THE GEOLOGY OF THE SPRINGBOK FLATS

by

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Abstract

The Springbok Flats constitutes an extensive tract of generally flat country extending from south of Bela Bela north-eastwards to Zebediela Location. This area is located within 28°00´ and 29°30´ east and 24°15´ and 25°30´ south with a total areal extent of approximately 8 000 km^2.

A comprehensive exploration programme commenced in 1976 and was completed in 1982. During the exploration programme 3 000 boreholes were drilled. These borehole data was re-interpreted in conjunction with downhole geophysical surveys in order to create a sedimentological database suitable for the reconstruction of palaeo-environments of the Karoo-aged strata in the Springbok Flats Karoo Basin (SFKB).

Structurally the SFKB comprises two elongated basins i.e. Roedtan Basin (north) and Settlers-Tuinplaats Basin (south). These two basins are bordered by pre-Karoo aged tectonic features i.e. Thabazimbi-Murchison lineament (northern boundary of the Roedtan Basin) and the Droogekloof Fault Zone (northern boundary of the Settlers-Tuinplaats Basin). These tectonic features were continuously active after the deposition of the Karoo strata in the SFKB resulting that the existing SFKB is considered to be a preserved Karoo-aged basin.

Stratigraphically the SFKB was subdivided into 7 distinctive lithostratigraphic units. Lithostratigraphic Unit 1 comprises glacier derived sediments and is correlated with the Dwyka Group of the Main Karoo Basin. Lithostratigraphic Unit 2 is a mega upward coarsening cycle resembling a deltaic deposit. This deltaic deposit is overlain by a cyclothem consisting of Lithostratigraphic Units 3 and 4 respectively. Lithostratigraphic Unit 3 is a composite coal zone. Based on selected seam horizons a coal zone resource of 3492 mt was demarcated. In areas adjacent to palaeotopographical highs uranium is associated with the coal

zone and a resource of 363.0 mt with an average grade of 0.40 kg/t U_3O_8 was calculated.

A prominent regionally developed disconformity marks the commencement of Lithostratigraphic Unit 5. A continuum of fluvial environments including alluvial fans, braided rivers, meandering river systems and anastomosed river systems was postulated as depositional environments for Lithostratigraphic Unit 5.

A lithostratigraphic unit, comprising basal calcrete conglomerates followed by intensely bioturbated siltstone and a lesser bioturbated sandstone respectively, constitutes Lithostratigraphic Unit 6. The texture and sedimentary structures of Lithostratigraphic Unit 7 which overlies Lithostratigraphic Unit 6 is compatible with a typical aeolian deposit. The termination of the Karoo-aged strata in the SFKB is marked by the presence of amygdaloidal basaltic lavas.

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Chapter 1. Introduction

1.1 Location

The Springbok Flats constitutes an extensive tract of generally flat country, extending from south of Warmbaths (Bela Bela) north-eastwards as far as Zebediela Location (Mellor, 1905). This area is located within 28º00' and 29º30' east and 24º15' and 25º30' south with a total aerial extent of approximately 8 000 km^2. The most important geological groups and intrusive rocks adjacent to and in the Springbok Flats Karoo Basin are summarized in Table. 1.1.

Table 1.1. Geological groups and intrusive rocks adjacent to and in the Springbok Flats Karoo Basin.

Geological group/intrusive rocks
Surficial deposits
Karoo Supergroup
Waterberg Group
Bushveld Igneous Complex
Transvaal Supergroup
Wolkberg Group

The most important towns, villages, roads, railway lines and drainage systems are depicted in Fig. 1.1. The recent changes in town names are reflected in Table 1.2.

Table 1.2. Town Names.

Old Name	New Name
Warmbaths	Bela Bela
Nylstroom	Modimohle*
Naboomspruit	Mookgophong

*Directly north-northeast of Nylstroom lies an isolated hill known as Kranskop, also referred to as Modimohle. Modimohle literally means “God has eaten” (Wagner, 1927). Prior to the advent of the white man, numerous human offerings, by chiefs of that part of the world, were conducted on the eastern and western sides of Kranskop.

1.2 Physiography

The Springbok Flats forms part of the Central Transvaal (Bushveld) Basin i.e. geomorphologic province 3 (King, 1967). Physiographically Wagner (1927) subdivided the Springbok Flats into four distinct areas i.e.

a) The Northern Springbok Flats
b) The Southern Springbok Flats
c) The Sand Bults
d) The Valley of the Nyl River

The Northern and Southern Springbok Flats are separated by the Sand Bults and are characterized by their level nature, the absence over vast areas of trees and scrub, the paucity of rock outcrops, the almost entire lack of well-defined water courses and the peculiar black and red soils (Wagner, 1927).

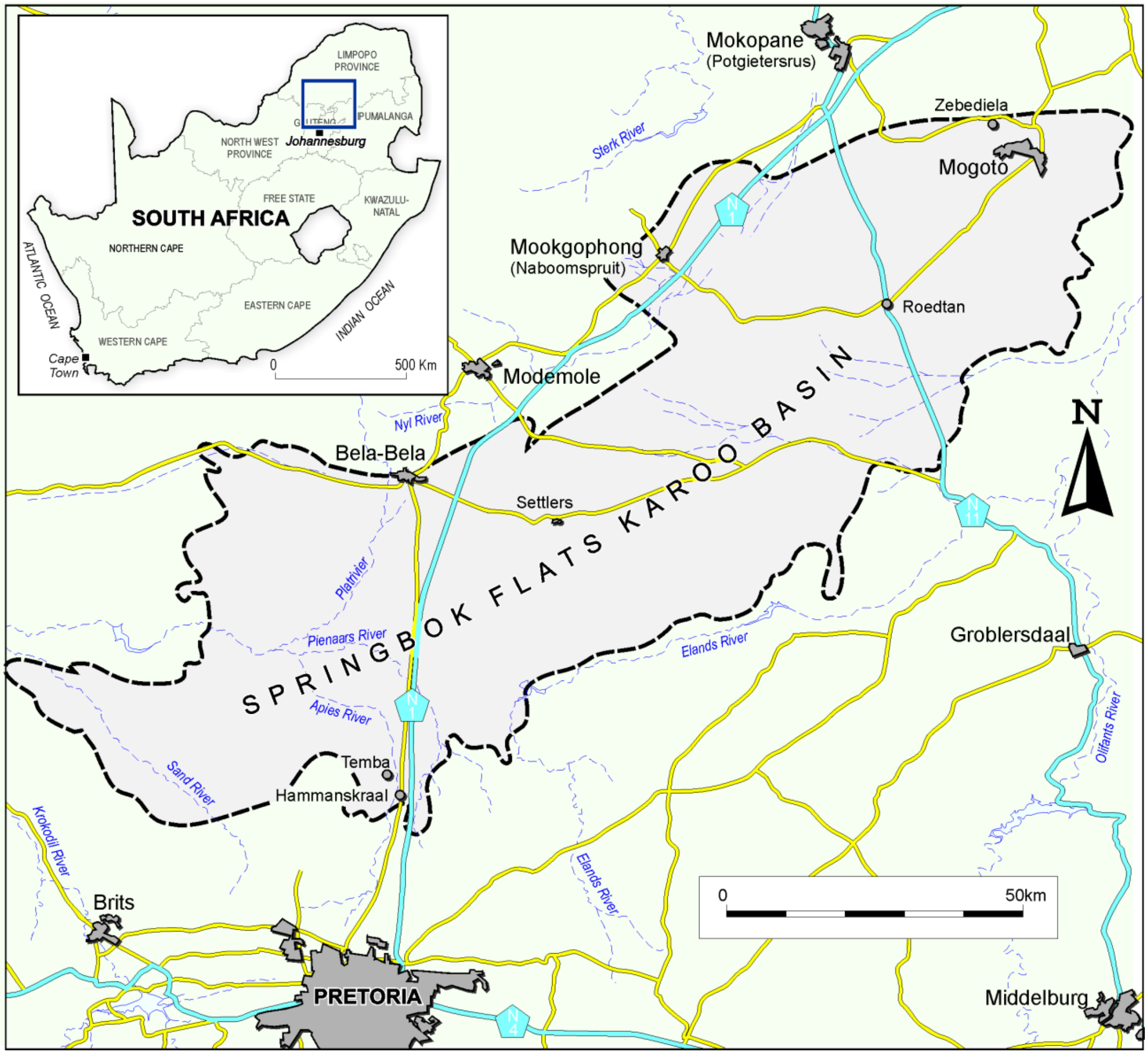


Fig. 1.1. Locality map of the Springbok Flats Karoo Basin.

Grasslands mark the areas occupied by black and red turf soil and are normally devoid of trees but support an abundant growth of dwarf, bush-like acacias such as *A. permixta* and *A. natalikia*. In certain areas belts of trees i.e. *A. litakonensis*, *A. spirocarpoides* and *A. benthami* traversed the underlying black soils.

1.2.1 Northern Springbok Flats

The elevation of the Northern Springbok Flats varies between 1036 and 1113 meters above mean sea level. The area has a general slope towards the Olifants River drainage system in the east. This area is interrupted, but not influenced, by the Valley of the Nyl River. The Northern Springbok Flats is a typically peneplain, traversed by an ancient river i.e. Nyl River (Wagner, 1927).

The Northern Springbok Flats is bounded by the Zebediela Fault in the west-northwest. This fault (refer Chapter 3) is pre-Karoo in age and possibly still active, based on earthquake activity occasionally noticed in the area and in Modimohle.

1.2.2 Southern Springbok Flats

Topographically the Southern Springbok Flats show somewhat greater relief than the Northern Springbok Flats as several topographically elevated areas traversed the area towards the south. The general elevation is more or less the same as the Northern Springbok Flats.

The Elands River and the Pienaars River border the Southern Springbok Flats in the east and south respectively, resulting in topographical slopes towards these drainage systems.

The most striking features of both the Northern and Southern Springbok Flats are the absence of well defined water courses and the complete absence of pans. Although the topography seems to be very flat, topographical undulations occur occasionally. Without detailed surface measurements it becomes impossible to state in which way water will flow or where culverts should be constructed. The absence of pans is assigned to the nature of the soils encountered. The soils are mainly heavy clay soils and when properly saturated with water, dry extremely slowly to form a surface deposit resistant to disintegration by deflation (Wagner, 1927).

1.2.3 The Sand Bults

The Sand Bults occur as an elevated area i.e. 15 – 60 m above the adjacent plains. The Sand Bults occur along the strike of an anticlinal flexure that separates the Northern and Southern Springbok Flats (refer Chapter 3).

The Sand Bults are well timbered supporting vegetation of seringe, vaalbosch, dikbast and marula trees. The Sand Bults are characterised, other than the adjacent flats, by the presence of pans. The sandy soils associated with the Sand Bults, when dry, are incoherent and will be influenced by wind erosion, resulting in the formation of pans (Wagner, 1927).

1.2.4 Valley of the Nyl River

The Valley of the Nyl River is the most striking topographical feature of the Springbok Flats. The confluence of the Great Nyl and its main tributary the Little Nyl River occurs between Bela Bela and Modimohle. Before the confluence both rivers depict ordinary features of the Waterberg area i.e. “broad, flat-bottomed, grass covered depressions” (Wagner, 1927). Below the confluence the Nyl River Valley is characterised by a shallow marsh with fairly well defined water courses. Towards the north-northeast the Nyl River Valley is barely incised below the level of the adjacent country. Well defined water courses are replaced by marshes except after heavy rain when nearly the whole valley is transformed into an enormous sheet of sluggish shallow water. During the late 1970’s, the width of the Nyl Valley east of Naboomspruit, was measured to be 3.5 km after a long period of seasonal rains.

Three causes (Wagner, 1927) probably contributed to the creation of the Nyl River Valley:

a) Faulting – Zebediela Fault
The Nyl River Valley attains its maximum width in areas where the Zebediela Fault depicts its maximum displacement. If this hypothesis is relevant, it presupposes that the Nyl River was influenced during tectonic activities along the Zebediela Fault.

b) Disintegration of Clarens Formation
Weathering of the Clarence Formation which the Nyl River traverses, could have resulted in the overloading of the river by sand. According to Wagner (1927) such overloading is incapable in itself of giving rise to a feature like the Nyl River Valley.

c) Changes in geology
Towards the north (south of Moorddrift) the geology of the floor rocks which the Nyl River traverses, changes from Karoo Strata to norites of the Bushveld Igneous Complex. Due to the more resistant nature of norites to erosion, a decrease in incision velocity of the Nyl River occurs in the area underlain by norites.

Practically the rate of erosion along the Nyl River is very low. If the postulated subsidence along the Zebediela Fault is still in progresss and accompanied by the incision resistance of the norites, the possibility that the Nyl River may seek a new course towards the east of Moorddrift, cannot be excluded.

1.3 Historical Research

Historical geological research in the SFKB was hampered due to a lack of surface outcrops, such that early publications mainly dealt with outcrops belonging to the Clarens Formation (Bushveld Sandstone). The first published geological map of the Springbok Flats was compiled by Dr. G.A.F. Molengraaff in 1902. On this map only the outcrop area of the Drakensberg Group (basaltic lava) is indicated. In 1905 and 1907 Mellor and Kynaston respectively published the results of research pertaining to the sandstones of Buiskop (east of Bela Bela) and notes on the correlation of the Bushveld Sandstone (Clarens Formation) and the overlying volcanic rocks (Drakensberg Group). In 1927, Wagner reflected on the borehole results obtained from two boreholes drilled on Diepsloot and Ludlow respectively. None of these boreholes intersected the coal bearing strata of the Springbok Flats Karoo Basin. Du Toit (1939) published a comprehensive stratigraphic column of the Karoo Supergroup in the Springbok Flats Karoo basin, based on borehole data obtained. The first comprehensive geological report regarding the geology of the Springbok Flats Karoo Basin was compiled by Visser and Van der Merwe (1959). Borehole data obtained from 27 boreholes drilled in the north eastern sector of the Springbok Flats coalfield was used to compile the report. During the period 1970 – 1973 the Geological Survey of South Africa (now Council for Geoscience) conducted further investigations in order to attempt to correlate the various coalfields of the Northern Province. Recent investigations by the author proved some of these correlations to be inaccurate.

Since 1973, General Mining and Finance Corporation Ltd (Gencor, Trans Natal Coal Corporation later Ingwe Coal Ltd) conducted a large scale exploration programme covering the entire Springbok Flats Karoo Basin. The author of this dissertation was appointed in 1977 as an exploration geologist by Trans Natal Coal Corporation. The responsibilities of this appointment included geological exploration and evaluation of the coal and uranium deposits encountered in the Springbok Flats Karoo Basin. More than 3 000 boreholes were drilled. The data derived from this programme was used for the purpose of this study.

1.4 Present Reseach

In 1979 Trans Natal Coal Corporation approved a request to use the borehole data of the Springbok Flats exploration programme for post graduate studies. However, in 1982 a moratorium was placed on the utilization of geological data for this research due to the sensitive nature of data relating to the presence of uranium in the coal. The project was shelved until 2005 when Ingwe Coal Pty Ltd requested to proceed with research in order to meet the requirements of the Department of Mineral and Energy Affairs pertaining to uncommitted resources. During 2005 Ingwe Coal Pty Ltd sold all the borehole data of the Springbok Flats to Holgoun Energy (Pty) Ltd. In 2007, Holgoun Energy (Pty) Ltd agreed to make the borehole data available for further research. Direct involvement in the Holgoun Energy (Pty) Ltd exploration programme, as a consulting geologist, meant that the old data could be verified and adapted according to the latest sedimentological research findings.

Since 1973 all the exploration boreholes were lithologically described utilizing a suite of downhole geophysical logs. All coal and uranium intersections were sampled and submitted to accredited laboratories.

During the period 1973 – 1982 a variety of geologists were employed by Trans Natal Coal Corporation. A large number of borehole descriptions reflects the personal flavour of certain geologists resulting that in some borehole data being only general descriptions and thus of little use in sedimentological research. During the exploration programme an attempt was made to drill at least one borehole per property under option to Trans Natal Coal Corporation. Based on the results obtained from this exploration drilling, targets were generated. Coal target areas were explored on a 1 km x 1 km drilling grid and the uranium target areas on a 500 m x 1 km drilling grid resulting that geological data is clustered and concentrated in the economically viable areas. Very little geological data pertaining to the sub-outcrop areas of the Karoo Supergroup are available due to the low economic potential of these areas. At least 1000 boreholes were personally described and/or revised using all available geophysical and analytical data. The personal information acquired, does not form part of the geological data available to the public domain. Any research, based on data other than the mentioned verified data, becomes futile as most of the borehole data does not reflect details relevant to sedimentological research.

Chapter 2. Exploration Techniques applied in the Springbok Flats Karoo Basin

2.1 Drilling

The main exploration technique that was applied during exploration for coal in the SFKB was NX and NQ sized diamond core drilling. In order to obtain larger samples, several 123 mm diameter core boreholes were also drilled.

In addition, approximately 300 non-directional deflections were also drilled in the uraniferous coal areas where the original boreholes yielded a radiometric uranium grade in excess of 0.20 kg/t. The deflections started ± 100 m above the coal zone. These coal zone intersections were stored for analyses i.e. geotechnical investigations, trace element analyses of coal ash, grindability, abrasiveness, and disequilibrium tests were conducted on some of these deflections.

The 123 mm drilling was completed in four stages. All these boreholes were drilled next to existing boreholes, which were carefully selected in order to obtain representative samples from the Settlers-Tuinplaats Coal Field. The coal samples from the first three stages were submitted to laboratories both local and international for liberation and liquefaction tests. Some of the cores recovered during stage four were stored underwater at company laboratories, for future research purposes.

Table 2.1 summarizes the total number of boreholes and deflections drilled in the different basins.

Table 2.1. Summary of boreholes drilled during the exploration program (1974 – 1982). Grand total: 1774.

*Percussion boreholes

Proposition	Number of boreholes drilled		
	NQ + NX original	Deflections	123 mm
Settlers-Tuinplaats and Roedtan Basins	1197	324	50
Warmbaths	43	—	—
Regional*	± 200	—	—
Total	1400	324	50

In addition to the abovementioned ± 700 exploration boreholes were drilled by Amcoal and J.C.I. All the borehole data was used to determine the geological history of the Springbok Flats Karoo Basin.

2.2 Geotechnical investigations

In order to predict the behaviour of the rock material during coal mining operations several geotechnical investigations were conducted by Dr. H. Olivier (Keevey, Steyn and Partners, Consulting Engineer, Internal Report).

The geotechnical studies revealed that the geomechanical behaviour of the rock masses during mining operations would be influenced by the rock material properties of the argillites, in particular the durability of Lithostratigraphic Unit 4 (refer Chapter 7). The assessment of rock durability showed that the majority of mudrocks that were tested had poor to very poor durability ratings.

During the exploration programme diamond drill cores were logged geotechnically in order to arrive at a more quantitative definition of the engineering properties of the Karoo strata. The following parameters recommended by Mr. R. Whate (Engineering geologist at the Chamber of Mines) were recorded on a routine basis:

a) Core loss

b) Fracture Frequency – the number of fractures in the core were counted for each defined lithological unit e.g.

$$\text{Fracture Frequency} = \frac{\text{Number of fractures per unit}}{\text{Total length of unit}} \times 100\ \%$$

c) R.Q.D – Rock quality designation. Within each defined lithological unit the R.Q.D was calculated by:

$$\frac{\text{Total length of pieces of core} < 0.10\text{ m in length}}{\text{Total core length recovered}} \times 100\%$$

d) Rock quality – a semi-quantative observation on the rate of breakdown of the rocks after exposure to the atmosphere. This rock quality is rated from 1 (good rock) to 4 (poor rock).

In addition to the above parameters, 10 meters of the immediate roof of the coal zone and the coal zone were photographed in order to preserve a permanent record of the condition of the core, prior to sampling. Only 150 boreholes were recorded in this manner.

2.3 Downhole geophysical surveys (wireline logging)

Wireline logging of completed boreholes was conducted by the utilization of downhole free hanging geophysical equipment. The purpose of these surveys was to assist in lithological descriptions, identification of lithological boundaries, the accurate determination of lithological thicknesses, identification of facies changes, the demarcation of uraniferous horizons associated with the coal zone and borehole correlations.

During the exploration programme in the SFKB the following geophysical surveys were continuously conducted in every borehole and where applicable in deflections:

a) Gamma Ray and Gamma Ray detail
b) Short spaced and long spaced density
c) Bed resolution density (BRD)
d) Caliper
e) Neutron – Neutron

2.3.1 Gamma ray surveys

The measurement of natural radioactivity in sediments and other geological formations has long been used as an indicator of different lithologies. High gamma ray levels in sediments are due to high levels of an isotope of potassium (K_{40}). In the SFKB the presence of uranium in the coal contributes to the majority of the radiation emitted.

Gamma ray equipment measures the total abundance of radioactivity and is calibrated to read in API units. One API unit is defined as $1/200^{th}$ of the difference between the low and high activity zones in the American Petroleum Institute gamma pit at Houston.

The gamma ray detailed surveys were conducted over the uraniferous coal horizons only. This survey recorded not only the number of gamma rays, but also their energy. This allows the elemental concentration of uranium to be determined.

A calibrated gamma-ray sonde was utilized for this purpose. The calibration was conducted at a pit provided by The Atomic Energy Board (now Nuclear Energy Corporation of South Africa) at Pelindaba on a weekly basis. The curve produced by the calibrated sonde was integrated applying Hook's Law and by applying the calibration coefficient, the grade of uranium in kg/t was calculated. Certain problems have arisen in the calculation of uranium grades associated with high grade uraniferous horizons especially where these horizons constitute very thin (<0.05 m) mineralised coal bands. It was assumed that these problems resulted from the inability of the sonde to resolve very thin bands which have an extremely high uranium content (>10 000 cps).

2.3.2 Long spaced (LSD) and short spaced (SSD) density surveys

The sonde that was utilized during the LSD and SSD surveys comprises a gamma ray resource (usually Cs 137) and two gamma ray detectors, typically about 0.15 m (SSD) and 0.40 m (LSD) from the gamma ray sources. Both the source and detectors are heavily shielded and collimated in order to ensure that emitted and detected gamma rays travel through geological formations encountered in the borehole.

The volume of rock analyzed by the density sonde depends upon source to detector spacing and as thick lithologies do not require high resolution, it is advantageous to use the LSD for geological evaluations and regional correlations.

2.3.3 Bed resolution density (BRD)

A BRD survey is a high resolution short spaced (source to detector = 0.15 m) density measurement. The coal zone in the SFKB comprises alternating bright coal and carbonaceous shale. The density of bright coal is diagnostic from which the lithologies encountered in the coal zone could accurately be described by utilizing the measurements of a BRD survey.

In the SFKB, BRD surveys were only conducted over the coal zone. The BRD survey data was used to:

a) Calculate the actual depth and thickness of the coal zone
b) Describe the different coal lithologies encountered in detail

c) Determine the amount and position of core losses in the coal zone
d) Correlate the different coal seams associated with the coal zone on a regional basis

The single sonde probe that was originally used during early stages of the exploration was influenced by natural radiation, resulting from the uranium in the coal zone. This problem was partially eliminated by the introduction of a trisonde probe with a different configuration i.e. a shrouded detector and a stronger 10 millicurie source.

2.3.4 Caliper surveys

The caliper probe is a mechanical arm with a hardened tip that is driven open against a spring when the probe is drawn upwards. As the borehole diameter varies, the arm moves in and out causing changes in resistance within the variable resistor to which it is mechanically connected. The caliper survey is used for borehole size corrections and in quality control pertaining to other log curves where caving may prevent correct identification of geological and quality features.

2.3.5 Neutron-Neutron surveys

The neutron probe responds to hydrogen and to a lesser extent to carbon and is in many ways a confirmation of the gamma ray probe results. The readings obtained over shale are high due to the OH-content in mica and possibly some free water in the parting planes. Coal intersections also give high readings because of the hydrogen and carbon but are invariably higher than the reading over shale intersections.

The neutron survey is useful especially when uranium occurs in coal. The presence of uranium effectively masks both the gamma ray and the density responses obtained from other surveys. The log produced from a neutron survey is probably the best and most consistent curve for correlation except in very shaly lithologies. The neutron probe is not affected by caving in boreholes and can be used in cased or uncased boreholes. The borehole log produced from a neutron survey is such that the picture it shows is relatively simple without the elaborations and detail of certain other logs resulting in correlations being distinct and exact.

Experience has shown that the neutron log is probably the most useful all round log for interborehole correlations.

2.4 Resistivity investigations

2.4.1 Murdoch surveys

During the period 1976 – 1980 Murdoch Geophysics (Australia) (Pty) Ltd. conducted several electrical resistivity surveys in the Springbok Flats. This geo-electric technique was used as an exploration tool for:

a) regional mapping to locate potential coal basins
b) locating structural features such as faults, changes in dip and palaeotopography

In order to utilize the resistivity method effectively it was necessary to take into account the following inherent problems encountered during surveys:

a) The dominant effect of the superficial zone on the apparent resistivity recorded at depth
b) The suppression of thin layers at depth

Once the maximum effective depth of penetration is reached, the contrast of a thin layer is so poor that it cannot be recognized anymore due to instrument constraints.

Depth of effective penetration becomes a problem when the location of the following is required:

i) flat lying coal seams
ii) coal seams under thick basalt cover
iii) structural anomalies affecting only a seam and not the entire succession

Recorded evidence suggests that the maximum effective depth of penetration is 300 meters for most of the common mapping problems i.e. the identification of coal seams at depth.

In view of the above mentioned, Murdoch's surveys were unable to reveal the following:

a) depth of basement rocks
b) position and/or presence of the coal zone

The latter exercise proved futile due to the relatively thin nature of the coal zone and the fact that large areas of the Springbok Flats are covered by the basalts of the Drakensberg Group.

2.4.2 Council for Scientific Industrial Research (CSIR) resistivity survey

The CSIR also conducted a resistivity survey to establish the feasibility of the resistivity technique of deep electrical soundings to determine the structure of the Karoo Basin and the topography of the pre-Karoo floor in areas where the

Drakensberg Group reached considerable thicknesses i.e. north of Settlers and Roedtan.

The results obtained are summarized in a report compiled by geophysicist Dr. J.S.V van Zyl (1987). Follow-up drilling based on the results of this survey revealed some discrepancies regarding the actual thickness of the Drakensberg Group.

2.5 Track Etch investigation

During the course of the exploration programme, Track Etch surveys were conducted to delineate potentially uraniferous areas. The Track Etch cups were buried along certain main roads in areas where possible mineralisation was expected.

The only positive results obtained from this investigation were restricted to areas in the vicinity of sub-outcrops or outcrops of the Bushveld Igneous Complex rocks. These anomalies were caused by alpha particles and could not be detected in the deeper parts of the basin.

2.6 Photogeological interpretations

During 1976 Dr. R. Ruker (Dr. Richard Ruker and Associates, 1976) compiled a photogeological map for the Springbok Flats. Subsequent drilling revealed that predicted lithological contacts and outcrops of Karoo rocks were incompletely mapped due to extensively cultivated areas and dense vegetation.

2.7 Water survey

Several hundred water samples were collected from existing privately owned water wells over the entire Springbok Flats Karoo Basin in an attempt to delineate uraniferous coal areas.

The analytical data obtained from this exercise proved to be negative regarding the presence of uranium in underground water, the reason being that the well aquifers are not hydrologically connected with the uraniferous coal zone.

2.8 Ground Magnetometer survey (Roedtan)

To determine the exact position of a transgressive dolerite sill on the farms Klipgat 618 KS, De Bults Punt 582 KS and Platlaagte 615 KS several north-south magnetometer traverses were conducted.

In areas where the Clarens and Elliot Formations of the Stormberg Group of the Karoo Supergroup crop out, the position of the dolerite sill could be accurately determined. However, the position of the dolerite in areas where the Drakensberg Group outcrops, was not discernible. The reasons for this being that the magnetic susceptibilities for both dolerite and lava are of the same magnitude. Henceforth no distinction is possible between lava and dolerite.

2.9 Verticality surveys

In order to establish the horizontal deviation between a borehole and its deflection at the top of the coal zone a multishot directional survey instrument was used in four boreholes and their deflections. The wedges used during the deflecting operation were of the non-directional type with a deflection angle of ± 1.5°.

The data obtained from the survey are listed in Table 2.2. In the Settlers area the deviation from the original borehole to the deflected borehole varied between 2.50 m and 3.08 m from the vertical. Previous tests conducted with a multishot Eastmen instrument also showed an average (horizontal) deflection of 2.5 m per one hundred metres of vertical deflection drilling.

Table 2.2. Deviation at top of coal: original boreholes versus deflection.

Borehole number	Depth to top of Coal Zone	Starting depth of wedge	Distance of wedge above Coal Zone	Horizontal deviation at top of Coal Zone
CH 663/3	409.0 m	311.0 m	98.0 m	2.95 m
DA 672/4	322.9 m	213.0 m	109.0 m	3.08 m
DL 619/17	268.0 m	158.0 m	110.0 m	6.85 m
HA 642/12	474.0 m	365.0 m	102.0 m	2.50 m

2.10 Computer applications

2.10.1 Data capture

All the boreholes drilled in the Settlers-Tuinplaats Basin have been captured into a single database. Data capture included both abbreviated lithological logs and relevant analytical data.

Apart from the advantage of being able to recover clean validated data, the database was also used in the determination of constant ash products from regression analyses in the Settlers-Tuinplaats Basin.

2.10.2 Determination of constant ash products

Manually selected coal horizons formed the basis of product selections. Data for the selected horizons were fed into the computer which then calculated a weighted average for the samples concerned. However, it was necessary to regularize the analytical data for each sample before this step could be taken. Many of the samples had little or no washed coal analyses, and the multi linear regression analysis method was used to derive formulae which, in turn were used to calculate coal quality values.

Once the sample analyses had been regularized and the coal qualities for the selected horizon calculated, a washability matrix (equivalent to a washabililty curve) was calculated for each coal seam. On the basis of this matrix it became possible to select constant ash products and report the yield and coal qualities for such products.

Chapter 3. Geological structure of the Springbok Flats Karoo Basin

3.1 Introduction

There is a well-known axiom in geology that the style of crustal deformation is often controlled by pre-existing structures, or in short, “old faults never die” (Silver et al., 2004). Crustal faults can be reactivated many times within the context of changing stress regimes. The Thabazimbi-Murchison Lineament/Shear Zone (TML) is one of the world’s best examples of such reactivations over time. The Thabazimbi-Murchison Lineament (TML) is characterized by fault-tectonic reactivation exhibiting normal, strike-slip and reverse faulting (Good and De Wit, 1997).

The TML is a prominent tectonic feature located towards the northern periphery of the Kaapvaal Craton. The TML commenced ~2.9 Ga ago and remained active until the Cenozoic Era. The TML constitutes a major Archaean terrain boundary on the Kaapvaal Craton as well as the northern boundary of the Springbok Flats Karoo Basin.

Tectonic events associated with the assembly of the Kaapvaal Craton impacted directly on the development and sedimentation associated with the Karoo Supergroup in Southern Africa.

3.2 Major tectonic events that affected the Kaapvaal Craton

A summary of the major tectonic events that impacted on the evolution of the Kaapvaal Craton over a period of ~3.1 Ga is presented in Table 3.1.

Table 3.1. Major tectonic events that impacted on the evolution of the Kaapvaal craton (McCarthy and Rubidge, 2005; Partridge et al., 2006; Watkeys, 2006; Catuneanu et al., 2005; Taljaard, 1948; exploration drilling results).

3100 Ma (Eon:- Archaean, Era:- Swazian): Most of the Kaapvaal Craton is stabilised but continued growth may have occurred at possible subduction zones on its northern en western margins.
2900 Ma (Eon:- Archaean, Era:- Randian): Subduction along the Kaapvaal Craton's northern margin led to compressional forces that activated large faults in the interior of the Kaapvaal Craton. These faults include the TML (Fig. 3.1.).
± 2714 - 2700 Ma: Collision between the Kaapvaal Craton and the Zimbabwe Craton took place at the Kaapvaal Craton's northern margin.
2650 Ma (Eon:- Archaean, Era:- Randian): Rifting of the Kaapvaal Craton occurred along old fractures in the crust (TML and Sugarbush Fault). The trough that formed was subsequently filled with Wolkberg sediments.
± 2060 (Eon:- Proterozoic, Era:- Vaalian): The Bushveld Complex commenced with the initial eruption of Rooiberg Lavas.
± 2023 Ma: Vredefort impact?
2000 - 1900 Ma (Eon:- Proterozoic, Era:- Mokolian): Sediments of the Olifantshoek Supergroup accumulated along the western side of the Kaapvaal Craton.
1900 - 1800 Ma (Eon:- Proterozoic, Era:- Mokolian): The rocks of the Olifantshoek Supergroup became folded and thrusted towards the east. This may be the result of the Ubendian event, a compressional event possibly linked to the collision of the Congo craton with the Kaapvaal-Zimbabwe Craton. The resulting metamorphosed area on the western side of the Kaapvaal Craton is known as the Kheis Province. The continental crust created along the western margin of the Kaapvaal-Zimbabwe Craton is known as the Ubendian belt (McCarthy and Rubidge, 2005).

1900 - 1700 Ma (Eon:- Proterozoic, Era:- Mokolian): The Waterberg and Soutpansberg groups formed on the Kaapvaal Craton. The interior of the Kaapvaal Craton may have developed rifts due to the collision with the Congo Craton. These rifts formed the depositories of the Waterberg and Soutpansberg Groups. Activation of structures like the TML, Palala Fault and maybe the Sugarbush Fault had a large influence on the Waterberg Group's development and aerial extension.
1600 - 1400 Ma (Eon:- Proterozoic, Era:- Mokolian): Rifting along the Ubendian belt between the Kaapvaal-Zimbabwe Craton and the Congo Craton occurred.
1100 Ma (Eon:- Proterozoic, Era:- Mokolian): Widespread intrusions of dykes across the Kaapvaal-Zimbabwe Craton (Timbavati gabbros and Umkondo Dolerites) occurred. The seas that formed (Ubendian rifting, 1600 - 1400 Ma) between the Kaapvaal-Zimbabwe Craton and Congo Craton and across Bushmanland terminated.
700 - 500 Ma (Eon:- Proterozoic, Era:- Namibian): Gondwana assembled. At about 700 Ma rifting occurred again between the Kaapvaal-Zimbabwe Craton and Congo Craton, as well as across the Namaqua-Natal Belt. 500 Ma ago, these rifts closed.
450 Ma (Eon:- Phanerozoic, Era:- Palaeozoic): Rifting took place across the southern Cape region. The sediments of the Cape Supergroup were deposited.
± 300 Ma (Eon:- Phanerozoic, Era:- Palaeozoic): Subduction along Gondwana's southern margin resulted in the interior experiencing compression. This compression led to the folding and thrusting of the Cape Supergroup, forming the Cape Fold Mountains. On the northern side of the Cape Fold mountains a retro-arc foreland system developed in which the Karoo sediments were deposited (Fig. 3.3.).
180 - 90 Ma (Eon:- Phanerozoic, Era:- Mesozoic): Gondwana break-up. This break-up can be divided into 5 stages: 1) **180-175 Ma**: A mantle plume rose beneath southern Africa, possibly beneath Mozambique. Some rifting took place, but no proper continental break-up occurred. Dolerites intruded. Karoo volcanism commenced. 2) **175-155 Ma**: Linking of major fracture systems occurred across Gondwana. Further extension and intrusions occurred. 3) **155-135 Ma**: Gondwana began to break up into eastern and western Gondwana. 4) **135-115 Ma**: West Gondwana also fragmented. Possibly also due to a mantle

plume. 5) **115-90 Ma:** The Falkland plateau separated from the Cape region. The interior of southern Africa experienced uplift.
20 Ma (Eon:- Phanerozoic, Era:- Cenozoic): Uplift, mostly in the east, in southern Africa.
5 Ma: Uplift, mostly in the east in Southern Africa. The Bushveld region, including the Springbok Flats Karoo Basin, experienced subsidence varying between ± 400 to 1000 m. Exploration drilling results revealed a displacement of 990 m along the Droogekloof Fault Zone east of Bela Bela.

3.3 Evolution of the Karoo basins (± 300 Ma, Eon:- Phanerozoic; Era:- Palaeozoic)

The onset of sedimentation of the Karoo Supergroup sequence across the Gondwana Supercontinent is placed in the Late Carboniferous, at around 300 Ma, following a major inversion tectonic event along the southern boundary of the Supercontinent.

Karoo sedimentation continued across Gondwana until the break-up of the Supercontinent in the mid Jurassic ± 183 Ma ago. Two major allogenic control processes impacted on the accumulation of sediments in the Karoo basins. These control processes were tectonism and climate. Tectonic regimes during the Karoo time varied from dominant flexural tectonic in the south to extensional along the northern margin of Gondwana respectively. The flexural tectonics experienced along the southern boundary resulted from subduction, accretion and mountain building along the palaeo-Pacific margin of Gondwana. The extensional processes along the northern margin of Gondwana were caused by spreading tectonic regimes along the Tethyan margin of Gondwana (Catuneanu et al., 2005). The Tethyan margin encompasses the Tethys Sea, a sea that is believed to have once separated Gondwana from Laurasia, the closing of which gave rise to the Alps and Himalayan Mountains (McCarthy and Rubidge, 2005).

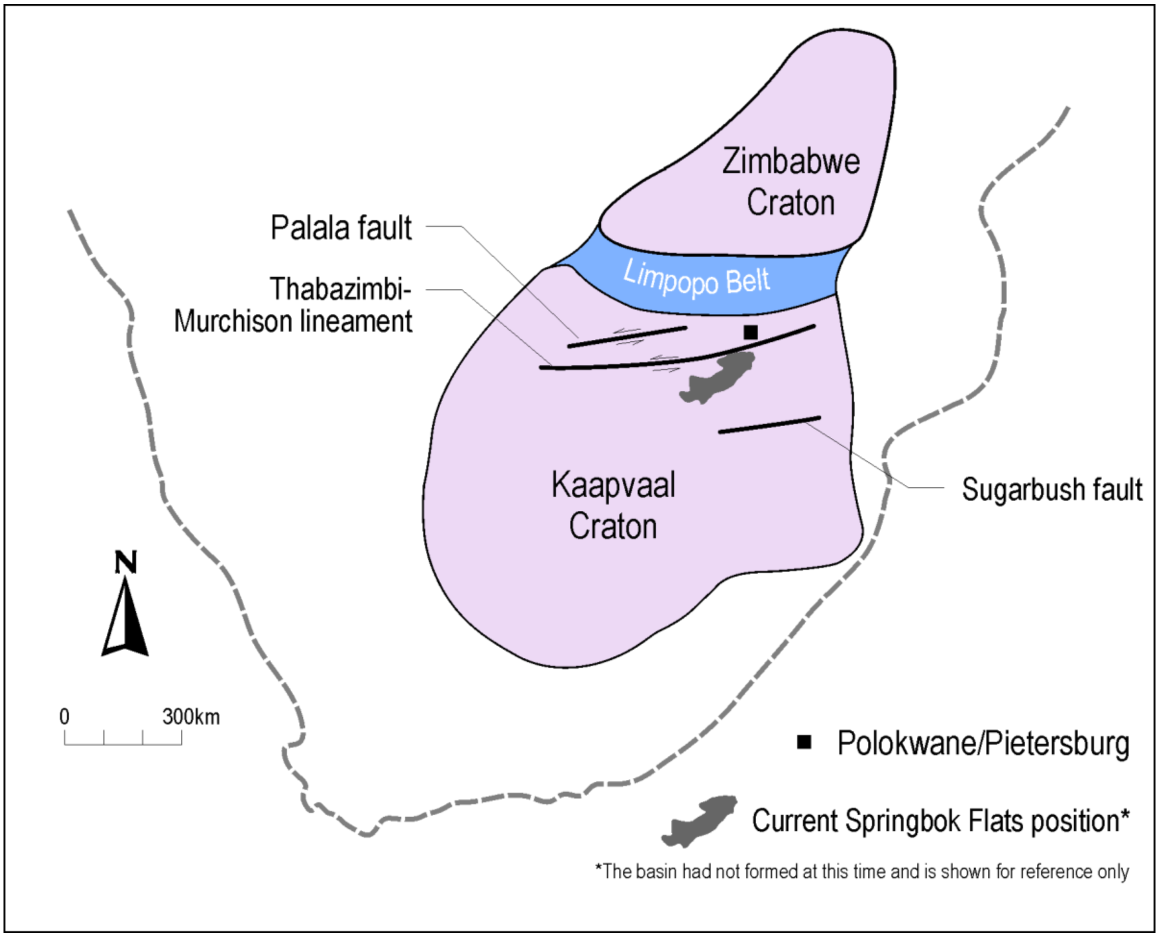


Fig. 3.1. During the period between 3 000 Ma and 2 650 Ma, the TML was formed, the Kaapvaal Craton and Zimbabwe Craton collided and the TML was reactivated. The position of the Springbok Flats is shown relative to these features (modified after McCarthy and Rubidge, 2005).

