plain for the deposited coal. The middle zone includes various sandstones and mudstones, also coaly shales and sandstones, and No. 2 coal seam, with plant root imprints. The thin but fairly extensive sandstone at the base of the middle zone is interpreted as the product of a transgression and the environment is seen as glaciolacustrine with a delta front approaching from the east – with deep water formation for the coals. In the upper zone are N facies (13.6 – 36.4 m thick) – sandstones, mudstones and coal seams, erosionally overlain by 16.5-30 m thick coarse, cross-bedded feldspathic sandstone; the S facies (10-33m) comprises immature coarse cross-bedded sandstone erosionally overlying No. 2 coal seam, and grading up into a 6 m thick, flaser bedded and wavy laminated mudstone with a thin, impure coal seam. A second immature coarse sandstone of c. 16 m thickness follows, which becomes carbonaceous and finer in its upper portion. This formation is interpreted as reflecting braided or meandering streams migrating onto a delta or flood plain.

3.8.8 Wellington Formation (Upper Dwyka equivalent)

Developed only in the S half of the main Karoo outcrop in the Ellisras basin, it is generally 20-30m thick, with a maximum of c. 160m in the SW and 180m in the SE. It comprises basal mudrocks with sandy lenses and small dropstones, coarsening upward to silty or even sandy rocks. In some boreholes the Wellington Formation starts with extensive fine- to coarse-grained sandstones. In other outcrops, limestones are up to c. 30 cm thick and are associated with sandy shales and feldspathic sandstones – also possibly in the basal part of the formation. It could have been formed in a large standing body of water, which was brackish or salty. The Carboniferous-Permian boundary could be in about the middle of the Wellington Formation, based on palynology.

3.8.9 Waterkloof Formation (Lower Dwyka equivalent) GES 0

The Waterkloof Formation consists of diamictite, mudstone and conglomerate. It occurs S of and along the N rim of the preserved Karoo strata, and also in the W part of the basin. The formation rests unconformably on Waterberg and older rocks, some of which exhibit deep weathering and palaeosols. Diamictite is over 9 m thick with local beds of sandstone or mudstone. In the SW, in place of diamictite, there is mudstone and rhythmite with common dropstones. The deposition of the formation could have been through a subaqueous outwash formed from reworked tills from glaciers retreating in the N and NE areas. The formation's mudstones are over 17 m thick and interpreted as glaciolacustrine.

3.9 Lithostratigraphic nomenclature selected for MSc thesis

Two of the above mentioned nomenclatures were selected for use in this thesis, the first being that utilised by the Council for Geoscience (which seems similar to that used on the Grootegeluk Coal Mine) and the second being that utilised by Siepker (1986). The main reason for selecting the nomenclature used by the Council for Geoscience was due to the fact that most of the borehole logs analysed in this thesis belonged to the Council. Changing their nomenclature would have proven difficult, more so since the accuracy of the core descriptions provided was questionable. Despite this handicap, the vast amount of data available (more than 800 boreholes plus descriptions), the good general spread of the available boreholes throughout the basin, the availability of longitude and latitude co-ordinates plus the availability of elevation readings per borehole, allowed for better plotting of cross-sections through the Ellisras Basin.

Siepker (1986) provided more accurate core descriptions from the various boreholes available to him. The Goedegedacht Formation which appeared in his work was not identified within logs from the boreholes supplied by the Council for Geoscience. For this reason the isopach maps further utilised in describing the preserved basin-fill were largely based on Siepker’s (1986) thesis data, as more accurate information is required to identify the various formations available.

CHAPTER 4

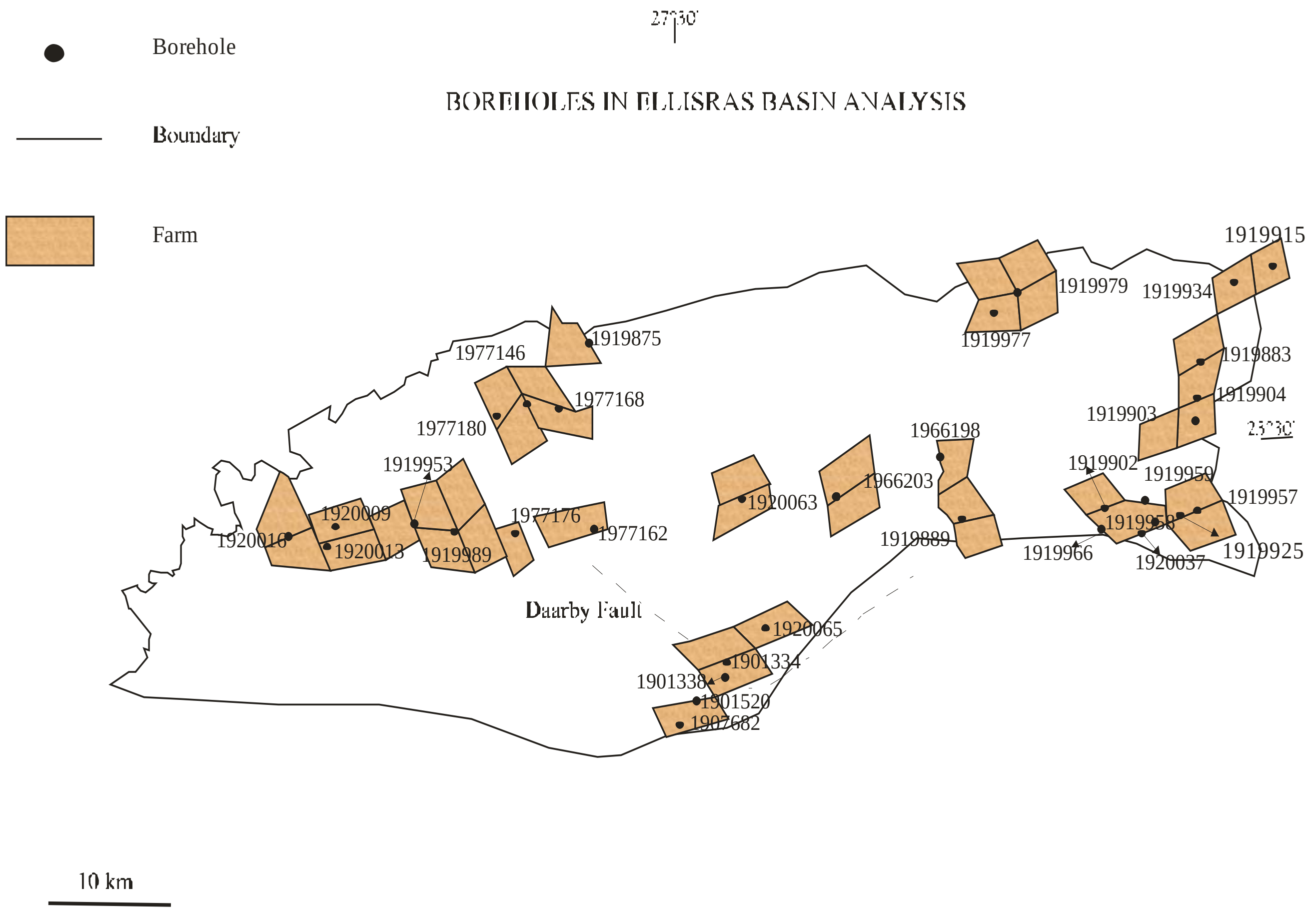
THE GEOMETRY OF THE PRESERVED ELLISRAS BASIN-FILL

4.1 Introduction

A large amount of time on this thesis was initially spent analysing and trying to order the database of borehole logs (approximately 830) supplied by the Council for Geoscience. The majority of these borehole logs lack any stratigraphic information and only a few of the holes could thus be usefully applied to basin analysis purposes. An electronic filing system has been set up ("Datamaster") to encompass these data. In order to reduce the vast number of holes to something manageable, four lines of boreholes across the preserved basin were selected, on the basis of maximum possible depth drilled, available stratigraphic and thickness data and the spread of borehole locations across the axis of the preserved basin: line 1 runs along the long axis of the basin in an approximately E-W direction, the other three lines (lines 2-4) are across the short axes of the basin, one each in the W, centre and E, and orientated at about 120 degrees (NNE-SSW) to line 1 (Fig. 1.2). Finally, 36 boreholes were selected (Figure 4.1, summarised from “Datamaster”).

For each of these lines, profiles have been constructed, showing the preserved stratigraphy and geometry of this Karoo-aged basin-fill. In most cases only a few of the stratigraphic units can readily be shown: the Dwyka (less often), the Vryheid Formation and the Grootegeluk Formation. From these profiles, the preserved basin-fill geometry can be observed and varies from one line to another - generally these lines reflect an overall preserved basin-type of shape, sometimes with subordinate sub-basins, and in one case, a half-graben type of geometry. The influence of major faults such as the Daarby Fault, are immediately obvious on these profile lines.

Figure 4.1: Map displaying Farms in which Analysed Boreholes were drilled



However, it is extremely important to emphasize that the currently preserved basin geometry and the geometry of the basin-fill sub-units at the time of deposition are in most depositories, very different. In order to better understand basin evolution, it is essential to try and reconstruct an approximation of synsedimentary basin-fill geometry. One of the best means of doing this is by constructing isopach maps (Figs. 4.2 to 4.9), illustrating the current thickness of chosen stratigraphic units - these are only an approximation of synsedimentary basin-fill geometry, as the effects of compaction and sediment loading are not corrected for in such isopach plots. Structural diagrams showing depth from a chosen datum to the bases of selected stratigraphic units have also been produced (shown in “Datamaster”), to better understand current basin geometry. All of these plots are based on thickness data extracted from both the Council for Geoscience boreholes as well as the unpublished 1986 MSc thesis of Eugene Siepker, which is the accepted standard reference source on the general geology of the Waterberg Basin. The great advantage of Siepker’s data compared to those from the Council for Gesocience, is that full stratigraphic information is available in Siepker's work. The descriptions of each of the selected boreholes used in these plots, including those of Siepker, are to be found in Tables 4.1 and 4.2 (sourced from “Datamaster”). Further descriptions of the wording used to describe various sections of the lithostratigraphic units are found in Appendix E.

The above analyses are intended to compare inferred and approximate synsedimentary basin evolution patterns with those of a post-depositional origin, and to try and relate each to a structural and plate tectonic framework of the history of Karoo sedimentation within southern Africa. In addition, these geometrical data will also be compared to inferred depositional environments, in order to make a cohesive contribution to concepts of the basin evolutionary history of the Waterberg (or Ellisras) Karoo Basin. This study is envisaged as a pilot basin analysis study rather than a definitive and final answer to a complex problem.