The significance of tectonic controls during the development of the Karoo Basin was first acknowledged by Rust in 1975. Subsequently, several synthesis and research papers were compiled emphasizing the importance of tectonism during the formation of the Karoo basin (Tankard et al., 1982; Turner, 1986; Johnson et al., 1996; Visser and Praekelt, 1996; Selly, 1997). Superimposed on the tectonic controls, climatic fluctuations also impacted on sedimentation indicating a shift from cold and semi-arid conditions during the Late Carboniferous to early Permian period, to warmer and eventually hot climates with fluctuating precipitation during the rest of Karoo times (Visser and Dukas, 1979; Visser, 1991 a, b).

The different types of tectonic regimes that existed along the southern and northern margins of Gondwana as well as changes in climatic conditions that prevailed, resulted that the lithostratigraphic nature of Karoo aged sediments changed significantly across the African continent. For this reason, the other Karoo aged basins, which show clear similarities with the main Karoo Basin of South Africa, are generally restricted to south-central Africa, whereas the Karoo age sequences preserved to the north of the equator are distinctly different. The distribution of Karoo age basins of south-central Africa is depicted in Fig. 3.3.

3.3.1 Tectonic regimes during Karoo Supergroup sedimentation

Within the context of plate tectonics, foreland systems are associated with convergent plate margins where orogenic belts form along the edges of the overriding continent (Fig. 3.2.). The resulting mountain ranges represent supracrustal loads that press the lithosphere down on both sides of the convergent plate margin, generating accommodation space for sediment accumulation via flexural deflection i.e. foreland basins (Catuneanu, 2004). The newly created depocentres are referred to as proarc foreland basins if situated in front of the orogenic belt on the overriding (retro-lithospheric) plate (Fig. 3.2.) or as retroarc foreland basins if situated behind the overriding plate. One important difference between the proarc foreland and retroarc foreland settings is that the retro-lithosphere is subjected to dynamic loading in order to create accommodation space. These additional mechanisms are related to sub-lithospheric forces. Sub-lithospheric loading of the overriding plate occurs, especially where subduction is rapid and/or takes place at a shallow angle beneath the retroarc foreland basin (Fig. 3.2.). This corner flow-driven dynamic loading generates accommodation space at continental scale with subsidence rates

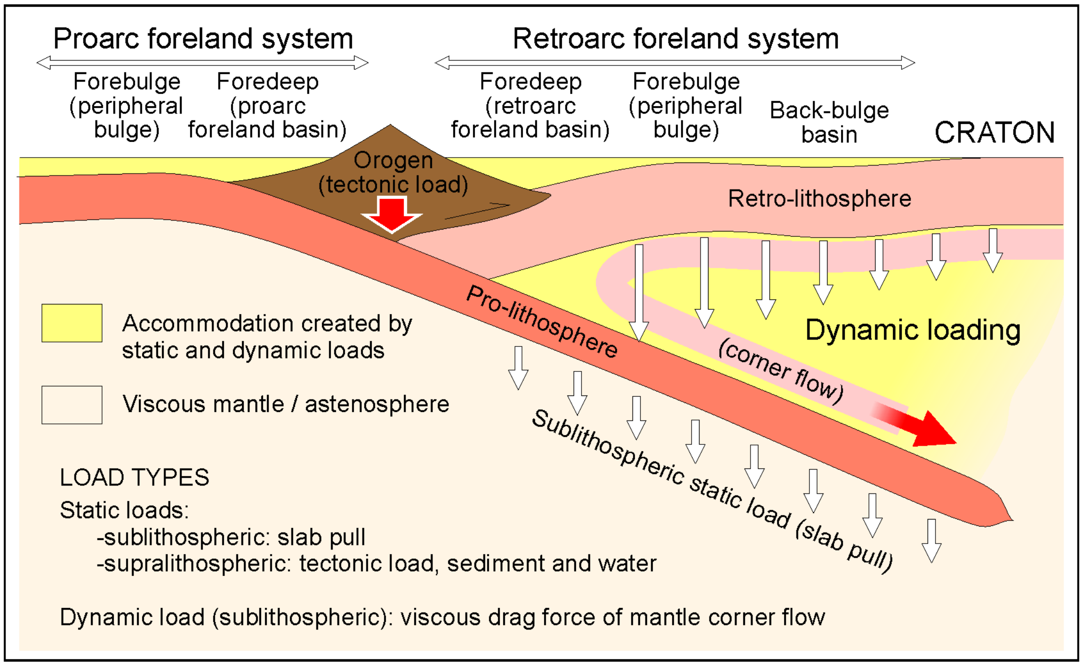


Fig. 3.2. Proarc and retroarc foreland systems (modified from Catuneanu, 2004).

decreasing exponentially with distance away from the origin in a cratonward direction (Fig. 3.2.), (Catuneanu, 2004).

Except for dynamic loading, all other types of supra and sub-lithospheric subsidence mechanisms relate to the gravitational pull of static loads imposed by the subducting plate, the orogen, or the water-sediment mixture that fills the foreland accommodation space created by lithospheric flexural deflection (Fig. 3.2.). The static tectonic load of the orogen and the sub-lithospheric dynamic loading are considered to be the primary subsidence mechanisms that control accommodation space and sedimentary architecture in the retroarc foreland settings (Catuneanu et al., 2005). Tectonic loading caused by orogens, though only one of several subsidence mechanisms, defines the characteristics of foreland systems. Foreland systems can be divided into flexural provinces i.e. foredeep (foreland basin), forebulge and back-bulge (Fig. 3.4.). Flexural

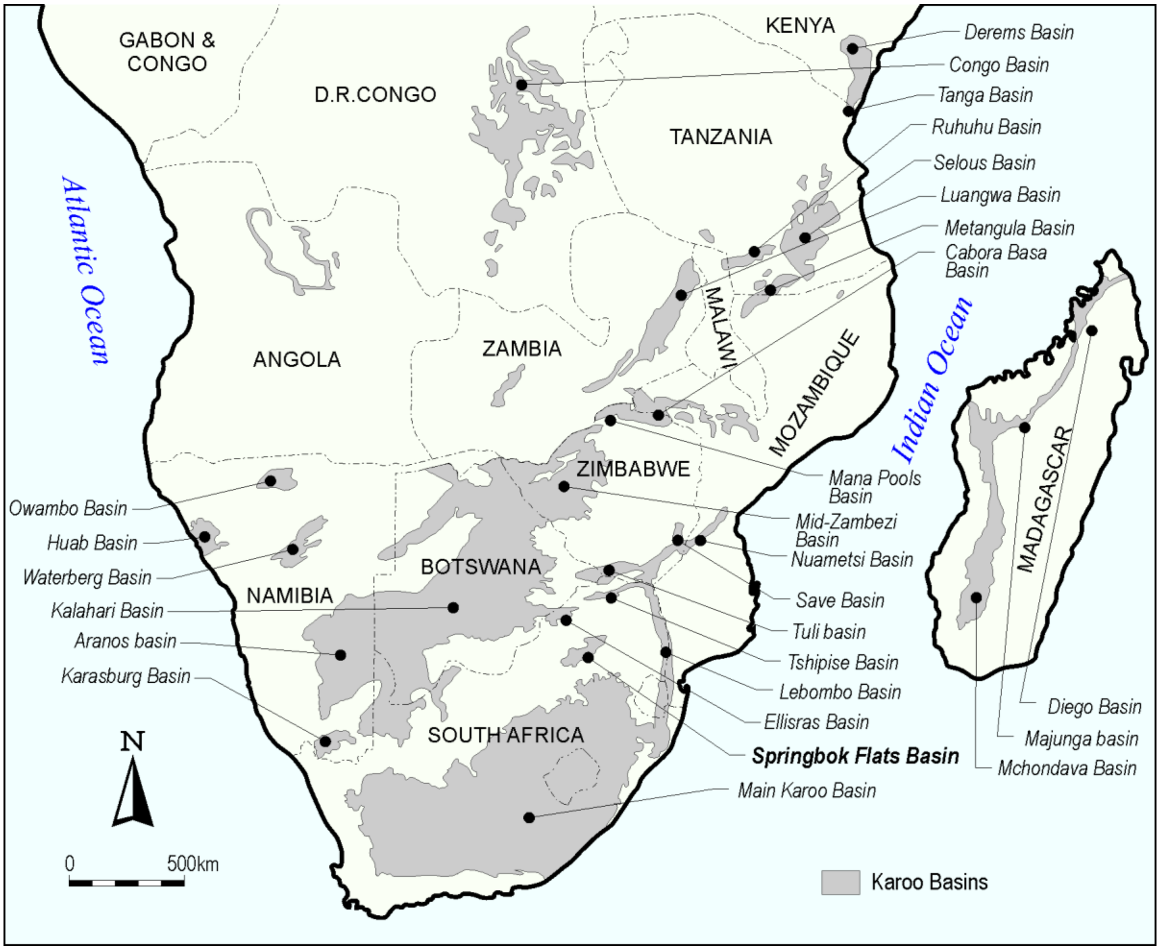


Fig. 3.3. The distribution of Karoo aged basins in South-Central Africa (modified after Catuneanu et al., 2005).

provinces are bordered by flexural hinge lines which are strongly controlled by the structures and composition of the underlying basement (Catuneanu, 2004). The position of flexural hinge lines is to a large extent influenced by the boundaries between basement blocks with different rheologies.

3.3.2 Tectonic regimes related to the convergent margin of Gondwana

This compressional event, associated with collision and terrane accretion led to the Pan-Gondwanian fold-thrust belt of which a small portion is preserved in

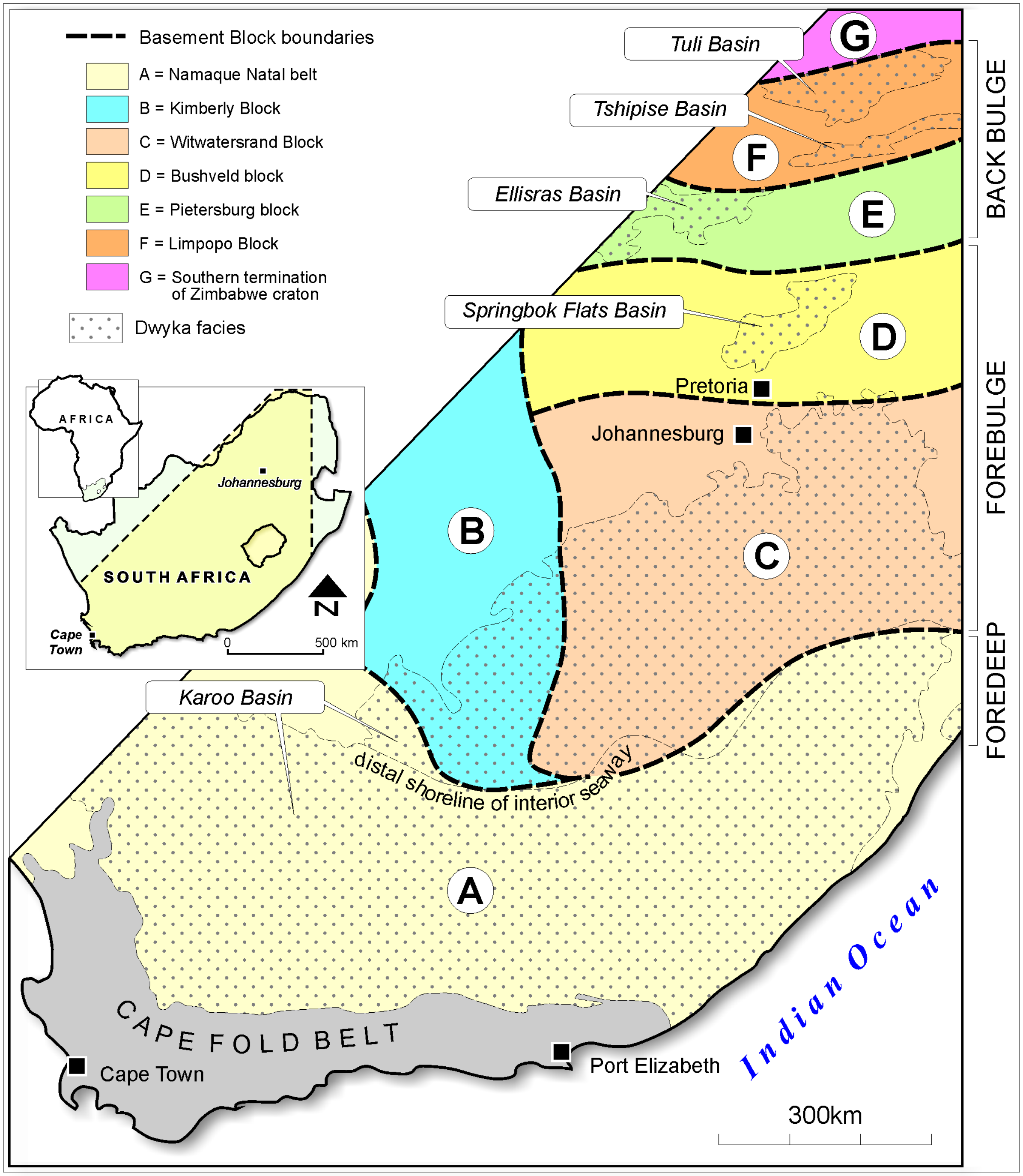


Fig. 3.4. Flexural provinces in the Karoo basins (modified after Catuneanu et al., 2005).

South Africa as the Cape Fold Belt (CFB). This orogen resulted in a supracrustal load that led to the formation of the Karoo retroarc foreland system which includes the main Karoo Basin as well as smaller Karoo basins as far north as the Tuli Basin (Fig. 3.4.)(Catuneanu et al., 2005).

The main Karoo Basin is largely underlain by a stable floor, comprising the Kaapvaal Craton in the north and the Namaqua-Natal Metamorphic Belt in the south and is bounded along its southern boundary by the Cape Fold Belt (CFB).

The Karoo foreland system was divided by Catuneanu et al. (2005) into three distinct flexural provinces (Fig. 3.4.) i.e. foredeep, forebulge and back-bulge. The position of the flexural provinces is largely controlled by structures in the underlying Karoo basement. The geophysical boundaries of the Kaapvaal Craton are depicted in Fig. 3.5. The inferred terrain boundaries coincide with the Colesberg lineament, the TML, the Houtrivier Shear Zone (HRSZ) and the Palala Shear Zone (PSZ)(Fig. 3.5.).

The foredeep of the Karoo foreland system is positioned north of the CFB and overlies the Namaqua-Metamorphic Belt towards the north. The forebulge flexural province includes the Kimberley and Witwatersrand terrain (Fig. 3.4.) which coincides with the Kimberley, Witwatersrand and Bushveld blocks of Catuneanu et al. (2005). The TML hinge line constitutes the northern periphery of the forebulge (Fig. 3.5.). The back bulge flexural province occurs between the PSZ flexural hinge line in the north and TML hinge line in the south (Fig. 3.5.). Flexural provinces B, C, D and E constitute the Kaapvaal Craton. Position G (Fig. 3.4.) indicates the southern peripheries of the Zimbabwe Craton.

The Springbok Flats Karoo Basin is situated in flexural province D and is bordered by the TML flexural hinge line in the north (Fig. 3.4.). No geophysical evidence could be obtained pertaining to the southern flexural hinge line of the

Bushveld Flexural Province as defined by Catuneanu et al. (2005). The southern boundary of flexural province D is probably not associated with tectonic features

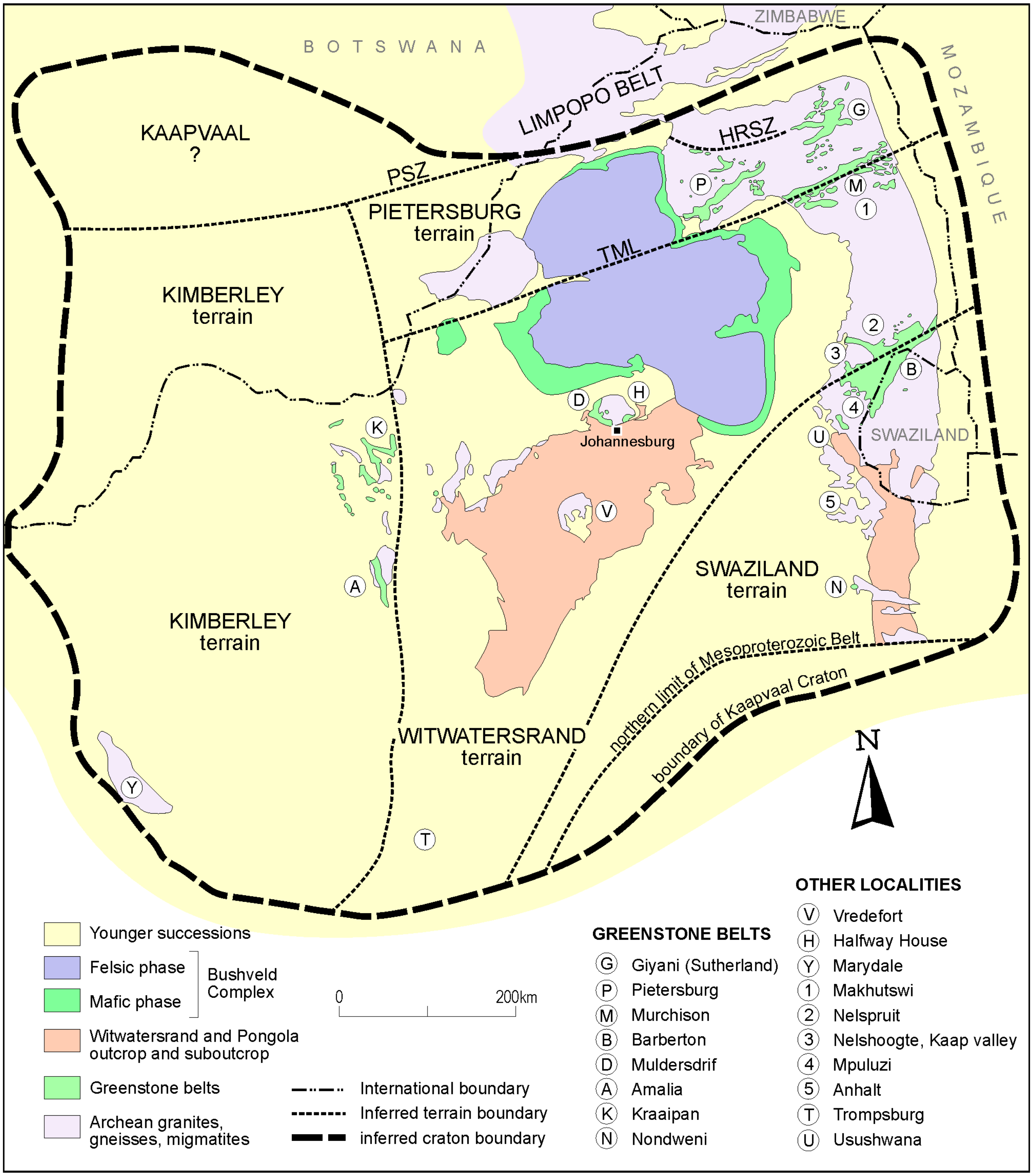


Fig. 3.5. Geophysical boundaries of the Kaapvaal Craton (modified after Eglington et al., 2004).

but rather reflects the boundary between different basement blocks i.e. the southern Witwatersrand block and the northern adjacent BIC block or Bushveld Flexural Province.

3.4 Regional tectonic setting of the Springbok Flats Karoo Basin

The Springbok Flats Karoo Basin (SFKB) is situated on the Kaapvaal Craton in a forebulge flexural province of the Main Karoo foreland system. The existing SFKB comprises two elongated NNE to SSW synclinal flexures (Visser and Van der Merwe, 1959) separated by an anticlinal flexure with the same strike. Several normal faults with a NNE to SSW strike are associated with the anticlinal flexure.

The synclinal flexure bordering the anticlinal flexure to the north is referred to as the Roedtan Basin (RB). The northern limit of the RB is the Zebediela Fault which forms part of the TML-tectonic regime. The synclinal flexure that developed south of the anticlinal flexure is defined as the Settlers-Tuinplaats Basin (STB) and is bordered by the Droogekloof Fault which also forms part of the TML-tectonic regime (Fig. 3.6.).

During the Late Carboniferous the forebulge was elevated above sea level, supporting the formation of continental ice sheets (Fig. 3.7.). In these elevated areas the ice sheet was grounded along a region that today extends from the Northern Cape, via the Witwatersrand to Mpumalanga. This elevated region or forebulge is referred to as the Cargonian Highlands (Fig. 3.8.) that existed during the commencement of the Dwyka Group glaciation (McCarthy and Rubidge, 2005). The SFKB developed as a basin contained within the Cargonian Highlands.

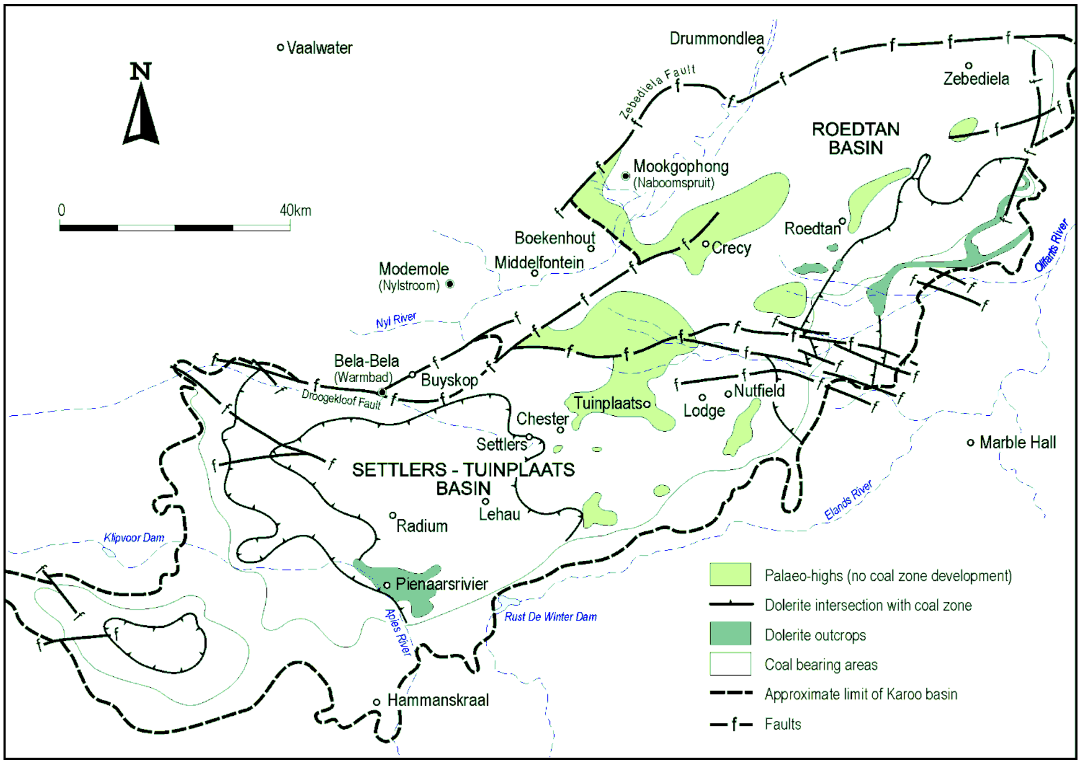


Fig. 3.6. General geological structure of the SFKB.

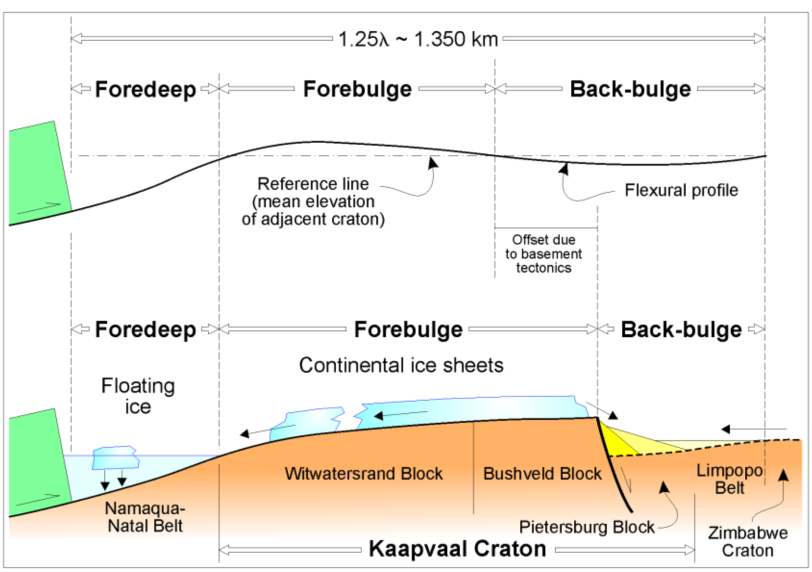


Fig. 3.7. Flexural and basement controls on the distribution of late Carboniferous Dwyka glacial facies in the Karoo basins (modified after Catuneanu, 2004).

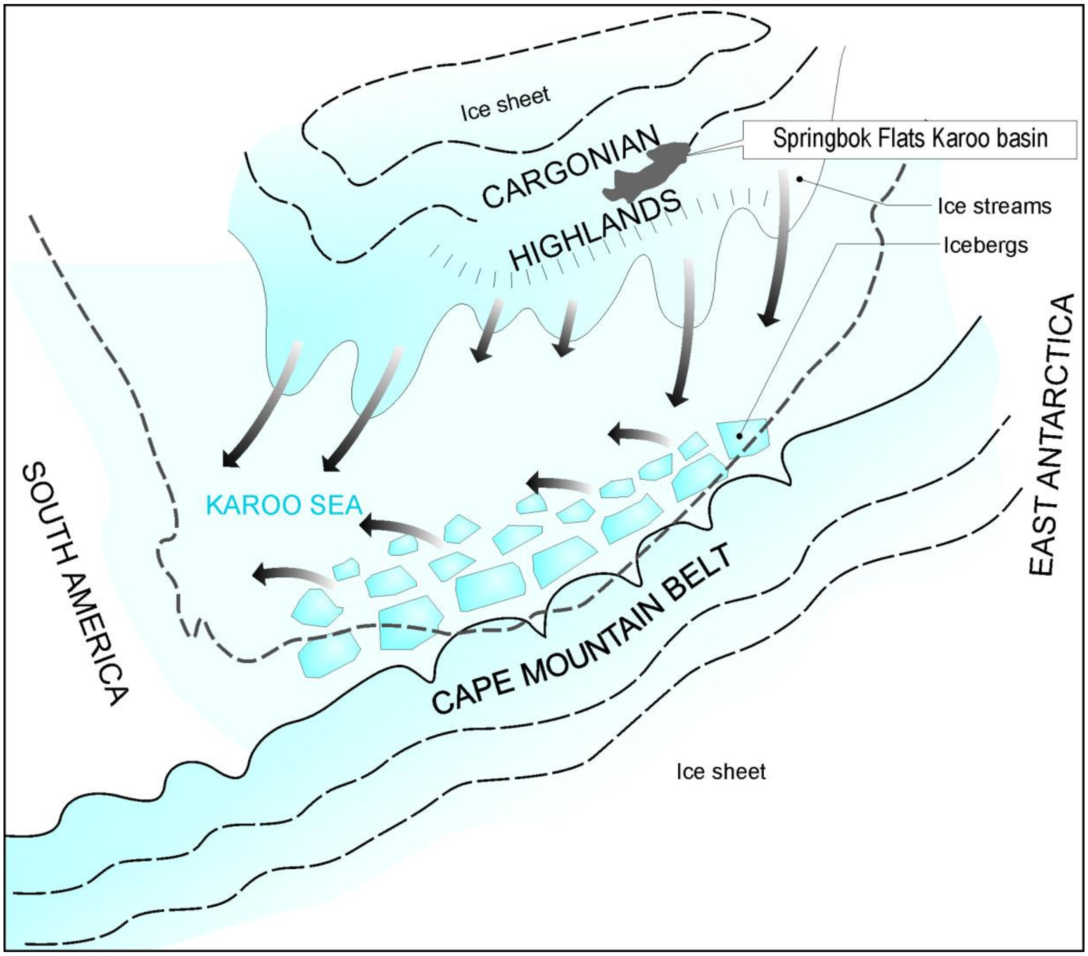


Fig. 3.8. Cargonian Highlands and the SFKB (modified after McCarthy and Rubidge, 2005).

The SFKB possibly represents only a remnant of a Karoo Basin with a much larger aerial extent than the existing SFKB. Reactivation of pre-Karoo faults after the deposition of the Karoo sediments in the SFKB resulted in the preservation of Karoo strata within existing geographical constraints. The SFKB occurs as a geographical depression encompassed by elevated pre-Karoo rocks.

The reactivation of pre-Karoo faults within the SFKB as well as the actual aerial extent of SFKB is evident from the following observations:

a) Current and previous exploration campaigns revealed no evidence that the pre-Karoo faults were active during the deposition of the Karoo strata in the Springbok Flats Basin. Sedimentation will only take place if a gradient caused by a coupling, is present. Such a gradient results from either uplift on the one side or subsidence on the other side. The magnitude of the gradient will also determine the rate of sedimentation as steeper gradients result in higher sedimentation rates. No substantial increase in sedimentation rates related to steeper gradients resulting from the reactivation of pre-Karoo faults could be defined in the SFKB.

b) Results obtained from borehole data reveal that major displacement occurred along a normal fault directly east of Bela Bela. This fault represents a reactivated fault related to the thrust and/or strike-slip Droogekloof Thrust Fault. Boreholes drilled directly north and south of this fault revealed that a dolerite sill was displaced by 990 m downwards towards the south. This suggests that the Karoo aged basalts had already extruded by the time this fault was reactivated. Du Toit (1939) confirmed this by stating that volcanicity must have commenced with the eruption of the dolerite magma, but that the latter probably continued to force its way through the Karoo strata for some time after the lava ceased reaching the surface. $^{40}Ar/^{39}Ar$ dating confirmed a short-lived Karoo igneous event (Duncan et al., 1997). Mafic rocks from Lesotho, Mariental and Keetmanshoop in Namibia and from the Lebombo area yield ages indicating emplacement at 183 ± 2 Ma. Based on the preceeding it can be concluded that the displacement of the dolerite sill post dates the emplacement of the mafic rocks and must therefore be younger than 183 ± 2 Ma.

c) Directly west of the town of Naboomspruit a remnant of the Clarens Formation directly overlies an outcrop of Nebo granite. This outcrop of Clarens Formation sediments occurs north of the Zebediela Fault which constitutes the northern boundary of the Roedtan Basin. South of the Zebediela Fault a thickness of ± 120 m of lavas of the Drakensberg Group was measured. By using the floor elevation of the Clarens Formation north and south of the Zebediela Fault a minimum displacement of 1000 m along the Zebediela Fault in this region is postulated. The time of reactivation of the Zebediela Fault is uncertain.

d) Basaltic lavas of the Drakensberg Group comprise alternating amygdaloidal and fine crystalline lavas which crop out in the vicinity of Pienaarsrivier located near the southern peripheries of the Settlers-Tuinplaats Basin. The average surface elevation of this area is ± 1140 m.a.m.s.l. Towards the west, alluvial gravels containing pebbles of the lavas of the Drakensberg Group outcrop in the upper courses of the Molopo and Groot Marico rivers. These gravels were deposited by a westward flowing river and occur at an elevation of ± 1570 m.a.m.s.l. Based on the preceding observations Taljaard (1948) concluded that the upper courses of this palaeo-river system were lowered to an elevation similar to the elevations encountered at Pienaarsriver. This decrease in elevation i.e. ± 425m is related to subsidence that occurred during the Palaeogene period 65 – 23 Ma ago (McCarthy and Rubidge, 2005).

e) In addition to the above mentioned subsidence McCarthy and Rubidge, (2005) postulated a further subsidence in the Springbok Flats dating to 5.0 Ma ago. This subsidence resulted in the preservation of an extensive flat region belonging to the African Erosion Surface, now known as the Springbok Flats. The continuous subsidence encountered in the SFKB occured over a time span of ± 180 Ma and might be related to continuous reactivation of pre-Karoo faults along the northern boundaries of the Roedtan and Settlers-Tuinplaats basins. The lack of sedimentological evidence that these faults were active during the Karoo Supergroup sedimentation lead to the conclusion that the subsidence encountered over a period of ± 180 Ma only resulted in the preservation of SFKB and did not impact on the sedimentary processes responsible for the deposition of the Karoo age strata.

f) The aerial distribution of the Karoo Supergroup as depicted on the 1:250 000 Geological Series i.e. 2528 Pretoria and 2428 Nylstroom were used to compile Fig. 3.9. In areas of shallow dipping strata mesas formed as a geomorphological feature. As the dip of the pre-Karoo strata increases cuestas will form,followed by homoclinal ridges as the strata dip increases. The various ridges of the Timeball Hill, Daspoort and Magaliesberg ranges near Pretoria represent typical homoclinal ridges (King, 1942). Trellised drainage patterns developed where drainage systems flow for considerable distances in the low lying areas between homoclinal ridges but also break through the homoclinal ridges by a “narrow, rocky gap or port” (King, 1942).

The major homoclinal ridges and other topographical elevated areas in the proximity of Pretoria and Johannesburg are depicted in Fig. 3.10. The drainage systems bear a total discordant relation to the topographical elevated areas which they traversed. Such a topographical pattern could, according to King (1942) be indicative of superimposed drainage systems.

The southern outcrop of the Karoo Supergroup sediments in SFKB reveals a peculiar elongated extension to the south near Hammanskraal that coincides with the Apies river drainage system (refer Fig. 3.10.) in that area. Superimposed drainage systems are not time constrained and therefore imply that modern drainage systems can reflect pre-existing drainage systems of the past.

The irregular distribution of Ecca Group sediments north-northwest of Witbank and northwest of Pretoria probably represents depositional environments that existed between homoclinal ridges. These homoclinal ridges constitute elevated areas prior to and during Karoo age sedimentation. The elongated extension of Ecca Group sediments near Hammanskraal that coincides with the modern Apies River drainage system can be related to a palaeo-thalweg that existed during Ecca times north of Pretoria as a "narrow, rocky gap or port". This thalweg was

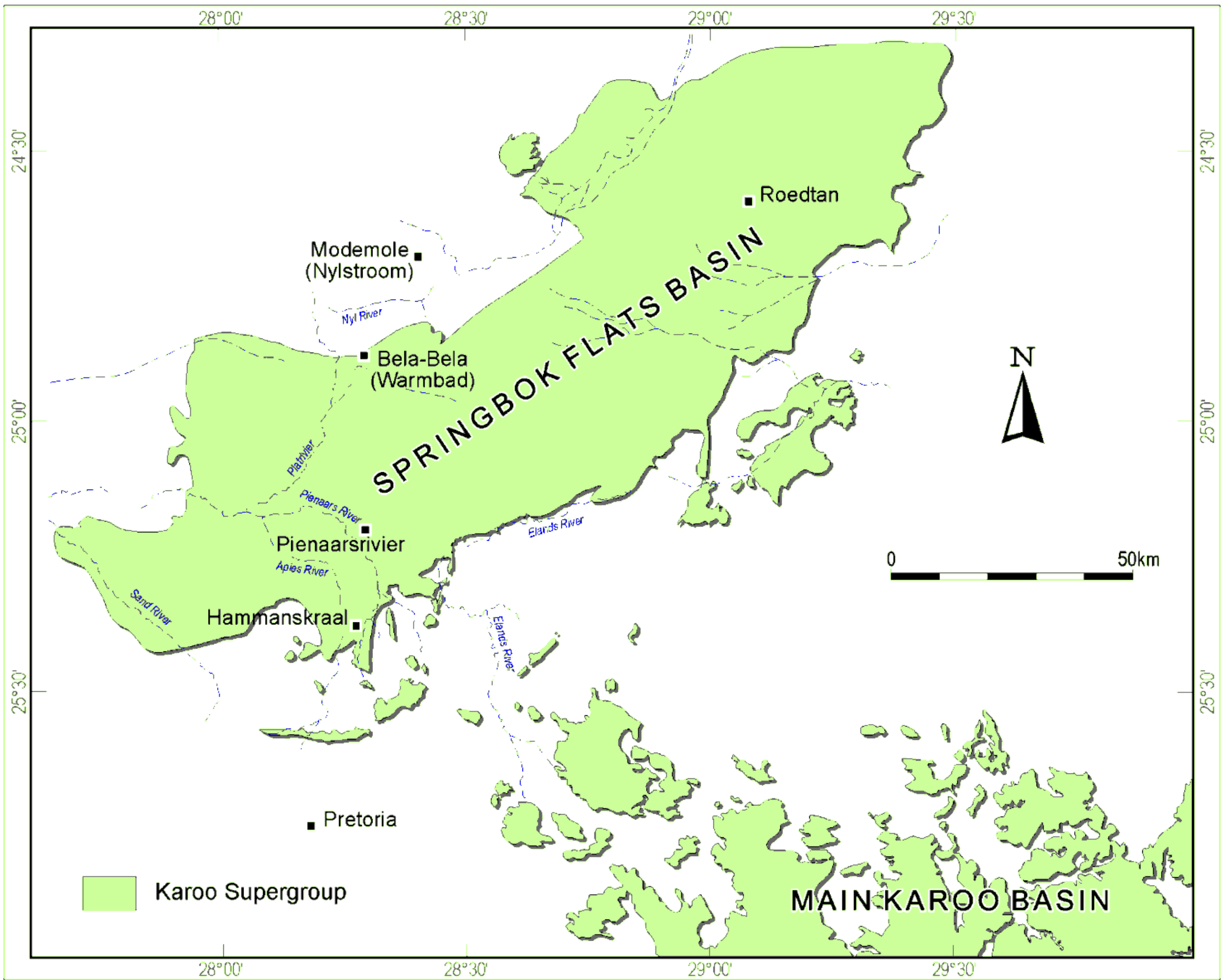


Fig. 3.9. Aerial distribution of the Ecca Group in the SFKB and northern part of the Main Karoo Basin.

probably caused by a palaeo-equivalent of the Apies River drainage system that incised the Magaliesberg and Daspoort homoclinal ridges, creating a possible "poort" between the Main Karoo Basin and the SFKB.

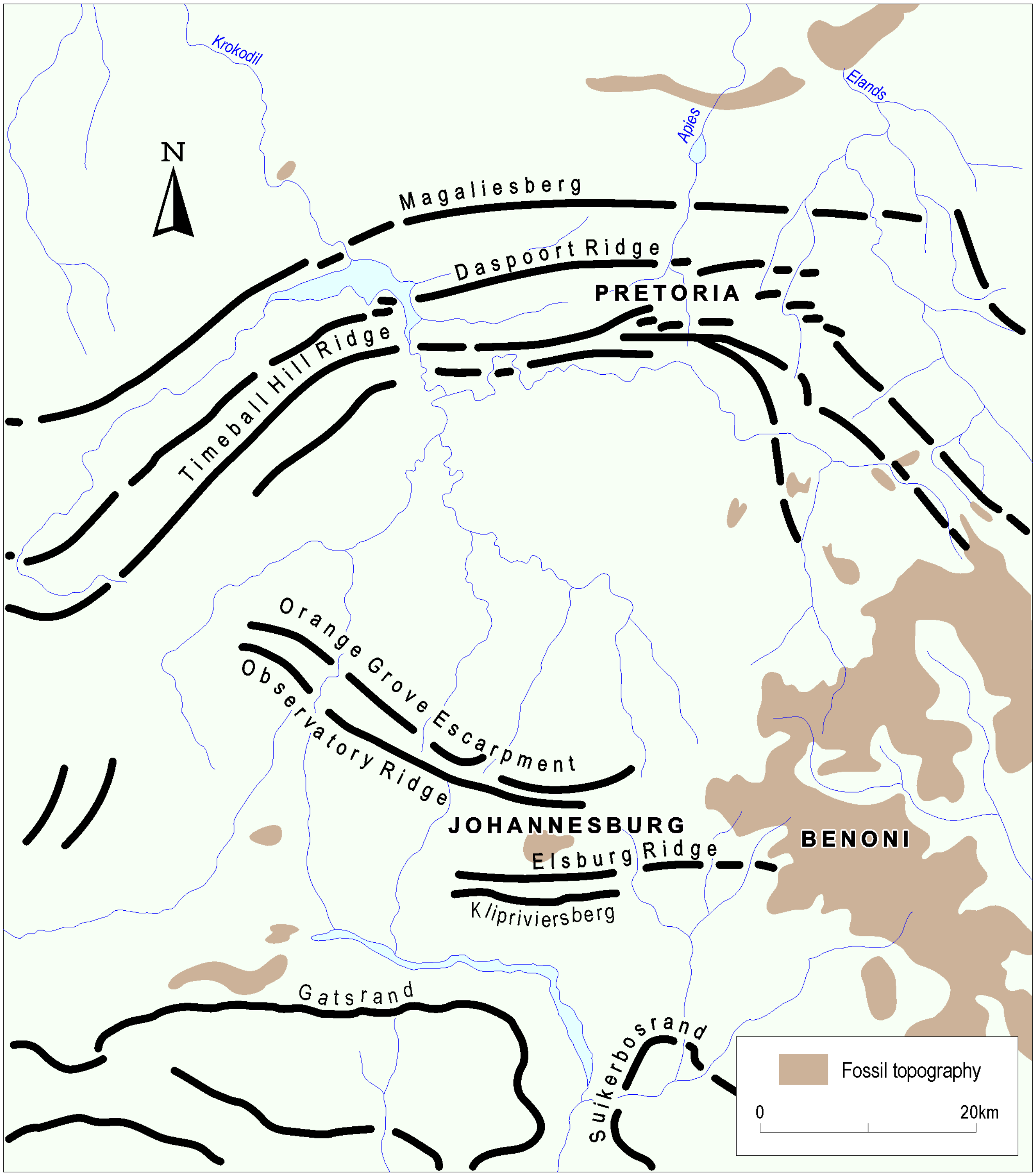


Fig. 3.10. Superposed drainage and fossil topography in Gauteng and Northern Province (modified after Wellington in King, 1942).

Very little geological data pertaining to the isolated Karoo Supergroup outcrops as depicted in Fig. 3.9, is available. The coal bearing strata, intersected during exploration endeavours (personal logging of exploration boreholes) comprises mainly carbonaceous shale with subordinate bright coal layers. These lithologies resemble to a large extent the lithologies of the coal bearing strata encountered in the Dwyka and Ecca Groups in the SFKB.

Based on the preceding it is concluded that the aerial extent of the Ecca Group in the SFKB was exceptionally larger than the existing outcrop areas today. A possible link between the Main Karoo Basin and the SFKB north of Pretoria, along the modern Apies River, is also postulated.

3.5 Karoo dolerite structure

In both the RB and STB dolerite sills, thicknesses in excess of 30 m, intruded the Karoo Supergroup. The location of these sills, where they intersected the coal zone, is depicted in Fig. 3.6. Numerous exploration boreholes in the Settlers and Roedtan areas were drilled in order to determine the position of these sills relative to Lithostratigraphic Unit 3 (coal zone), as these sills impacted on the distribution of potential exploitable coal. Where these sills intruded in close proximity of the coal, total devolatilisation of the coal occurs.

The position of the dolerite sills was, to a large extent, determined by the pre-Karoo topography in both the Roedtan and the Settlers-Tuinplaats basins. In the Settlers-Tuinplaats Basin a prominent palaeo-topographical high divided the basin in an eastern Tuinplaats Sub-Basin and a Western Settlers Sub-Basin. The dolerite sill in the Settlers Sub-Basin outcrops directly north of Pienaarsriver. From this outcrop in a north-northeasterly direction the sill bifurcates in numerous sills resulting that a very complex dolerite structure was encountered in the area south of Bela Bela. The thickness of the dolerite sill in this area varies between 30m and 100m. Directly west of Pienaarsriver, borehole data reveals the presence of 11 and 16 dolerite intersections in two boreholes respectively. A similar situation was encountered in three boreholes drilled north of Radium, where between 7 and 12 dolerite intersections were described. The compilation of a dolerite structure map for the area south of Bela Bela was hampered by the lack of relevant geological data pertaining to the Karoo strata below the coal zone, as virtually no exploration boreholes were drilled to the Karoo Supergroup floor rocks. This results in uncertainties pertaining to the actual number of dolerite sills in depth, the subsurface extent thereof and the nature (bifurcations) of these sills. It is uncertain whether these dolerite sills represent bifurcated sills and dykes or only dykes. Du Toit (1954) mentioned that in the absence of volcanic pipes, the possibility exists that narrow dykes can be considered as feeders for the Karoo volcanicity. As no volcanic pipes were described or encountered during the exploration drilling programme the possibility that the large number of dolerites encountered at the mentioned localities in fact acted as feeders for the Karoo volcanicity, cannot be ruled out.

By taking the floor of the coal zone as a datum, it is evident that the geometry of the dolerite sills in both the Roedtan Basin and the Settlers-Tuinplaats Basin resembles the palaeo-topography of these basins (Fig 3.6.) i.e. the sills occur below the coal in the topographical low lying areas and transgressed through the strata in the proximity of palaeo-topographical highs. In the proximity of palaeo-topographical highs these sills bifurcate resulting in numerous sills that impacted on coal qualities. A possible resolution for this transgressive nature of the sills in areas affected by palaeo-topographical highs is probably manifested in the fact that these highs acted as hillocks and that compaction of Karoo strata over these highs resulted in the formation of weak zones i.e. major and minor compaction features. These weak zones probably constitute areas of less resistance and were ideally suited as pathways for intrusives such as dolerite sills. No dolerite sills, however, were encountered in the Tuinplaats Sub-Basin.

A dolerite sill, similar in nature and mode of intrusion as the sill in the Settlers-Tuinplaats Basin, occurs in the Roedtan Basin. Here, the sill outcrops in the south-eastern perimeters of the Roedtan Basin (Fig. 3.6.) and strikes in a NNE-SSW direction. The thickness of this sill seldom exceeds 50m. In order to determine the position of the dolerite sill in the Roedtan Basin, several north-south ground magnetic traverses were conducted. The position of the dolerite sill in areas where lavas of the Karoo Supergroup crop out is not discernible. The reason for this being that the magnetic susceptibilities for both the dolerites and lavas are of the same magnitude. Henceforth, no distinction between lava and dolerite sills in areas overlain by lavas, is possible.

Very few or no dolerite dykes have been intersected during the exploration drilling programme, although undoubtedly, dykes will be encountered during future mining operations especially in areas towards the south of Bela Bela.

Chapter 4. Regional surface geology adjacent to the Springbok Flats Karoo Basin

The SFKB constitutes a preserved Karoo-aged basin resulting from the reactivation of pre-Karoo aged tectonic features. The SFKB is therefore enclosed by rocks varying in age from ~1.9 Ga to ~2.7 Ga years. Detailed descriptions of the pre-Karoo aged rocks are important in order to establish the provenance of Karoo aged sediments and to relate the arenaceous sediments encountered to pre-Karoo aged successions. In order to compile a geological map of the pre-Karoo rocks underlying the Karoo Supergroup in the SFKB the surface geology was used and extrapolated into the SFKB to determine the aerial extent of the pre-Karoo rocks. The following stratigraphic units (excluding the Penge Formation) occur in direct contact with the Karoo Supergroup in the SFKB (Table 4.1.).

Table 4.1. Regional pre-Karoo surface geology (Geological Series, Pretoria 2528 and Nylstroom 2428, 1:250 000).

SUPERGROUPS	GROUPS	FORMATIONS/SUBGROUPS	IGNEOUS COMPLEXES	AGE GA*
	Waterberg*			~1.9
	Rooiberg*			~2.06
	Pretoria*			~2.36
	Chuniespoort*	Duitschland*		~2.48
		Penge		~2.56
Transvaal		Malmani*		~2.65
Supergroup		Black Reef*		
	Wolkberg*			~2.686
			Bushveld Igneous Complex (BIC)	~2.05

*The distribution of the stratigraphic units (Table 4.1) is depicted in Fig. 4.1.

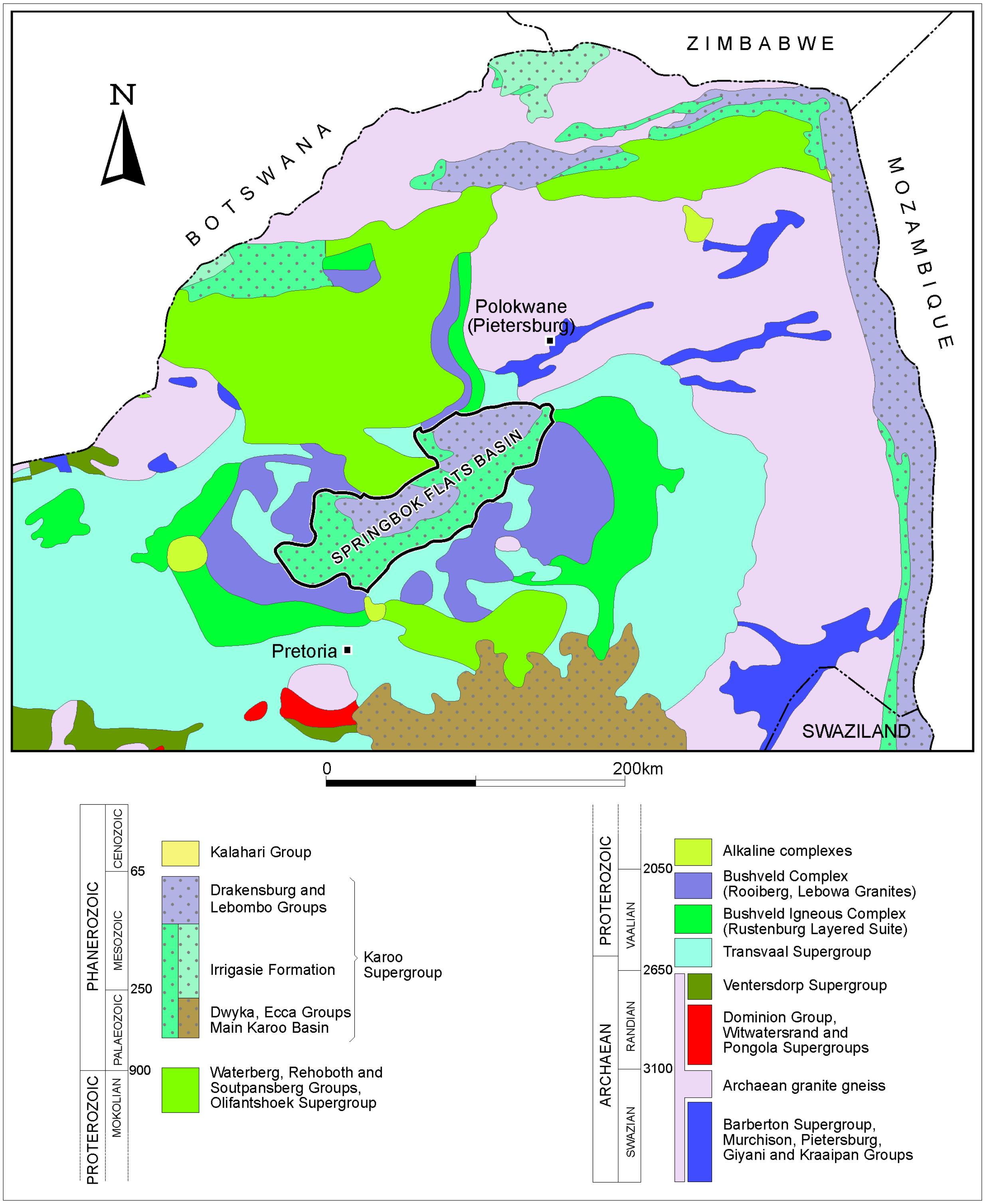


Fig. 4.1. Regional surface geology adjacent to the SFKB.

4.1 Stratigraphic units of pre-Karoo age (>354 Ma)

4.1.1 Wolkberg Group ~2.7 Ga

The oldest stratigraphic unit in direct contact with the Karoo strata is sedimentary and volcanic rocks of the Wolkberg Group. The Wolkberg Group is in contact with the Karoo strata in the Roedtan Basin along the Zebediela Fault (part of the TML).

Around 2.65 Ma renewed rifting of the Kaapvaal Craton commenced, controlled by ancient sutures in the crust. A rift developed in an area between the Ysterberg Fault (part of the TML) and Sugarbush Fault. Arenaceous and argillaceous sediments with intercalated basaltic lavas were deposited in the rift trough. These deposits constitute part of the Wolkberg Group.

4.1.2 Transvaal Supergroup (Fig. 4.2.)

The period of rifting which resulted in the deposition of the Wolkberg Group was followed by thermal subsidence (McCarthy and Rubidge, 2005). The entire Kaapvaal Craton subsided below sea level creating a large shallow continental shelf on which the sedimentary rocks of the Transvaal Supergroup were deposited. As the Kaapvaal Craton subsided, river systems which drained the craton were drowned and covered by beach and shallow marine deposits during a transgression. This gave rise to the conglomerate, sandstone and mudstone deposits of the Black Reef Formation (McCarthy and Rubidge, 2005).

Continuous subsidence of the Kaapvaal Craton resulted in the formation of a shallow sea (McCarthy and Rubidge, 2005) in which cyanobacteria thrived. These photosynthesising bacteria consumed carbon dioxide and caused the precipitation of calcium carbonate from sea water. These calcium carbonate deposits were later dolomitized to form the Malmani Subgroup (Eriksson and Truswell, 1974 and Eriksson et al., 1975).

A tidal palaeo-environmental model for the Malmani Subgroup, ranging from supratidal, flat stromatolitic mats to intertidal columnar stromatolites, with a subtidal zone characterized by giant stromatolitic domes was postulated (Eriksson et al., 1974 and Eriksson, 1975).

The Duitschland Formation consists of mudstones, carbonaceous mudrock, limestone and dolomite with subordinate conglomerates, diamictites and lavas. The palaeo-environment of deposition was defined as the final shallow regressive facies of the Malmani-Penge epeiric sea and minor glaciation (Clendenin, 1989).

A radical change in the depositional environment marked the commencement of the deposition of the Pretoria Group sediments. The shallow submerged continental shelf on which the Chuniespoort Group was deposited terminated, resulting in the disappearance of the cyanobacteria. A brief uplift in the Chuniespoort palaeo-environment resulted in the creation of a shallow marine environment. Large volumes of argillaceous and arenaceous sediments were deposited, preventing the growth of stromatolites. The palaeo-depositional environmental change involved a change in the source area rather than a change in the environment itself. The cause(s) of this change is uncertain (McCarthy and Rubidge, 2005).

The deposition of the Transvaal Supergroup was terminated by the eruption of basaltic and rhyolitic lavas of the Rooiberg Group. Controversies, whether the Rooiberg Group is part of the Transvaal Supergroup or Bushveld Igneous Complex is evident from literature (SACS, 1980; Buchanan, 2000). For the purpose of this research the Rooiberg Group is considered to be part of the Bushveld Igneous Complex event.

4.1.3 Bushveld Igneous Complex (BIC)

The Bushveld Igneous Complex (Fig. 4.1.) formed at about 2061 Ma ago in a very short period of time (McCarthy and Rubidge, 2005), when lava erupted onto the sediments of the Transvaal Supergroup. This lava sequence, known as the Rooiberg Group, consists mainly of two types of lava. During the Rooiberg formation basaltic lava erupted and was followed by the eruption of rhyolitic lava. After the eruption of the Rooiberg lavas an intrusive event took place during which magma of a predominantly basic nature intruded below or into the Rooiberg Group (Hatton and Schweitzer, 1995). These intrusive rocks are referred to as the Rustenburg Layered Suite (RLS). This intrusive event was followed by the Lebowa Granite Suite (LGS), which intruded between the RLS and the Rooiberg Group (Cawthorn et al., 2006 and McCarthy and Rubidge, 2005). The Bushveld Complex also contains rocks of the Rashoop Granophyre Suite (RGS) (SACS, 1980). These rocks may occur above and/or below the Lebowa Granite Suite (Cawthorn et al., 2006).

The following is a brief description of the major units found in the Bushveld Complex as described by various researchers. A simplified stratigraphical column of the Bushveld Complex and a regional cross section across the BIC are depicted in Fig. 4.3. and 4.5.

<u>Rooiberg Group</u>

The Rooiberg Group has been shown to be temporally and possibly genetically related to the Bushveld Igneous Complex (RLS, LGS and RGS) and not to the Transvaal Supergroup (Hatton et al., 1995 and Cawthorn et al., 2006). Although with some uncertainties, rocks from the RLS revealed ages close to 2.06 Ga (Cawthorn et al., 2006). The Nebo Granite of the LGS gave an age of 2.054 ± 2 Ma (Walraven and Hattingh, 1993 and Cawthorn et al., 2006). The intrusive rocks of the RGS have an age of 2.053 ± 2 Ma (Coertze et al., 1978 and Cawthorn et al., 2006).

The Dullstoom Formation (Fig. 4.4.) in the lower part of the Rooiberg Group was initially considered to be part of the Pretoria Group of the Transvaal Supergroup (SACS, 1980). However, the ages of the abovementioned four units (Rooiberg Group, RLS, RGS & LGS) are relatively close to each other. This similarity in ages as well as the close spatial relationship (Buchanan, 2006) between the Rooiberg Group and the Bushveld Complex suggests that the Rooiberg Group is part of the Bushveld Complex rather than part of the Transvaal Supergroup. Schweitzer et al., 1995 suggested that the Dullstroom Formation and the overlying Damwal Formation should rather be combined with the upper two formations, the Kwaggasnek- and Schrikkloof Formations, to form the entire volcanic Rooiberg Group sequence.

Rustenburg Layered Suite

The Rustenburg Layered Suite (RLS) represents a complete mafic magma differentiated series of rock types such as dunite, pyroxenite, norite, gabbro, anorthosite, magnetite- and apatite-rich diorite (Cawthorn et al., 2006). The mafic rocks of the RLS are the major source of South Africa's exploitable platinum group metals, as well as chromium and vanadium.

Rashoop Granophyre Suite

The Rashoop Granophyre occurs at several localities in the BIC as sheet-like intrusions. The dominant type of granophyre is the "Stavoren Granophyre", which occurs widespread in the BIC and chemically closely relates to the Rooiberg Group (felsites), (Eales, 2001). This suggests that the felsites of the Rooiberg Group and Stavoren Granophyre might have had the same magma source. However, these granophyres intruded some time after the Rooiberg Group because they occur between the Rooiberg Group and the Rustenburg Layered Suite (Eales, 2001). Other granophyres formed by re-melting of the

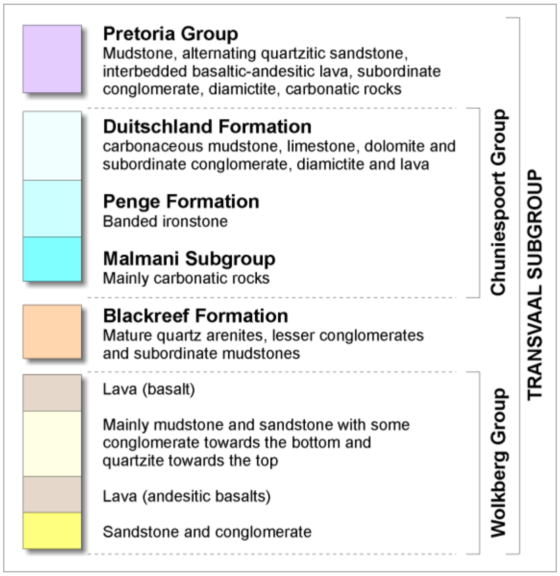


Fig. 4.2. Simplified stratigraphic column of the Transvaal Supergroup (after Eriksson et al., 2006).

Fig. 4.3. Simplified "stratigraphic column" of the Bushveld Igneous Complex (after Cawthorn et al., 2006).

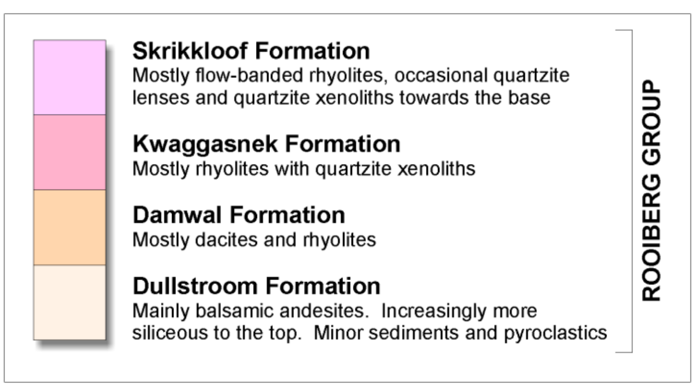


Fig. 4.4. Simplified stratigraphic column of the Rooiberg Group (after Cawthorn et al., 2006).

Rooiberg Group felsites, caused by the intrusion of the RLS, making it younger than the RLS.

Lebowa Granite Suite

The following description is a summary of publications from Cawthorn et al., 2006 and Eales, 2001. The Lebowa Granite Suite (LGS) can be subdivided into various granites. The four most abundant granites in this suite are the Nebo Granite, Bobbejaankop Granite, Klipkloof (Lease) Granite and the Makhutso Granite. The main characteristics of these granites are:

1) Nebo Granite: Coarse, pink to grey (even white) granite, consisting of alkali feldspar, quartz with minor mafic minerals.
2) Bobbejaankop Granite: Medium to coarse grained red granite, consisting of altered alkali feldspar (red colour) with (mafic) biotite that is usually altered to chlorite.
3) Klipkloof Granite: Medium to fine grained pink to grey granite with a low mafic mineral component. Typically it occurs as irregular dykes and sills in the Nebo- and Bobbejaankop Granites.
4) Makhutso Granite: Least abundant of the Lebowa Granites. The Makhutso Granite comprises medium grained grey coloured biotite-rich granite.

The granites of the Lebowa Granite Suite are characterised by differentiation and variations in mineralogy. The mafic mineral component of the Nebo Granite varies upward from 14% hornblende to 1 – 2% biotite at the top. Trace elements Ba, RB and Sr display major variations through the Nebo granite i.e. (Sr x Ba)/Rb (trace element differentiation index) varies from ± 4000 at the base to < 10 at the top. These trends continue into the Bobbejaankop and Klipkloof Granite. Extreme degrees of fractionation are also evident from the abundance of incompatible elements such as B and F.

The last phase of the Lebowa Granite Suite comprises the emplacement of the Makhutso Granite. The Makhutso Granite does not display continuous fractionation as evident from the other granites. It has a high content of mafic minerals and its trace element chemistry resembles on average, that of the Nebo Granite.

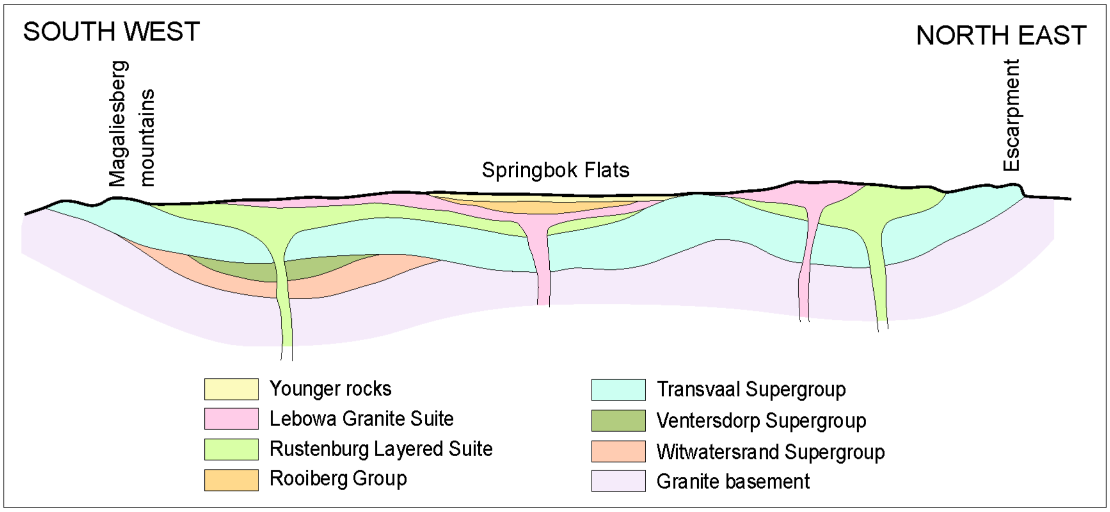


Fig. 4.5. Schematic geological cross section through the BIC (modified after McCarthy and Rubidge, 2005).

4.1.4 Waterberg Group

The Waterberg Group comprises the last of the major sedimentary accumulations to form on the Kaapvaal Craton during the Proterozoic Eon.

The main Waterberg Basin comprises two sub-basins, the northern Warmbath Basin and the southern Middelburg Basin. Sediments of the Waterberg Group in the Waterberg Basin constitute the northern boundary of the Settlers-Tuinplaats Basin along the Droogekloof Fault Zone.

Sediments of the Waterberg Group were deposited mainly by fluvial processes resulting from rifting on the Kaapvaal Craton (McCarthy and Rubidge, 2005). The Palala Fault, TML and the Sugarbush Fault were active during this rift period, resulting in the creation of asymmetrical troughs that today host the Warmbath Sub-Basin of the Waterberg Group. The Lithostratigraphic subdivisions of the Waterberg Group are depicted in Table 4.2.

Table 4.2. The lithostratigraphic subdivisions of the Waterberg Group in the northern, eastern and central portions of the Waterberg Basin are depicted (Jansen, 1982).

Subgroup	Formation	Generalized lithology
Kransberg	Vaalwater	Mainly alternating sandstone, siltstone & shale
	Cleremont Sandstone	Coarse-grained sandstone
	Mogalakwena Conglomerate	Coarse-grained sandstone & grit
Matlabas	Makgabeng Sandstone	Predominantly fine-grained sandstone
	Setlaole Grit	Sandstone, grit & conglomerate
Nylstroom	Alma Graywacke	Feldspathic greywacke, grit & mudstone
	Swaershoek Sandstone	Conglomerate, sandstone, trachytic lava

4.1.5 Elandskraal Volcanic Complex

The Elandskraal Volcanic Complex is a pre-Karoo volcanic complex situated ± 60km north of Pretoria in the proximity of Pienaarsriver (Fig. 4.6.). The Complex forms part of the Pilanesberg Alkaline Province that intruded between 1.45 and 1.20 Ga ago. The Elandskraal Complex forms part of the Pienaarsriver subprovince of the Pilanesberg Alkaline Province (Verwoerd, 2006).

The Pienaarsriver sub-province magma intruded along a NNW trending line referred to as the Franspoort line (Frick and Walraven, 1985). An airborne magnetic survey conducted by the Geological Survey of South Africa (now Council of Geoscience) identified circular magnetic anomalies beneath the Karoo strata in the area between Bela Bela and Pretoria. A geophysical evaluation of the data was interpreted as possible pre-Karoo volcanic centres. In 1975 three exploration boreholes were drilled on a selected anomaly near Pienaarsriver. Drilling results revealed the presence of mafic and felsic alkaline lavas below the Karoo strata (Frick and Walraven, 1985). The geographical extent of these pre-Karoo intrusions is uncertain.

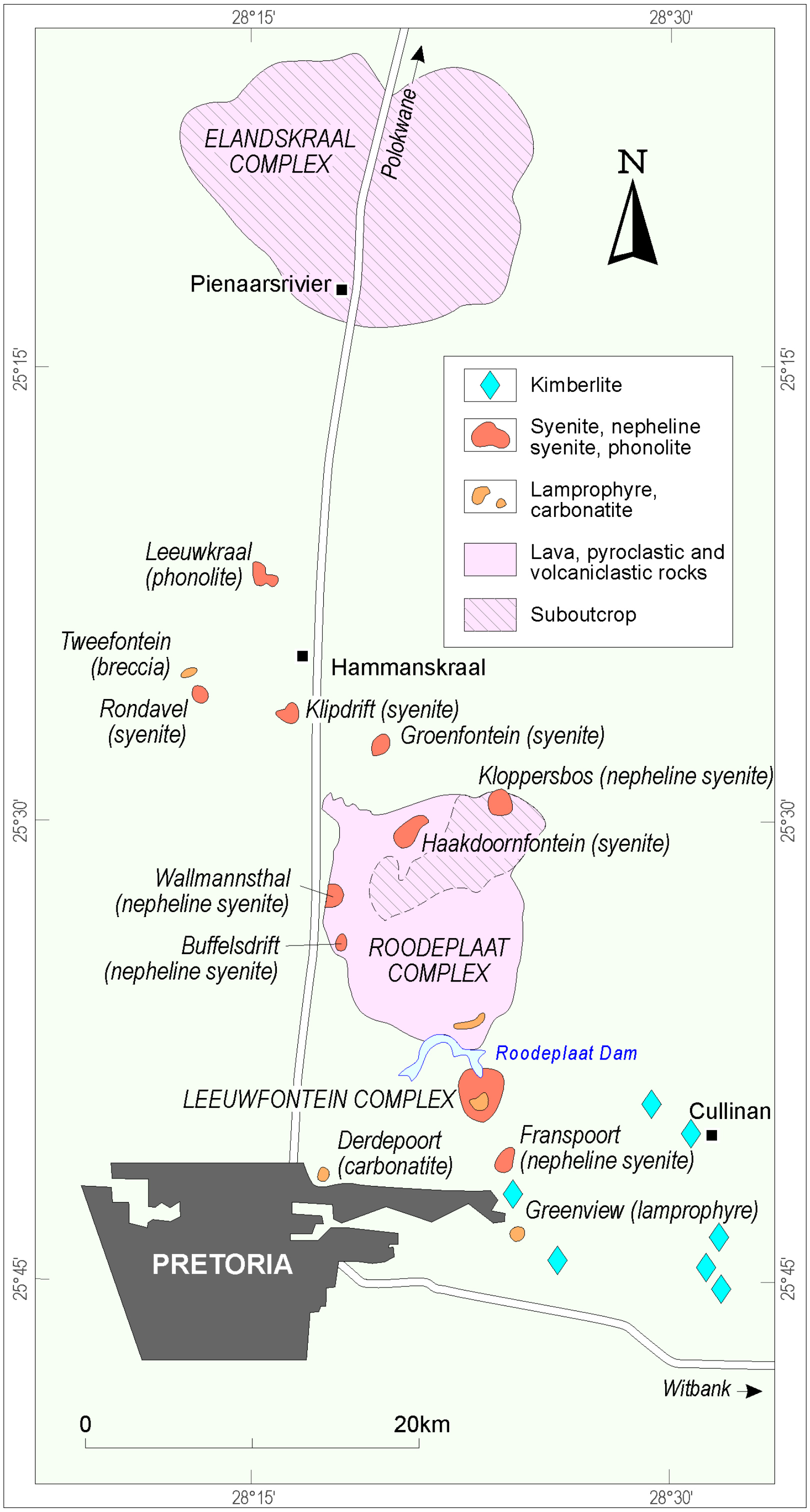


Fig. 4.6. Alkaline complexes north and northeast of Pretoria (modified after Verwoerd, 2006).

Chapter 5. Geology and Palaeo-topography of the pre-Karoo floor in the Springbok Flats Karoo Basin

5. 1 Introduction

The importance of the geology and palaeo-topography of the pre-Karoo floor are vested in the impact thereof on coal distribution and uranium mineralization in the SFKB (refer Chapter 8). Very little or no published data pertaining to the geology below the Karoo strata in the SFKB is available. During the different exploration endeavours over the last ± 60 years, 20% of all the exploration boreholes drilled, intersected pre-Karoo strata.

The different floor strata encountered during exploration activities were compared with the mapped data along the peripheries of the SFKB. Data from outside the SFKB was extrapolated into the basin towards similar strata encountered below the Karoo Supergroup. Table 5.1 depicts the pre-Karoo strata encountered in the SFKB.

Table 5.1. Pre-Karoo strata in the SFKB.

Top (youngest)	Elandskraal Volcanic Complex	
	Waterberg Group	
	Bushveld Igneous Complex	Lebowa Group
		Rashoop Granophyre Suite
		Rustenburg Layered Suite
		Rooiberg Group
Bottom (oldest)	Transvaal Supergroup	

The geology of the pre-Karoo floor rocks is depicted in Fig. 5.1. The two synclinal flexures i.e. the northern Roedtan Basin and the southern Settlers-Tuinplaats Basin are separated by an anticlinal flexure comprising primarily sediments of the Waterberg Group. These two basins are bordered by the Zebediela Fault Zone and the Droogekloof Fault Zone respectively (Fig. 5.1.).

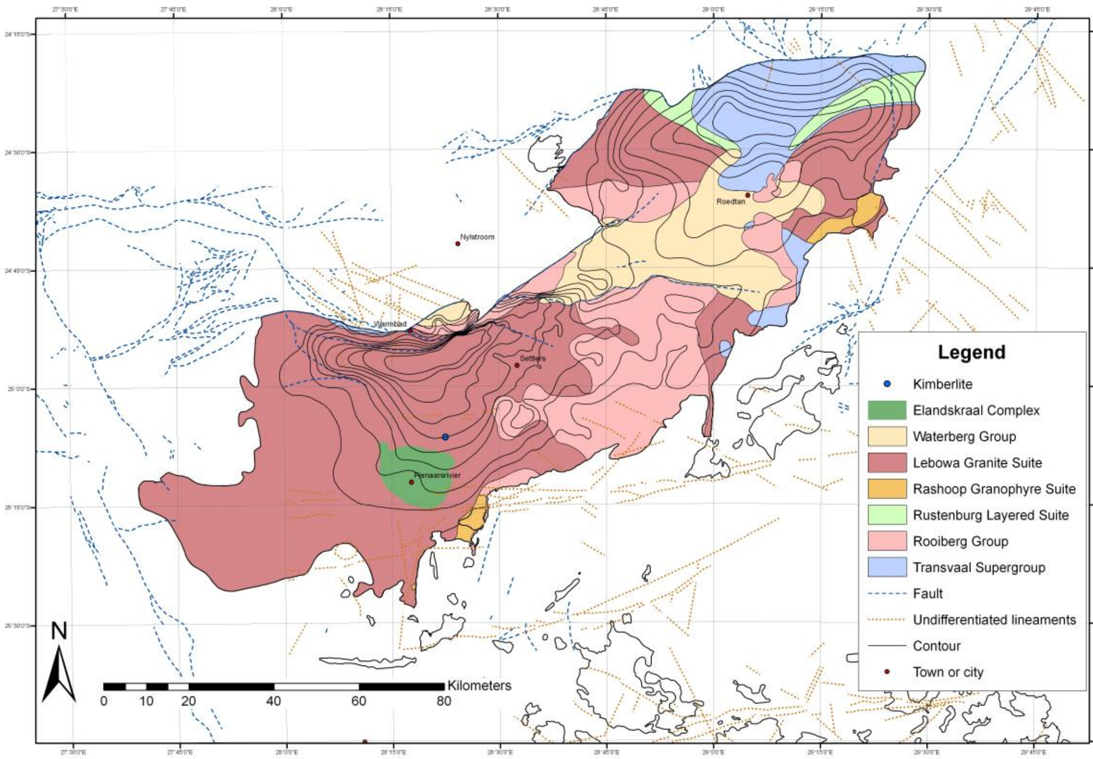


Fig. 5.1. Geological map of the SFKB depicting the pre-Karoo lithologies, topography and major tectonic structures (contours = floor elevation meters above sea level of pre-Karoo surface).

5. 2 Roedtan Basin

Lithostratigraphic units of the Waterberg Group and the Transvaal Supergroup constitute the major pre-Karoo sedimentary rocks encountered in the Roedtan Basin. Towards the eastern and western sub-outcrop areas of the Transvaal Supergroup, the Rustenberg Layered Suite is in contact with the Transvaal Supergroup. Towards the north, south and southeast of Roedtan, sediments of the Waterberg Group were intersected. The Rooiberg Group occurs towards the north, north-west, north-east and to the south of the Waterberg Group sub-outcrop areas. The eastern and western boundaries of the Roedtan Basin are demarcated by the Lebowa Suite Granites. Within the Lebowa Granite Suite, the Rashoop Granophyres occur east of Roedtan (Fig. 5.1).

5.3 Settlers-Tuinplaats Basin

The geology of the pre-Karoo rocks is dominated by the Lebowa Granite Suite. Sediments of the Transvaal Supergroup occur directly west of Bela Bela in association with the Droogekloof Fault Zone. Sediments of the Waterberg Group occur north-east of Bela Bela. In this area the Waterberg Group overlies the Rooiberg Group. With the exception of the Elandskraal Volcanic Complex the larger area south of Warmbath is underlain by the Lebowa Granite Suite. South-east of the Elandskraal Volcanic Complex, rocks of the Rashoop Granophyre were intersected. Towards the eastern peripheries of the Settlers-Tuinplaats Basin the Rooiberg Group sub-outcrops.

5.4 Palaeo-topography of the Springbok Flats Karoo Basin

The pre-Karoo palaeo-topography is the most important feature that impacted on the distribution and deposition of the lowermost stratigraphical units of the Karoo Supergroup in the SFKB. The same borehole data that was used to compile the pre-Karoo geology was used to compile a palaeo-topographical map of the pre-Karoo surface.