4.2 Methodology in creating Structural Diagrams

The Council for Geoscience data were selected for this exercise as its boreholes were relatively well spread across the Ellisras basin in comparison to Siepker's (1986) data, and the Council's logs each also had GPS co-ordinates as well as an elevation reading. The structural diagrams (Fig. 4.10) allow for viewing of the cross-sections of the basin through the lines 1 to 4, as seen in Fig. 1.2. The following points summarise the steps taken to construct the diagrams:

- Boreholes considered to be properly spaced along the length of each line (lines 1 to 4), to have considerable depth as well as being located as close as possible to lineaments such as the Daarby Fault, were selected.
- Readings were then taken of the upper and lowest depths of the main stratigraphic units such as the Grootegeluk, Vryheid and Dwyka (where possible). For example, one borehole may have the upper reading of the Grootegeluk at 45m whilst the formation's lowest depth, or floor, is at 120m. This is done for all selected boreholes in each line.
- The elevation height of each borehole is noted and adjusted accordingly so as to place other boreholes on an equal datum.
- A diagram is drawn from start to finish of the line (left to right for line 1; right to left for lines 2 to 4).

4.3 Methodology in creation of isopach maps

Both Siepker's (1986) and Council for Geoscience boreholes were selected for the drawing of the isopach maps. Siepker's (1986) boreholes were also plotted along four lines of his own, which are not related to those used in this thesis (and shown in Fig. 2.1 and 4.1). Coal seams 1 and 2 as well as the coal and non-coal sections of the Grootegeluk Formation were better outlined in the Council for Geosciences data. Siepker (1986) would otherwise refer to any coal-like matter as consisting of mudstone and coal whilst the Council for Geoscience would separate the coal from mudstone or any other non-coal layer. Siepker's data are more applicable to the drawing of isopachs displaying the total Grootegeluk thickness or that of the total Goedgedacht Formation depth - the Goedgedacht Formation is not identified in any of the Council for Geoscience borehole logs. Any mention of A-A, B-B, C-C or D-D in

Siepker's data relates only to the lines in his thesis mentioned above, and can be ignored in this thesis. Attention is instead given to the boreholes found on each line, which are then divided according to their stratigraphy as well as coal and non-coal sections. The following steps were taken towards plotting isopach maps for the Grootegeluk Formation (total thickness), Grootegeluk (only total coal thickness), Grootegeluk (total thickness of non-coal beds), Goedegedacht Formation, Coal Seam 1 (only coal), Coal Seam 1 (non-coal), Coal Seam 2 (only coal) and Coal Seam 2 (non-coal):

- The selected boreholes were first highlighted by hand from a copy of Fig. 4.6 of Siepker (1986), which includes a locality map with borehole positions.
- Tracing paper was placed on his Fig. 4.6 and the highlighted boreholes were plotted onto it together with their identity numbers.
- Plotting of the Council for Geoscience boreholes onto the map was done differently:
    - As the approximately 830 boreholes logs provided by the Council were in an electronic format that was compatible with ARCView software, it was possible to plot each individual borehole on an electronic map of the Ellisras area utilising the mentioned software.
    - Once plotted, the 36 Council for Geoscience boreholes selected were highlighted by hand and re-plotted onto the Fig. 4.6 map of Siepker (1986). The use of one map for plotting all these various boreholes allows for a shared platform to use in comparing final results.
- Since Siepker's (1986) thesis has no numerical data defining the actual depths and thickness for each section of his boreholes, measurements were made from the various cross-sections in his thesis of each borehole, mainly from Figs. 4.2 to 4.5 and 5.33 of Siepker's (1986) thesis - using the scale rule shown on each map as a reference. Fig. 5.33 includes displays of the Goedgedacht extension towards the eastern end of the basin. The collected data were then tabulated.
- Once all required boreholes were tabulated, a model known as "Datamaster" was created with the purpose of extracting the thicknesses of each formation, including their coal and non-coal sections as well as coal seams (mainly seams 1 and 2) per borehole. The thicknesses from the Council of Geoscience data

are further plotted in a column chart displaying the measured depths (thereby providing thicknesses also) in each of the boreholes, plotting being done per line (Figs. 4.11 to 4.14).

For each isopach map shown, major faults as known from surface geology today are plotted as reference locations, these faults are also displayed in Fig. 2.1.