The regional pre-Karoo palaeo-topography within the SFKB is depicted in Fig. 5.2. The position of the two synclinal flexures i.e. the Roedtan Basin and the Settlers-Tuinplaats Basin and the anticlinal flexure or topographical high which separates the two basins are outlined in Fig. 5.2. The two elongated topographical lows i.e. Roedtan and Settlers-Tuinplaats Basins are associated with the Zebediela - and Droogekloof Fault Zones which border these basins to the north respectively.

Irregularities in the pre-Karoo topography limited the development of coal in areas adjacent to topographical highs. The major pre-Karoo topographical high-lying areas that impacted on coal development occur in the vicinity of Settlers and Tuinplaats (Fig. 5.2.).

A geological cross section (Fig. 5.3.) compiled by using borehole data depicts the Roedtan and Settlers-Tuinplaats Basins with accompanying geology and topography of the pre-Karoo floor. The cross section also indicates the elevated anticlinal flexure zone separating the two synclinal flexures/basins.

The Kaapvaal Craton comprises a rigid mass of rock approximately 40 km thick with an average bulk density of ± 2.7 g/cc. Rocks of the BIC have a bulk density ± 3.2 g/cc. When the BIC intruded, based on the differences in bulk densities, it has been calculated that an additional 8 km thickness of dense material was added to the crust. This additional material resulted in the base of the crust sagging into the hot plastic underlying mantle. This subsidence is known as isostatic adjustment and caused the centre of the BIC intrusion to sag and the layering of the intrusion to tilt inwards resulting in a basin with a roughly saucer shaped geometry. This isostatic adjustment not only impacted on the layered rocks of the BIC, but also affected the underlying sediments of the Transvaal Supergroup (McCarthy and Rubidge, 2005).

The resistant nature to weathering of sediments of the Waterberg Group in the proximity of the SFKB, gave rise to the spectacular scenery around Bela Bela. The age of the Waterberg Group is not well established due to the scarcity of suitable material for dating. No radiometric ages have been obtained on rocks of this Group. However, new U-Pb baddeleyite crystallisation ages have been reported by Hanson et al. (2004) for dolerite sills intruded into the upper

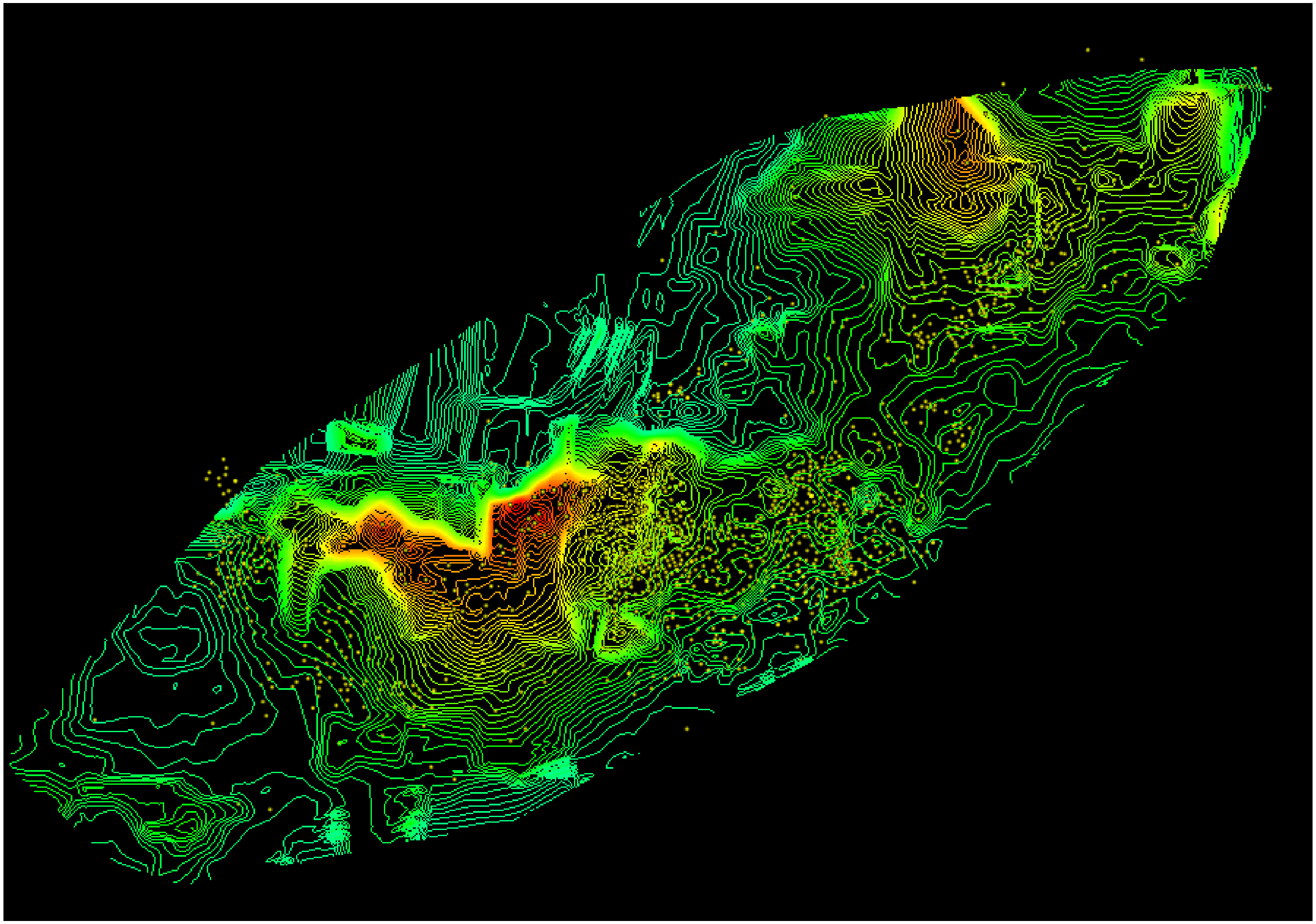


Fig. 5.2. Pre-Karoo palaeotopography in the SFKB.

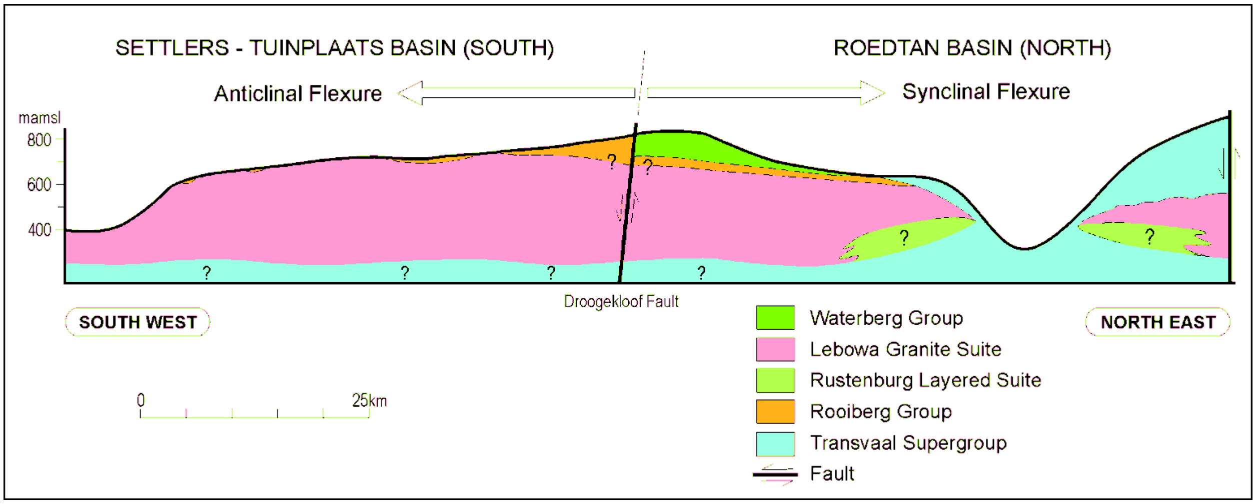


Fig. 5.3. Geological cross section over the Roedtan and Settlers-Tuinplaats Basins depicting the geology and palaeotopography.

Waterberg Group. The data indicates that between 1879 Ma to 1872 Ma dolerites intruded into the Waterberg Group during voluminous magnetism associated with the development of the Soutpansberg Rift Basin (Barker et al., 2006). The Waterberg Group comprises the last of the major sedimentary accumulations to form on the Kaapvaal Craton. No further major geological events are recorded on the craton until the commencement of the Karoo Supergroup.

As previously discussed (Chapter 3) most of the known pre-Karoo faults in and around the SFKB were re-activated after the deposition of the Karoo Supergroup. A pre-Karoo topography, similar to the modern topography around Warmbaths, is anticipated for areas where the Waterberg Group constitutes the pre-Karoo floor rocks i.e. the anticlinal ridge that separates the northern Roedtan and southern Settles-Tuinplaats Basins.

Exploration boreholes that intersected the granites of the BIC revealed a weathered zone on top of the granites that varies from a few centimeters to more than a meter. This weathered zone is absent in boreholes that intersected the Rooiberg – and the Waterberg Groups. It is possible that the granitic rocks of the BIC were more amenable to alteration and weathering than other rock types that constitute the floor rocks of the SFKB. The Waterberg Group is considered to be the oldest red bed deposit on earth i.e. 1872 – 1879 Ma (Hanson et al., 2004). A period of ± 1300 Ma has lapsed since the termination of the Waterberg Group deposits and the commencement of the Karoo Supergroup in the SFKB. No geological records pertaining to this period (i.e. 1300 Ma) exists. It is assumed that continuous processes of weathering and erosion were active over a period of ± 1300 Ma on the pre-Karoo surface. The possibility exists that the geomorphology of the granitic terrains were chemically and mechanically altered by weathering during and after the deposition of the Waterberg Group. Such an assumption, if valid, could possibly account for the even palaeo-topography of the BIC in comparison with the rugged palaeo-topography encountered elsewhere in the SFKB.

Chapter 6. Secondary environment deposits

6.1 Surficial deposits

The secondary deposits that are referred to include mainly deposits developed on the African Erosion Cycle surface, which developed during the Miocene epoch between 5 and 24 Ma ago in the SFKB. On this surface, thick soil profiles comprising mainly black and reddish brown turf are developed. Sandy soils are restricted to the anticlinal flexure that separates the two elongated basins. The black turf soils are indicative of deep weathering and thicknesses in the excess of 20 m were encountered during exploration. Associated with the black soils are several well developed calcrete horizons. Calcrete forms under moderately and dry conditions (<250 mm/annum), by the precipitation of calcium carbonate in subsurface soils when rising ground water with sufficient dissolved calcium salts, evaporate. Morphologically these deposits comprise mainly powdery and nodular calcrete (Martini, 1987).

Palygorskite deposits are associated with calcrete overlying the Drakensberg Group. Palygorskite forms as a residual deposit often on top of calcrete underneath a black turf soil horizon (Martini, 1987). Research conducted by Heystek and Schmidt (1953) on the palygorskite deposits in the SFKB indicated that the underlying lava of the Drakensberg Group weathers progressively from montmorrillonite to palygorskite. Interbedded palygorskite deposits occurring in a single calcrete horizon, could be the result of transported material rather than in situ weathered products.

The black turf soils encountered in the SFKB are indicative of areas of poor drainage conditions hosting both calcrete and gypsum deposits. The concentration and accumulation of gypsum in these poorly drained black turf soils were enhanced by the weathering of pyrite occurring in the underlying lavas (Coetzee, 1961; Brabers, 1976).

The thickness of calcrete and gypsum deposits varies over short distances. The presence of a palaeotopography that resulted from the uneven weathering of the underlying lavas could be the reason for the lateral variation in these weathered profiles (Dürr, 1953).

No detailed research pertaining to the regional distribution of calcrete and gypsum in the SFKB was conducted to date. The possibility that the black turf soils constitute a network of poorly defined drainage systems and that the associated calcrete horizons represent possible alluvial terraces, cannot be excluded.

6.2 Early Man of the Springbok Flats

Towards the end of January 1929, a road construction party in the Springbok Flats, excavating calcerous material for road building purposes, discovered a human skeleton and bones of the extinct buffalo (*Bubulus bainii*) and a large Equid, *Equus capensis*. The skeleton was excavated at a depth of ± 1.0 m. The bones of the skeleton are impregnated with calcium carbonate and except for the larger bones, badly broken. The skull was mostly broken into small pieces, but fortunately the mandible was well preserved.

The Springbok Flats Man is probably one of the most unusual and problematic prehistoric human fossils. The mandible of this fossil man presents a number of features which distinguishes it from other South African human fossil remains. In his original description Broom (1929) in Schepers (1941) highlighted some of the most important features of this mandible. In 1941, Schepers discussed the morphological and metric features of the mandible and attempted to establish its place in the evolution sequence. The following is a summary of the main features of the mandible as described by Schepers (1941).

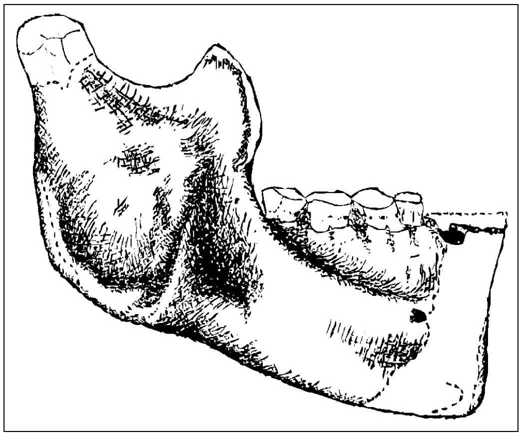


Fig. 6.1(a). The mandible of Springbok Flats man: Norma lateralis.

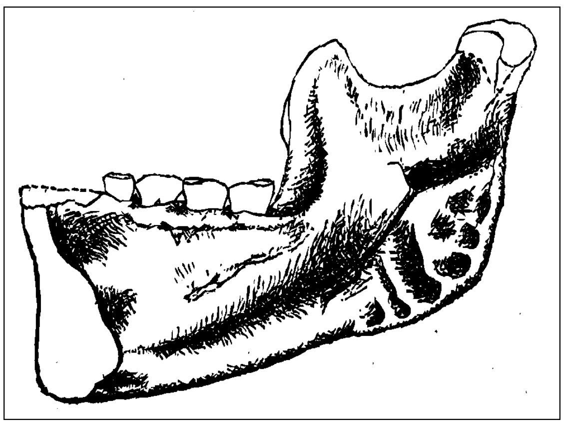


Fig. 6.1(b). The mandible of Springbok Flats man: Norma medialis.

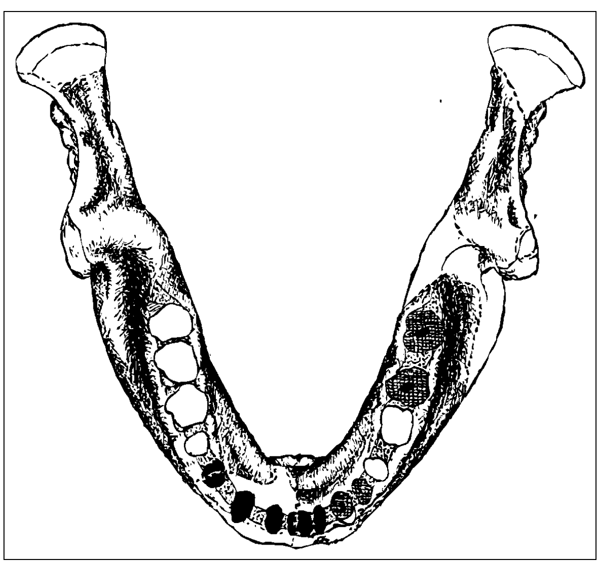


Fig. 6.1(c). The mandible of the Springbok Flats man: Norma verticalis.

The metrical features were compared with those of mandibles of other species. The great length (Fig. 6.1. a,b) of the Springbok Flats mandible is remarkable and even exceeds that of the gigantic Mauer jaw. Further, it was noted that the teeth are small and are not proportionately as great as the mandible length and yet this measurement is only exceeded in the Neanderthal race. The angle of the chin lengths is considerable and about the same as that of Cromagnon man.

The massiveness of the mandible of the Springbok Flats man is one outstanding morphological feature (Fig. 6.1., c). Extreme thickening of the bone in the angle region of the jaw indicates conspicuous muscular ridges. These muscular markings are most unusually prominent in the Springbok Flats mandible (Fig. 6.1., c).

The superimposition of contour tracings of various fossil mandibles on that of the Springbok Flats man's mandible resulted in Schepers (1941) concluded that a close correspondence between the Springbok Flats mandible and that of the Fish Hoek mandible exists (Fig. 6.2.). This, according to Schepers (1941) suggests that the latter might be a pedomorphic derivative of the former.

The teeth of the Springbok Flats man are small and badly worn. The manner in which the teeth have been worn is the result of prolonged usage. The overall characteristics of the Springbok Flats mandible suggest that it is that of a middle-aged individual, although the worn nature of the teeth is indicative of a senile jaw. The teeth of the Springbok Flats man were either very soft or they were roughly used.

The common features that exist between the Springbok Flats man and the Cromagnon man may only be the result of parallel evolution and adaption to certain common functions although the Springbok Flats mandible seems to be the more primitive of the two. The gap between the Springbok Flats mandible,

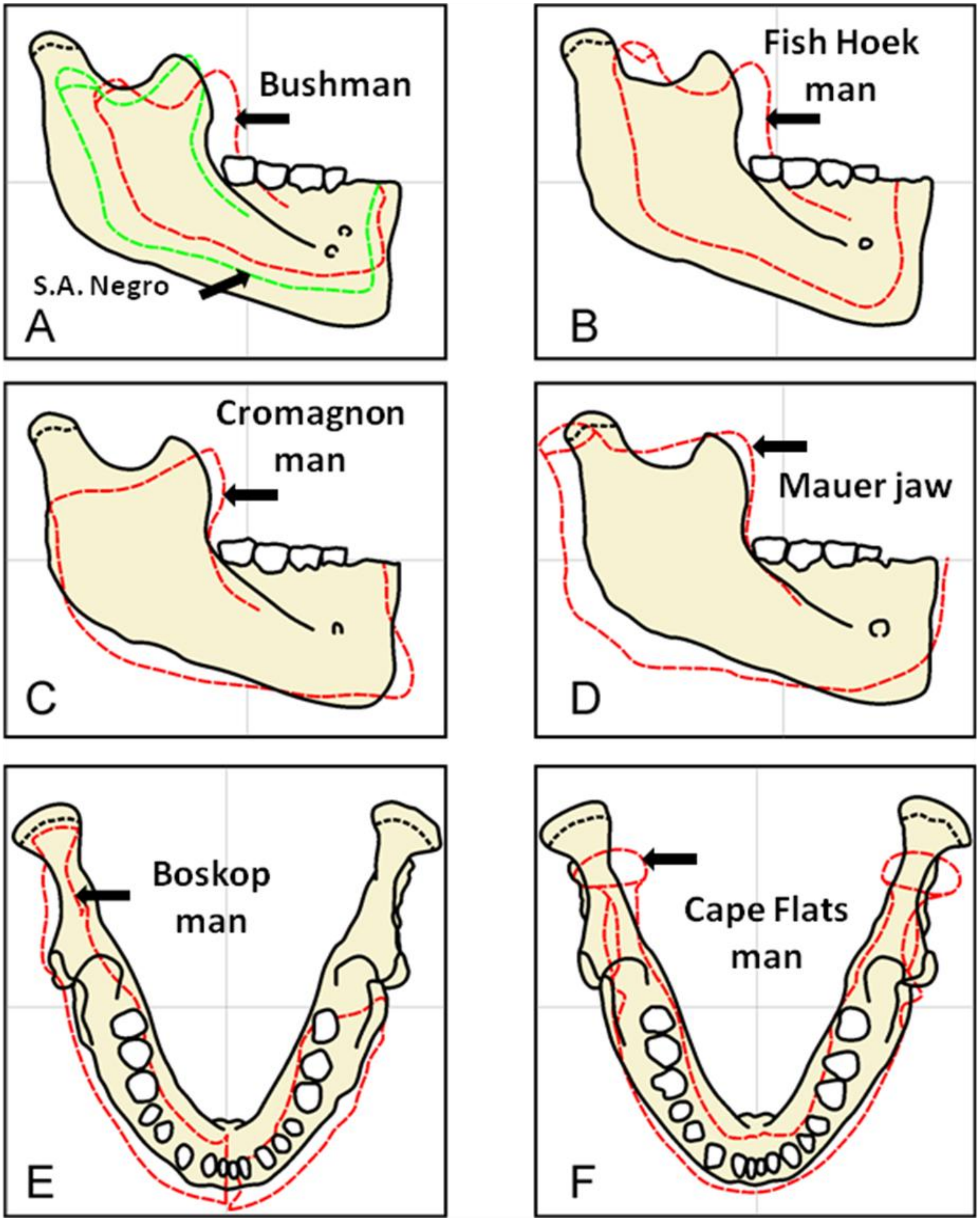


Fig. 6.2. Superimposition of contour tracings of various mandibles on that of the Springbok Flats man (continuous line);

a: dotted line - Bushman, interrupted line – S.A. Negro

b: Fish Hoek man

c: Cromagnon man

d: Mauer jaw

e: Boskop man

f: Cape Flats man.

(modified after Schepers, 1941).

the Neanderthal and the Mauer types is too great to bridge and the intervening forms may have to be sought for in Africa.

The "Middle Stone Age" man was widely spread and had "Boskop" characteristics i.e. exceptional brain capacity. The Springbok Flats man is considered to be of the Middle Stone Age (Du Toit, 1939).

The limb bones of the Springbok Flats skeleton were briefly described by Broom (1929) in Schepers (1941) and were reinvestigated by Toerien and Hughes (1955) (Fig. 6.3.). The outstanding skeletal features of the Springbok Flats man can be summarised as follows (Toerien and Hughes, 1955):

a) The bone of the lower limb indicates that the Springbok Flats man was a tall and robust individual.
b) The bone of the upper limb, especially the forearm and hand, are relatively slender.
c) The limb skeleton is very different from that of a South African black person.
d) The limb seems to be very similar to some of the East African skeletons, the Mapungubwe and some Hottentot skeletons.
e) The limb is also remarkably similar to some Cromagnon skeletons.

6.3 Stone Implements

Over the entire Springbok Flats fragments of rocks were noted as a result of their outline and regularly flaked character which have clearly been shaped by primitive man to serve as tools for his use. These stone implements are clearly the hunting equipment of primitive people who roamed the Springbok Flats at a time when they teemed with game of every description (Van Riet Lowe, 1929). The weathered condition of the stone implements also indicates that they are of considerable antiquity. The implements were made of felsitic and quartzite rocks.

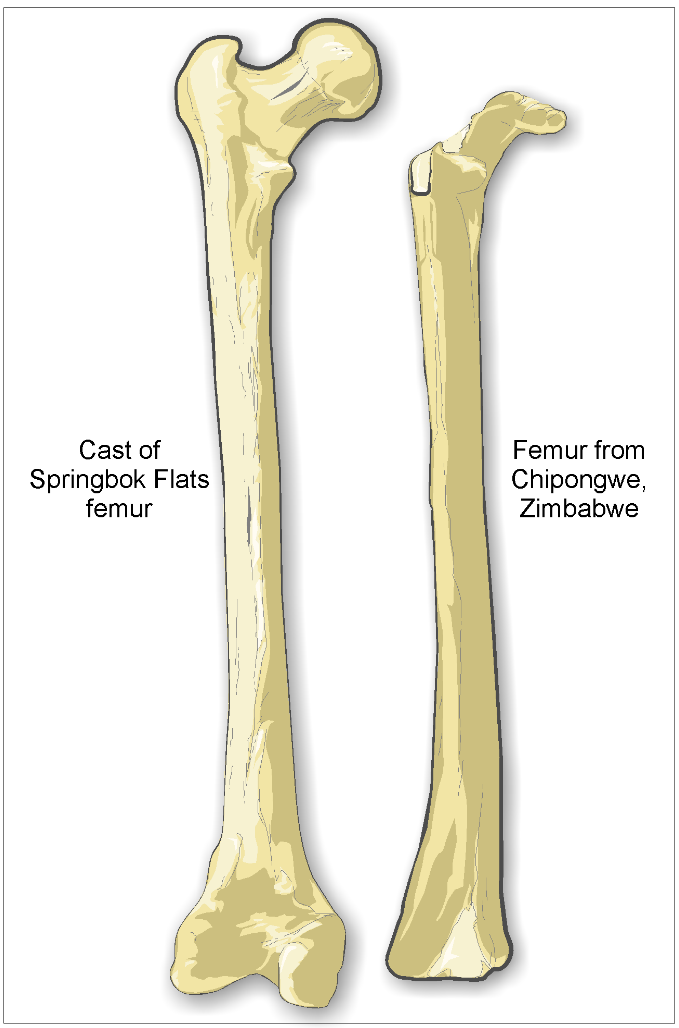


Fig. 6.3. Limb bones of the Springbok Flats skeleton (modified after Toerien and Hughes, 1955).

Stone implements collected by a certain Mr. Bishop-Brown, a road construction worker, and Mr. Frylinck were studied by Van Riet Lowe (1929). The implements collected by Bishop-Brown in an area around Tuinplaats are typically Middle Stone Age, but advanced and suggestive of a Neanthropic influence. The implements comprise mainly felsites. A typical factory site was discovered by Frylinck near Roedtan and implements in all stages of manufacturing were recovered from this site. The material used for manufacturing also comprises felsites. Implements from the Tuinplaats area are depicted in Fig. 6.4. The Tuinplaats implements undoubtedly form a homogeneous collection and show a common lithicultural horizon (Van Riet Lowe, 1929). According to Van Riet Lowe (1929), "it is impossible on the Tuinplaats evidence alone to say that Bushveld man manufactures such implements (Fig. 6.4.) as those illustrated here, yet it is important to note that the age of some specimens is apparently very much the same as that of the bones and when it is remembered that no implements other than Middle Stone Age types have been found within many miles of Tuinplaats, the occurrence – though it proves nothing – is provocative".

In conclusion it can be stated that the skeleton bones, antelope and extinct buffalo bone fragments in association with the stone implements can be indicative of an individual who practised an advanced Middle Stone Age industry between 200 000 and 35 000 years ago. According to McCarthy and Rubidge (2005) the principle tool types of the Middle Stone Age industry are side scrapers and points. Middle Stone Age industries are associated with modern humans (*Homo sapiens sapiens*) who sometimes crafted the implements to make spears and knives.

All modern humans appear to be descendants of a single woman, the so-called Mitochondrial Eve. She was one of a group of about 10 000 archaic *Homo sapiens* with advantageous traits that gave her descendants a selective advantage (i.e. language or greater intelligence). This population appears to have spread rapidly and did not interbreed with other archaic Homo species that existed at the time. By 30 000 years ago, hominid diversity had apparently vanished and *Homo sapiens sapiens* was evidently the only survivor (McCarthy and Rubidge, 2005).

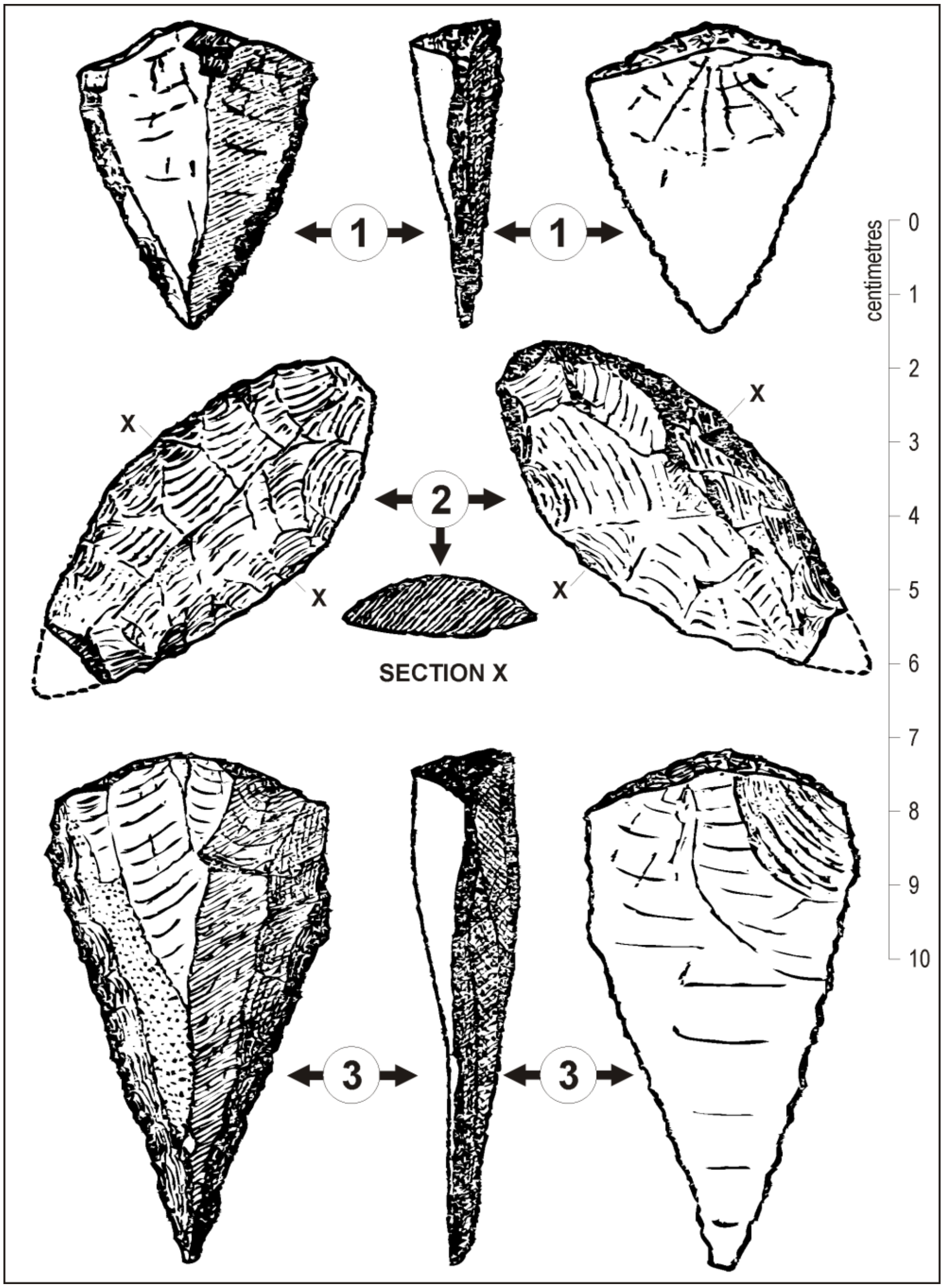


Fig. 6.4. Stone implements from the Tuinplaats area (modified after Van Riet Lowe, 1929).

Chapter 7. Stratigraphy and Depositional Environments, Karoo Supergroup, Springbok Flats Karoo Basin

7.1 Introduction

In the opening paragraph of the textbook of Krumbein and Sloss i.e. Stratigraphy and Sedimentology (1963) the authors quoted the definition for stratigraphy as compiled by Grabau (1913). According to Grabau stratigraphy can be defined as "the inorganic side of historical geology, or the development through the successive geological ages of the earth's rocky framework or lithosphere". This definition entails the original concept of stratigraphy as that part of the geological science concerned with the description, organization and classification of stratified rocks.

The emphasis Grabau placed on organic processes and organic factors widened his definition to such an extent that palaeontology became an integrated part of stratigraphy. Over the years the scope of stratigraphy has continued to enlarge. Stratigraphy can now be considered as "the integrating discipline which combines data from almost all other branches of earth science in a form, from which historical geology emerges as a natural product" (Krumbein and Sloss, 1963).

Studies undertaken in stratigraphy are mainly applied to solve problems pertaining to palaeogeography, historical geology and/or economic geology. Interpretative stratigraphy is the final phase of stratigraphic studies in which collected data is subjected to interpretation and synthesis. It is noteworthy that the words chosen by Grabau in 1913 as the final paragraph of his monumental principles of stratigraphy remain appropriate today: "When the science of stratigraphy has developed so that its basis is no longer purely or chiefly palaeontological and when the sciences or lithogenesis (sedimentation) of orogenesis and of glytogenesis (gradation) as well as of biogenesis, are given their due shade in the comprehensive investigation of the history of our earth, then we hope that palaeogeography, the youth daughter science of stratigraphy, will have attained unto that status which will make it the crowning attraction to the student of earth history” (Krumbein and Sloss, 1963).

The concept of palaeogeography and specifically palaeotopography is to a large extent underestimated as one of the cornerstones of stratigraphy and palaeo-reconstruction. Palaeotopography impacts directly on the nature and aerial distribution of sedimentary deposits and should therefore form the basis of any basin analysis study.

The current concepts and terminology applied to the classification of the stratrigraphic column are the products of more than two centuries of gradual evolution. The early concepts were dominated by the strict interpretation of the Book of Genesis, the first book of the Bible. Under the direct influence of this book, geological time was considered to amount to a few thousand years. Sediments were ascribed to the action of the biblical flood and fossils were interpreted as evidence of creatures engulfed by the flood, inventions of the devil or figure stones. During the early 1800’s researchers like Hutton and Lyell created certain stratigraphic concepts that withstood the test of time. There is no justification for the belief that the evolutionary processes shared by Hutton and Lyell are now near completion and that no further changes may be anticipated (Krumbrein and Sloss, 1963).

7.2 Historical background regarding the stratigraphy of the Springbok Flats Karoo Basin

The Springbok Flats owes its name to the large herds of Springbok which formerly roamed the area, but which have lately been reduced in numbers that the appropriateness of the name Springbok Flats threatens in a few years to be rather historical than real (Mellor, 1904).

The evolution of Karoo stratigraphy in the Springbok Flats over the last 80 years is depicted in Table 7.1. Outcrops of Karoo strata in the Springbok Flats are virtually non-existent. Early researchers like Mellor (1904, 1905) and Kynaston (1907) focused primarily on surface geology which included the Bushveld Sandstone (Clarens Formation), Bushveld Amygdaloids (Drakensberg Group) and glacial conglomerates (Dwyka Group). Numerous waterwells drilled in certain areas were of great assistance in unraveling the subsurface geology in areas devoid of any outcrops. The first subsurface coal occurance was reported by Mellor (1904) in boreholes drilled in the proximity of Pienaarsrivier Station.

Research conducted by Wagner (1927) revealed the presence of a northern and southern basin separated by ‘sand bults’ (Wagner, 1927). The lack of borehole data in the southern basin hampered further research.

The first comprehensive stratigraphic column of the Springbok Flats Karoo Basin was compiled by Visser and Van der Merwe (1959). Borehole data from 27 boreholes was used to compile the stratigraphic column as depicted in Table. 7.1.

In 1976 and again in 1986 De Jager compiled stratigraphic columns. The differences between the two versions are indicated in Table 7.1. S.A.C.S (1980) diverted from previous nomenclature by introducing new formations and by combining previous existing lithostratigraphic units into a single unit i.e. Irrigasie Formation. Roberts (1992), Snyman (1998) and Johnson et al. (2006) revised the stratigraphic column again and it is assumed that the version of Johnson (2006) will prevail for the time being.

The preceding literature research revealed a common shortcoming pertaining to the actual definition of lithostratigraphic units. The researchers neglected to define sedimentological parameters used to define lithostratigraphic units.

Table 7.1. Stratigraphy of the SFKB (historical).

<table>
<tr><th>Wagner</th><th>Du Toit</th><th>Visser & Van der Merwe</th><th>De Jager</th><th>SACS</th><th>De Jager</th><th>Roberts</th><th>Snyman</th><th>Johnson et al.</th></tr>
<tr><th>1927</th><th>1939</th><th>1959</th><th>1976</th><th>1980</th><th>1986</th><th>1992</th><th>1998</th><th>2006</th></tr>
<tr><td>Amygdaloid basalt</td><td>Amygdaloid basalt</td><td>Drakensberg basalts stage</td><td>Drakensberg stage</td><td>Letaba Formation</td><td>Letaba Formation</td><td>Letaba</td><td>Letaba Formation</td><td>Lebombo Group</td></tr>
<tr><td>Bushveld sandstone</td><td>Bushveld sandstone</td><td>Cave Sandstone stage</td><td>Cave Sandstone stage</td><td>Clarens sandstone formation</td><td>Clarens sandstone Formation</td><td>Clarens</td><td>Clarens Formation</td><td>Clarens Formation</td></tr>
<tr><td></td><td>Bushveld marls</td><td>Red Beds stage</td><td>Red Beds stage</td><td rowspan="3">Irrigasie Formation</td><td>Elliot Formation</td><td>Elliot</td><td>Worthing Formation</td><td rowspan="3">Irrigasie Formation</td></tr>
<tr><td></td><td></td><td>Molteno stage</td><td>Molteno stage</td><td>Molteno Formation</td><td>Molteno</td><td>Codrington Formation</td></tr>
<tr><td>Ecca Series</td><td>Ecca Series</td><td>Ecca Series</td><td>Beaufort Series</td><td>Beaufort Group</td><td>Beaufort</td><td>Lehau Formation</td></tr>
<tr><td></td><td>Upper Ecca shales</td><td rowspan="3">Upper Ecca stage</td><td rowspan="3">Middle Ecca stage</td><td rowspan="4">Ecca Group</td><td></td><td>Coal Zone</td><td>Warmbad Formation</td><td rowspan="4">Hammanskraal Formation</td></tr>
<tr><td></td><td>Middle Ecca coal shales</td><td>Vryheid Formation</td><td>Vryheid</td><td>Turfpan Formation</td></tr>
<tr><td></td><td>Lower Ecca shales</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Middle Ecca stage</td><td>Lower Ecca stage</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Glacial conglomerates</td><td>Dwyka Series</td><td>Dwyka Series</td><td></td><td></td><td>Dwyka</td><td>Merinovlakte Formation</td><td>Dwyka Group</td></tr>
</table>

Biostratigraphic contacts based on trace fossil occurrences or the absence thereof were ignored during the compilation of the stratigraphic columns as depicted in Table 7.1.

The purpose of this research will be to focus on the description of lithostratigraphical units in order to establish mappable units characterized by unique sedimentological and biological parameters relevant to each individual unit.

Lithostratigraphic units encountered in the Springbok Flats will be described in terms of:

a) texture:
   i. roundness
   ii. grain size
b) colour
c) mineral composition
d) sedimentary structures
e) deformation structures
f) organic structures
g) fossils

The grain sizes, roundness and packing density of the arenaceous sediments were determined by using a Loock-ruler. Dr. J.C. Loock (Department of Geology, UFS) designed the Loock-ruler as an exploration tool for field geologists (Fig. 7.1.). The grain size categories are in accordance with the Udden-Wentworth scale (Blatt et al., 1972) for granule size sediments to very fine grained sandstone. Images of grains for the determination of roundness also forms part of the Loock-ruler design (Blatt et al., 1972).

Based on the preceding an attempt will be made to correlate the stratigraphic subdivisions in the Springbok Flats with subdivisions of the Karoo Supergroup in the Main Karoo Basin.

Fig. 7.1. Loock-ruler.

7.3 Stratigraphy of the Springbok Flats Karoo Basin

Trans Natal Coal Corporation Ltd embarked on a major exploration programme in 1976 in order to evaluate the coal potential of the entire Springbok Flats Karoo Basin. A total number of 2400 boreholes and deflections were drilled in the period 1976 – 1982. In addition, AmCoal drilled 600 boreholes, mainly in the western part of Settlers-Tuinplaats Basin, as from 1982 onwards.