Figure 4.2: Goedgedacht- with Siepker (1986) Borehole Numbers

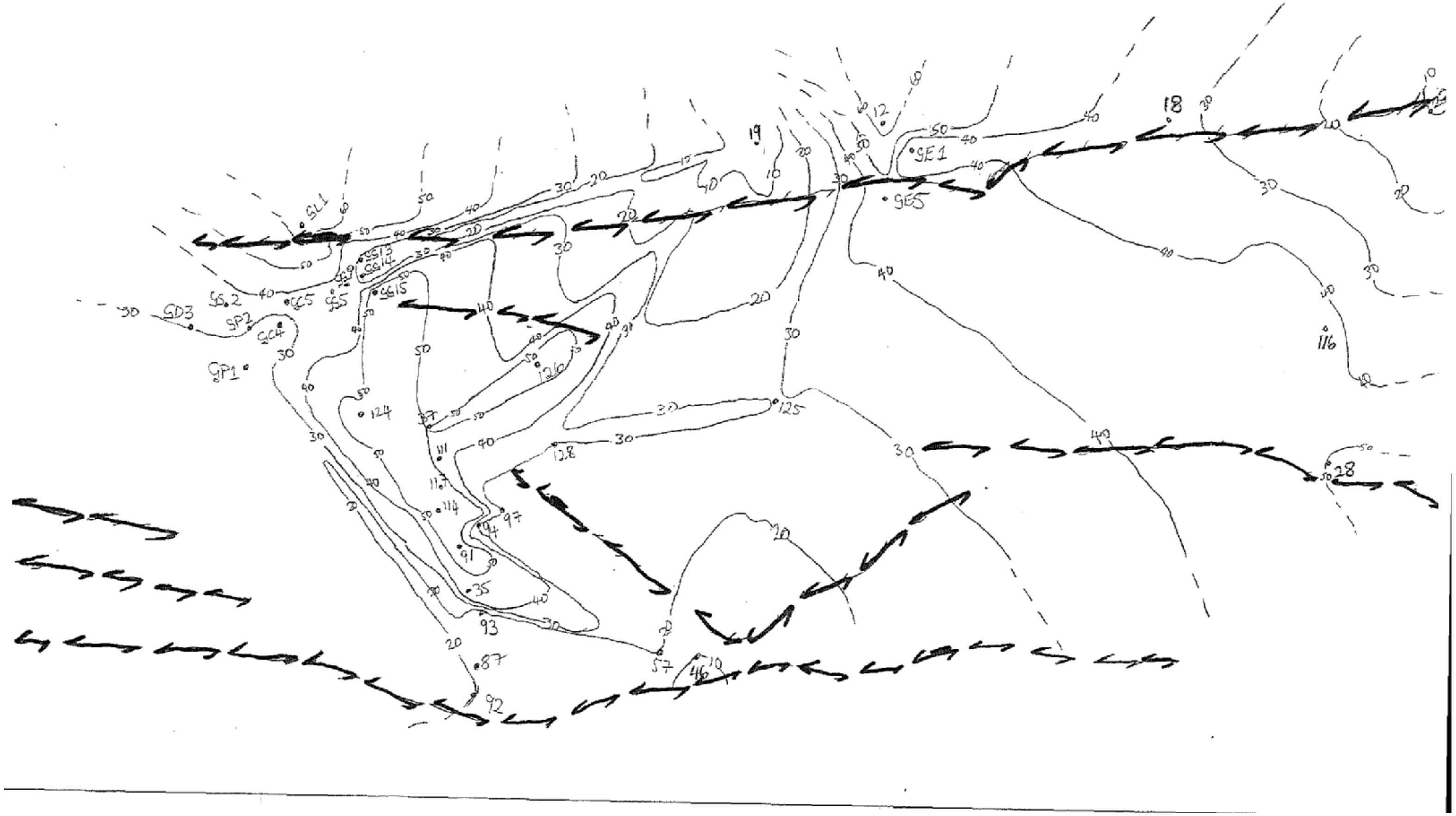


Figure 4.3: Grootegeluk- with Siepker (1986) Borehole Numbers

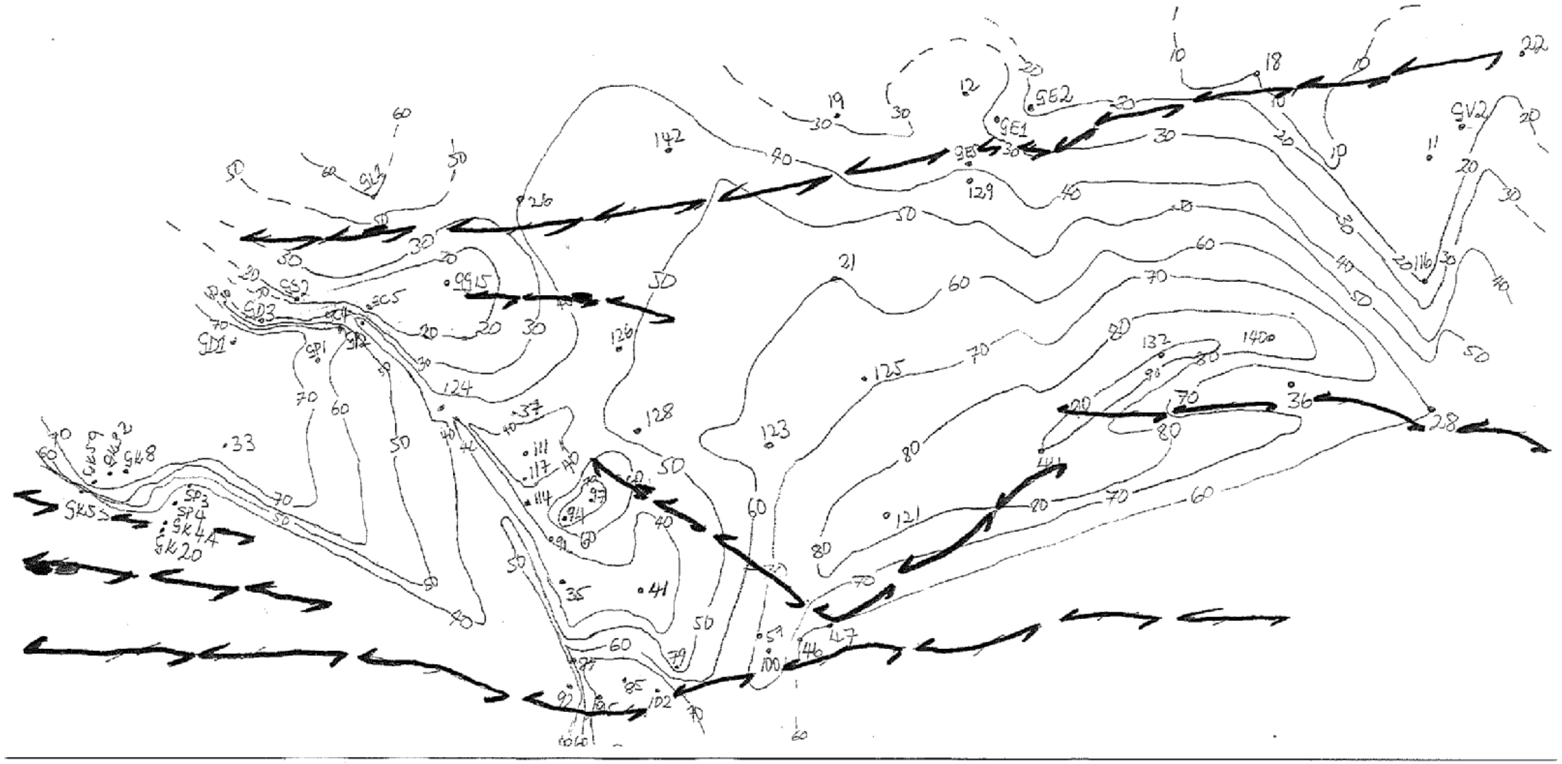


**Figure 4.4: Grootegeluk (Coal)- with
Council for Geoscience Borehole Numbers**

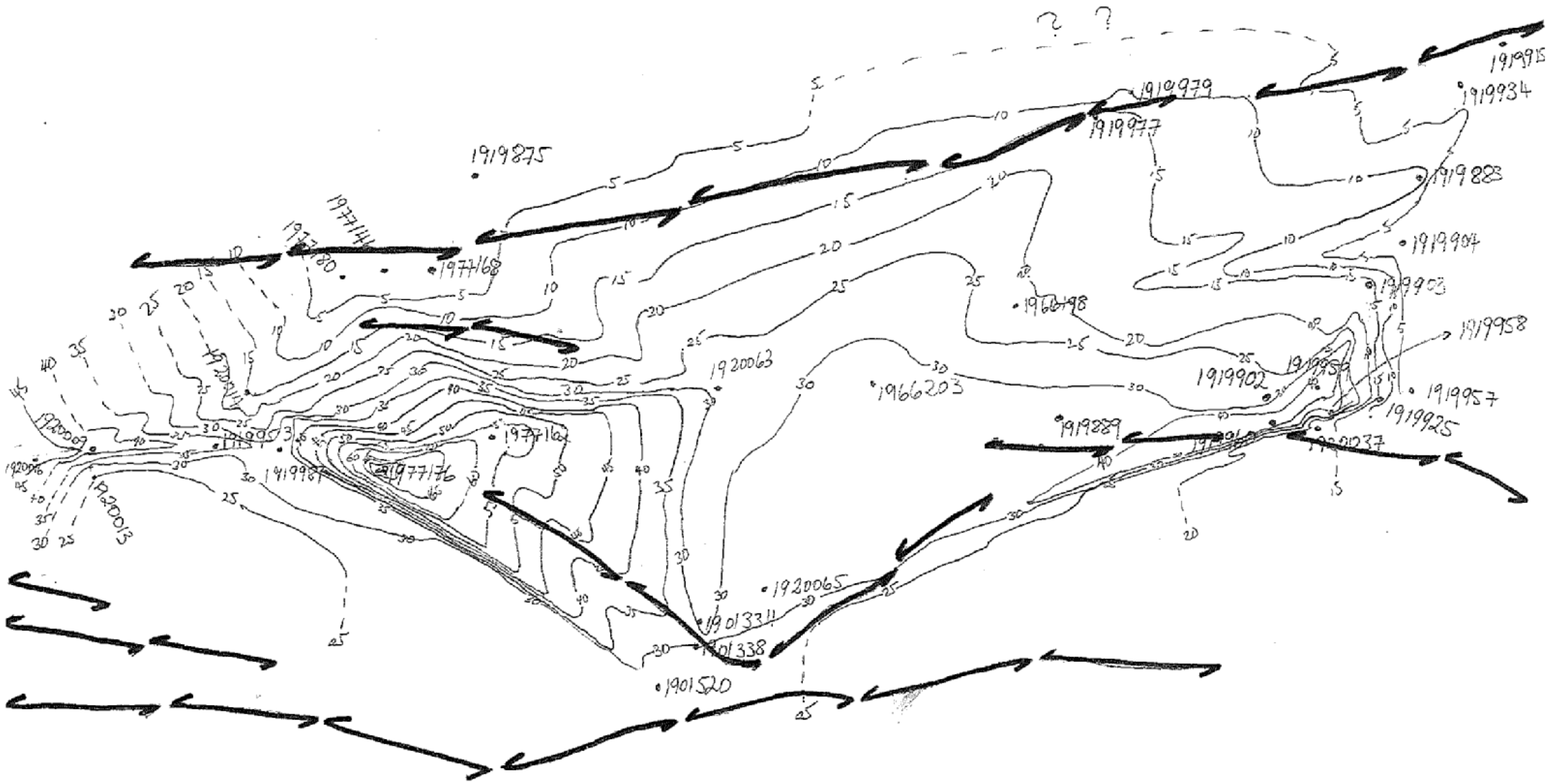


Figure 4.5: Grootegeluk (None Coal)- with Council for Geoscience Borehole Numbers

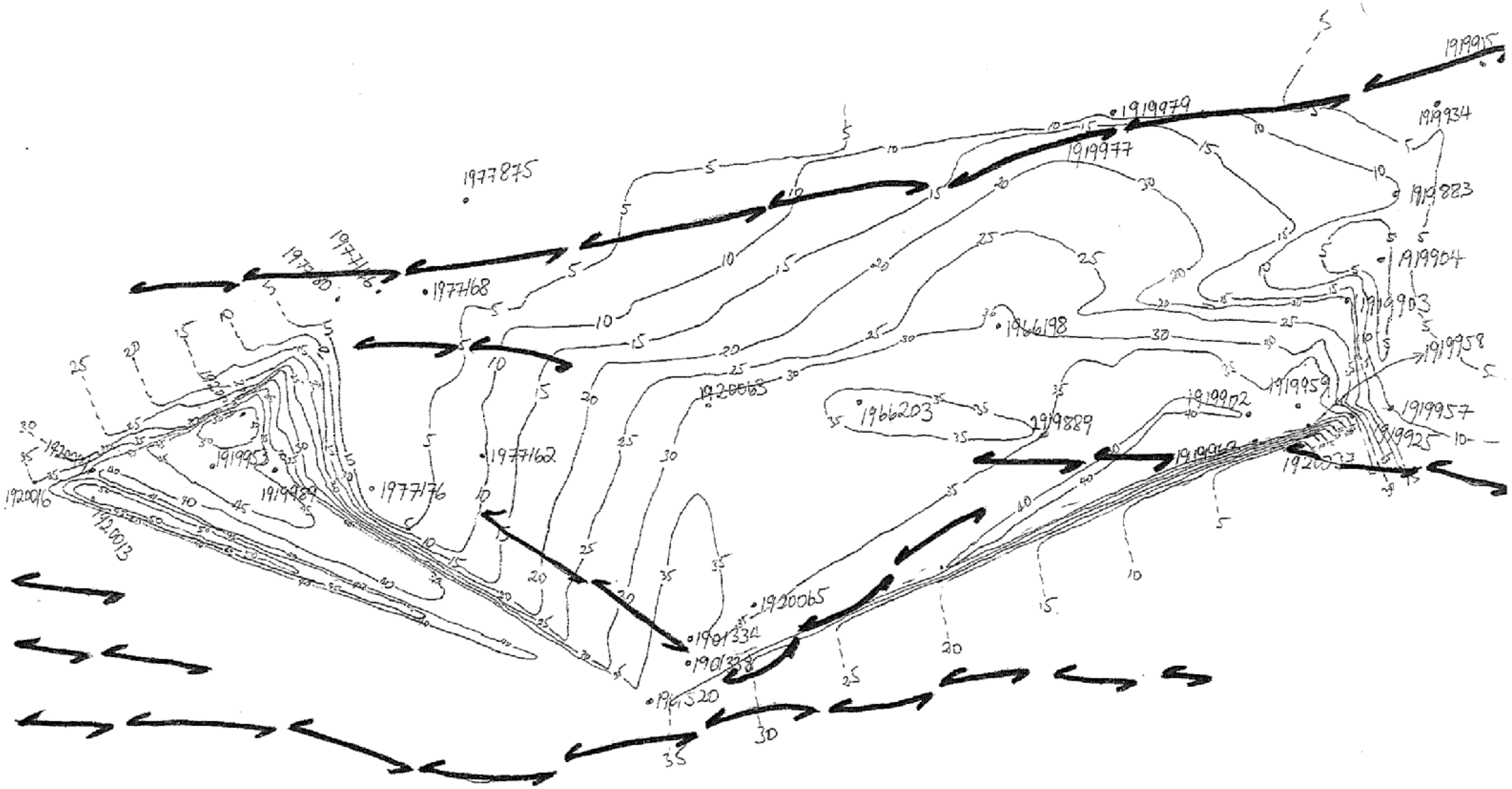


Figure 4.6: Seam 1 (Coal)- with Council for Geoscience Borehole Numbers

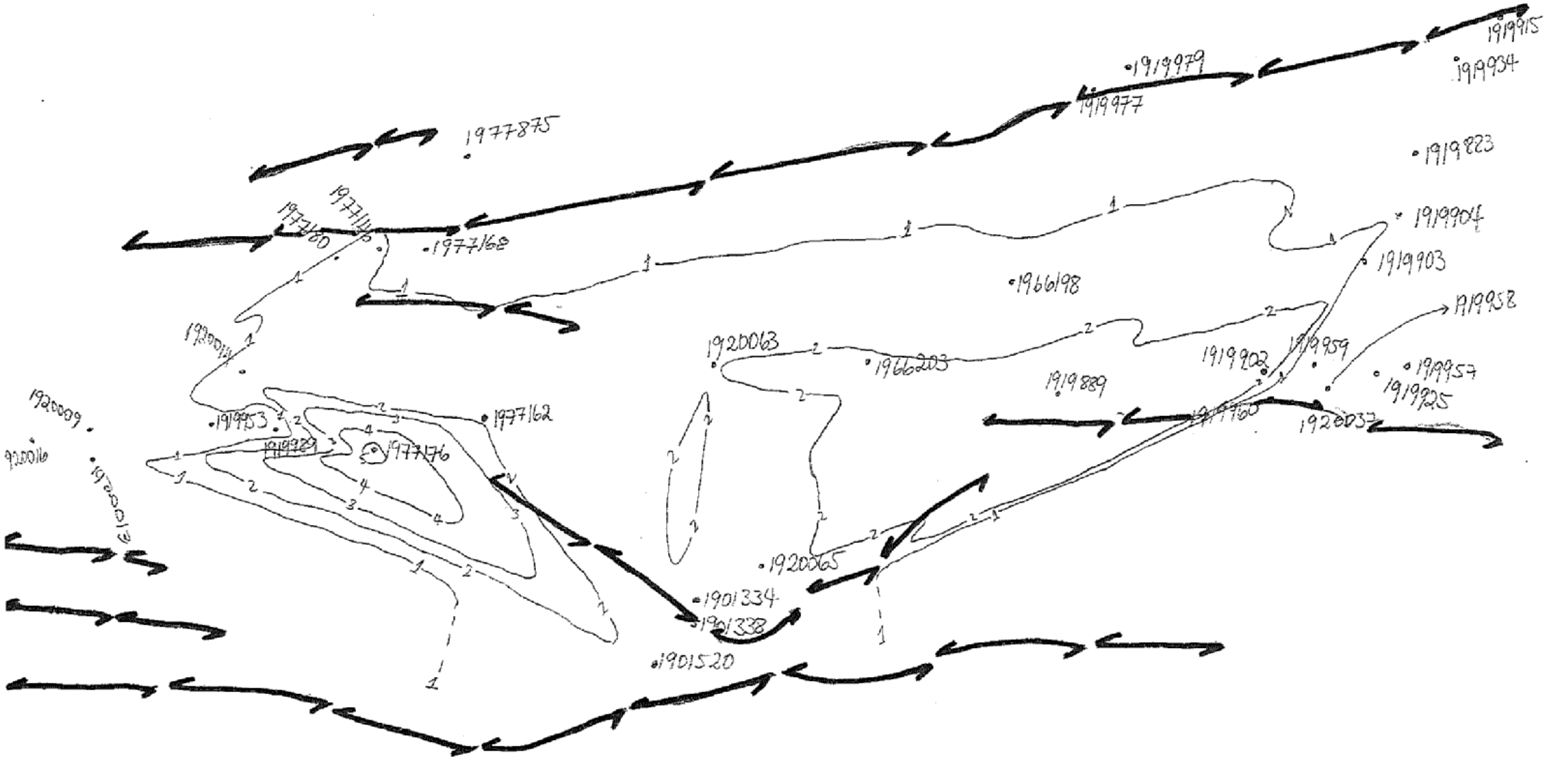


Figure 4.7: Seam 1 (None Coal)- with Council for Geoscience Borehole Numbers

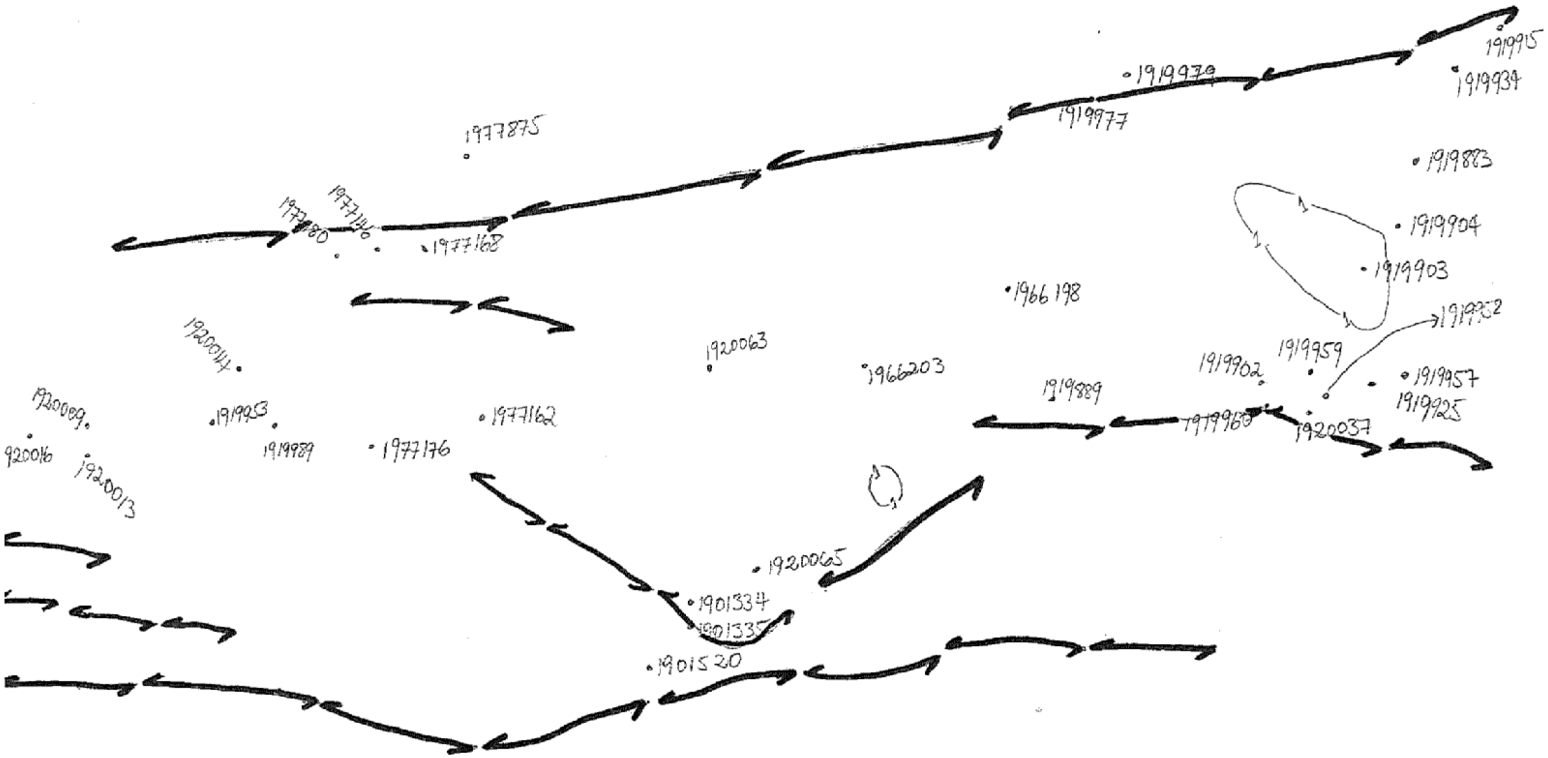


Figure 4.8: Seam 2 (Coal)- with Council for Geoscience Borehole Numbers

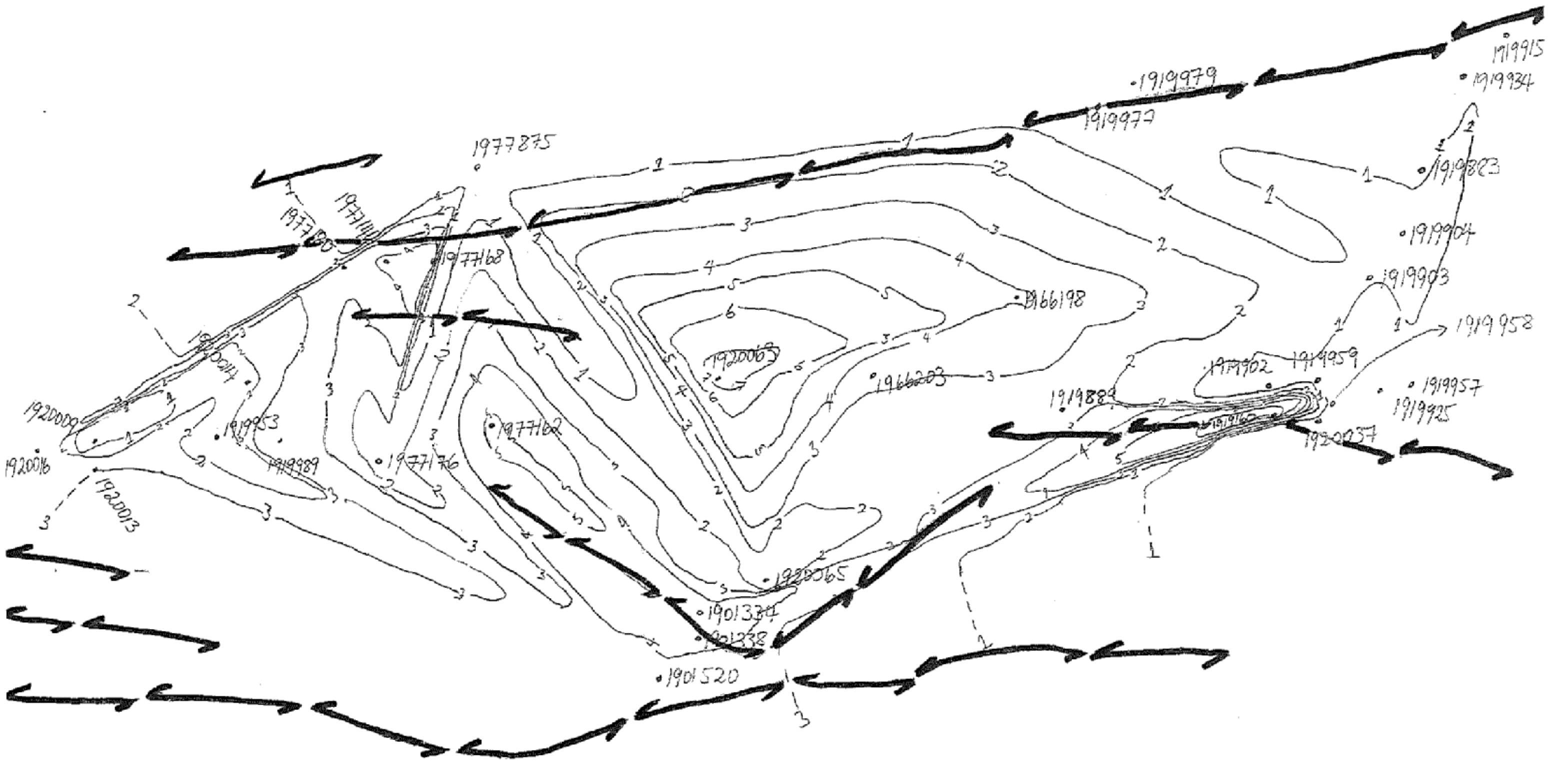
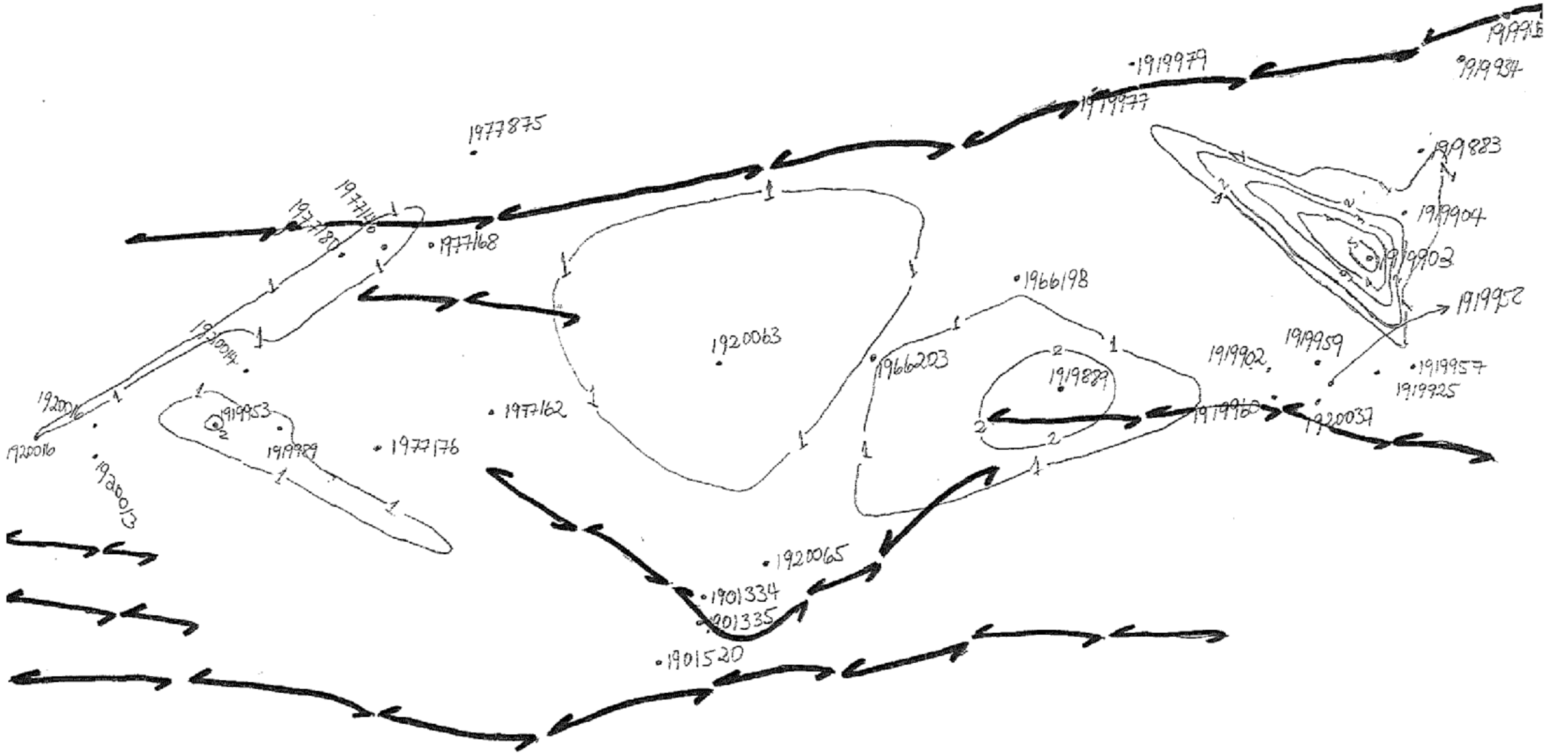