All boreholes drilled by Trans Natal Coal Corporation Ltd were geophysically logged using downhole geophysical equipment. For each borehole the following geophysical logs were provided:

a) Long Spaced Density (LSD)
b) Short Spaced Density (SSD)
c) Bed Resolution Density (BRD)
d) Neutron-Neutron (NE-NE)
e) Total Gamma Ray
f) Detailed Gamma Ray

These logs were used to lithologically describe borehole intersections, to define lithological units, to describe coal intersections in detail (i.e. 2 cm intervals), to identify uraniferous horizons associated with the coal and to calculate an in situ uranium grade (kg/t) for all uranium horizons.

The geophysical data obtained in conjunction with detailed sedimentological descriptions on selected boreholes were used to compile a comprehensive stratigraphical column for the Springbok Flats Karoo Basin.

Seven lithostratigraphical units were identified. Each unit will be described in accordance with the sedimentological features mentioned.

7.3.1 Lithostratigraphic Unit 1

7.3.1.1 Lithology

Lithostratigraphic Unit 1 represents glacial derived sediments and comprises the basal part of the Karoo Supergroup which overlies the pre-Karoo formations unconformably.

Kynaston (1904) reported the presence of glacial conglomerates on the farms Slagboom 513 and Toitskraal 421 in the southeastern portion of the Springbok Flats along the course of the Elandsriver. The glacial conglomerates directly overlie red granite of the Bushveld Igneous Complex (BIC) and comprise granitic and highly polished Waterberg Group quartzite more than 1.0 m in diameter. The matrix of the glacial conglomerate comprises yellow arenaceous material while lenticular sandstone lenses are also present.

The glacial conglomerates are overlain by shales, grits and sandstone. The shale horizon occurs between the glacial conglomerate and overlying arenaceous sediments.

The aerial extent of these glacial derived sediments is unknown. During the exploration programme (1979 – 1982) 359 boreholes intersected pre-Karoo formations. Of this only 20% intersected glacial derived sediments. The different lithologies encountered in the glacial derived sediments of Lithostratigraphic Unit 1 are depicted in Fig. 7.2. – 7.5. Lithostratigraphic Unit 1 as developed in the Settlers-Tuinplaats Basin is depicted in Fig. 7.2. and 7.3, lithologies associated with the

Droogekloof Fault (Fig. 7.4.) and lithologies encountered in the Roedtan Basin (Fig. 7.5.).

Lithostratigraphic Unit 1 in the Settlers-Tuinplaats Basin is characterized by well developed upward fining cycles. The basal part of Lithostratigraphic Unit 1 comprises diamictite and coarse grained to gritty sandstone (Fig. 7.2.). The pebbles comprise mainly angular felsite, granite and quartzite fragments in a dark grey argillaceous matrix. The diamictite has a low packing density and the pebble sizes vary between 0.20 to 0.60 cm in diameter. No preferred orientation of the pebbles was observed. Well defined upward fining cycles were identified of which the two lower cycles do not contain any argillaceous material (Fig. 7.2.)

The upper part of Lithostratigraphic Unit 1 comprises conglomerates, coarse grained to fine grained sandstone with intercalated carbonaceous shale and bright coal layers occurring at the top of upward fining cycles. The conglomerates contain mainly angular felsite, quartzite and minor granite pebbles ranging in size from 0.10 to 0.26 cm in diameter in a fine grained arenaceous matrix. Horizontal bedding occurs at the base of most cycles with flaser bedding towards the top of certain cycles. A grey weakly carbonaceous shale with scattered coarse granite felsite and quartz fragments occurs at the top of Lithostratigraphic Unit 1. This carbonaceous shale horizon is overlain by a grey shale devoid of any arenaceous material. This shale defines the lower contact of Lithostratigraphic Unit 2.

The two profiles in Fig. 7.2. represent intersections 1.8 km apart. Irregularities in the pre-Karoo topography contributed to the large variation in thickness and sedimentary properties encountered.

Lithostratigraphic Unit 1 intersections in close proximity of a palaeo-topographical high near Settlers are depicted in Fig 7.3. The intersections differ from those in Fig. 7.2. in that the intersections in Fig. 7.3. contain a coal horizon close to the underlying pre-Karoo rocks. The thickness of the coal horizon varies from 0.36 m to 2.5 m. The coal horizon comprises mainly carbonaceous shale and dull coal. The sandstone intersected varies from medium to coarse grained, grey in colour and massively bedded. Unlike the sandstone encountered in Lithostratigraphic Unit 2, the sandstones in Lithostratigraphic Unit 1 do not contain any micaceous material.

Intersections of Lithostratigraphic Unit 1 which are associated with the Droogekloof Fault on the anticlinal ridge that separates the Settlers-Tuinplaats Basin from the northern Roedtan Basin are depicted in Fig. 7.4. A prominent diamictite was intersected directly south of the Droogekloof Fault, north-northwest of Bela Bela. The diamictite is characterized by a prominent carbonaceous argillaceous matrix with irregular thin bright coal laminae in places. The diamictite contains angular to subrounded felsite, quartzite and granite pebbles from the Transvaal Supergroup, BIC and Waterberg Group. Subordinate thin varve shale layers occur within the diamictite.

Well developed coal horizons were intersected in areas associated with the Droogekloof Fault. The coal horizons vary in thickness from 7.0 m to 10.2 m. In one of the intersections two coal horizons were developed (Fig. 7.4). The uppermost coal horizon consists of alternating diamictite and carbonaceous shale with intermittent bright coal laminae. In the other intersection, the coal horizons comprise alternating layers of greyish shale, carbonaceous shale and coal dull. Grey, fine grained micaceous sandstone of Lithostratigraphic Unit 2 directly overlies the coal horizon with a sharp non-erosive contact.

Lithostratigraphic Unit 1 as developed in the Roedtan Basin is depicted in Fig. 7.5. Basal conglomerates and diamtictite constitute the lower divisions of Lithostratigraphic Unit 1. The conglomerates contain rounded to angular pebbles of quartzite and red and green argillites of the Transvaal Supergroup and Waterberg Group. The matrix comprises grey to green fine grained arenaceous material. The coal horizon is characterized by carbonaceous shale and dull coal. Prominent upward fining cycles were developed in the arenceous portion while the shales are grey and carbonaceous with scattered coarse ground granules of felsite and granite origin. The sandstones are mainly coarse grained to gritty, immature, massively bedded with grains comprising felsite and granite granules. The diamictite intersected comprises pebbles and angular fragments of quartzite, argillite, vein quartz and granite in a prominent argillaceous matrix.

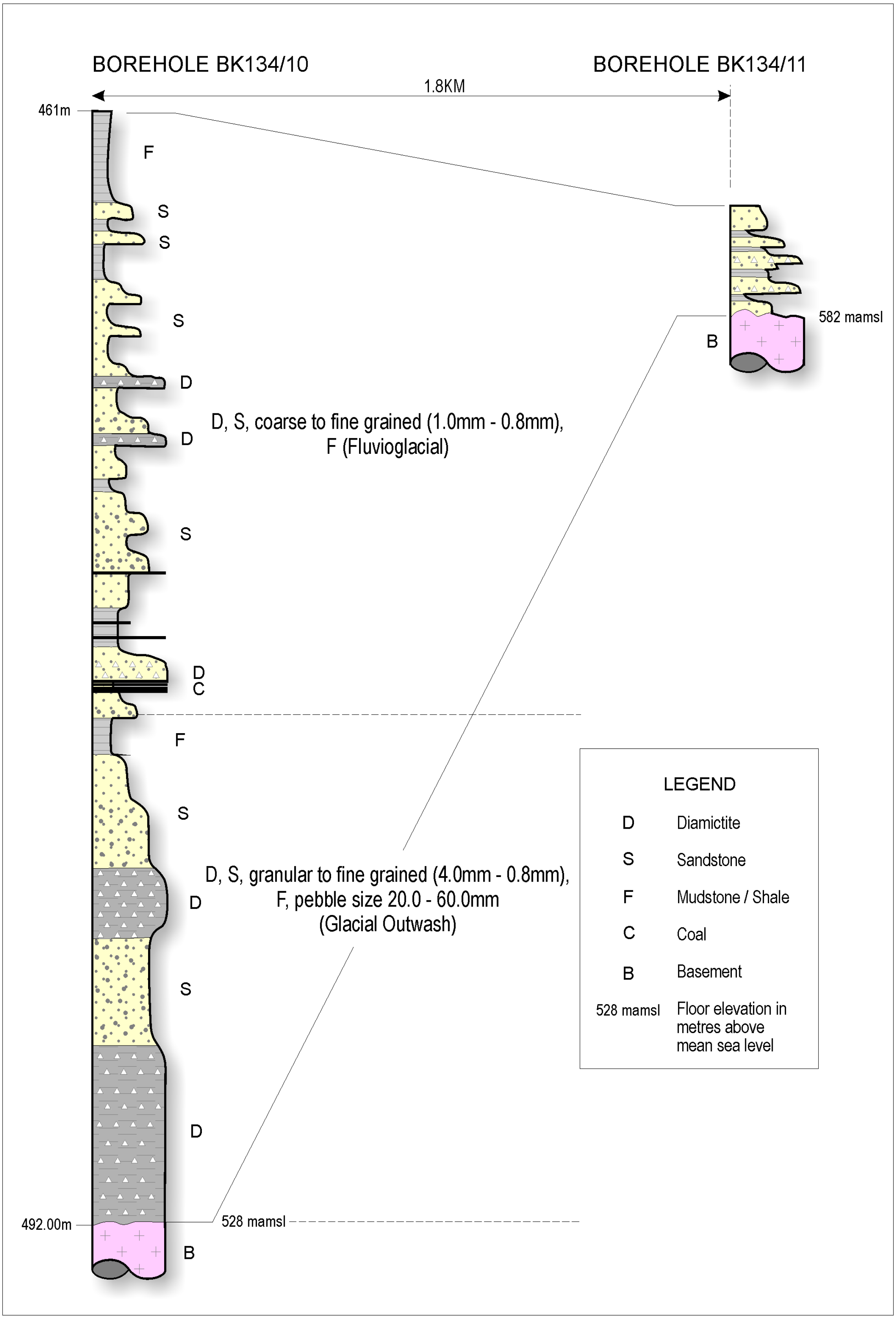


Fig. 7.2. Vertical profiles through Lithostratigraphic Unit 1 (Settlers-Tuinplaats Basin).

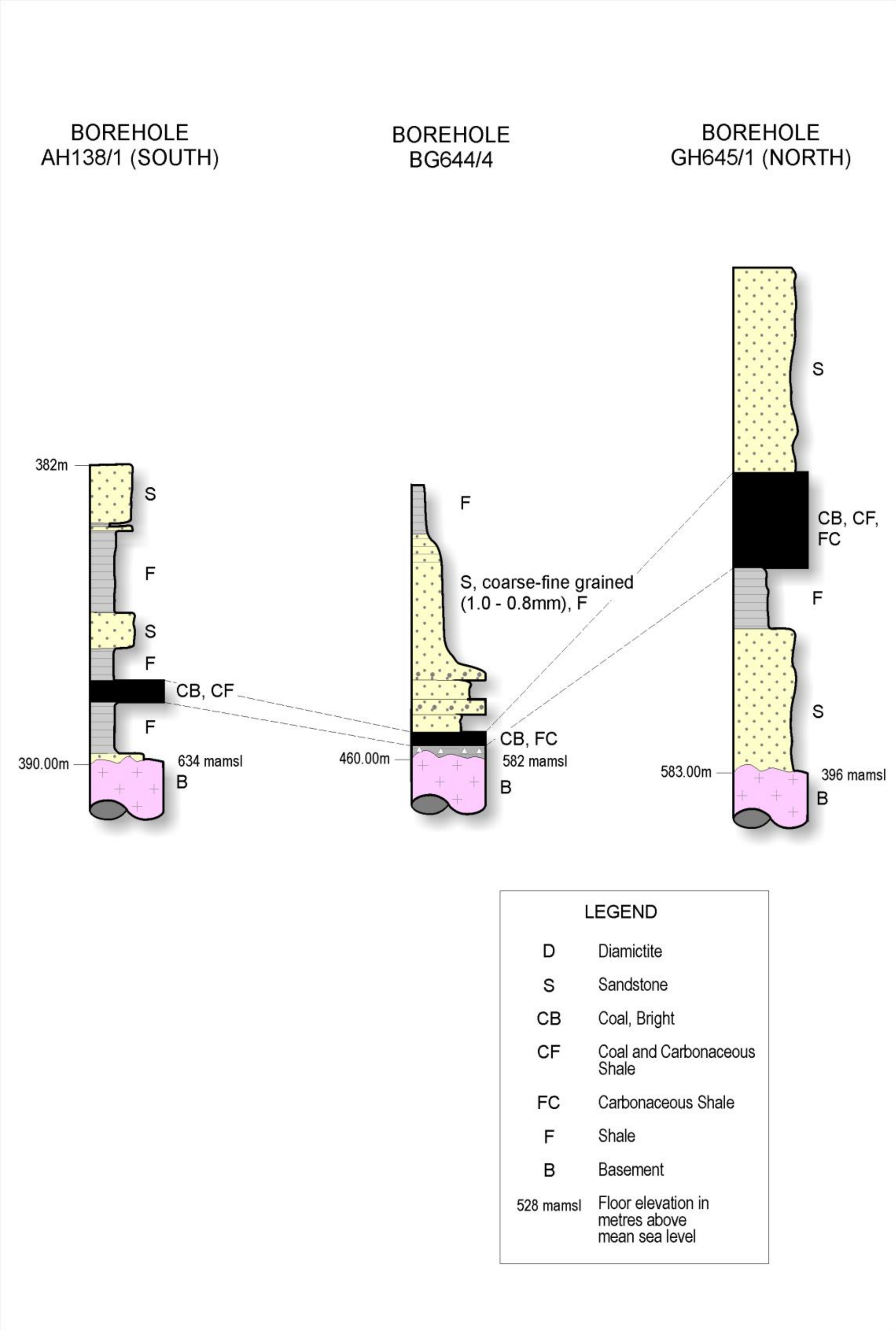


Fig. 7.3. Vertical profiles depicting Coal Seam development in Lithostratigraphic Unit 1.

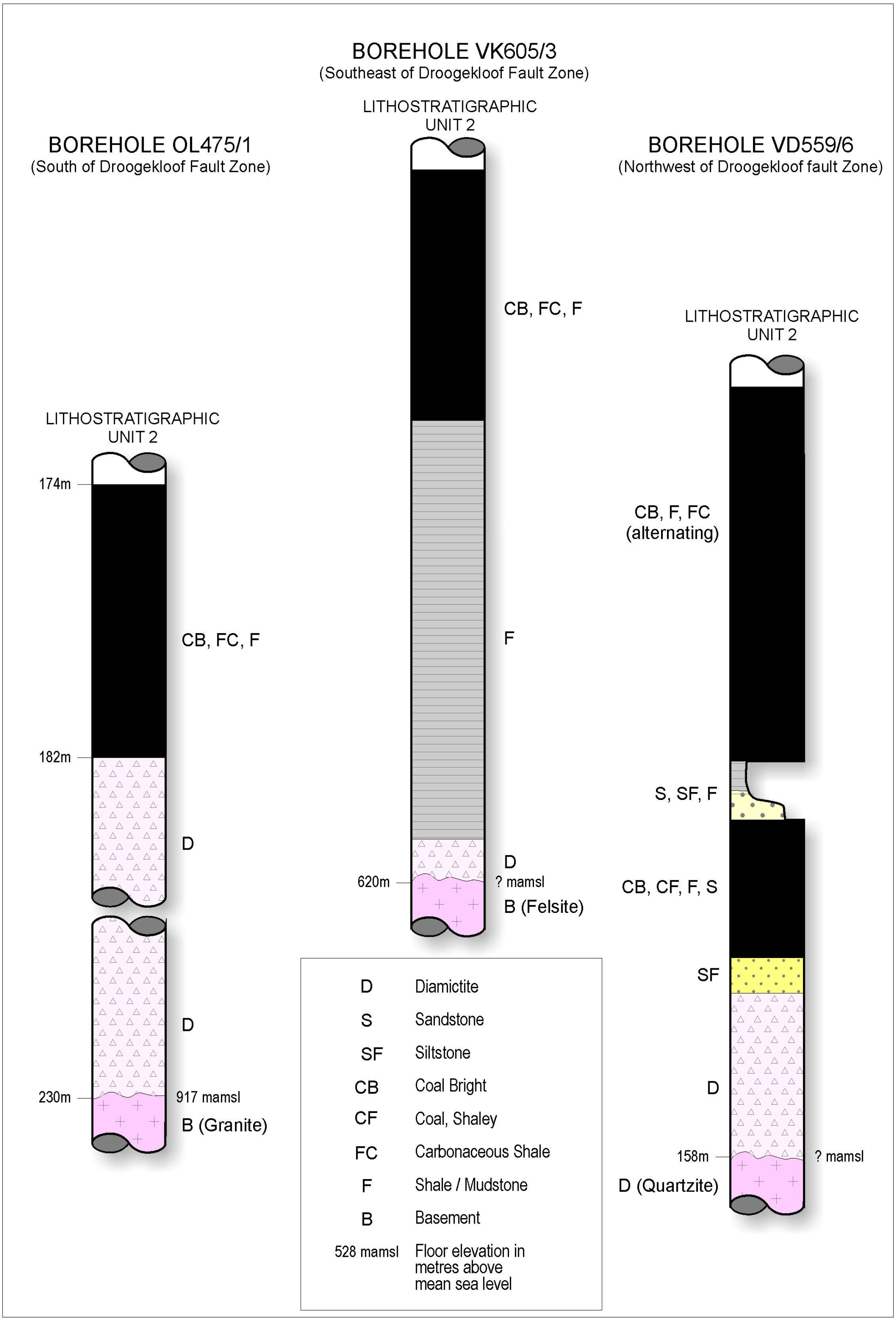


Fig. 7.4. Variations in Coal Seam lithologies and thicknesses in close proximity of the Droogekloof Fault Zone (Lithostratigraphic Unit 1).

Based on the preceding lithological description Lithostratigraphic Unit 1 can be subdivided into 4 distinct lithological units i.e.

a) Mudstone unit (top)
b) Sandstone/siltstone (upward fining cycles)
c) Conglomerates/sandy diamictite (upward fining cycles)
d) Massive diamictite (bottom)

7.3.1.2 Depositional Environments

- **Basin configuration**

The Springbok Flats Karoo Basin was severely affected by post-Karoo faulting. The lack of sufficient data meant that the actual extent of the Springbok Flats Basin could not be determined. Structural contours of the basement (Fig 3.6.) show that the Settlers-Tuinplaats and Roedtan Basins are elongated basins along active post Karoo faults.

- **Depositional Environments**

Sedimentation in a glacial environment as indicated by the texture and composition of the rocks and the close relationship between clast and matrix composition will be different in different parts of a basin (Visser and Van den Berg, 1980). There are reasonable grounds to assume, based on the preceding characteristics of sediments that the basal sequence of the Karoo strata in the Springbok Flats Karoo Basin represents glacial and proglacial deposits.

Considering the diamictite and associated deposits it becomes evident that deposits in Lithostratigraphic Unit 1 represent more than one glacial sub-environment. The massive diamictite was probably deposited subglacially from an englacial or basal tractional zone in the presence of abundant meltwater. The sandstone deposits associated with the diamictites resemble deposits in close proximity of the glacier where glacier debris was reworked by meltwater streams during rapid melting of the ice. The relatively thick sandstone unit showing upward fining cycles represents

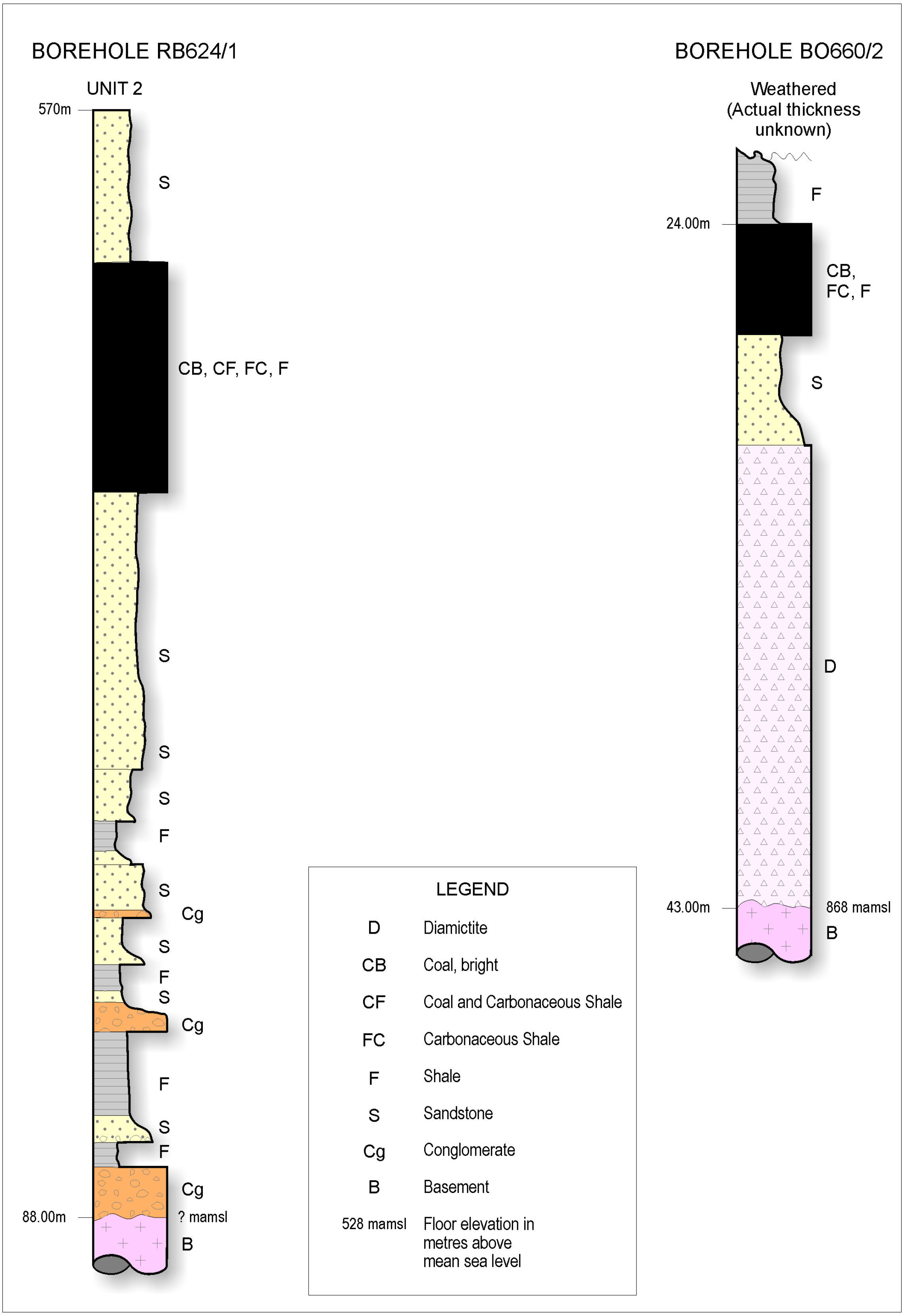


Fig. 7.5. Vertical profiles through Lithostratigraphic Unit 1 (Roedtan Basin).

proximal outwash deposits. Horizontal bedding, lack of overbank deposits and the association with grit, favour deposition in the upper flow regime. The sedimentological characteristics of this unit fit that of braided stream deposits which are associated with glacial environments (Miall, 1977).

The deposition of carbonaceous shales and siltstone took place in a shallow lacustrine reducing environment conducive for the accumulation and preservation of carbonaceous detritus.

Lithostratigraphic Unit 1 represents glacial retreat sedimentation with sub-glacially deposited material being overlain by proximal outwash sediments close to the ice margin. As the ice retreated further, distal arenaceous outwash sediments were deposited while fine grained sediments, carbonaceous shales and coal were deposited in shallow lacustrine environments (Visser and Van den Berg, 1980).

- **Direction of Ice Flow**

The lack of proper outcrops and subsurface borehole data hampered any effort to determine an ice flow direction. The pre-Karoo structural contour map reveals two E-NE trending linear structures associated with Settlers-Tuinplaats and Roedtan Basins respectively. Ice flow directions perpendicular to these trends are very unlikely. The close relationship between clast composition and bedrock based on the existing borehole data favours an east-to-west flow direction.

In conclusion, it seems reasonable to accept that the ice retreated towards the east and it is postulated that the ice also came from this direction. Local obstructions in the pre-Karoo floor and fault troughs could have caused local diversions in the ice flow direction resulting in the dumping of glacial derived material which caused anomalous thicknesses adjacent to local obstructions.

7.3.2 Lithostratigraphic Unit 2

7.3.2.1 Lithology

A generalized geological profile of Lithostratigraphic Unit 2 is depicted in Fig. 7.6. As in the case of Lithostratigraphic Unit 1, not enough data is available to determine the aerial distribution or facies changes that might occur within Lithostratigraphic Unit 2.

Lithostratigraphic Unit 2 directly overlies Lithostratigraphic Unit 1 with a sharp non-erosive contact. Four distinct sedimentary facies were identified (Fig. 7.6.). The initial exploration programme was designed to demarcate potentially exploitable coal. In areas where exploitable coal was intersected boreholes were stopped ± 6.0 m

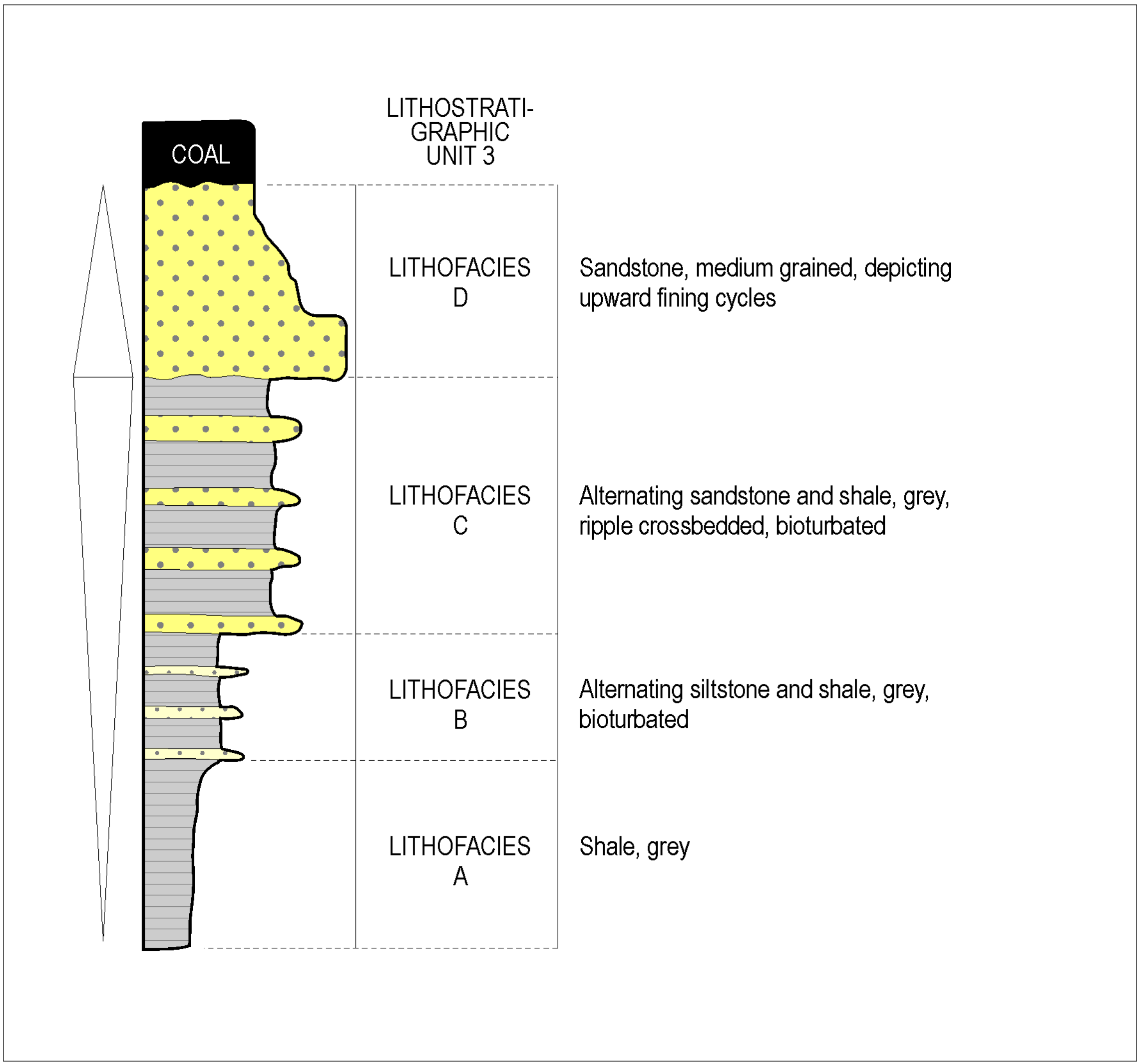


Fig. 7.6. Generalized geological profile: Lithostratigraphic Unit 2.

below the coal. The result of this exploration method is that lateral facies changes as well as the geometry of Lithostratigraphic Unit 2 could not be determined. However, the available data reveals that the composition and aerial extent of Lithostratigraphic Unit 2 were largely influenced by the pre-Karoo topography. Towards the palaeo-topographical highs Lithostratigraphic Unit 2 totally peters out resulting in younger sediments directly overlying pre-Karoo formations.

- **Lithofacies A**

Lithofacies A is a grey to dark grey carbonaceous shale. This shale directly overlies Lithostratigraphic Unit 1 with a sharp contact. Lithofacies A is characterized by the absence of granular inclusions which distinguishes it from the carbonaceous shale of Lithostratigraphic Unit 1. Lithofacies A is very thinly laminated and contains abundant carbonaceous detritus throughout.

- **Lithofacies B**

The contact between Lithofacies A and the overlying Lithofacies B is gradational. A gradual increase in fine grained arenaceous sediment towards the top of Lithofacies A marks the gradation between the two Lithofacies.

Lithofacies B comprises mainly siltstone, greyish, micaceous with interbedded sandstone, grey, fine grained, laminated and ripple crossbeddded towards the top. The first appearance of biological activities in the form of horizontal, vertical and subvertical burrows occur in Lithofacies B. In certain areas original sedimentary structures were destroyed by this bioturbation. The characteristics of the bioturbated horizons as mentioned, resemble the characteristics of the Skolithos Ichnofacies as defined by Frey (1975). A gradual increase in coarser grained arenaceous material occurs at the transition from Lithofacies B to C.

- **Lithofacies C**

The contact between Lithofacies B and C is a gradational contact characterized by an increase in coarser material towards the top of Lithofacies C. Lithofacies C comprises mainly sandstone, fine to medium grained, light coloured to greyish, feldspathic and micaceous. The sandstone is finely bedded with abundant ripple crossbedding. Bioturbation is a common feature. The diameter of the burrows varies between 3.0 mm and 10.0 mm. The bioturbation also resembles burrows associated with the Skolithos Ichnofacies (Frey, 1975) (Fig. 7.7.).

- **Lithofacies D**

Lithofacies D overlies Lithofacies C with a sharp contact. Lithofacies D comprises sandstone fine to medium grained, whitish to greyish in well defined upward fining cycles varying in thickness between 0 and 30.0 m. These cycles are characterized by a graded bedded basal horizon, followed

Fig. 7.7. Bioturbation in Lithofacies C: Lithostratigraphic Unit 2.

by ripple crossbedded and horizontally bedded horizons respectively. The sandstone is feldspathic with abundant micaceous minerals. Bioturbation occurs, but is not as prominent as in the lower facies. No rootlet bioturbation was encountered.

7.3.2.2 Depositional Environments

Melting of the ice caps resulted in the deposition of Lithostratigraphic Unit 1 as discussed. The deposition of Lithostratigraphic Unit 1 was followed by an increase in water depth that probably resulted from tectonic activities along pre-existing faults or flooding that resulted from melting of the ice caps. This increase in water level resulted in transgressive ravinement. Thus, an interface between environments i.e. a lake environment and a more terrestrial environment developed (Beukes, 1984).

The depositional interface or transitional environment is a function of many variables like rate of influx of land derived sediment, tidal regime, current systems, climate and the relative movements of land and water masses. The nature of the transitional deposits basically reflects the strengths of two processes; the rate of injection of land derived sediments; and the ability of marine processes to redistribute these sediments. Fluctuations in the position of the depositional interface relative to the land may be caused by sedimentation, tectonism or eustatic changes in water level such as that caused by melting ice. In terms of sedimentation the accommodation space available in a body of water (lake) and the quantity of material supplied to the basin will result in transgressions and/or regressions. When the accommodation space in a basin exceeds the volume of sediments deposited in the basin, transgression will take place. Regression will take place if the accommodation space in the basin is insufficient to accommodate the influx of land derived sediments and when the accommodation space in a basin is equal to the influx of sediments, stationary conditions will prevail.

During a regression an environment conducive for the development of deltaic deposits will result, while during a period of stationary conditions, accumulation of plant material can be equal to the rate of subsidence in the depositional environments resulting in the formation of coal deposits.

Lithostratigraphic Unit 2 comprises an upward coarsening cycle capped by an upward fining cycle. It is postulated that Lithostratigraphic Unit 2 represents a deltaic sequence. Unit A is defined as pro-delta deposits. Unit A is followed by Units B and C which resemble delta slope and delta platform deposits respectively. Unit D comprises upward fining cycles which are assigned to the distributary channel environment (Selley, 1969).

Lithostratigraphic Unit 2 was deposited during a regression that followed a transgression that resulted from the influx of water, either from basin subsidence or from excess water derived from ice cap melting. An uplift in the sediment resource area resulted in an influx of sediments into the lake which did not have the ability to rework and/or re-distributed these sediments. The end result of this process was a regression during which the sediments of Lithostratigraphic Unit 2 were deposited.

7.3.3 Lithostratigraphic Unit 3

7.3.3.1 Lithology

Lithostratigraphic Unit 3 constitutes the most important lithostratigraphic unit in the Springbok Flats as this unit hosts potential exploitable coal and uranium resources.

Lithostratigraphic Unit 3 occurs between argillaceous sediments assigned to Lithostratigraphic Unit 4 and the predominantly arenaceous sediments of Lithostratigraphic Unit 2. The contact between Lithostratigraphic Unit 3 and the underlying Lithostratigraphic Unit 2 is sharp and non-erosive.

The development of Lithostratigraphic Unit 3 is to a large extent affected by the pre-Karoo topography. The influence of topography on Lithostratigraphic Unit 3 development is borne out by the difference between Lithostratigraphic Unit 3 floor elevation and thickness (Fig. 7.8.).

To demonstrate the influence of topography on Lithostratigraphic Unit 3 several cross-sections similar to those in Fig. 7.9. and 7.10. were compiled for both the

Settlers-Tuinplaats and Roetdtan Basins respectively. This research revealed the following:

a) In the main coal bearing areas Lithostratigraphic Unit 3 comprises the Upper, Middle and Lower Seams.

b) The Lower Seam has the largest aerial distribution and thins out towards the palaeo-highs.

c) In the proximity of the palaeo-highs Lithostratigraphic Unit 3 has partly been eroded during the deposition of Lithostratigraphic Unit 5 resulting in variations in Lithostratigraphic Unit 3 thickness over relatively short distances.

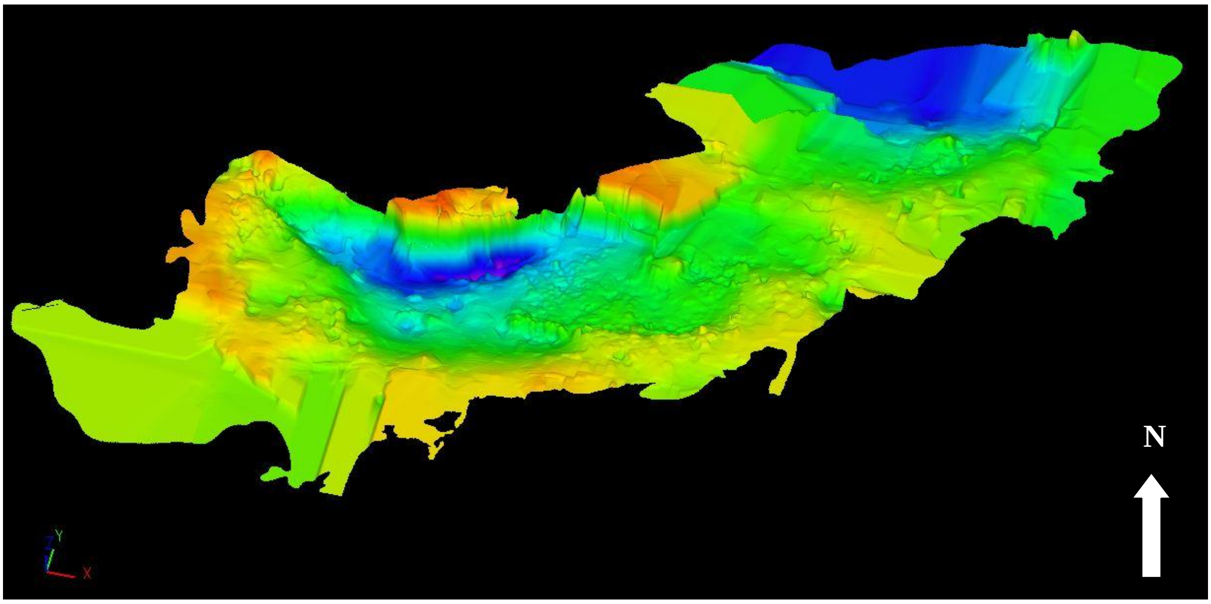


Fig. 7.8. Palaeotopography of Lithostratigraphic Unit 3.

d) As the palaeo-highs are approached first the Upper Seam peters out, followed by the Middle Seam and Lower Seam respectively.

e) The general nature of Lithostratigraphic Unit 3 is that of a cyclic deposit comprising alternating grey and/or carbonaceous shales and bright coal or banded bright coal.

f) The thickness of Lithostratigraphic Unit 3 ranges from nil near palaeo-highs to 9.0 m in the deeper part of the basins.

➢ Application of Wireline Logs

Wireline logging, as a tool to assist in the description of sedimentary rocks and associated coal was employed by the utilization of downhole free hanging equipment. Various geophysical logs were produced to assist in:

a) Coal seam qualitites
b) General lithological descriptions and
c) Depth discrepancies between the original borehole and its deflection.