Figure 4.9: Seam 2 (None Coal)- with Council for Geoscience Borehole Numbers



CHAPTER 5

DISCUSSION

5.1 Introduction

This chapter attempts to draw together all the information previously mentioned with the aim of creating a theory relating to the formation of the Ellisras (Karoo) Basin and its sedimentary fill. Bumby and Guiraud (2005) discuss the formation of African basins in a general and large-scale context, during the Phanerozoic period. Two models by Catuneanu et al. (1998) and Turner (1999) are also discussed, which refer to the possible formation of the main Karoo Basin, and the implications thereof for the Ellisras basin.

5.2 The Retro-arc Foreland System (Catuneanu et al., 1998)

As discussed in the previous sections of this thesis, Catuneanu et al. (1998) recognised a direct relationship between episodic uplift in the Cape fold belt and the progradation of sediments onto the craton. After collision, the weaker pan-African basement of the Cape Fold Belt shortened more in comparison to the more rigid crust of the Precambrian Kaapvaal craton (Bumby and Guiraud, 2005). This resulted in more localized orogenic loading on the southern edge of this part of Gondwana and formation of the Main Karoo Basin and related smaller basins further to the north, such as the Ellisras Basin.

The resulting flexural tectonics and dynamic subsidence within the main Karoo Basin led to the formation of a retroarc foreland system, further explained in the Stratigraphy chapter of this thesis, plus related intracratonic basins to the north (Catuneanu et al., 2005) - see also Fig. 2.5.

5.3 Mantle Plume Thermal Uplift (Turner, 1999)

Turner (1999) has challenged this application of the retro-arc foreland basin model and chose to relate age data, stratigraphic and stacking patterns, as well as small amounts of volcanic detritus within the upper Karoo formations, to mantle plume-linked thermal uplift and the onset of early rifting, to the southeast of the preserved Main Karoo Basin, close to the later Agulhas Falkland fracture zone (Catuneanu et al., 2005). Turner's (1999) concerns include the non-marine upper Karoo succession, which is dominated by upward-fining sequences, rather than coarsening-upward sequences that tend to be associated with the modelling of non-marine type foreland basins. Thus, according to Turner (1999), the upper Karoo units in the Main Basin are related to extension associated with Gondwana break-up rather than purely orogenic unloading in the Cape Fold Belt (Bumby and Guiraud, 2005). This extension is thought to have resulted from the presence of a plume along an elongated source situated and aligned along the northeast and southeast of South Africa at about 230 Ma (Turner, 1999). The evolution of African Phanerozoic basins (and subsequently of the Ellisras Basin) must also be considered in view of periodic plumes located under the African plate (Bumby and Guiraud, 2005). If this scenario outlined by Turner (1999) were to be accurate then the evolution of the Ellisras Basin could have been influenced by thermal up- and down-welling activity near and/or below its surface, perhaps even related to the failed triple junction rift along the borders of South Africa, Zimbabwe and Mozambique. One arm of the triple junction is situated between Mozambique and Zimbabwe, another between the borders of South Africa and Zimbabwe with the last one located along what is now known as the Lebombo Range (see Fig. 1.1). This may explain why the neighbouring basins within this region seem to have a graben-related structure as seen in Table 5.2, which is typical of rift zones. The graben structures could also be explained by the fact that the formation of the Karoo Supergroup occurred through an initial compressive system before commencing to an extensive regime, which could be related to the break-up of Gondwana.

5.4 Geological Structures observed in the Ellisras Basin

This section will aim at discussing possible structural features that played a role during sedimentation within the Ellisras Karoo Basin. An as yet unpublished airborne magnetic map of the basin was made available to the author via Coaltech 2020 from Dr. S. Fourie of the CSIR, and provides a visual summary of anomalous magnetically-defined linear features within the preserved basin and its floor rocks. These features reflect concentrations of magnetic minerals, presumably along faults, dykes, shear zones and other linear geological features. By comparing these linear features with isopach patterns for certain units within the basin-fill, some idea can be gained of possible synsedimentary structural features active during Karoo deposition in this basin. Some of the “lineaments” detected on the magnetic map were more obvious from isopach patterns first and were only then defined, sometimes vaguely only, on the magnetic map – if such poorly defined “lineaments” were found in more than one isopach map, they were considered as possibly significant and included in a set of such “lineaments” marked onto the magnetic map (in white, and labelled with letters – A, B, C, D, E, Z, G - for identification’s sake).

The following is thus a summary of similarities noted between the isopach maps presented in chapter 4 and a map showing the Ellisras Basin’s anomalous magnetically-defined linear features , Fig. 5.1 (obtained via Dr. S. Fourie, 2008).

5.4.1 Seam 1 (Non/Coal)

Not enough data available to allow for interpretation.

5.4.2 Seam 1 (Coal)

1. The southwestern area of greater thickness defined by two “lineaments” between boreholes 192009 and 1901520 as well as the one between boreholes 1920014 and 1977162 (in the west of basin) seems related to the B-lines on the magnetic map.
2. Towards the northwest of the basin between boreholes 1920014 and 1977146 is a seam 1 thickness pattern (“lineament”) that may be related to the Z-lines.
3. The southeastern linear thickness pattern observed between boreholes 1920065 and 1919959 seems related to the A-lines.

5.4.3 Seam 2 (Non/Coal)

1. To the west of the basin is a non-coal occurrence with a linear pattern, between the boreholes 1920016 and 1977875, which runs parallel to the Z-lines (magnetic data, Fig. 5.1).

2. To the south west is a second linear occurrence of non-coal sediment, trending to the southeast near the boreholes 1919953 and 1919989, which seems to run parallel to the magnetic B-lines.
3. Near the central-eastern part of the basin is the greatest thickness of non-coal sediment within the No. 2 coal seam, defined by southeasterly linear trends, which seem related to the magnetic D-lines.
4. Towards the centre of the basin, between the boreholes 1966203 and 1966198 and boreholes 1920065 and 1919960, is an occurrence of non-coal sediments whose apparent boundaries trend to the northeast, and which are possibly related to the magnetic A-lines.

Seam 2 (Coal)

1. In the west and southwest of the basin is an area of variable coal thickness (between 1 and 3 m thick) whose boundaries display linear trends in a NE-SW direction (between boreholes 1920016 and 1977875 - seems influenced by Z magnetic “lineaments”), and a NW-SE direction (between boreholes 192009 and 1901520 - possibly partly controlled by the B1-line).
2. Towards the centre of the basin an occurrence of thicker coal, defined by the boreholes 1977162 and 1920063 in the east to west direction and boreholes 1977875 and 1920065 from north to south, exhibits linear trends that are roughly SE-NW, which seem parallel to the C-lines of the magnetic map.
3. Towards the northeast of the basin, a set of parallel isopach lines trending towards the southeast are approximately parallel to the D-lines of the magnetic map.
4. In the lower half of the basin towards the southeast is a narrow linear occurrence of much thicker coal, enveloping the borehole 1919160, which seems influenced by the A1-line on the magnetic map.
5. In the north-central parts of the preserved basin are linear isopach lines which seem to run parallel to the Zoetfontein Fault; coal thicknesses decrease towards this fault, which marks the boundary of the Southern Marginal Zone of the Limpopo Mobile Belt.

5.4.5 Grootegeluk (Non/Coal)

1. In the west of the preserved basin, is an area of greater non-coal sediment thickness, which is defined by linear margins, trending NW-SE between boreholes 1920013 and 1901520, as well as between boreholes 1977176 and 1901520, which are parallel to the magnetic B1-line. Along its northern margin, this area trends to the northeast between boreholes1920016 and 1977146, a trend that seems related to the Z and/or E lines.
2. The long northeast trending linear pattern of rapid thickness changes between boreholes 1901520 and 1919957 (southeastern margin of the basin) seems to be parallel with the A lines and/or possibly even with the Z line, as seen with the lineament between 1920016 and 1977146 described under (1).
3. The wedge shaped, east-trending area of thinning non-coal sediment to the east of the basin, between boreholes 1966198 and 1919904, is aligned along an approximately E-W trend, which may be related to the “G-wedge” feature marked on the magnetic map.

5.4.6 Grootegeluk (Coal)

1. A strong linear trend of rapidly changing coal thicknesses between boreholes 1901520 and 1919989 seems influenced by the magnetic map line B2, and is also parallel to line B1.
2. The A magnetic lines seem to have had influence in approximately three areas of coal thickness isopach lines, namely between boreholes:
    a. 1920065, 1919960 up to 1919925 (southeastern margin);
    b. Along the axis of 1966198 and 1919904 (central eastern area); and
    c. The parallel trending lines running approximately to the NE, from 1966203 and further north, until they intersect the preserved northern margins of the Ellisras Basin.
3. Possible influence of the Z magnetic line on parallel thickness trends between boreholes 1977180 and 1920009.
4. A linear thickness distribution pattern also exists along the current position of the northwest trending limb of the Daarby Fault, but this pattern may also have been influenced by synsedimentary faults following a direction parallel to the B-lines on the magnetic map.

5. The linear pattern of rapidly changing yet parallel isopach lines between boreholes 1977162 and 1920063 seems influenced by the A3 magnetic line, and may continue eastwards on towards borehole 1919883, possibly also being related to the feature discussed above under 2(b).

5.4.7 Grootegeluk (total thickness: non-coal and coal)

1. The strong linear trend in isopach lines oriented NW-SE, along boreholes 87, 124, and GC4 in the southwest of the basin, may have been influenced by the C1 line.
2. Synsedimentary activity along the magnetic B1-line may have affected deposition of the Grootegeluk Formation as seen by the linear pattern of isopachs trending WNW-ESE between boreholes 92 and 33, in the southwest of the preserved basin.
3. The linear isopach trend defined along boreholes 132 and 140, towards the southeast of the preserved basin, could have been influenced by the A2-line on the magnetic map. Parallel contour lines trending along a similar direction can also be seen up to the north-central part of the basin.

5.4.8 Goedgedacht

1. Linear thickness patterns between boreholes 87 and GP1 are approximately parallel to the C1 magnetic line.
2. The NE-oriented linear area of increased thickness towards borehole 126 (western part of the basin) seems to have a relation to the Z magnetic line. Note that the Z magnetic “lineaments” are deflected at their northern-most tips towards a southeastern direction.
3. A linear area of c. 30 m thickness running along the direction of boreholes 128 and 125, may fall under the influence of the A3 magnetic line.
4. A linear pattern of reduced thickness along the northern margin of the basin and stretching ENE from boreholes GG13 and GG14, seems influenced by a possible fault (the E-line on the magnetic map), which obliquely intercepts the Zoetfontein fault. A linear pattern of westward increasing thickness, running

from boreholes 22 to GE1, could have been influence by the Zoetfontein Fault/ Palala Shear Zone.

Table 5.1: Summary of observed geological "structures" ("lineaments") in Fig. 5.1 and their inferred influence for specific isopach thickness patterns

	A lines	B lines	C lines	D lines	E line	Z lines	G wedge	Others
Seam 1 coal	X	X				X		
Seam 2 non-coal	X	X		X		X		
Seam 2 coal	X	X	X	X		X		
Grootegeluk non-coal		X			X	X	X	
Grootegeluk coal	X	X				X		NW limb of Daarby Fault
Grootegeluk total	X	X	X					
Goedgedacht	X		X		X	X		Zoetfontein Fault

From this table it is apparent that the A, B and Z magnetic lines probably played a role during deposition of the entire sequence for which isopach maps were constructed, whereas the C, D and E lines appear to have been active only intermittently, with D active in lower stratigraphic levels and the other two higher up. However, it should also be noted that the D lines are basically parallel to the B lines, and that the Z and E lines are on an approximate "A-trend". Examining the geographic locations of the various magnetic lineaments within the preserved basin, one can argue for a long-lived influence of the set of A and Z (and maybe E also) lines across much of the basin, with the B and D set of lines being also long-lived, but active in the western and eastern extremities of the basin. The C lines are possibly the youngest set, and their influence is limited to the western part of the preserved basin. The NW limb of the Daarby Fault and the Zoetfontein Fault might have been active during deposition relatively later in basin history; it is noted that the former fault limb is essentially parallel to the B-D line set. Overall, the most intense influence of linear magnetic features seems to have been in the far western part of the basin. The greatest magnetic lineament influence stratigraphically was apparently for the Seam 2 coal level, and the Goedgedacht Formation.

If one assumes that the magnetic lineaments shown in Fig. 5.1 illustrate important long-lived structural trends in the Kaapvaal craton basement and within the overlying Waterberg Group succession, then the following can be noted:

(1) the B-D trend is essentially parallel to a pervasive approximately NW-SE structural grain, which is well known within the Kaapvaal craton and these magnetic lineaments may thus reflect reactivation of basement structural architectural features during the Karoo sedimentation. It is also noticeable in Fig. 5.1, that this grain stops abruptly along the Zoetfontein Fault, marking the boundary between the Kaapvaal craton and the Central Zone of the Limpopo Mobile Belt.

(2) The A, Z and E lines in Fig. 5.1 are largely defined by thickness features from the various isopach maps and these thus likely reflect synsedimentary patterns of creation of accommodation space during Karoo deposition, rather than reactivation of earlier structural architecture; locally, they cut across the pervasive B-D trend, but do not appear to displace these magnetic lineaments. The A-Z-E trend runs approximately WSW-ENE, at a low angle to the Zoetfontein and Eenzaamheid Faults, which effectively bound the preserved Ellisras Karoo Basin.

(3) The C magnetic lines are likely a young feature that affected only Karoo strata, syndepositionally, and faulting and subsidence along these lines in the far west of the preserved basin may have led to stronger reactivation of earlier structural features in basement and Waterberg rocks, thereby explaining the apparently greater degree of lineament influence within this part of the depository.

Miall (2000) notes that forces associated with intraplate stress may re-activate or otherwise modify basement or cover structures and can lead to structural re-activation that tends to be localised and conforms to variable trends of heterogeneity in the basement. Miall (op. cit.) further notes that in a general sense, all sedimentation is syntectonic and all tectonism is syndepositional.

The Soutpansberg Group (encompassing the fill of the Soutpansberg Trough) still requires extensive work and research to be able to better understand its geological history (Johnson et al., 2006). A number of theories exist concerning its tectonic setting and they include:

- Jansen (1975 a, b), proposes that the Soutpansberg rocks accumulated in a narrow graben-like structure, an aulacogen (a fault-bounded trough or graben that developed as a rift between two more or less parallel faults) developed from the edge of the craton in the east towards its interior.
- Barker (1976) opposed Jansen's (1975 a, b) theory as there was an absence of marine sediments and the observed palaeocurrent distribution pattern apparently negated the earlier proposal.
- Cheney et al. (1990) believed that the Soutpansberg Group was once much more extensive than the 50 km wide aulacogen. They thus proposed that the Soutpansberg rocks were deposited in a broad basin rather than a rift environment and that the strata had been preserved and not originally deposited, in the observed graben-like structure.
- Johnson et al. (2006) consider a combination of the above models. Perhaps only the lower Soutpansberg rocks (Sibasa and Fundudzi Formations) may have been deposited in graben-like structures whilst the upper sedimentary units (Wyllie's Poort and Nzhelele Formations) were probably laid down in a broad basin. Johnson et al. (2006) thus surmise that the lower Soutpansberg rocks would represent a syn-rift sequence and the upper rocks a post-rift sequence. Together, this would then comprise an essentially "steer's head" (cf. White and McKenzie, 1988) basin geometry.

Bordy (2000) refers to the Tshipise Basin's narrow or half-grabens, believed to have been formed during the deposition of the Dwyka Group beds; this could also relate to the formation of a similar graben structure in the Ellisras Basin, all of which were possibly influenced by the Soutpansberg Group's tectonic history, as discussed by Johnson et al. (2006). The isostatic loading of the ice formed during the Dwyka era may have possibly influenced the re-activation of older faults and long-lived structures along the boundary of the Ellisras Basin, thus leading to continuous tectonic movement during Karoo deposition, obviously also influenced by ongoing sediment loading during deposition of the entire succession.

Bordy (2000) also identifies graben-like structures in the Tuli Basin and describes them as being due to faults which form part of the late- to post-Karoo fracture system, which broadly follows the axis of the Limpopo Belt. The Karoo rocks of the basin are considered to be flexurally downwarped along an ESE axis and subsequently downfaulted by a combination of NE and ENE trending fractures. Similar lineaments are mostly visible in the west and south of the Ellisras Basin, as seen in Fig. 5.1, Z (the A-Z-E line trend). Meanwhile, an almost comparable set of similar trending faults is noted in the Tshipise Basin and is believed (Bordy, 2000) to be representative of post-Karoo and post-Waterberg faults, which tend to have an ENE trend. According to Jansen (1975 a, b) the Soutpansberg Trough probably developed in a narrow ENE-WSW (Limpopo parallel) trending trough after re-activation occurred between the Central and Southern Marginal Zones. This point may also relate all the above-mentioned Karoo basins to the Soutpansberg trough.

In addition, Bordy (2000) also postulates a model within this region in which the first of two right-lateral strike-slip faults was responsible for the generation of the Tuli, Nuanetsi and Tshipise Basins **(**Fig. 2.1**)**. This tectonic displacement occurred along pre-existing ENE and NE trending faults during the sedimentation of the lower part of the Karoo Supergroup. The dominant fault pattern of the Tshipise, Nuanetsi and Tuli Basins is regarded as being a modified southward extension of the East African Rift system, within a failed rift triple junction (Fig. 1.1). This fits in with the discussion by Johnson et al. (2006), linking the deposition of the lower Soutpansberg Basin to a syn-rift sequence. It also strengthens the case that the

Ellisras Basin's structural development was similarly influenced by the same rift sequence - most probably the failed triple junction rift.

Extensional structures associated with the East African Rift system trend N-S, ESE and ENE in the Lebombo Monocline, as well as ENE and WNW in the Limpopo area. Whilst there are no visible N-S lineament trends in the Ellisras Basin, those with ESE, ENE and WNW trends are present - though not enough evidence exists to relate these lineaments to the other basins - but assumptions towards this line of thought could be justified based on the above mentioned information as well as the similar age and proximity of the basins to each other.

The southern boundary in the Notwani Sector, located in Botswana as seen in Fig. 2.4, is bounded by an east-northeast - trending lineament whose surface expression may be in the form of shear zones but more often is a pronounced zone of monoclinical flexuring in the rocks of the Waterberg Group (Crocket and Jones, 1974). The latter authors note that evidence exists that some of these boundary zones of structural disturbance were initiated in pre-Waterberg times and may have been active features while the Waterberg rocks themselves were being laid down.

Both the Palapye and Notwani sectors of the Kalahari (Karoo) Basin (Fig. 2.4) show evidence of post-Waterberg Group structural disturbance along the margins of the regions underlain by these Waterberg rocks. Both the northeastern and southwestern flanks of the Palapye Sector are bounded by northwest- or west-northwest trending fault zones (Crocket and Jones, 1974).

Arnott and Williams (2007) observed that within their study section in Mmamabula East (see Fig. 2.6), the coal bearing sediments were generally flat lying with minor regional undulations postulated to be associated with similar undulations in the pre-Karoo floor rock (Fig.s 2.9 to 2.11). Deposition of the coal seams over this pre-existing basement high, led to coal seam elevations increasing gradually towards this feature, resulting in increased weathering in the area immediately above the palaeo-high (Arnott and Williams, 2007). Within the Mmamabula South study area (area location in Fig. 2.6), eleven separate faulted blocks with throws of up to 50 m between faulted blocks were noted (Arnott and Williams, 2007). These faults have divided the Mmamabula South project area into eleven separate faulted blocks (seemingly representing graben-like structures as seen in the Ellisras Basin).