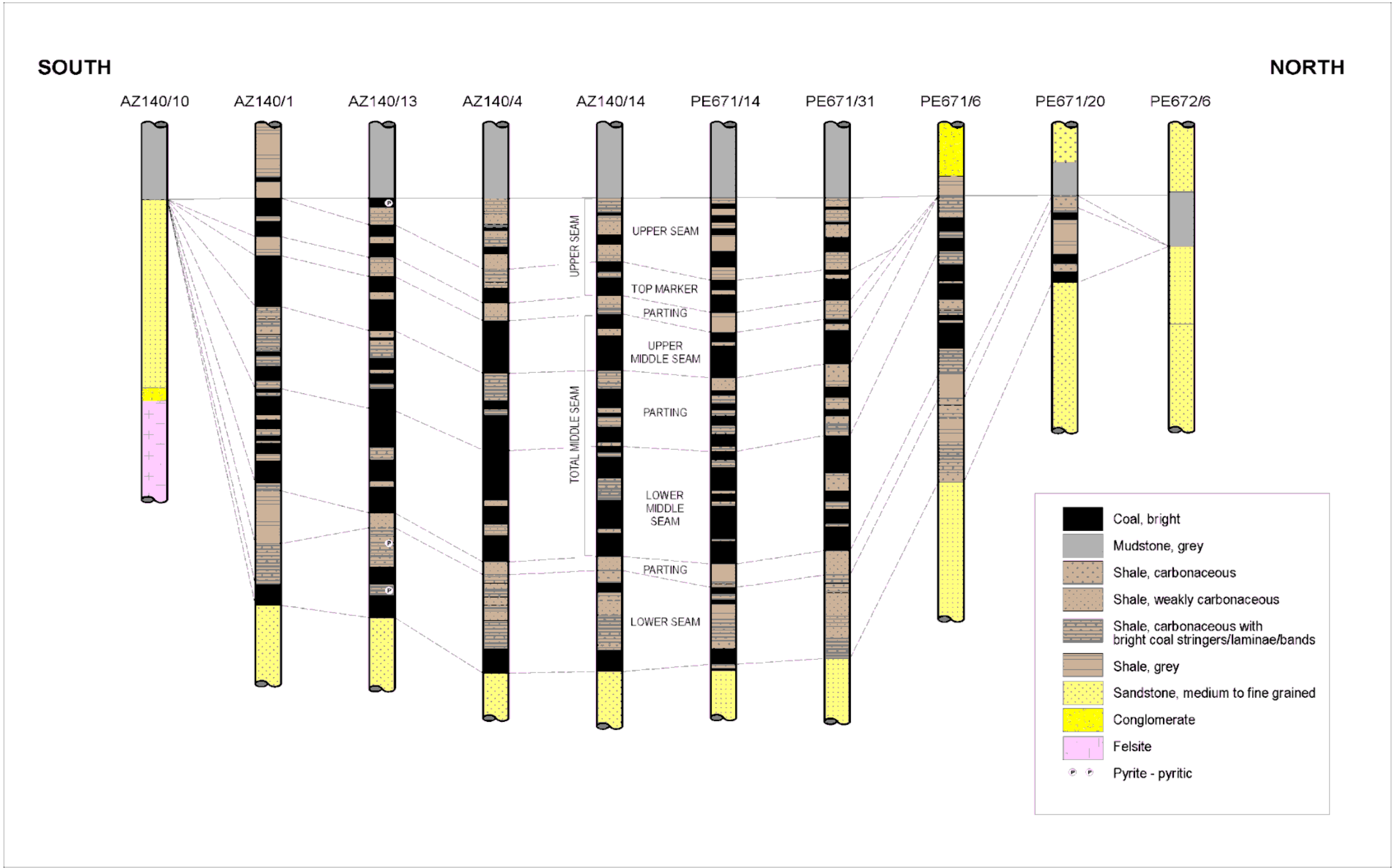


Fig. 7.9. Geological section through Lithostratigraphic Unit 3 in the Settlers-Tuinplaats Basin.

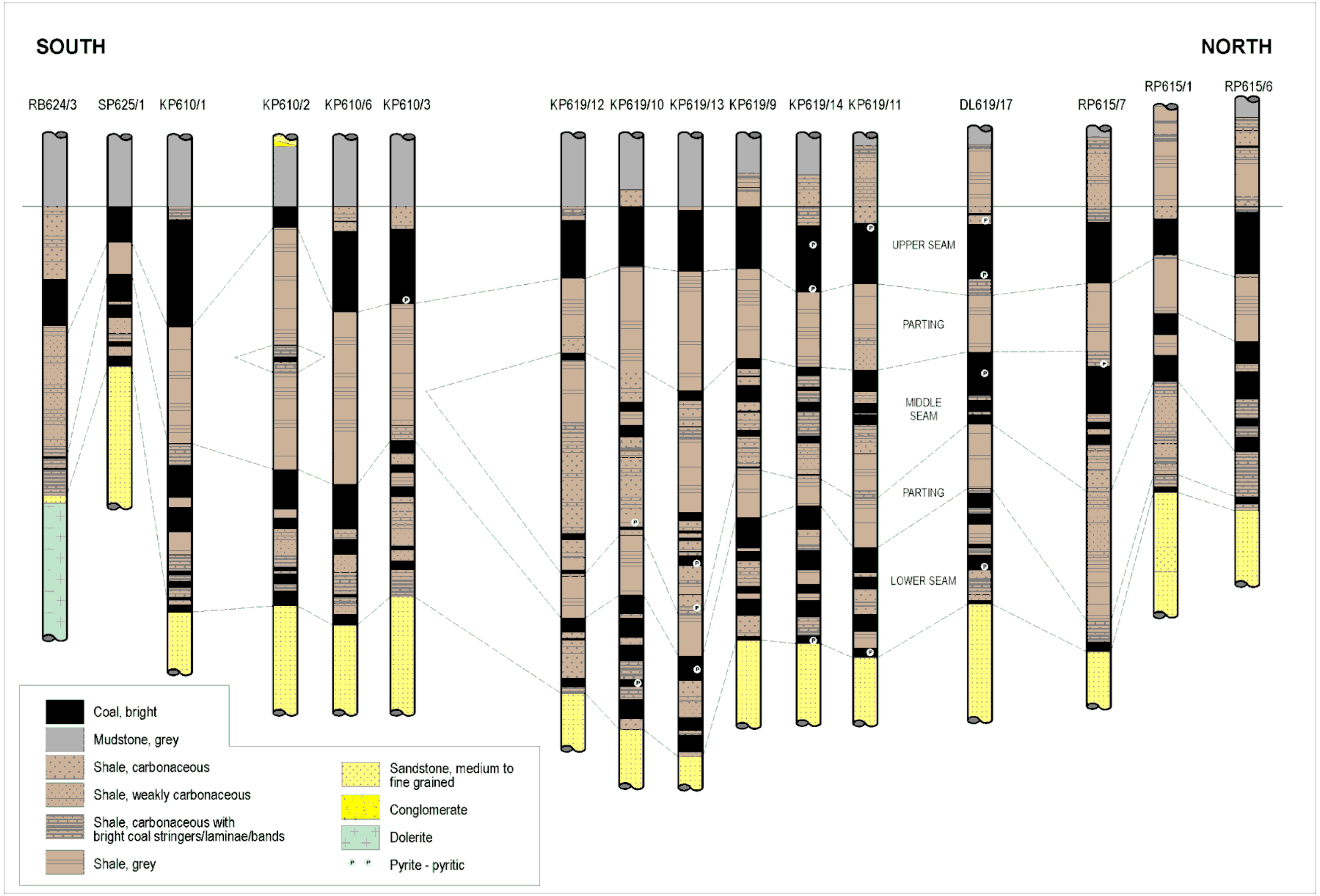


Fig. 7.10. Geological section through Lithostratigraphic Unit 3 in the Roedtan Basin.

The Bed Resolution Density (BRD) surveys were continuously used to:

a) determine the actual depth of the coal zone.
b) obtain a detailed description of the coal based on the variations in densities encountered.
c) determine core losses quantitatively.
d) serves as a tentative guide as to the qualities of the coal i.e. raw ash.
e) correlate coal seams.

However, the following limitations in using the BRD-log were encountered:

a) Pyrite in the side wall of the coal intersection. Due to the increase in density the counts per second registered by the detector are reduced, thus showing bright coal as shale on the log.
b) Single sonde probe influenced by increased natural radiation resulted in the overestimation of the coal qualities. This problem was resolved by using a trisonde probe which has a different configuration, i.e. a shrouded detector and a stronger (10 millicurie) source.

Utilization of the above mentioned geophysical logs in conjunction with detailed borehole descriptions, were used to determine the lithological variations encountered in Lithostratigraphic Unit 3. The data obtained was used to delineate sub-Basins, characterized by specific coal seam development, within Lithostratigraphic Unit 3.

In addition to the BRD-surveys a short spaced Neutron-Neutron probe was used in conjunction with the BRD-surveys for defining seam boundaries and thus seam thicknesses in the presence of high natural gamma radiation. The Neutron-Neutron probe utilizes a counter that is not sensitive to gamma radiation and therefore overcomes the problem pertaining to seam boundaries in radioactive horizons.

The utilization of the above mentioned geophysical tools in all boreholes drilled eliminated discrepancies regarding seam thicknesses and lithological description.

Fig. 7.11 depicts how the coal zone (Lithostratigraphic Unit 3) was described in accordance with geophysical data obtained from a Long Spaced Density and BRD-surveys.

➢ Settlers-Tuinplaats Basin

Lithological variations encountered in Lithostratigraphic Unit 3 in the Settlers-Tuinplaats Basin resulted in the demarcation of five sub-basins within this field. These sub-basins are the Northern, Southern, Tuinplaats, Driefontein and Warmbaths sub-basins respectively. In these sub-basins the best developed coal seam is the Middle Seam, however the best developed coal horizon within the Middle Seam is characterized for each sub-basin viz:

a)	Northern sub-basin:	Total Middle Seam
b)	Southern sub-basin:	Lower Middle Seam
c)	Tuinplaats sub-basin:	Upper Middle Seam
d)	Driefontein sub-basin:	Upper Middle Seam
e)	Warmbaths sub-basin:	Middle Seam

The variations in lithologies encountered in Lithostratigraphic Unit 3 are depicted in Fig. 7.12. – 7.14. for three of the above mentioned sub-basins.

➢ Northern sub-Basin (Fig. 7.12.)

In the Northern sub-basin, Lithostratigraphic Unit 3 is fully developed and comprises an Upper, Middle and Lower Seam respectively. Both the Upper and Lower Seams contain thick intercalated shale horizons which rendered these seams uneconomical for future mining.

➢ Southern sub-Basin (Fig. 7.13.)

In the Southern sub-basin only the Middle Seam and Lower Seam are developed. A carbonaceous shale above the Middle Seam probably represents the Upper Seam. The Lower Middle Seam represents the exploitable coal horizon in this resource

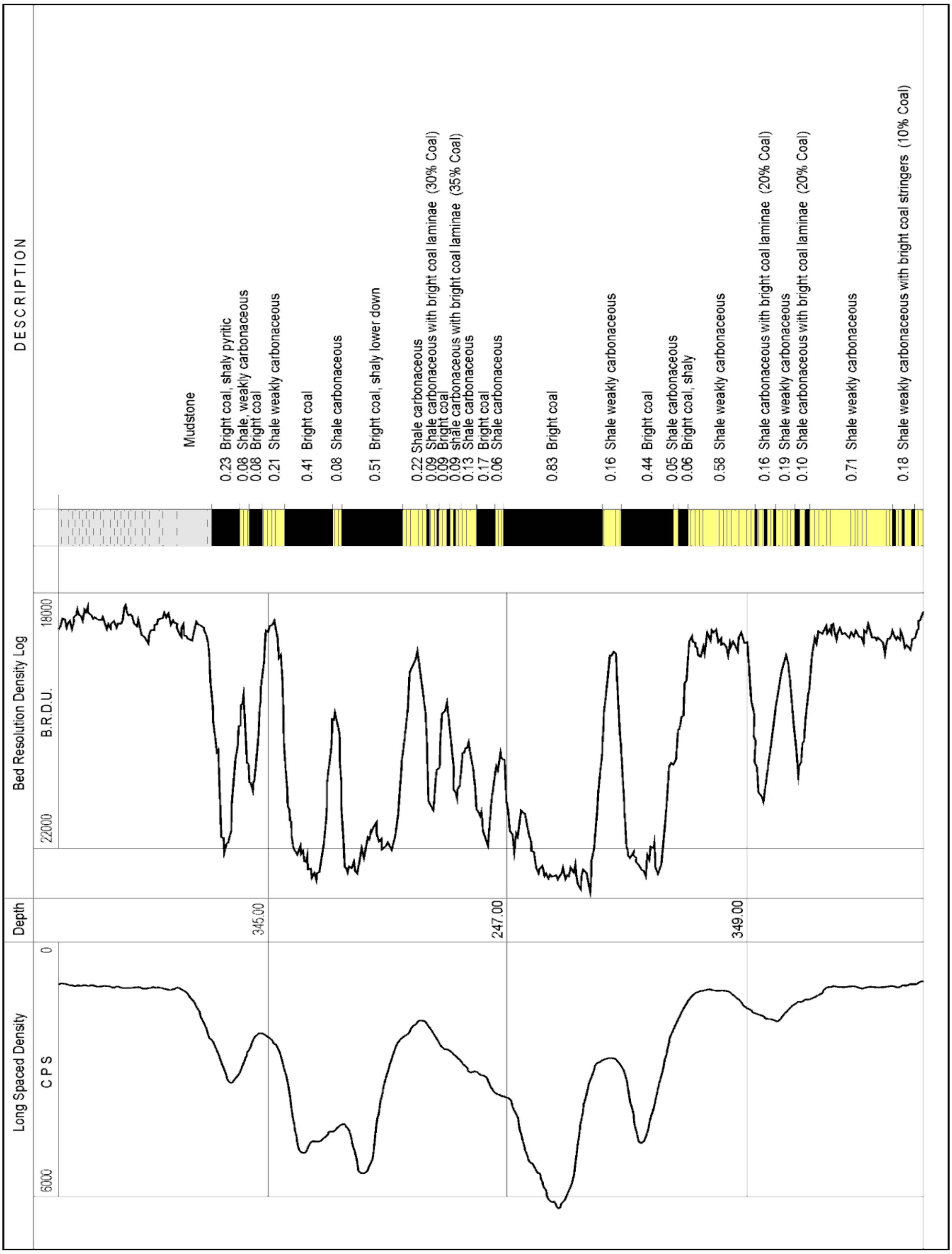


Fig. 7.11. Applications of geophysical logs in describing Lithostratigraphic Unit 3.

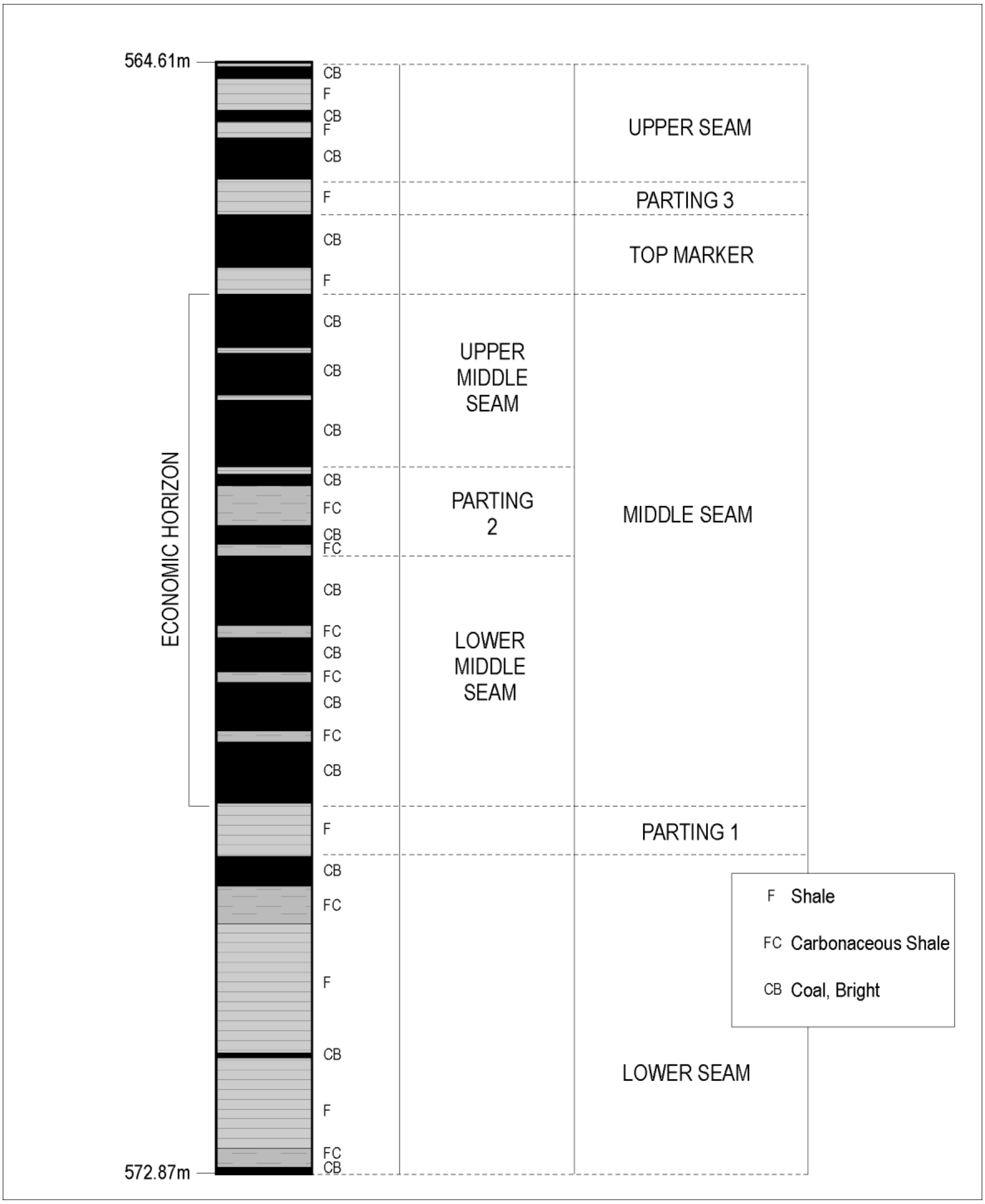


Fig. 7.12. Vertical profile through Lithostratigraphic Unit 3 – Northern sub-Basin.

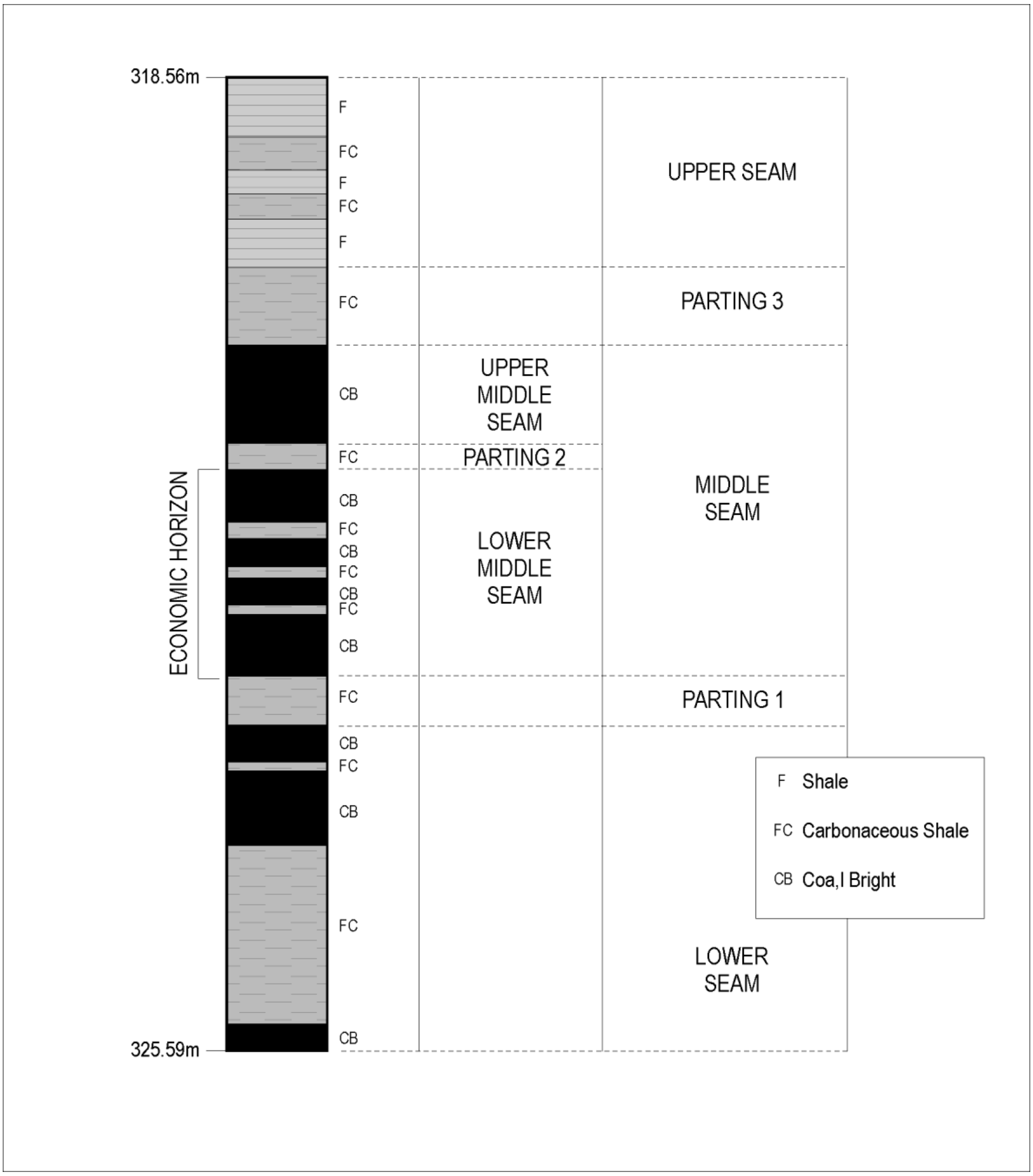


Fig. 7.13. Vertical profile through Lithostratigraphic Unit 3 – Southern sub-Basin.

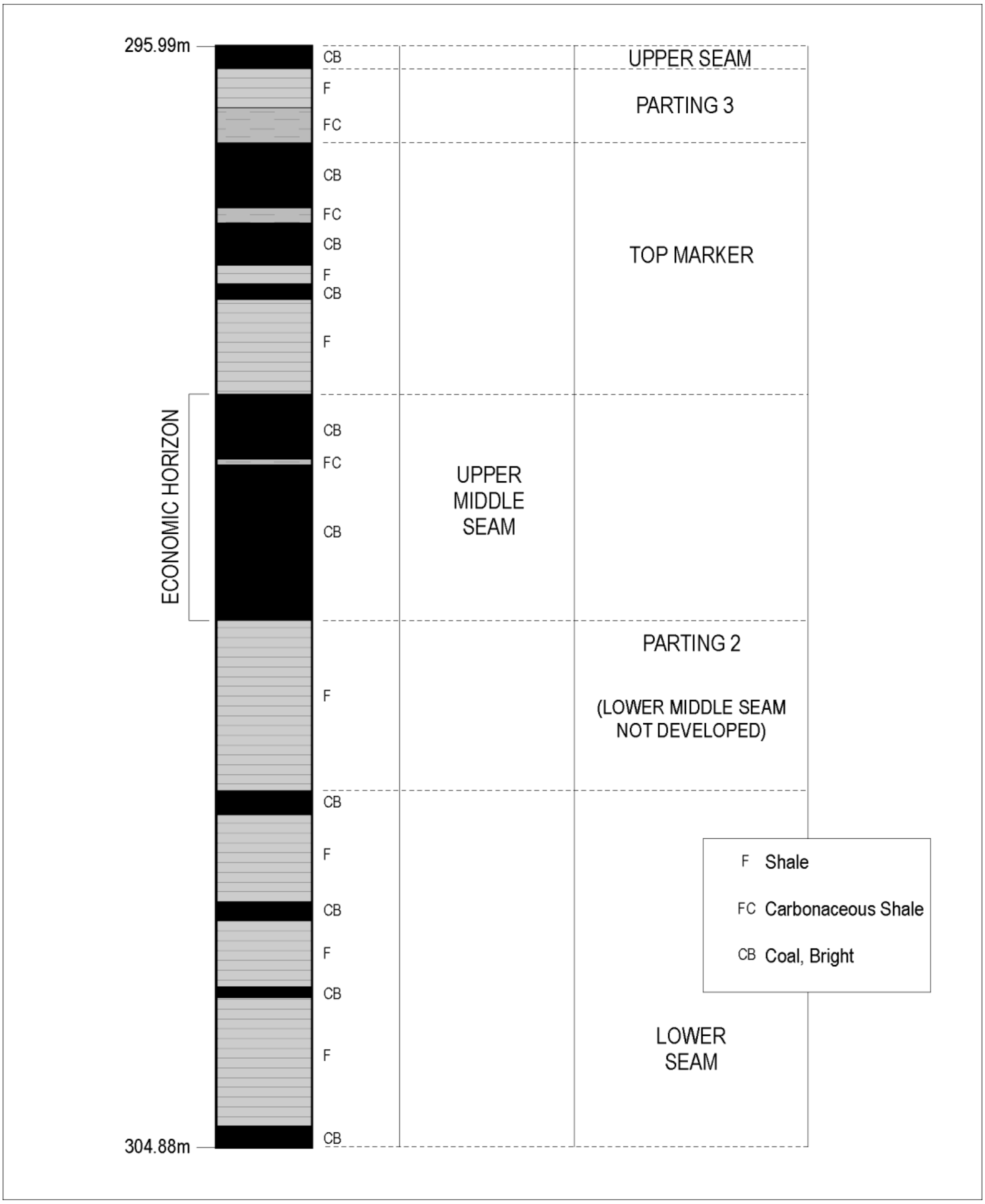


Fig. 7.14. Vertical profile through Lithostratigraphic Unit 3 – Tuinplaats sub-Basin.

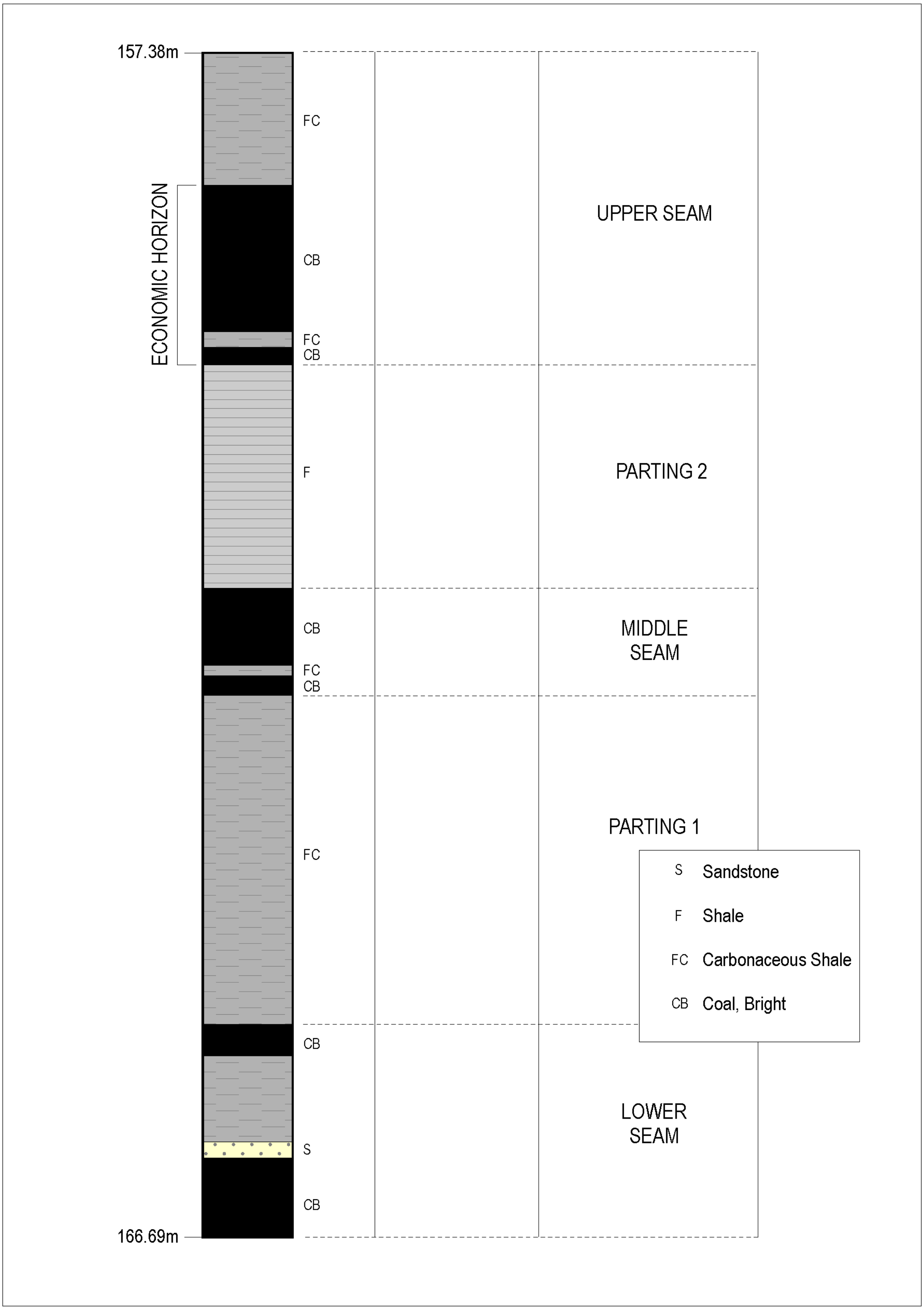


Fig. 7.15. Vertical profile through Lithostratigraphic Unit 3 – Roedtan Basin.

area. Towards the east of the resource area the interbedded shale layers as indicated in Fig. 7.13., become very prominent causing the Lower Middle Seam to be of poor quality.

- **Tuinplaats sub-Basin (Fig. 7.14.)**

The coal lithologies encountered in the Tuinplaats sub-Basin are depicted in Fig. 7.14. The Upper Middle Seam constitutes the potential economic coal horizon in this area. The Upper Seam, Lower Middle Seam and Lower Seam comprise mainly carbonaceous shale with subordinate bright coal layers.

The stratigraphic position of the Top Marker is indicated in Fig. 7.14. Depending on the thickness and quality of the shale parting between the Upper Middle Seam and the Top Marker, the Top Marker can be added to the Upper Middle Seam for future mining considerations.

- **Driefontein sub-Basin**

Towards the east of a palaeo-high the isolated Driefontein sub-Basin was demarcated. This area is also characterized by the development of the Upper Middle Seam.

- **Warmbaths sub-Basin**

A transgressive dolerite sill constitutes the western boundary of both the northern and southern sub-basins. West of this transgressive sill a vast area (Warmbath sub-Basin) occurs. Here, coal qualities were largely influenced by the same transgressive sill which resulted in the devolatilization or total burning of the coal towards the east.

After the termination of Ingwe’s exploration programme other companies like AmCoal (Pty) Ltd and J.C.I embarked on exploration drilling in the Warmbath sub-basin. At least 600 boreholes were drilled, primarily by AmCoal (Pty) Ltd. Borehole data of these boreholes were obtained from the Council of Geoscience.

Lithostratigraphic Unit 3 in the Warmbath sub-basin corresponds to the lithologies encountered in the northern and southern sub-basins respectively. The Middle Seam is well developed and constitutes a possible mining horizon towards the southern perimeters of the Warmbath sub-basin. The parting between the Upper Middle Seam and the Lower Middle Seam contains a high percentage of coal. In these areas the Total Middle Seam can be considered as a potentially mineable horizon.

The data obtained from the Council of Geoscience is characterized by inconsistent lithological descriptions regarding Lithostratigraphic Unit 3. None of these boreholes were drilled to basement meaning that the actual position and thickness of the dolerite sill underlying Lithostratigraphic Unit 3 could not be determined.

Borehole intersections indicating thin coal and burnt coal were used to demarcate areas not affected by palaeotopography and/or dolerite intrusions.

The first occurrence of a possible torbanite deposit in Lithostratigraphic Unit 3 was reported by Du Toit (1939). A compounded coal seam in excess of 8.0 m occurring in the basal part of the Bushveld marls (Elliot Formation) was described on the farm Vangheining. Chemical analysis revealed a high ash %, high volatile (35% - 53%) content coal. Follow-up drilling by AmCoal (Pty) Ltd revealed the presence of torbanite in six of the exploration boreholes drilled on Vangheining. The torbanite occurs in Lithostratigraphic Unit 3 which is not part of the Elliot Formation as described by Du Toit (1939). No chemical analysis of the torbanite intersections could be obtained. A high ash %, high volatile % and a high heat value (MJ/kg) characterize a typical torbanite deposit.

The clustering and quality of data as well as borehole discrepancies preclude a comprehensive interpretation of Lithostratigraphic Unit 3 in the Warmbaths sub-basin.

➢ Roedtan Basin

Lithostratigraphic Unit 3 in the Roedtan Basin comprises three coal seams similar to that of the Settlers-Tuinplaats Basin (Fig. 7.15). Certain differences exist between seams developed in the Settlers-Tuinplaats and Roedtan Basins. The following are some characteristics of the Roedtan Basin in comparison with the Settlers-Tuinplaats Basin.

a) In the Settlers-Tuinplaats Basin, the Middle Seam is the prominent seam, whereas the Upper Seam is of importance in the Roedtan Basin.
b) The Upper Seam in the Roedtan Basin comprises mainly bright coal whilst the Upper Seam in the Settlers-Tuinplaats Basin comprises alternating carbonaceous shale and bright coal laminae.
c) The Middle Seam in the Roedtan Basin has a very erratic distribution.
d) The partings between the different seams in the Roedtan Basin comprise mainly grey, weakly carbonaceous shale.

The economic potential and resources of Lithostratigraphic Unit 3 in both the Settlers-Tuinplaats and Roedtan Basin will be discussed in Chapter 8.

7.3.3.2 Depositional Environments

The major sedimentological and coal characteristic of Lithostratigraphic Unit 3 are summerised in Table 7.2.

Table 7.2. Major sedimentological and coal characteristics: Lithostratigraphic Unit 3.

Characteristics	Remarks
(a) Sedimentological Architecture	Cyclic, comprising alternating bright coal, subordinate mixed coal (banded coal) and carbonaceous shale.
(b) Contacts	The contacts between the coal seams and carbonaceous shales vary between sharp and gradational. The contacts between the coal seams and underlying carbonaceous shale bands are predominantly sharp. The contacts of the coal seams with overlying carbonaceous shale bands are gradational.

(c) Secondary minerals	*Pyrite occurs throughout Lithostratigraphic Unit 3 and comprises both organic and inorganic pyrite (see Chapter 8). *Siderite occurs primarily in the lower seam as isolated nodules. *Calcite associated with cleats occurs in all the coal seams. *Uranium (refer Chapter 8).
(d) Macerals	Vitrinite: Average 84%. Inertenite: Average 6%. Exinite: Average 2%.
(e) Coal type	Mainly bright with subordinate mixed coal (banded coal) layers at the contacts with bright coal and overlying carbonaceous shale.
(f) Rootlet bioturbation and/or root imprints	Absent
(g) Palaeosols/seat rocks	*Not present at the lower contact between Lithostratigraphic Unit 3 and underlying Lithostratigraphic Unit 2. *Palaeosols present where Lithostratigraphic Unit 5 overlies the coal.

The preservation of organic material in sedimentary environments can only take place in the absence of oxygen. To prevent the oxidization of organic material, the accumulated organic material needs to be covered by sediments directly after accumulation in the depository. Continuous peat formation is the result of a near perfect balance between rate of subsidence in the depositional environment and the rate of accumulation of organic material (Francis, 1961). If subsidence in the depositional environment exceeds the rate of organic material accumulations either arenaceous or argillaceous sediment can be deposited above the underlying organic material. Should the accumulation of organic material exceed the rate of subsidence in the depositional environment oxidization of the organic material will occur and thus hamper the coal formation processes. From the preceding it is evident that the architecture of a coal deposit reflects the stability of the depositional environment during the coal formation processes (Tavener-Smith, 1962). Alternating coal and shale are thus indicative of variations in the rate of subsidence experienced in the depositional environment. Thick intercalated coal seams in coal zones (SFKB) are indicative of periods where subsidence and organic material accumulations were virtually in equilibrium.

Variations in climate conditions and rate of subsidence in the proximity of and in the coal depositional environment will also have an impact on the plant communities and thus on the development of individual coal seams (Gosh, 1975).

The cyclic nature of Lithostratigraphic Unit 3 in the SFKB is assigned to fluctuations in waterlevels caused by variations in subsidence rates in the depositional environment during the coal formation period. The contacts between the coal seams (i.e. Lower, Middle and Upper Seams) and the underlying shales are always sharp, while the nature of the upper contacts of the coal seams with the shales are more gradational. This implies that conditions, after the deposition of the shales, changed rapidly in order to accommodate the accumulation and preservation of organic material. A gradual change in the depositional environmental conditions, i.e. increase water depth due to subsidence, resulted in the gradational upper contact of the coal seams with the shales. No arenaceous sediments were encountered in Lithostratigraphic Unit 3. It is postulated that the intercalated shale partings in Lithostratigraphic Unit 3 were deposited during pulsating subsidence and accompanied increase water levels due to transgressions the depositional environment experienced. The high sulphur content of the coal in Lithostratigraphic Unit 3 i.e. > 2.0 % is according to Horne et al. (1978) indicative of coal that formed under brackish water conditions.

Each coal seam as present in Lithostratigraphic Unit 3 reflects to local conditions that prevailed during the deposition thereof. Such conditions include palaeotopography, type of plant communities, rate of accumulation and nature and rate of plant degradation or biochemical coalifications (Adams, 1960).

The aerial distribution and qualities of the coal seams in the SFKB were largely influenced by the palaeotopography as discussed. Under waterlogged protected conditions, organic matter undergoes a process of gelification with extensive tissue conversion and volatile rich vitrinitic organic matter (Falcon, 1986).

The petrographic analysis done on coal samples of the Middle Seam of Lithostratigraphic Unit 3 are characterised by the high vitrinite content of the coal i.e. 84%. Vitrinite forms only under anaerobic conditions (Money and Drysdall, 1975) while the presence of inertinite, i.e. 6%, is indicative of aerobic conditions. The high vitrinite content is also indicative of high rainfall and a high water table (Murchison et al., 1968). The high vitrinite content and low inertinite content of SFKB coal corresponds thus to deposits accumulated in reducing environments under cold conditions. Shallow, open-water distal environments, lagoons, ponds and distal deltaic settings typically accumulate very fine wind- and waterborne organic and inorganic matter such as algae, spores and pollens. Known as exinite, these components impart a high hydrogen and volatile matter content to host sediments and are in some cases extremely valuable for oil or liquid hydrogen production by direct heating methods (pyrolysis)(Falcon, 1986a). The torbanite that occurs in the Warmbath sub-basin in Lithostratigraphic Unit 3 could have been the result of algae accumulations in isolated ponds that existed during the deposition of the coal seams. Although no petrographic analysis was done on this torbanite occurrence, the high volatile content can be indicative of the presence of exinite, a major maceral of torbanite.

Pyrite in coal is usually of an early diagenetic origin and forms through the reaction of Fe^{++} with H_2S. Fe^{++} is soluble in acid, reducing conditions whilst H_2S is formed by bacterial sulphate reduction and the decomposition of organic sulphur compounds. In most sediments dissolved sulphate is the dominant source of H_2S. Because of the stability field of pyrite as far as Eh is concerned, pyrite is preferentially associated with vitrinite coal beds.

Siderite is stable under weakly alkaline, reducing conditions and its deposition may well have to do with the equilibrium reaction:
$Fe(HCO_3) \longleftrightarrow FeCO_3 + CO_2 + H_2O$ which controls the solution of iron under reducing conditions. If equilibrium is disturbed through the addition of CO_2 by organic decay, acid conditions result and more iron goes into solution as $Fe(HCO_3)_2$. However, if CO_2 is extracted from the system, more alkaline conditions result and siderite ($FeCO_3$) is precipitated. In peat swamps the extraction of CO_2 could be accomplished through compaction, diffusion and/or absorption by plants. Siderite nodules or concretions which are present in Lithostratigraphic Unit 3 may well have formed at an early diagenetic stage during compaction of the peat and after the depletion of H_2S by the precipitation of pyrite. An alternative to the preceding process entails the formation of siderite through the reduction of ferric hydroxide to ferrous hydroxide by carbon. Ferrous hydroxide could react with carbon dioxide to form ferrous carbonates (Beukes, 1984).