The coal seams tend to be poorer in quality and quantity (perhaps even thickness) towards the deeper parts of the Kalahari Basin, which may suggest that some differential tectonic movements affected the Kalahari Basin during coal formation (Rust, 1975). It should be borne in mind that the Ellisras Basin is really an offshoot of the much larger Kalahari Basin.

Crocket and Jones (1974) make mention of increasing evidence of the existence of major vertical movements of portions of the crust during middle and later Precambrian time in southern and eastern Botswana, as well as in adjacent areas. All these structures, which are found in Botswana but near the Ellisras Basin, could possibly be related to the formation of the South African Karoo basins and their respective coalfields since, according to Arnott and Williams (2007), the intracratonic Soutpansberg Trough influenced the formation of the Ellisras, Mmamabula and Mopane basins/sub-basins and was re-activated during late Permean to early Triassic era.

Table 5.2: Summary of geological structures, which may relate to the Ellisras Basin, found in neighbouring basins

Basin or Geological Structure	**Similarity in Structural Geology**
Soutpansberg Trough (pre-Karoo)	• Re-activated during late Permian to early Triassic times (Arnott and Williams, 2007). • Intracratonic trough, which influenced the formation of the Ellisras, Mmamabula and Mopane coalfields (Arnott and Williams, 2007). The dominant fault pattern of the Tshipise, Nuanetsi and Tuli Basins is regarded as being a modified southward extension of the East African Rift system (within failed triple junction) whose

Basin or Geological Structure	**Similarity in Structural Geology**
	extensions also trend ENE and WSW in the Limpopo area (Bordy, 2000). - Probably developed in narrow ENE-WSW (Limpopo parallel) trending trough (Jansen, 1975a) after re-activation occurred between the Central and Southern Marginal Zones (Jansen, 1975b) of the Limpopo mobile belt.
Tshipise (Karoo)	- Half-graben structures (Bordy, 2000) - Post-Karoo and post-Waterberg faults, with ENE trend (Bordy, 2000)
Tuli (Karoo)	- Graben-like structures in the Tuli Basin possibly due to faults forming part of the late to post-Karoo fracture system (Bordy, 2000) - Presence of NE and ENE trending fractures
East African Rift System	Extensional structures trend N-S, ESE and ENE in the Lebombo Monocline as well as ENE and WNW in the Limpopo area
Notwani Sector of Botswana (Fig. 2.4) (Karoo)	Bounded to the south by an east-northeast trending lineament
Palapye Sector Botswana (Fig. 2.4) (Karoo)	NW or W-NW trending fault zones bounding both the northeastern and southwestern flanks of the sector
Ellisras	Lineaments mainly trend towards SE to ESE, NE to ENE, E-W and WNW to NW directions.

Possible scenarios for the formation of the Ellisras Basin

Arnott and Williams (2007) find that the coalfields of the Ellisras, Mmamabula and Mopane coalfields (Fig. 1.3) developed within the greater intracratonic Soutpansberg trough, which was re-activated during late Permian to early Triassic times; this viewpoint correlates with the work of Siepker (1986) who discusses continuous tectonic activity occurring within the mentioned timeframe, as further outlined in text below. The findings of this thesis support this view of continuous tectonic activity during most of the Ellisras basin-fill.

Siepker's (1986) assumption is that the Ellisras Basin represents part of a pre-Karoo glacial valley infilled by Karoo strata. According to Siepker (1986) the northern part of the basin, underlain by ultramafic rocks of the Limpopo mobile belt (c. 3.3 Ga – 2.0 Ga), with granites, gabbros and norites of the Bushveld Igneous Complex (c.2.05 Ga) to the east, represents an inferred palaeohigh (Siepker, 1986). The quartzites and conglomerates of the Waterberg Group (c. 2.05 – 1.8 Ga underlying the Karoo succession to the south represent a palaeolow area within this model.

In addition, being essentially a fault-bounded basin (MacRae, 1988), an increase in sediment loading–related subsidence of the Ellisras Karoo Basin due to deposited material may have also contributed towards the re-activation of the bounding faults during subsequent higher Karoo sedimentation. The inferred repeated tectonic instability can also be noted through the changes in the perceived energy levels of the depositing media of the Ellisras basin-fill, from the early Carboniferous period, as already indicated by Siepker (1986). MacRae (1988) suggests that the sediment accumulation in certain sections of the Ellisras Basin was indicative of periods of palaeoslope rejuvenation resulting in sandstones, grits and minor conglomerates, alternating with periods of stasis when extensive coal seam deposition occurred. MacRae (1988) discusses the possibility of basin subsidence creating a wet environment conducive to the formation of marshy areas, and once subsidence slowed coal seams were formed. However, the coal isopach maps produced here suggest that deposition of coal was uneven, reflecting variable accommodation space for coal across the basin, and pointing to the possibility that tectonism and uneven basin floor subsidence remained active even during coal deposition. It should also be remembered, in this context, that the thickest coals, those of the Grootegeluk Formation, essentially comprise interlayered coal and ash beds, and the numbers 1 and 2 coal seams also have significant non-coal beds within these coal successions. This continued deposition of clastic sediment, which presumably interrupted deposition of coal, suggests that clastic sediment inflows were ongoing throughout coal formation, and this can logically be tied to an active tectonic setting for the entire basin and its Karoo history.

In Siepker's (1986) depositional model, the following outline of sequential geological events is made of the Basin's possible history:

1. Sedimentation within most Karoo-aged basins throughout southern and eastern Africa began during the Late Carboniferous (Bumby and Guiraud, 2005). The base of the Karoo succession of the Ellisras basin (Dwyka Group) consists of diamictite in the northern part of the basin and muddy rhythmite towards the south. The inference is that ice with moraine entered the basin essentially from the north, and that proximal coarse tillite was deposited along the northern part of the basin, with finer, muddy rhythmites being laid down to the south, possibly in a lacustrine setting (cf. Miller, 1996). Although this depositional scenario in the Siepker (1986) model may support Siepker's assumption that the early basin was a pre-glacial valley, it does not really support any specific mode of early "valley" (cf., basin) formation. Intraplate stresses related to the Main Karoo foreland system may have re-activated or otherwise modified basement or cover structures and could have led to structural re-activation and basin initiation, as outlined in the Catuneanu et al. (1998, 2005; see also, Bordy, 2000) model, in concert with Miall's (2000) thoughts on intraplate stresses. This also supports Arnott and William's (2007) view that the (greater) Soutpansberg trough (which, in their view, includes the Ellisras and Mmamabula coalfields) was re-activated during the late Permian, a time period near the estimated deposition time of the Dwyka Group, through to the early Triassic era.
2. In the Phanerozoic time period, Africa (and Gondwana) migrated from the South Pole northwards towards approximately its present latitude and the fill of preserved basins reflects a concomitant change in palaeoclimate (e.g., Bumby and Guirard, 2005). The formation of a swamp environment contributed towards the

deposition of No.1 Coal seam in the Ellisras basin. One may also assume that there was little tectonic activity during this specific period, as coal requires a stable environment to form. The No. 1 Coal seam thickens gradually towards the south of the preserved basin, with a possibly tectonically controlled area of greater subsidence accumulating more coal in the west of the basin (Fig. 4.6). The trending of fluvial channels, represented by sandstone units within the No.1 Coal seam was E-W (Siepker, 1986). This concurs with Bordy's (2000) description of depositional environments and palaeo-drainage patterns, which also trend towards the E and NE to WSW within the Tuli Basin's Ecca Group. This coal seam deposition was followed by probable tectonic activity (or, alternatively, climate change) as indicated by a thin laterally extensive coarse-grained sandstone unit. One condition necessary for the increase in transporting current strength is a change in slope possibly caused by tectonic uplift of source area or downthrow of distal depositional terrain (e.g, faults). What followed next was the deposition of mudstone, indicating a calmer environment that allowed for the settling of finer particles, out of suspension. Overlying this formation is coarse-grained sandstone (Siepker, 1986) (Table 1.1), which requires a high-energy environment for deposition, thus indicating a resumption of tectonic activity followed by a more stable environment as indicated by the deposition of a coal seam- the No.2 Coal seam, as also indicated by Siepker (1986).

3. As with the first coal seam, the second was also related to east-west trending fluvial channels (Siepker, 1986). It is interesting to note though, as observed in Table 5.1, an increase in inferred influence of magnetic lineaments, and thus possibly also in tectonic activity, during the deposition of the coal layers. In the centre of the basin is another possibly tectonically controlled area of greater subsidence, indicated by thicker coal seams (Fig. 4.8). Structural lineaments seem to create distinct borders around this subsided area with a sharper change in coal thickness seen towards the western border

of the area. This may indicate more complex tectonic movement than that shown by east-west fluvial trends noted by Siepker (1986) and MacRae (1988).

4. Deposition of the Grootegeluk Formation is considered to have occurred in a period of basin infilling and poor drainage, together resulting in the deposition of a 100m thick interlayered coal and mudstone succession. The mud was most likely introduced into the basin from an external source in cyclicity with the deposition of coal, as a result of cyclic basin subsidence and/or periodic mud input (Siepker, 1986). This external source may have been situated towards the north of the basin (palaeohigh) and deposited in a southerly direction (palaelow) - this is indicated by the thickness changes of coal towards the south of the basin, as seen in Fig. 4.4. The Grootegeluk coal seams also possibly had a tectonically controlled area of greater subsidence accumulating more coal in the west of the basin, as with coal seam No. 1 (Fig. 4.4). These observations from the isopach maps point towards active structural movements along the S to SW section of the preserved Ellisras Basin. The trend is also visible in Fig. 4.3 (showing total Grootegeluk Formation thickness).
5. The Molteno Formation consists mainly of sandstone and indicates a steeper palaeoslope with accompanying high energy levels due to renewed uplift (Siepker, 1986).
6. The Elliot Formation indicates a gentler palaeoslope with a decrease in energy levels. This is shown by the presence of fining-upward sandstone units with mudstone or siltstone at the top (Siepker, 1986).
7. The Clarens Formation consists of a 100m thick, medium to coarse-grained, massive, well sorted sandstone with single pebble veneers scattered throughtout the formation and is mainly interpreted by Siepker (1986) as being mainly of aeolin origin.
8. Volcanism in the Drakensberg Formation terminated deposition in the basin. The Daarby Fault was active after the deposition of the

volcanic material, as in the east, one section of the fault has left the basalts intact (Siepker, 1986).

The Ellisras basin was created in an area known to have structural lineaments that were cyclically re-activated over time, such as the Melinda fault (Jansen, 1982), Zoetfontein fault (Brandl, 1996) as seen in Table 5.3, as well as the Sunnyside Shear Zone (Brandl, 1996). These ancient (Archaean-Palaeoproterozoic) lineaments were most probably influenced by the tectonic instability caused by tectonic activity such as remobilisation of the Limpopo Belt (at c. 2.0 Ga; Bumby and van der Merwe, 2004), or the intrusion of the Bushveld Complex (c. 2058 ± 0.8 Ma; Buick et al., 2001), which are considered to have been active just prior to early Waterberg deposition (Jansen, 1982; Barker et al., 2006), as well as by the creation of the Soutpansberg Trough. Movement along the Limpopo Mobile belt as tectonic re-activation due to continuous tension in the Karoo era in the Soutpansberg and Limpopo fault zones occurred, controlled the formation of the Karoo sediments and finally acted as conduits for the extrusion of basalts which terminated the Karoo era (Barker, 1983). Figs. 4.3 to 4.6 clearly indicate a continuation of these movements during the deposition of coal in the basin. These figures provide an indication that coal can be deposited in tectonically active areas, provided there is a lull in activity, thus, allowing for the breakdown and diagenesis of carbonaceous material. Studies have indicated that east-northeast - trending fractures have been rejuvenated in post-Karoo times (Barker, 1983). Other studies have concluded that the coal/sandstone accumulations (specifically referring to the Coal seams 1 to 4) were indicative of periods of palaeoslope rejuvenation with a transport direction towards the east (McRae, 1988). This palaeoslope rejuvenation may also indicate, as mentioned by Siepker (1986), that material was most likely introduced into the basin from an external source as a result of cyclic basin subsidence and/or periodic mud input. Figs. 4.3, 4.4, 4.5 and 4.6 also indicate what could be a localised fluvial trend from north to south and/or southwest which also existed during coal deposition, perhaps showing that fluvial flow may have also existed in other directions besides that of the generally accepted E-W trend.

This thesis has studied previous literature on neighbouring Karoo basins with the sole aim of relating it to the Ellisras Basin’s development through time. The isopach maps are in agreement with most of the findings noted in previous work on the Ellisras Basin and strongly show that there was considerable tectonic instability during depositional processes in the basin. The results of this thesis, with regards to structural lineaments exposed by the isopach maps, have correlated well with similar linear trends seen in Dr. S. Fourie's visual summary (Fig. 5.1) of anomalous magnetically defined linear features within the preserved basin. These isopach maps confirm the opinion that the basin was formed during a period of constant and cyclical tectonic movement.

The thesis' cross-section profiles of the basin show a close relationship between the Ellisras basin and the related Karoo basins as well as the basin's extension into Botswana- located in the Mmamabula East area- in terms of the typical graben structures indicating that the Ellisras basin was also affected by the compressions and extension episodes already documented in this thesis. The cross-section drawings have also given an indication of the relative thicknesses of the Vryheid and Grootegeluk Formations throughout the basin, from east to west, including the coal seams situated in each formation. In addition, they have also shown typical signatures of basins as indicated by the tendency of the Ellisras basin to thin out towards the outer edges. Further studies done in this thesis also show an almost similar deposition of similar formations for each neighbouring Karoo Basin. The basins show similar depositional cycles as seen in the Main Karoo Basin, starting with the Dwyka (glacial period) to the Drakensberg volcanic time period. Save for a few differences, the thesis was able to show that this pattern held well for the Karoo basins.

The main area of difference in thought is with Siepker (1988) who indicated that the Goedgedacht Formation was mainly deposited only in the southwestern sections of the basin. Further study has shown that the formation is found throughout the basin from west to east. This point can be observed in Siepker's own work as seen in his thesis' Fig. 5.33, where depth/thickness measurements are given for the Goedgedacht formation all the way to the east of the Ellisras Basin.

Table 5.3: Structural activity which may have influenced and controlled the development of the Ellisras Basin

Main Structural Events	**Stratigraphic Group/Age**	**Comments**
Limpopo Mobile Belt (LMB)	Archaean Eon/ approx 3300 Ma to c. 2.0 Ga	Considered as (1) a product of a late collision between the Zimbabwe and Kaapvaal cratons (Light, 1982; van Reenen, 1987; De Wit, 1992; Roering et al, 1992; or (2) major transpressive tectonic event (Kamber et al, 1995; Holzer et al, 1998). Despite extensive studies in this area there is still no consensus about the geological processes that formed this province, their timing or geotechnical setting (Johnson et al., 2006). East to west trend.
Palala Shear Zone (PSZ) and Mahalapye Straightening Zone (MSZ)	Limpopo Mobile Belt/ active shortly before and during emplacement of 2058 Ma Bushveld Complex- ceased before 2042 Ma (Brandl, 1996).	PSZ separates the (LMB's) Southern Marginal Zone from the Central Zone and is also the northern boundary of the Waterberg Basin (as well as of the Ellisras Basin)- Callaghan, 1987. The PSZ is possibly an intracratonic transpression zone (crustal convergence whereby rocks can be faulted upward to form a

Main Structural Events	Stratigraphic Group/Age	Comments
		positive flower structure) caused by oblique SMZ/Kaapvaal Craton-CZ convergence (Brandl, 1996). It has a sub-horizontal mineral-elongation lineation trending ENE and is left lateral with up to 100km of displacement. It probably continues to the west as the MSZ.
Triangle (TrSZ) and Magogaphate (MSZ) Shear Zones	Limpopo Mobile Belt (Post-Bushveld)	Contact point between the Central Zone and the Northern Marginal Zone. Both the PSZ and MSZ are considered by Van Reenen (1987) to have been formed by post-Bushveld Complex lateral shearing within the LMB. The TrSZ seems to have an ENE trend whilst the trend for the MSZ is approx E-W.
Beitbridge Complex	Limpopo Mobile Belt	Supercrustal rocks within the Central Zone, LMB
Palapye Sector Faults	Post-Waterberg	These faults are located in the northeastern and southwestern flanks of the Palapye Sector and trend northwest or west-northwest (Crocket and

Main Structural Events	**Stratigraphic Group/Age**	**Comments**
		Jones, 1974)
Zoetfontein and Melinda Faults	Zoetfontein Fault (active from post-Waterberg to post-Karoo era, Crocket and Jones, 1974). Melinda Fault (post-Palala Shear Zone) Bumby, 2000.	Situated in northern margin of Ellisras Basin. Reactivated along common structure, which was active during pre-Karoo times but not during Karoo deposition (Brandl, 1996). Zoetfontein has downthrow to north and Melinda has downthrow to the south (Brandl, 1996). Melinda Fault is a representation of the late re-activation of the Palala Shear Zone. Zoetfontein Fault shows movement between the ages of post-Waterberg and pre-Karoo, as well as during a post-Karoo period. It also shows a syn-Waterberg presence of a fault scarp (Crocket and Jones, 1974). Both faults have ENE trend, Brandl, 1996.
Eenzheimheid		Downthrow to the north, up to 250m (Brandl, 1996). Trends in E-W direction.
Daarby Fault	Fairly recent, displaces Triassic formations as seen	Up to 300m downthrow near GCM **(=??)** (Brandl,

Main Structural Events	**Stratigraphic Group/Age**	**Comments**
	on 2326 geological map.	1996). Has western northwest trending branch and eastern, east-northeast striking branch (Brandl, 1996).
Abborttspoort and Beaufort Shear Zones	Re-activated in pre- and post-Karoo eras (Brandl, 1996).	Ductile structure, left lateral as with the Beaufort Shear Zone (Brandl, 1996). Both shear zones seem to have E-W trend.

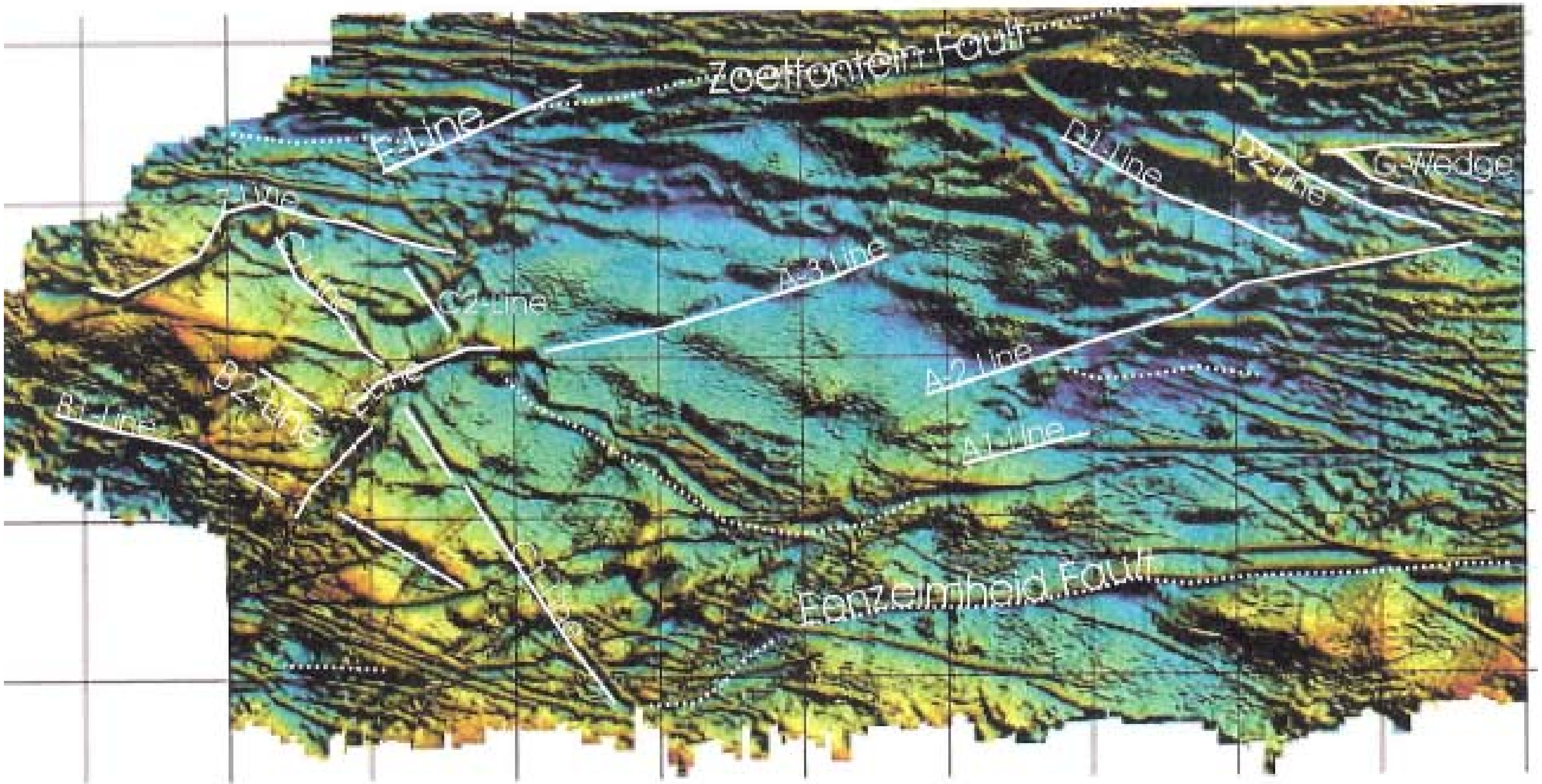


Figure 5.1: Outline of Lineations in Ellisras Basin, adopted from work by Fourie (2008)

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