No evidence of rootlets/rootlet bioturbation or the presence of a palaeosol below the Lower Seam could be identified at the contact between Lithostratigraphic Unit 3 and the underlying Lithostratigraphic Unit 2. According to Money et al. (1975) the vegetation during the coal formation in the northern hemisphere was more luxuriant due to a more tropical climate. In contrast, due to cooler climate after the glaciations period in the southern hemisphere, the vegetation during the coal formation period was dwarfish. A prominent seasonal climate change based on well preserved growth rings in fossilized tree trunks (Plumstead, 1966) is postulated. Dwarfish vegetation, according to Watson (1958), will not have a great leaching effect on underlying soils, resulting that no prominent palaeosols will be preserved.

The lack of rootlets and prominent palaeosols at the base of Lithostratigraphic Unit 3 leads to the conclusion that the organic material, responsible for coal formation, drifted into the depositional environment rather than growing in situ. The fact that individual coal seams, as discussed, can be correlated over large distances, probably supports a drift/raft mechanism as the transportation agent for organic material accumulation in the depositional environment. The conditions during the formation of the coal zone in Lithostratigraphic Unit 3 in the peat swamp that existed during Ecca Groups times in the SFKB are summarized in Table 7.3.

Table 7.3. Coal formation in the SFKB (after Falcon, 1986).

Environmental characteristics	Conditions in the SFKB
Watercover	Oscillating
Acidity	Medium
Atmospheric O2	Partly present
Chemical conditions	Reduction and minor oxidation
Organic Activity	Actinomycles, aerobic and anaerobic bacteria
Mode of plant decomposition	Peatrification
Peat type	Woody with humic colloids
Microlithotype	Vitrite, clarite, trimacerite, vitrinerite
Lithotype	Vitrain (bright coal)
	Clarian (banded bright coal)
Coal type	Humic

In conclusion it is postulated that the palaeotopography in the SFKB controlled the palaeoenvironments resulting in the demarcation of different sub-basins each with its own characteristical coal seam assemblage. The palaeotopography according to Adams (1960) also controls the type of plant community, rate of organic matter accumulation, nature and rate of plant degradation or biochemical coalification. A protected palaeo-environment existed during the coal formation period in the SFKB resulting in the accumulation of organic matter in waterlogged conditions. Pulsating changes in water levels during the deposition of Lithostratigraphic Unit 3, caused by subsidence of the basin and accompanied by transgression resulted in the cyclic nature of the coal zone. The absence of features such as rootlets/rootlet bioturbation and palaeosols lead to the conclusion that the organic material drifted into the depositional environment and probably did not grow in situ.

7.3.4 Lithostratigraphic Unit 4

7.3.4.1 Lithology

The argillaceous sediments of Lithostratigraphic Unit 4 comprise khaki, purple and dark grey mudstones. The contact between Lithostratigraphic Unit 4 and the underlying Lithostratigraphic Unit 3 is gradational in nature. Ferruginous staining is a common feature in the mudstones of Lithostratigraphic Unit 4.

Lithostratigraphic Unit 4 is not developed on the elevated portions of the pre-Karoo floor. The thickness of Lithostratigraphic Unit 4 varies from nil to a maximum of 60.0 m, the latter being recorded in areas away from the topographical high lying areas in the deeper parts of the basins.

The basal part of Lithostratigraphic Unit 4 is characterized by the abundance of carbonaceous detritus that gradually decreases in abundance towards the upper portions of the Lithostratigraphic Unit 4. Lithostratigraphic Unit 4 is disconformably overlain by Lithostratigraphic Unit 5. A major hiatus, occurs at the contact between Lithostratigraphic Units 4 and 5. In areas adjacent to the palaeo-topographical highs, a prominent palaeosol is present at the top of Lithostratigraphic Unit 4 which marked the contact between Lithostratigraphic Units 4 and 5 (Fig. 7.16.). This palaeosol varies in thickness from a few centimeters to more than a meter.

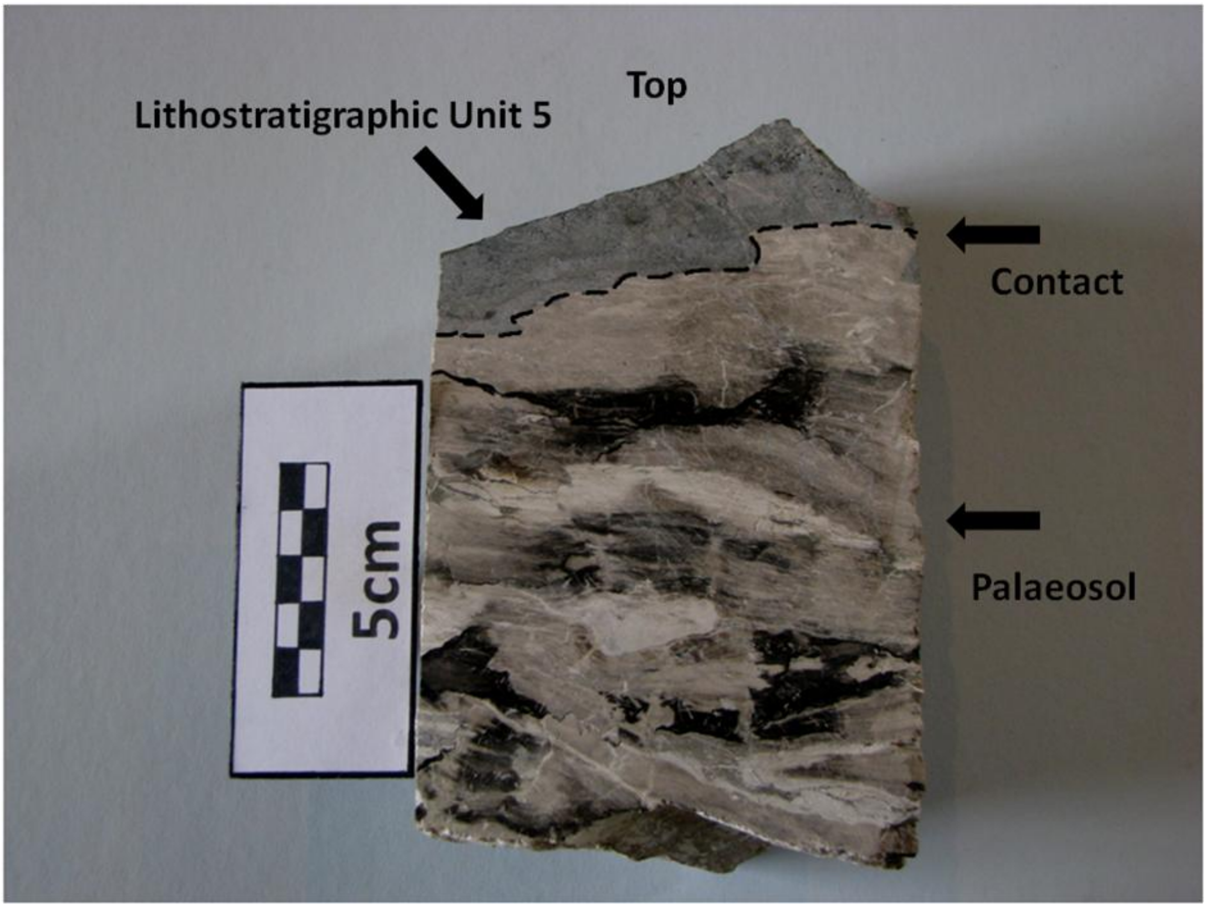


Fig. 7.16. Palaeosol between Lithostratigraphic Units 4 and 5.

In close proximity of the palaeo-highs especially east of Settlers Village the minimum thicknesses of Lithostratigraphic Unit 4 were encountered. In these areas Lithostratigraphic Unit 4 has been denudated during the deposition of Lithostratigraphic Unit 5, or was not deposited, causing the latter to be in contact with Lithostratigraphic Unit 3. No arenaceous sediments were encountered in Lithostratigraphic Unit 4.

7.3.4.2 Depositional Environment

Subsidence of the basin, following the deposition of Lithostratigraphic Unit 3, resulted in a low influx of argillaceous material that resulted in the formation of Lithostratigraphic Unit 4. This process took place gradually as marked by the gradational contact between Lithostratigraphic Units 3 and 4. The deposition of Lithostratigraphic Unit 4 played a major role in the preservation of the coal associated with Lithostratigraphic Unit 3. The deposition of the argillaceous material shielded the underlying coal from external processes that could impact on the development of coal.

The hiatus represented as a palaeosol that developed at the top of Lithostratigraphic Unit 4 marked a period during which Lithostratigraphic Unit 4 was exposed to atmospheric conditions. The duration of exposure is uncertain, but reveals a period of no deposition prior to commencement of Lithostratigraphic Unit 5. This hiatus is also indicative of a change in atmosphere and climatic conditions in the Springbok Flats Karoo Basin. A geological period characterized by the deposition of carbonaceous material in a reducing environment during cold conditions was followed by a period during which strata composed of sandstone, siltstone, mudstone and conglomerates with a predominantly red colour due to the presence of ferric oxide, was deposited. These sediments were deposited during cold, wet and oxidizing conditions.

7.3.5 Lithostratigraphic Unit 5

7.3.5.1 Introduction

A commodity driven exploration programme is, in most instances, characterized by detailed geological measurements and analysis regarding the economically viable horizon(s) and the pre-eminently poor geological description of overlying rock formations. During the Ingwe (Pty) Ltd exploration endeavours in the Springbok Flats Karoo Basin the geological formations overlying the economic viable coal and uranium deposits were described in very general terms. Only about 60% of all the

boreholes drilled in the Springbok Flats Karoo Basin obtained sufficient sedimentological data that can assist in palaeoenvironmental reconstructions.
The sedimentological boundaries of Lithostratigraphic Unit 5 have been defined by two prominent disconformities. The lower disconformity was defined based on sedimentary criteria i.e. a basal conglomerate associated with a buried soil profile and the upper disconformity by palaeontolgical criteria i.e. the occurrence of a conglomerate characterized by abundant fossil bone fragments (Krumbein and Sloss, 1963).

When making a hand specimen identification of a rock sample, the geologist's experience and the application of certain geological parameters play a major role. From this data he can normally identify basic lithologies, such as sedimentary, igneous and metamorphic rocks. Sedimentary rocks can further be subdivided into sandstone, siltstone, shale and/or mudstone. With increased experience in specific lithologies recognition of types of sandstone, siltstone, shale and/or mudstone is usually straightforward with experience. The preceding is relevant, especially when geologists are working on their own. However, when a team of geologists is responsible for borehole logging and interpretation, synergy in terms of rock description becomes a major issue. In order to eliminate these discrepancies amongst geologists, Ingwe (Trans Natal Coal Corporation) embarked on a wireline logging programme. A wireline log gives a continuous record of measurements made in a borehole by a probe able to respond to variations in some physical properties of rocks through which the borehole is drilled. The reasons for wireline logging include one or more of the following:

- Determine depth to lithological boundaries
- Determine actual thickness of lithological units
- Identify lithological units
- Determine mineral grade (i.e. uranium)
- Correlation between boreholes.

In order to obtain the above mentioned data the essential geophysical tools used during the Trans-Natal exploration programme included the following:

➢ Gamma Ray Measurements

In most sedimentary sequences, high gamma ray levels are due to high levels of isotopes of potassium (K_{40}), although uranium concentrations contribute to the majority of the radiation emitted.

The presence of a low K_{40} content shows reduced levels of gamma ray activities. Limestones generally show the lowest levels of K_{40} concentrations followed by coal and sandstone respectively. High gamma ray activities are indicative of uraniferous sediments.

➢ Density Measurements (Density logs)

The wireline tool used for density measurements actually measures electron density which is related to bulk density. The volume of rock examined by the density tool depends upon the spacing between the source and detector of the density tool.

Arenites have a density of 2.65 g/cc with shales ranging between 2.2 and 2.8 g/cc.

➢ Neutron-Neutron log

This log essentially, responds to hydrogen and to a lesser extent to carbon and is in many ways a confirmation of the gamma ray log.

Readings over shale lithologies are high due to the OH-content associated with mica and some free water in the parting planes. Coal also gives high readings due to higher hydrogen and carbon content. Readings over sandstone lithologies vary due to the effect of water in sandstones of different porosities.

Geophysical data acquired from these logs in association with borehole data were used to eliminate discrepancies based on the human factor.

7.3.5.2 Lithology

The utilization of geophysical logs in conjunction with sedimentological borehole data is illustrated in Figures 7.17. – 7.19. The lithological variations encountered in Lithostratigraphic Unit 5 are also depicted in the above mentioned figures.

The geophysical and borehole data reveals the presence of four distinct sedimentary facies in areas where Lithostratigraphic Unit 5 is fully developed. The aerial distribution of these facies is largely controlled by sedimentary environments and to a lesser extent by the tectonic environments that prevailed during the deposition of Lithostratigraphic Unit 5.

The four facies encountered are:

a) Basal Unit or Lithofacies Gm (conglomerate and sandstone)
b) Lithofacies Sf (sandstone and mudstone)
c) Lithofacies Fs (siltstone)
d) Top Unit or Lithofacies F (mudstone)

➢ **Lithofacies Gm**

The basal unit of Lithostratigraphic Unit 5 comprises alternating conglomerates and coarse grained to granular sandstones in poorly defined upward fining cycles (Fig. 7.20.). The pebble sizes of the conglomerate vary from + 2.0 mm to 40.0 mm. With the exception of poor graded bedding no other sedimentary structures were observed. The pebbles are mainly sub-angular to sub-rounded (second order) quartz and quartzite pebbles of the Transvaal Supergroup and Waterberg Group and constitute 90% of the total pebbles encountered (Fig. 7.21.). No preferred pebble orientation could be observed in the borehole cores. Minor jasper, black argillite, granite, felsites and sandstone clasts of Lithostratigraphic Unit 2, mudstone clasts of Lithostratigraphic Unit 4 and coal clasts of Lithostratigraphic Unit 3 were identified. The matrix of the conglomerates is mainly arenaceous material comprising angular to sub-angular quartz, quartzite and felsite grains. The matrix resembles to a large extent the different types of pebbles encountered, although the roundness is more angular and fragmented than the accompanied pebbles. The packing density varies considerably resulted that the conglomerates vary from clast to matrix supported types and have a typical greyish colour. Lithostratigraphic Unit 5 directly overlies either the mudstones of Lithostratigraphic Unit 4 or the coal measures of Lithostratigraphic Unit 3.

In areas where Lithostratigraphic Unit 5 overlies Lithostratigraphic Unit 4 a prominent palaeosol has developed (Fig. 7.16.) and abundant mudstone clasts occur in the basal Lithofacies Gm (intraformational conglomerate). Carbonaceous detritus, coal and shale clasts occur in Lithofacies Gm where it overlies Lithostratigraphic Unit 3. The contact of Lithofacies Gm with underlying sediments is always sharp and erosive.

The conglomerates higher up in Lithofacies Gm resemble the basal conglomerate to a large extent but differ in terms of pebble size (smaller) and the absence of coal and shale clasts.

The conglomerates of Lithofacies Gm and accompanied sandstone have a typical greyish colour which distinguishes this facies from overlying sediments within Lithostratigraphic Unit 6. Another important characteristic of Lithofacies Gm is the subordinate development of argillaceous intercalations (Fig. 7.22.).

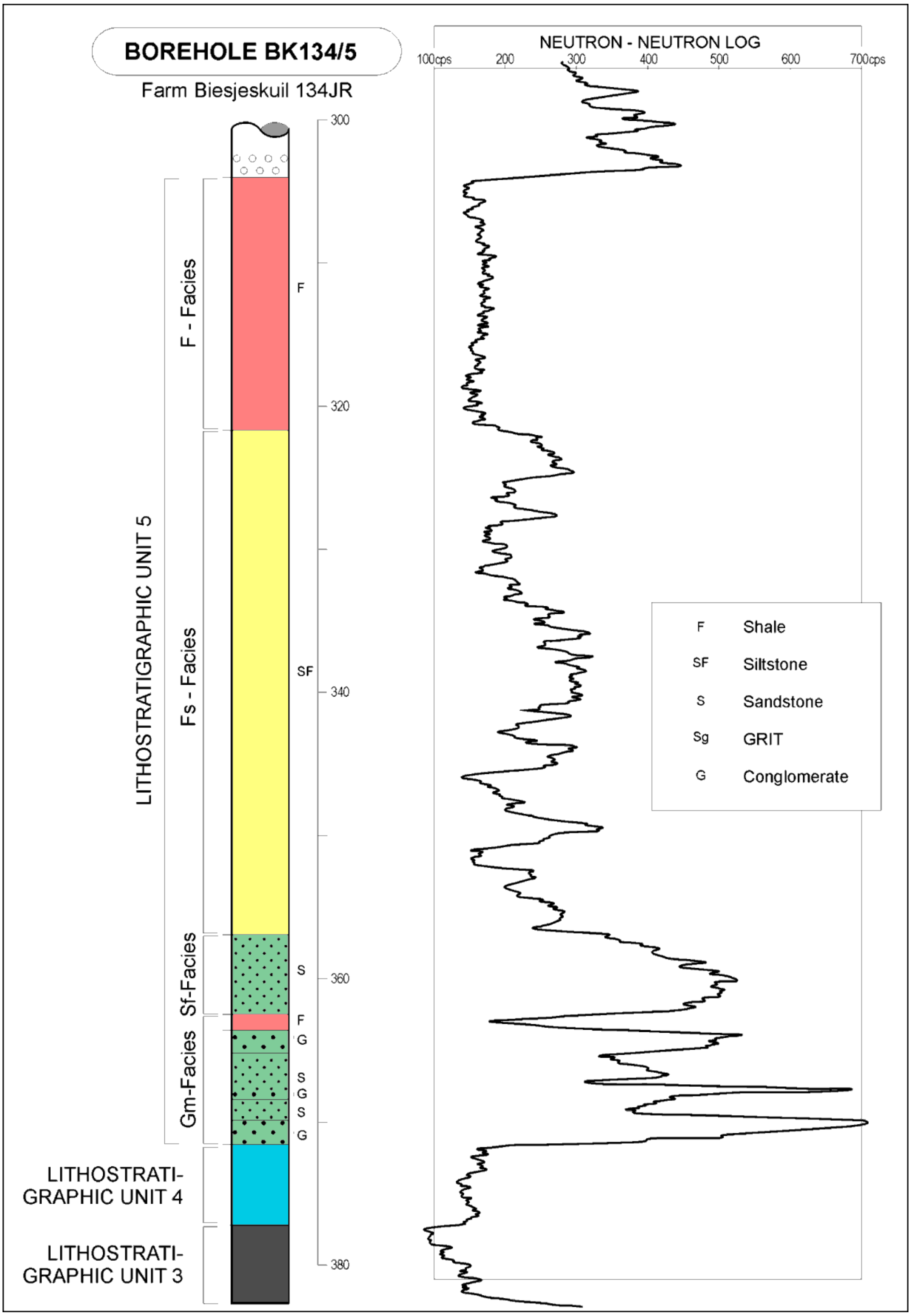


Fig. 7.17. Lithologies of Lithostratigraphic Unit 5 using a Neutron-Neutron wireline log.

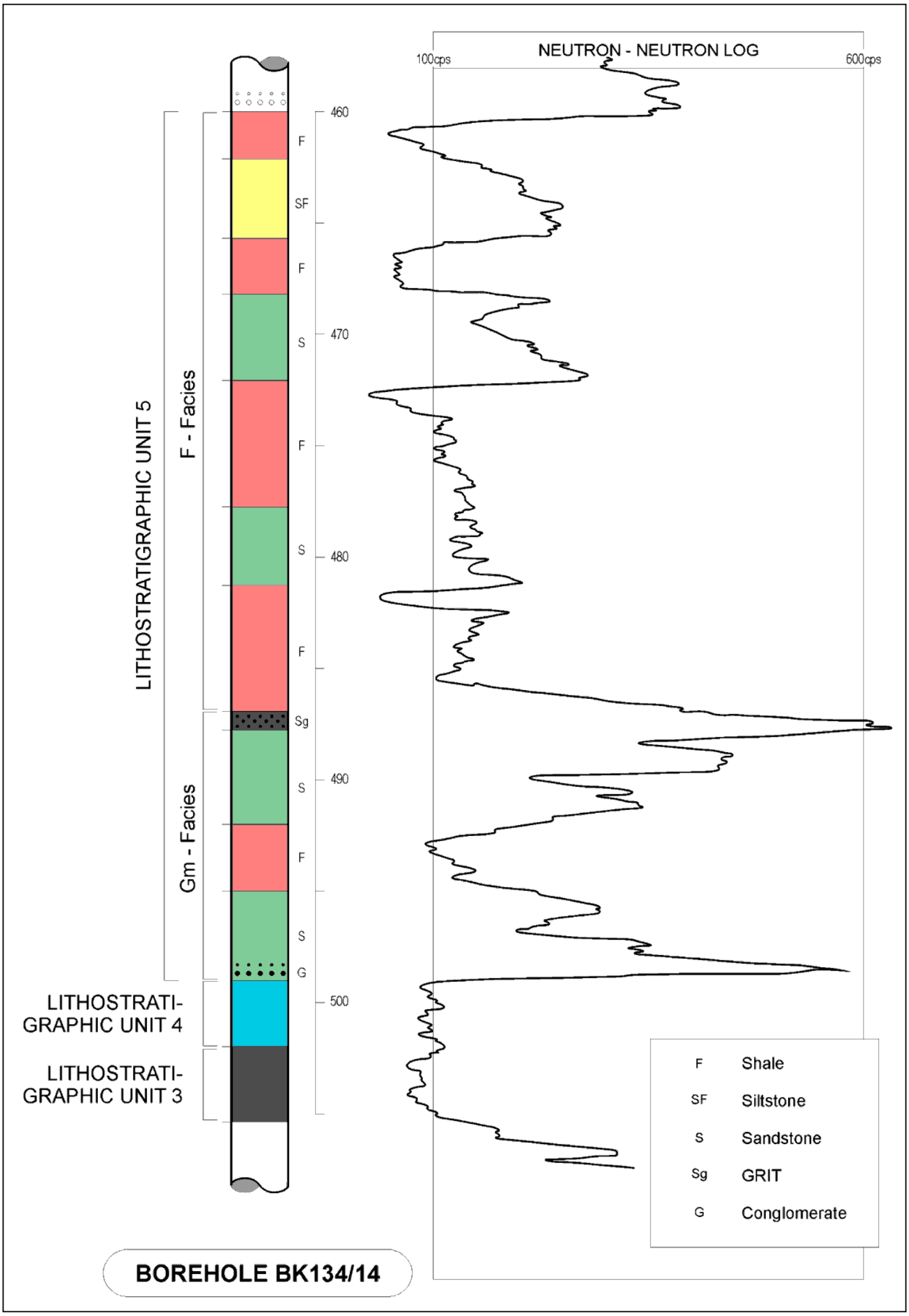


Fig. 7.18. Variations in lithologies encountered in Lithostratigraphic Unit 5.

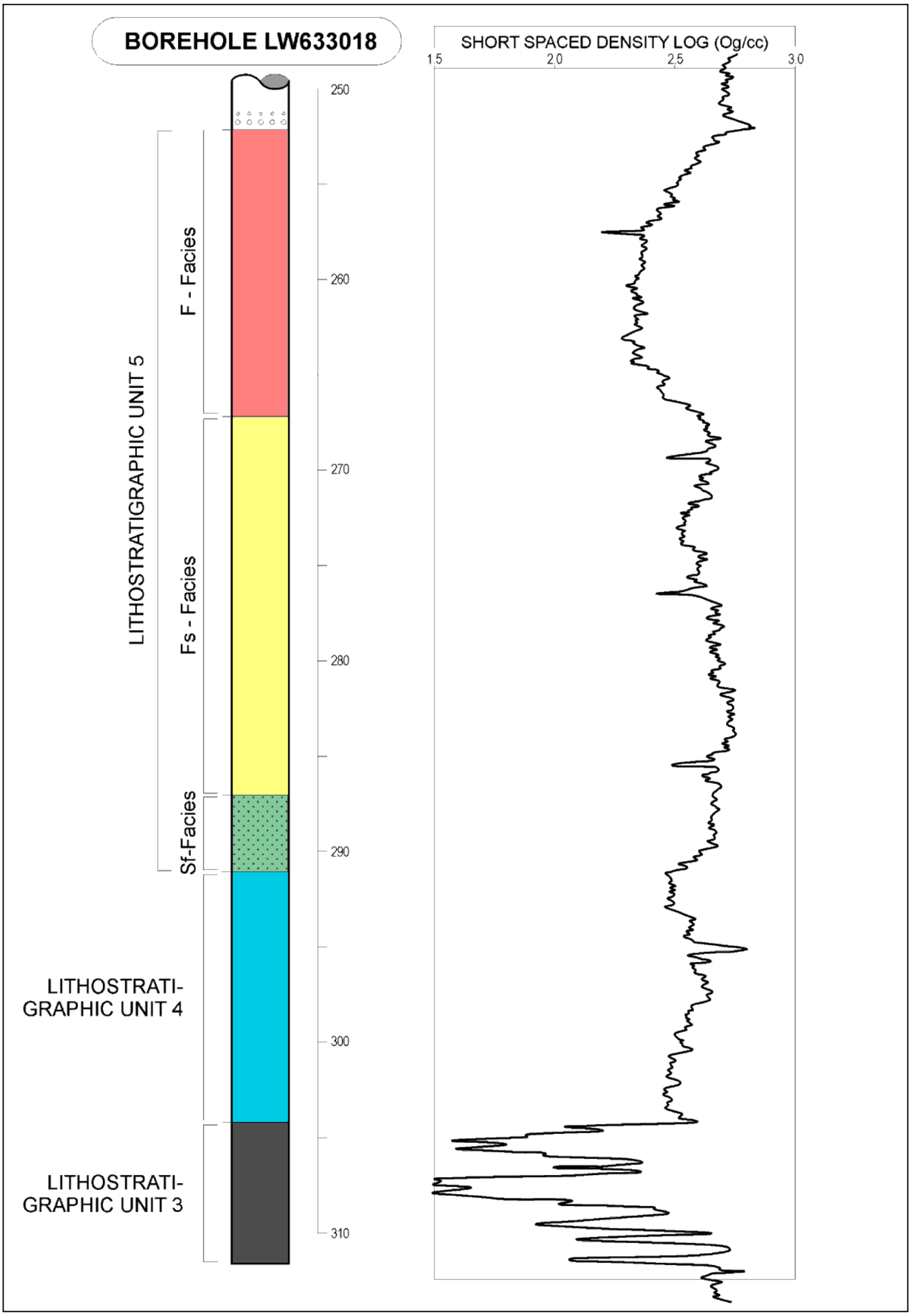


Fig. 7.19. Lithologies of Lithostratigraphic Unit 5 using a short spaced density wireline log.

Fig. 7.20. Poorly defined upward fining cycle Lithofacies Gm.

Fig. 7.21. A typical Lithofacies Gm intersection.

➢ Lithofacies Sf

Lithofacies Sf conformably overlies Lithofacies Gm. The contact between these two units was taken at the top of the uppermost upward fining cycle of Lithofacies Gm. Contrary to Lithofacies Gm, properly developed upward fining cycles (fifth order cycles) with accompanied sedimentary structures characterise Lithofacies Sf. Most of the upward fining cycles are capped by greyish to khaki coloured mudstone layers.

Grain sizes encountered in the basal parts of the upward fining cycles varies between very coarse grained ≤ 2.0 mm to very fine grained 0.062 mm. The grains comprise mainly quartz, quartzite and subordinate felsite grains. Up to 18 individual

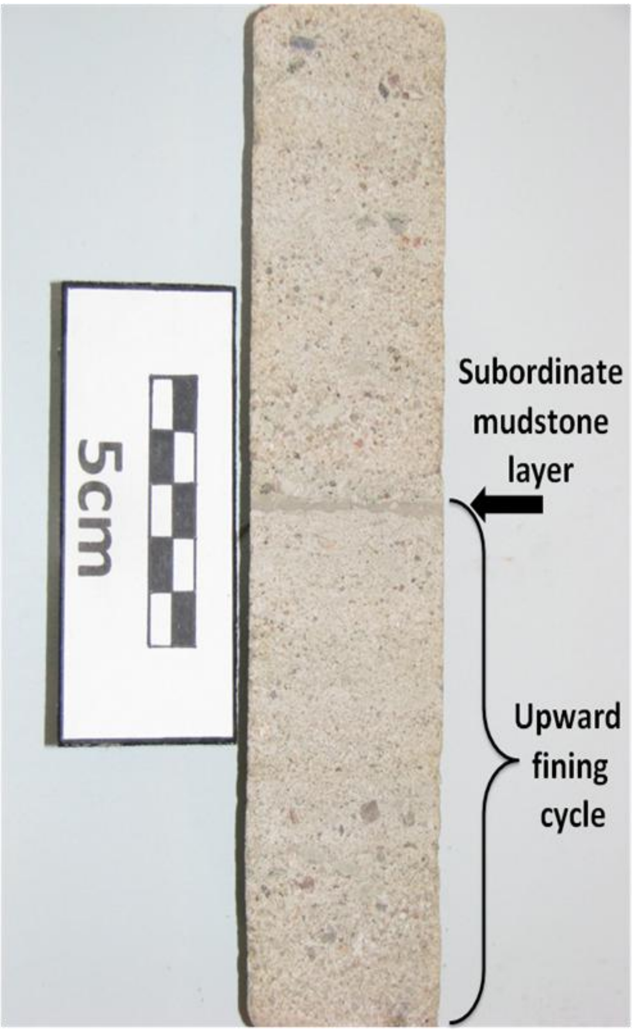


Fig. 7.22. Poorly defined upward fining cycle with subordinate argillaceous intercalations: Lithofacies Gm.

cycles were described in certain boreholes. Where the cycles are fully developed the following sedimentological characteristics are present:

Bottom:	Graded bedding, sharp lower contact, greyish, cycles towards the top become reddish brown.
Middle:	Horizontal bedding and/or ripple crossbedding greenish grey, becomes reddish brown towards the top.
Top:	Mudstone, greyish to reddish brown or thinly laminated siltstone.

Mudstone clasts, derived from underlying cycles, occur in the basal part of some cycles. A subtle change in colour from greenish grey to reddish brown occurs towards the top of Lithofacies Sf.

Fossilized wood fragments were encountered in only one borehole which intersected this lithofacies. Unfortunately the specimen was too small for positive identification. A plant imprint was recovered during a recent exploration programme. The specimen was submitted to the Bernard Price Institute for Palaeontological Research for identification and was described as “amorph carbon matter”. No pollen could be isolated to assist in identification (Bruce Rubidge, personal communication, 2011).

- **Lithofacies Fs**

A coarse grained siltstone (1/164 mm) to very fine grained (1/8 mm) sandstone overlies Lithofacies Sf conformably. Lithofacies Fs varies in colour from purple to greyish. Reddish brown mudstone intercalations occur towards the base of this facies.

Lithofacies Fs is mainly massive in appearance although thinly laminated, ripple crossbedded and contorted bedded horizons occur towards the lower part of the facies. The thickness of this facies varies from nil to ± 35.0 m. No trace fossils or any remnants of fossils were encountered in Lithofacies Fs.

Historically, Lithofacies Fs was considered to be part of the Worthing Formation (refer Table 7.1.) or Red Beds Stage (refer Table 7.1.). The criteria used by Roberts (1998) to define the lower contact of the Worthing Formation is not clearly defined. The appearance of the uppermost proper sandstone layer was used by Ingwe Coal to define the contact between the Molteno Stage and Red Beds Stage (refer Table 7.1.). As sandstone layers in Lithofacies Sf cannot be correlated with one another, this effort also seems to be futile and scientifically incorrect. The relationship of Lithofacies Fs with the underlying Lithofacies Sf as depicted in Fig. 7.17. – 7.19. leads to the conclusion that Lithofacies Fs is part of the Lithostratigraphic Unit 5 as the contact between the two facies is gradational and that Lithofacies Fs constitutes part of a larger upward fining cycle starting with Lithofacies Gm at the base (Fig. 7.17. – 7.19.).

- **Lithofacies F**

Lithofacies F comprises a dark reddish brown mudstone which overlies the underlying Lithofacies Fs with a sharp contact (Fig. 7.17. – 7.19.). The mudstone is massive and is characterized by prominently developed slickensided horizons. Scattered calcareous nodule horizons occur occasionally in Lithofacies F. A regionally developed hiatus marked the termination of Lithofacies F.

Lithofacies Gm, Sf, Fs and F constitute a large upward fining cycle bounded by two hiatuses. This cycle is considered to be a lithostratigraphic unit and must not be seen as a separate unit to be incorporated into overlying sediment to form the Irrigasie Formation as postulated by Johnson (2006).

The absence of any trace fossils also distinguishes this lithostratigraphic unit from the overlying sediments of Lithostratigraphic Unit 6.

7.3.5.3 Palaeotopography

The palaeotopography prior to the deposition of Lithostratigraphic Unit 5 is depicted in Fig. 7.23. The palaeotopography largely resembles the palaeotopography of the pre-Karoo topography (refer Fig. 6.1.). The borehole data used to compile Fig. 7.23.

vary from dense concentrated data in the coal and uranium bearing areas to scattered data in less economically important areas. The two synclinal flexures as well as the anticlinal flexure that separates the two synclinal flexures as discussed in Chapter 5 are still well preserved (Fig. 7.23.).

The deepest part of Lithostratigraphic Unit 5 occurs in areas adjacent to the major faults i.e. Droogekloof Fault Zone (Settlers-Tuinplaats Basin) and the

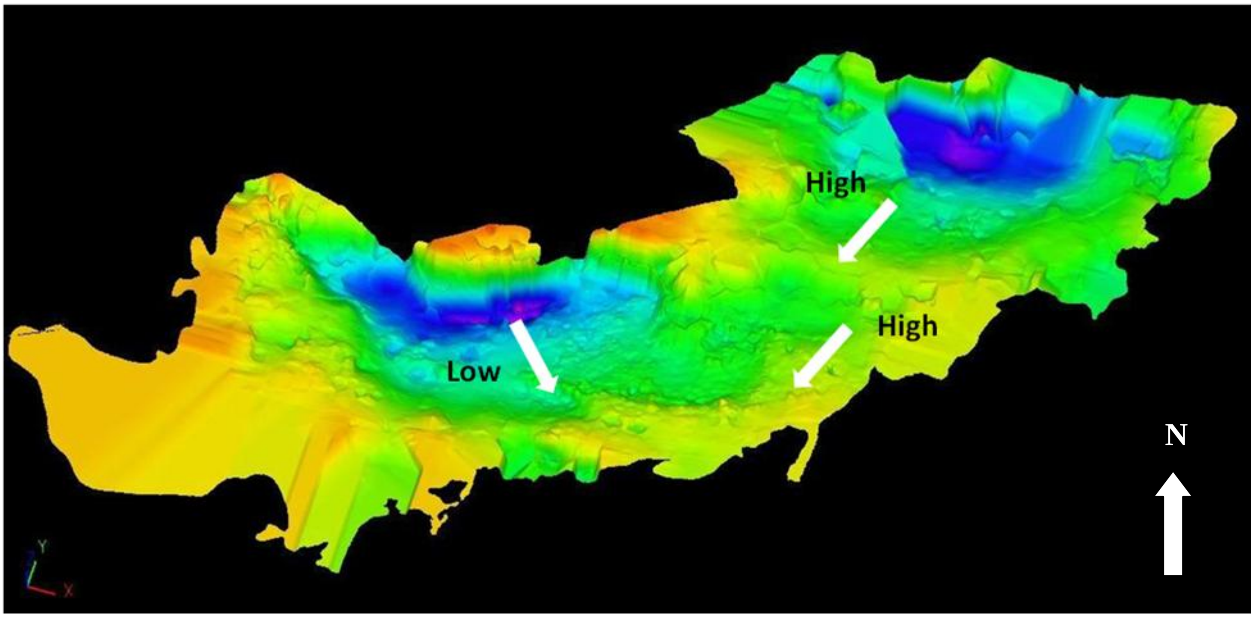


Fig. 7.23. Palaeotopography of Lithostratigraphic Unit 5.

Zebediela Fault (Roedtan Basin). The northern limits of Lithostratigraphic Unit 5 are defined by the abovementioned fault zones. Not enough borehole data pertaining to the aerial distribution of Lithostratigraphic Unit 5 in the southern portions of the SFB are available resulting in a sedimentological/palaeontological reconstruction of the palaeo-environments and palaeotopography being problematic.

The most striking palaeotopographical feature is an east-west striking palaeo-high situated towards the southern peripheries of the Settlers-Tuinplaats Basin (Fig. 7.23. white arrows). Directly south of this high, a prominent topographical low occurs. The possibility that this feature and its easterly extension constitute a fault hinge line that developed during the displacement of the Karoo Strata along the Droogekloof

Fault Zone, cannot be ruled out. Recent drilling (2010) revealed the displacement of Lithostratigraphic Unit 3 on the farm Roodekopjes 167 JR in proximity of the eastern extension of this tectonic feature (± 50 m displacement towards the south). A second palaeotopographical high occurs towards the eastern boundary of Settlers-Tuinplaats Basin (Fig. 7.23. white arrow). This topographical high is a southeasterly extension of the anticlinal flexure and constitutes a prominent feature in terms of coal and uranium distribution. A well preserved palaeotopographical low lying area is present between the two topographical high lying areas (Fig. 7.23. white arrow). The irregular floor topography of Lithostratigraphic Unit 5 is well illustrated in Fig. 7.23., especially in those areas adjacent to topographical highs. The impact of these floor irregularities and the facies distributions in Lithostratiphic Unit 5 will be discussed later.

The lack of sufficient borehole data in the Roedtan Basin hampers a detailed reconstruction of the palaeotopography of Lithostratigraphic Unit 5 in this basin. The available data reveals the development of irregular floor topography directly north of the Roedtan Settlement.

7.3.5.4 Facies distribution

The regional distribution of Lithostratigraphic Units 3 and 4 were largely influenced by the presence of palaeotopographical high and low lying areas. The topographical highs resemble hillocks rather than topographical mountainous areas. Despite their low relief, these palaeotopographical irregularities played a major role during the deposition of Lithostratigraphic Unit 5 including the associated lithofacies encountered within this Unit.

An area, based on borehole density and borehole descriptions, lying between 28˚15´ E to 29˚0´ E and 24˚45´ S to 25˚15´ S was selected for detailed studies. A detailed palaeotopographical map for this area was compiled (Fig. 7.24.). Areas where the palaeotopography impacted on the aerial distribution of Lithostratigraphic Units 3 and 4 are indicated. The palaeotopographical features that existed prior to the deposition of Lithostratigraphic Unit 5 comprise two major drainage channels and major topographical highs towards the northern and southern boundaries of the Settlers-

Tuinplaats Basin (Fig. 7.24.). The drainage channels represent broad, shallow topographical low lying areas of which the slopes adjacent to the channel are less than 1° towards the centre of the low. The general dip of these drainage channels is towards the north and does not exceed 1°.

The aerial distribution of Lithofacies Gm is depicted in Fig. 7.25. The major, as well as secondary drainage patterns interpreted from the palaeotopographical map are also indicated in Fig. 7.25. A very close relationship between the aerial distribution of Lithofacies Gm and palaeotopography as evident from Fig. 7.25 exists. Lithofacies Gm occurs mainly in topographical low lying areas and is to a large extent also influenced by a secondary drainage pattern associated with the two major topographical low lying areas.

Lithofacies Sf occurs over the entire area and no specific association between aerial distribution and palaeotopography could be established. As Lithofacies Sf comprises entirely upward fining cycles not even an increase/decrease in the number of cycles, associated with the palaeotopographical irregularities, could be ascertained. This observation is based on existing borehole data and the possibility that detail, pertaining to cycle development within Lithofacies Sf, was neglected during borehole descriptions. An aerial distribution pattern similar to that of Lithofacies Gm was recognised for Lithofacies Fs. The impact of palaeotopography on the aerial distribution of Lithofacies Fs is evident from Fig. 7.26. Lithofacies Fs occurs within the major topographical low lying areas that existed prior the deposition of Lithostratigraphic Unit 5 and was also influenced by secondary drainage patterns associated with the major drainage features.

Lithofacies F constitutes the top of Lithostratigraphic Unit 5 and resembles a blanket deposit which covers the entire Springbok Flats Karoo Basin. Based on available data no association between the aerial distribution of Lithofacies F and palaeotopography could be established. The only resemblance between Lithofacies F and palaeotopography is manifested by the presence of more than one calcrete horizon (paleosol) within Lithofacies F in palaeotopographical low lying areas.

The study of Lithostratigraphic Unit 5 entailed the following research methodologies i.e.

a) The identification and description of major and minor lithologies
b) The study of lithofacies associations and internal facies relationships
c) The study of lithofacies geometry and the aerial distribution thereof

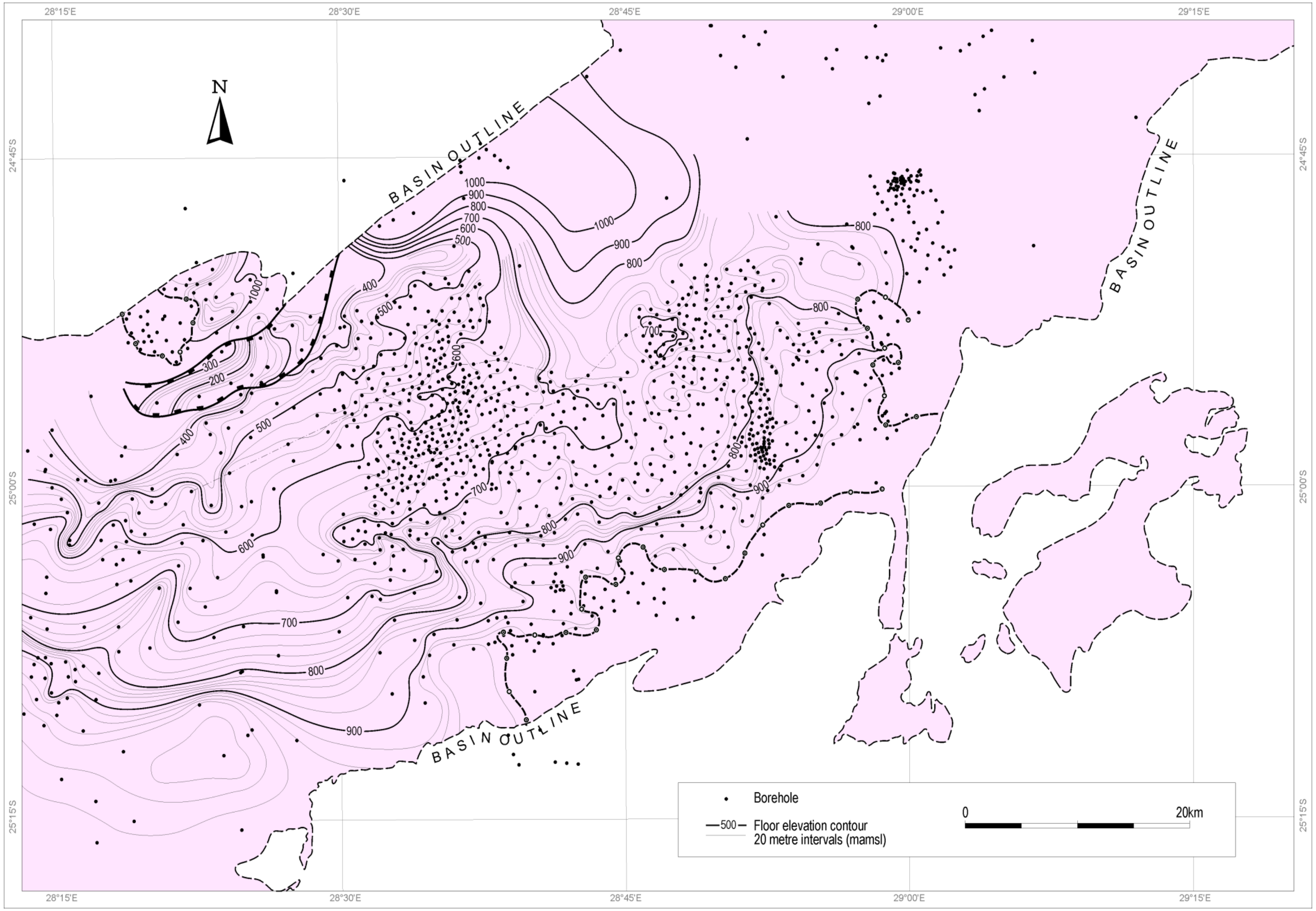


Fig. 7.24. Detailed palaeotopographical map: Lithostratigraphic Unit 5.

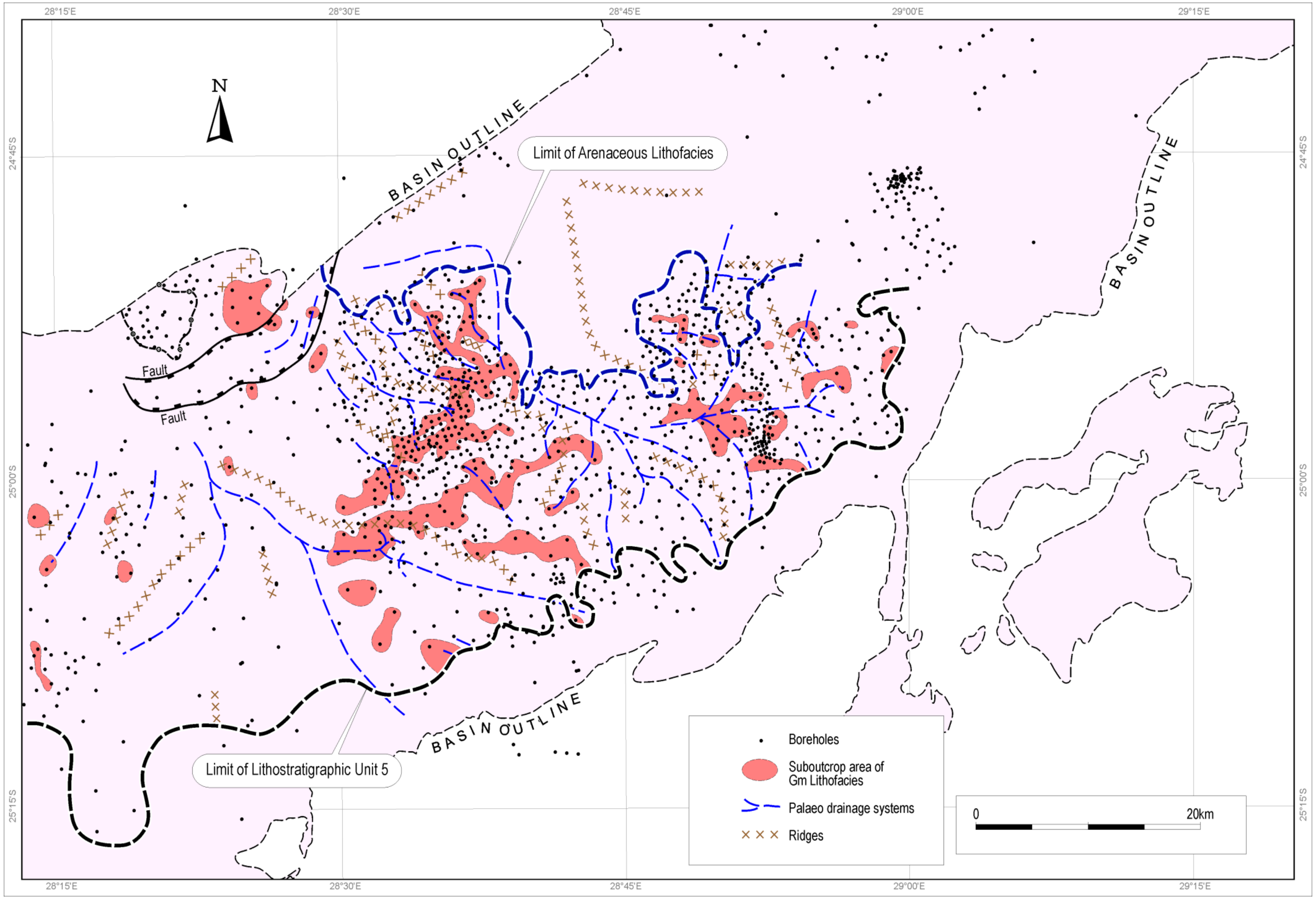


Fig. 7.25. Aerial distribution: Lithofacies Gm.

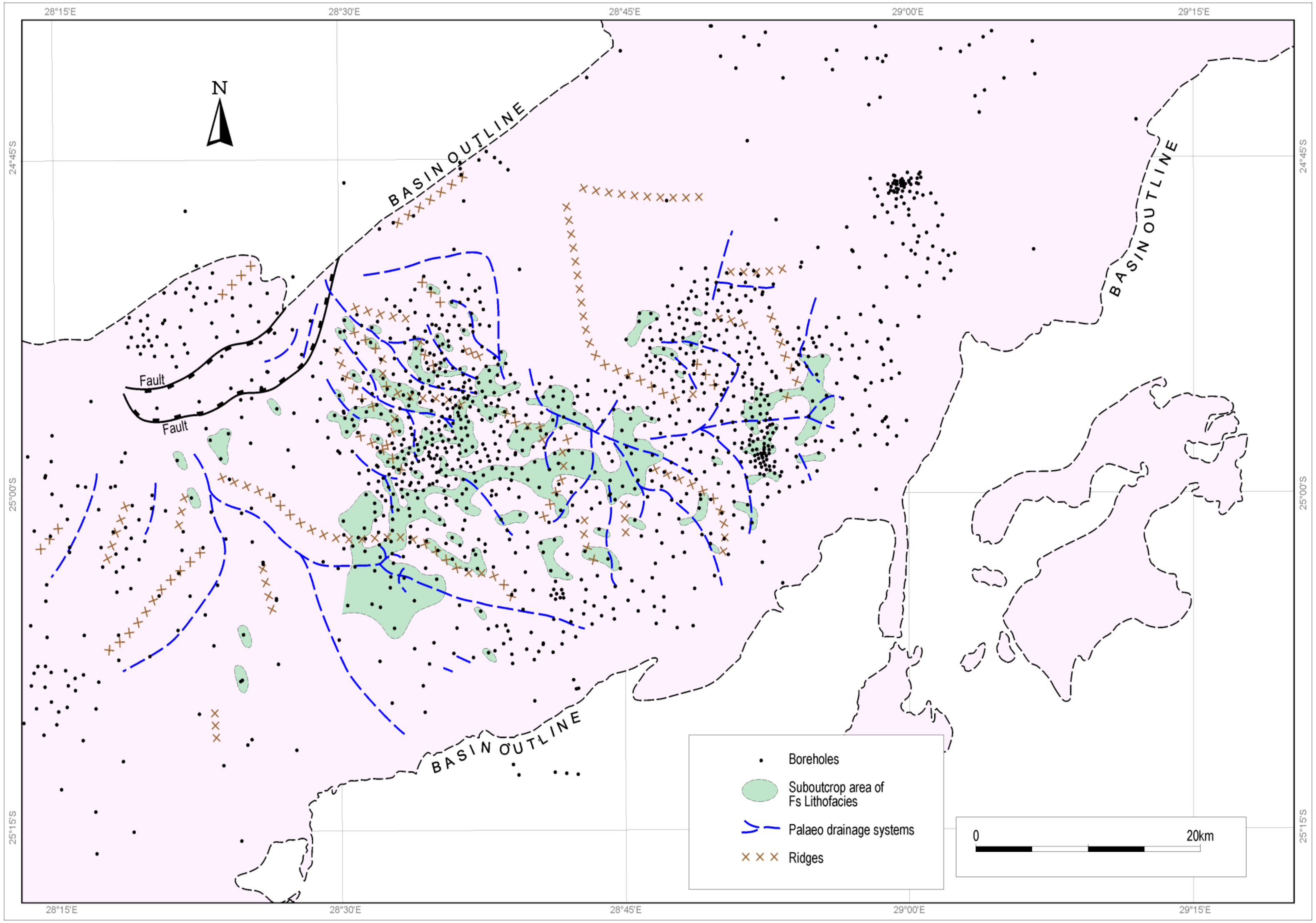


Fig. 7.26. Aerial distribution: Lithofacies Fs.

The results emanating from this study revealed that Lithostratigraphic Unit 5 was most likely deposited in a fluvial environment in which variables such as river discharge, sediment load, channel width, channel depth, stream velocity, and bed roughness continuously interacted with one another. The interaction of these variables resulted in distinctive fluvial features such as size and geometry of channels, their sinuosity and ability to migrate, associated compounded bars and the development of overbank deposits. Based on the preceding it becomes possible to distinguish between different types of fluvial systems although no distinct boundaries between these systems/depositional environments exist. A continuum of fluvial environments resulted and includes the following:

a) Alluvial fans and fan deltas.
b) Braided rivers and braidplains.
c) Meandering river systems.
d) Anastomosed river systems (Einsele, 2000).

The reconstruction of above mentioned fluvial environments becomes very difficult especially when only subsurface data is available. Modern 3D seismic surveys are being used in order to demarcate ancient fluvial systems. During Ingwe's exploration programme such luxuries as geophysical surveys were not considered, meaning that other more simplistic methods were used in order to reconstruct palaeodepositional environments. The method applied during the research was to analyse the proportions of bed load and suspended load in channel fills and in the flood basin environment in order to determine the mode of sediment transport. In the case of Lithostratigraphic Unit 5 the sedimentary fill of the fluvial basin was subdivided into channel sediments and associated finer grained basin sediments. This approach was based on the large variation in grain sizes encountered and was used to reconstruct the palaeo-environment in which sediments/lithofacies of Lithostatigraphic Unit 5 were deposited.

7.3.5.5 Depositional environments

- **Lithofacies Gm**

A minimum period of 30.0 Ma lapsed since the deposition of Lithostratigraphic Unit 4 and the commencement of Lithostratigraphic Unit 5 (see Chapter 8). It is uncertain what happened in the Springbok Flats Karoo Basin during this period. The only significant feature that was identified is the palaeosol that developed at the top of Lithostratigraphic Unit 4 in close proximity of the palaeotopographic high lying areas. A comparison between the palaeotopography of Lithostratigraphic Unit 3 and 5 revealed similarities regarding topographical high and low lying areas (Figs. 7.8. and 7.23.).

An area with sufficient sedimentological data was selected to compile a generic depositional model for Lithofacies Gm. This area coincides with the western drainage system as depicted in Fig. 7.24. and includes the farms Hanover, Napier, Petersburg, Darling, Chester, Lincoln and Dublin.

The fluvial system as depicted in Fig. 7.27. comprises a northward draining system with a width/depth ratio of 120:1. The width/depth ratio is indicative of a broad shallow drainage system. This system hosts Lithofacies Gm at the base.

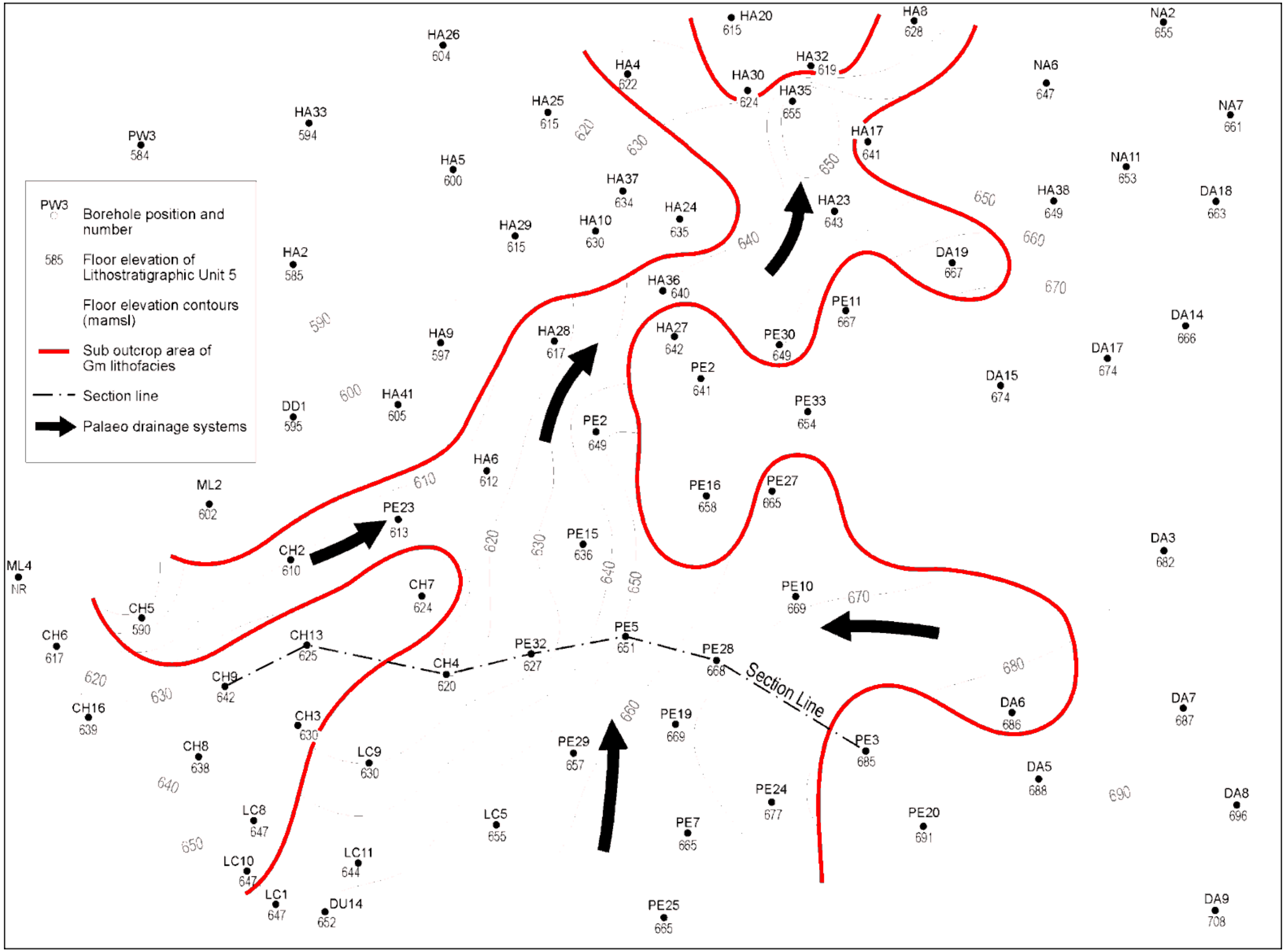


Fig. 7.27. Palaeotopography: Lithostratigraphic Unit 5 (selected area).

A detailed W – E cross section revealing the characteristics of the Lithofacies Gm across the drainage system depicted in Fig. 7.28.

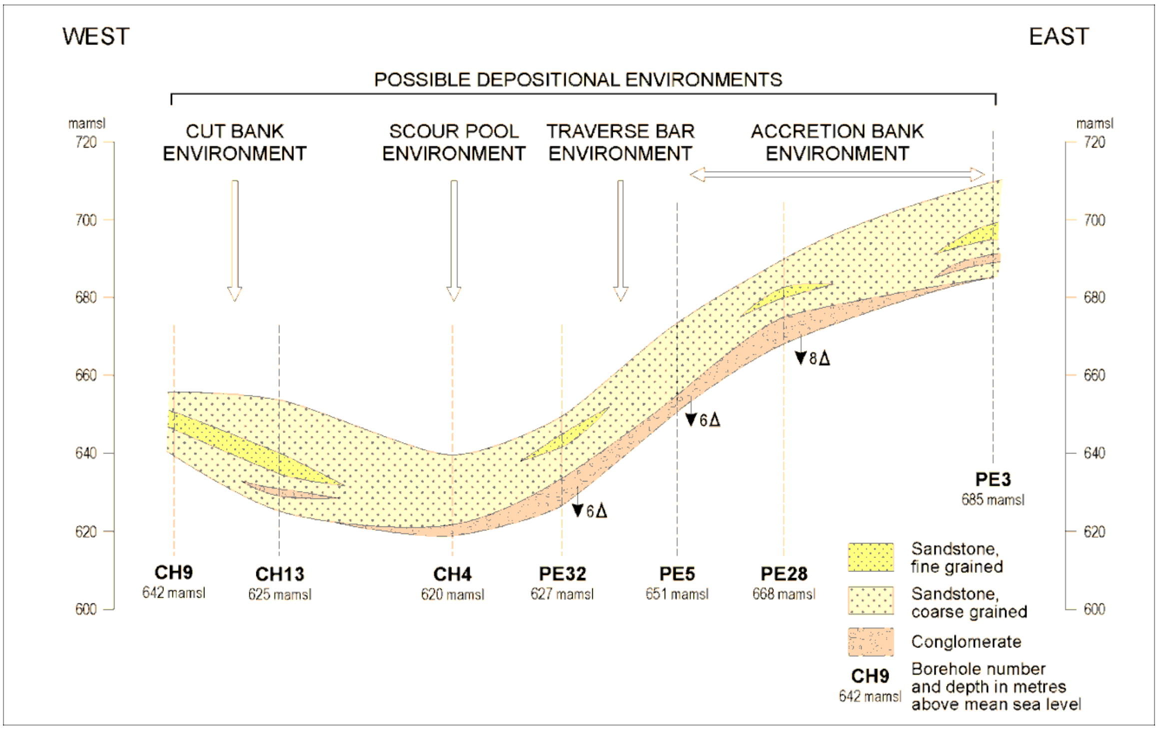


Fig. 7.28. Geological cross section: Lithofacies Gm.

In borehole CH666/4, drilled in the deepest part of the drainage system, a 2.0 m massive bedded conglomerate constitutes Lithofacies Gm. No intercalated sandstone beds were encountered in the conglomerate. Towards the east of borehole CH666/4 prominent upward fining cycles are developed in boreholes PE673/32, PE673/5 and PE673/28. These cycles comprises basal conglomerates overlain by massive or horizontally bedded coarse grained sandstone, varying in colour from greyish to light coloured. The grains are angular to sub-rounded and comprise primarily quartz and quartzite material. From the preceding description it can be inferred that the deposit is dominated by bedload i.e. carry and deposited of mainly gravel and sand. The conglomeratic beds of the Lithofacies Gm, comprise 70% of the total thickness of the succession. According to Miall (1977) the massive bedded nature of the conglomerates resembles longitudinal bars and possible lag deposits. The most important depositional processes involved, are assigned to lateral accretion (Einsele, 2000).

Lateral migration and sudden abandonment of channels due to avulsion cause upward fining cycle channel fill sequences. Such autocyclic sequences i.e. sequences that are controlled by processes taking place within the sedimentary basin itself, are considered to be the most distinctive feature of this type of braided river deposits (Einsele, 2000). The processes involved are migration and superposition of channel systems. Individual beds or cycles/bedsets of these type of sequences usually show limited stratigraphic continuity as evident from the aerial distribution of Lithofacies Gm (refer Fig. 7.24).

It is concluded that Lithofacies Gm represents longitudinal bars, deposited during lateral accretion, followed by downstream and upstream accretion processes.

The preponderance of quartz and quartzite pebbles in Lithofacies Gm inferred to reflect a source situated towards the south, southwest and east of the SFKB. The absence of granitic and igneous derived pebbles eliminates the Bushveld Igneous Complex as possible source rocks for Lithofacies Gm. Possible source rocks for Lithofacies Gm may include arenaceous sediments assigned to the Transvaal Supergroup and the Wilgerivier Formation of the Waterberg Group. The possibility that the Dwyka Group, which outcrops towards the south of the existing SFKB, also acted as a source rock for Lithofacies Gm, cannot be ruled out.

The aerial extent of Lithostratigraphic Unit 5 is uncertain due to the fact that this Unit was denudated in the west, south and the east of the SFKB leaving behind only a remnant of the original depository. The southern extent of the Karoo Supergroup sediments along the 28˚15´ E and 29˚0´ E longitude area could possibly be indicative of thalwegs that existed during the deposition of Lithostratigraphic Unit 5.

Pebble size measurements in Lithofacies Gm exhibit a gradual decrease in size from south to north (Settlers-Tuinplaats Basin) and from southeast to northwest in the Roedtan Basin. A facies analysis based on the lateral distribution of the different lithofacies encountered in Lithostratigraphic Unit 5 reveal a lateral change from dominant arenaceous and argillaceous facies in the south to only argillaceous facies i.e. Lithofacies F in the north. This change in facies architecture is assigned to an increase in distance from the source rocks and can be applied to determine the direction of transport. Based on the preceding a transport direction from the south to the north is postulated.

➢ Depositional environment: Lithofacies Sf

Lithofacies Sf comprises numerous well defined thin upward fining cycles that conformably overly the underlying Lithofacies Gm. Lithofacies Sf occurs over the entire SFKB and is not influenced by floor irregularities. Lithofacies Sf is bordered towards the north by sediments assigned to Lithofacies F. The predominant colour of Lithofacies Sf is greyish to reddish brown. The sandstones are immature and comprise primarily quartz and quartzite material. Grain sizes vary between very coarse to fine grained giving rise to a distinctive upward fining architecture. Intercalated mudstone layers vary in colour from greyish below to reddish brown at the top.

The lack of vegetation is thought to have resulted in a predominance of weakly channelized bed streams during the deposition of Lithofacies Sf. Sheets of sand developed in broad, virtually unconfined channels. Aggradation and progressive abandonment of these channels occured slowly or during single flood events. In either case, upward fining cycles are the common result (Miall, 2010). The upward fining cycles which resulted from the preceding events are commonly between 1.0 m and 3.0 m thick. The cycles show an upward transition from a scoured base, coarse grained sandstone through horizontally bedded finer grained sandstone, ripple crossbedded, fine grained sandstone and in some instances mudstone.

The overall characteristics of Lithofacies Sf resemble the depositional model as described by Miall (2010). It is therefore concluded that Lithofacies Sf was deposited on a distal braid plane bordering a playa lake.

The source rocks of Lithofacies Sf are probably the same as for Lithofacies Gm. Reworking of Lithofacies Gm could also have provided material for Lithofacies Sf. A gradual decrease in grain sizes from south to north in the Settlers-Tuinplaats Basin and from southeast to northwest in the Roedtan Basin lead to the conclusion that the sediment transport direction was from south to north in the Settlers-Tuinplaats Basin and from southeast to northwest in the Roedtan Basin.

The gradual change in sediment colour from greyish (Lithofacies Gm) to reddish brown (Lithofacies Sf) is indicative of a gradual change in climatic conditions that prevailed during the deposition of above mentioned facies. The colour of each sedimentary bed must be regarded as a problem in itself to which simple rules cannot be applied without danger of serious error (Blackwelder, 1925, quoted by Twenhofel, 1932 in Rust, 1959). The greyish colours of Lithofacies Gm probably owes their colour to disseminated carbonaceous material originated from Lithostratigraphic Units 3 and 4. Sedimentation probably took place under conditions of low temperature, low evaporation, high humidity and high precipitation. The absence of evaporates in Lithofacies Gm supports this model (Rust, 1959). A progressive change from the preceding climatic conditions to a warmer and drier climate resulted in a dominant red colour indicative of dry and oxidising conditions during the deposition of Lithofacies Sf and younger sediments.

- **Lithofacies Fs**

Lithofacies Fs conformably overlies Lithofacies Sf. The aerial distribution of this lithofacies is depicted in Fig. 7.26. The close association of the lithofacies and the palaeodrainage system as depicted in Fig. 7.26 indicate that the palaeotopography impacted on the aerial distribution of these drainage systems. The massive bedded character of this lithofacies can be interpreted as deposition of beds under upper flow regime conditions i.e. high velocity, under flashy discharge conditions (Miall, 2010). The channels in which these deposits occur are normally poorly defined or absent. According to Bracken, 1987 (in Miall, 2010) these deposits do not exhibit a very high preservation potential. During a peak discharge event the flow extended as a shallow sheet over a broad area beyond the confines of the original poorly defined channel resulting in the deposition of horizontally bedded sand deposits. The massive bedded nature of Lithofacies Fs and the association thereof with pre-existing palaeodrainage systems lead to the conclusion that Lithofacies Fs complies with a flashy, emphemeral sheetflood deposit associated with a sand-bed river system (Miall, 2010).

➢ Lithofacies F

The aerial extent of the arenaceous sediments of Lithostratigraphic Unit 5 i.e Lithofacies Gm, Sf and Fs are depicted in Figs. 7.25 and 7.26. North of this boundary only Lithofacies F represents Lithostratigraphic Unit 5. Lithofacies F is characterized by the absence of arenaceous sediments, the presence of calcisols and a typical reddish brown colour. Lithofacies F overlies the underlying Lithofacies Fs conformably with a sharp contact (refer Fig. 7.17 - 7.19). The actual aerial extent of Lithofacies F is unknown due to large scale modern denudation that took place after deposition. Based on borehole data it is evident that Lithofacies F was deposited over the entire existing SFKB and the palaeotopography did not impact on the aerial distribution of this facies.
Borehole data revealed that more than one calcisol horizon occurs north of the boundary between the arenaceous sediments of Lithostratigraphic Unit 5 and Lithofacies F. The same tendency was observed in areas where the major drainage systems as depicted in Fig. 7.23 occur below Lithofacies F.

Lithofacies F represents the distal part of the depositional environment in which the sediments of Lithostratigraphic Unit 5 were deposited. Lithofacies F represents a distal playa lake/flood basin environment. A gradual decrease in sediment supply accompanied by a lowering in the depositional baselevel across the entire SFKB resulted in a southern (Settlers-Tuinplaats Basin) and southeastern (Roedtan Basin) progradation of a playa lake/flood basin environment. This progradation resulted in Lithofacies F being deposited over the entire SFKB.

A limited range of chemical sediments occurs in the SFKB. The most important of these sediments are palaeosol and pedogenetic carbonates. The pedogentic carbonates or calcretes (calcisol) developed where floodplain or playa lake deposits were exposed to surface weathering processes for extended periods of time (thousands of years) (Miall, 2010). Rain infiltration leaches dissolvable ions downwards, whereas evaporation and capillary groundwater flow during dry periods concentrate the same ions near the surface. The result is the development of carbonate cement that coalesces into nodules and these, in turn coalesce into more or less continuous carbonate substrata.

Calcrete horizons constitute useful marker beds and yield information regarding basin stratigraphy. These types of deposits are also of considerable value in the study of large scale basin architecture. Calcrete horizons may extend for tens of kilometers across flood plain and playa lakes and are therefore amongst the most extensive mappable units within a fluvial system.

The presence of calcrete horizons towards the top of Lithofacies F is indicative of periods of no sedimentation during which conditions prevailed that were condusive for the development of pedogenetic carbonate. The presence of these carbonates towards the top of Lithofacies F also marks the termination of Lithostratigraphic Unit 5.

7.3.5.6 Conclusions

The four lithofacies as present in Lithostratigraphic Unit 5 comply to a large extent with the facies model for a terminal fan as defined by Kelley and Olsen (1993). Due to the fact that the actual aerial extent of Lithostratigraphic Unit 5 is unknown and that no directional sedimentary structures could be measured, the typical radial geometry of the proposed terminal fan model could not be determined. The typical facies model for terminal fans with associated facies as compiled by Kelly and Olsen (1993) is depicted in Fig 7.29. The relationships between the terminal fan model and Lithostratigraphic Unit 5 are summarised in Table. 7.4.

Table 7.4. Relationship between a terminal fan model and Lithostratigraphic Unit 5 (also refer to Fig. 7.29.).

Terminal Fan: Facies Associations	Lithostratigraphic Unit 5: Facies Associations
Feeder Channel	Lithofacies Gm
Distributary Channel	Lithofacies Sf
Sheetflow	Lithofacies Fs
Flood Basin	Lithofacies F

Lithofacies Gm as encountered represents probably only part of the major feeder zone whilst Lithofacies Sf and Fs correspond to proximal and distal fan zones. Lithofacies F represents the flood basin zone of the terminal fan environment.

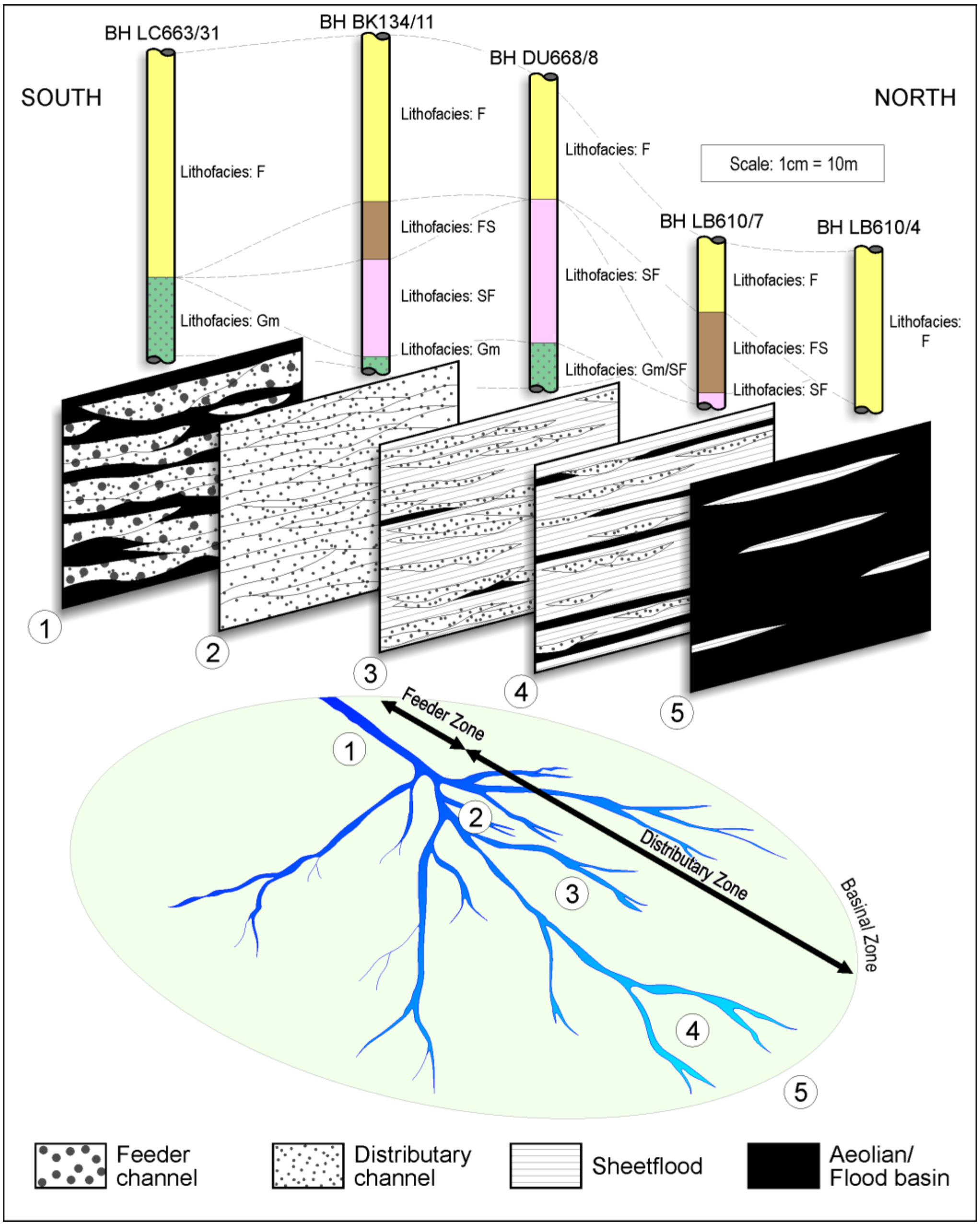


Fig. 7.29. A facies model for terminal fans with accompanied borehole intersections of the SFKB (modified after Einsele, 2000).

The recognition of terminal fans is based on the identification of facies characteristics indicative of a progressive downstream decrease in

a) Fluvial discharge.
b) Channel depth and width.
c) Lateral and vertical connectivity of channel fill elements.
d) Evidence of channelised flow.
e) Systematic increase in:

- Sheet flood deposition
- Playa deposits and
- Channel bifurcation

With the exception of the systematic increase in channel bifurcation the preceding elements, needed to define a typical terminal fan deposit, occur in Lithostratigraphic Unit 5. It is therefore concluded that Lithostratigraphic Unit 5 represents a typical terminal fan deposit.

7.3.6 Lithostratigraphic Unit 6

7.3.6.1 Lithology

A valuable tool that can be used in the identification of regionally developed marker beds is downhole wireline surveys. These marker beds distinguish themselves by a recognizable type of log deflection. The presence of calcrete horizons are characterised by high density intervals on the density logs or an increase in counts per second over these horizons when neutron-neutron logs are utilized.

A distinct change in counts per seconds on the neutron-neutron logs (refer Fig. 7.17) directly above the Lithofacies F, represents a calcrete pebble conglomerate that occurs over the entire SFKB. Since the formation of the calcrete, to the commencement of deposition of the calcrete pebble conglomerates, a major hiatus developed. The actual duration of this hiatus is uncertain but could have extended over thousands of years before the deposition of the calcrete conglomerates.

A lithostratigraphic unit, comprising basal calcrete conglomerates followed by intensely bioturbated siltstone and a lesser bioturbated sandstone respectively, constitute Lithostratigraphic Unit 6.

A generalized stratigraphic column of Lithostratigraphic Unit 6 is depicted in Fig. 7.30. Three distinct lithofacies were identified i.e.

a) Basal Lithofacies Cc.
b) Lithofacies Fs.
c) Upper Lithofacies S.

- **Lithofacies Cc**

Lithofacies Cc comprises numerous well defined upward fining cycles. The lowermost cycles (Fig. 7.31) consist of a calcrete pebble conglomerate overlain by a medium to fine grained and mainly massive bedded greyish sandstone. The pebble shapes vary between bladed and equant (Blatt et al., 1972).

The sorting of these conglomerates varies between poorly and very poorly sorted. The packing density of the basal conglomerates is high with the subordinate matrix comprising mainly greenish-grey argillaceous material. A distinct decrease in pebble size occurs from the lowermost conglomerates upwards. Despite this decrease in pebble sizes, the uppermost conglomerates are mainly matrix supported conglomerates (>50% matrix) in which case the matrix is similar to that encountered in the lower conglomerates (Fig. 7.32). The contacts between the conglomerates and the overlying sandstone units are always sharp (Fig. 7.31).

From the basal part of the Lithofacies Cc upwards, the thickness of conglomerate layers becomes thinner with a corresponding increase in sandstone thickness. In this part of the succession prominent upward fining cycles with sedimentary

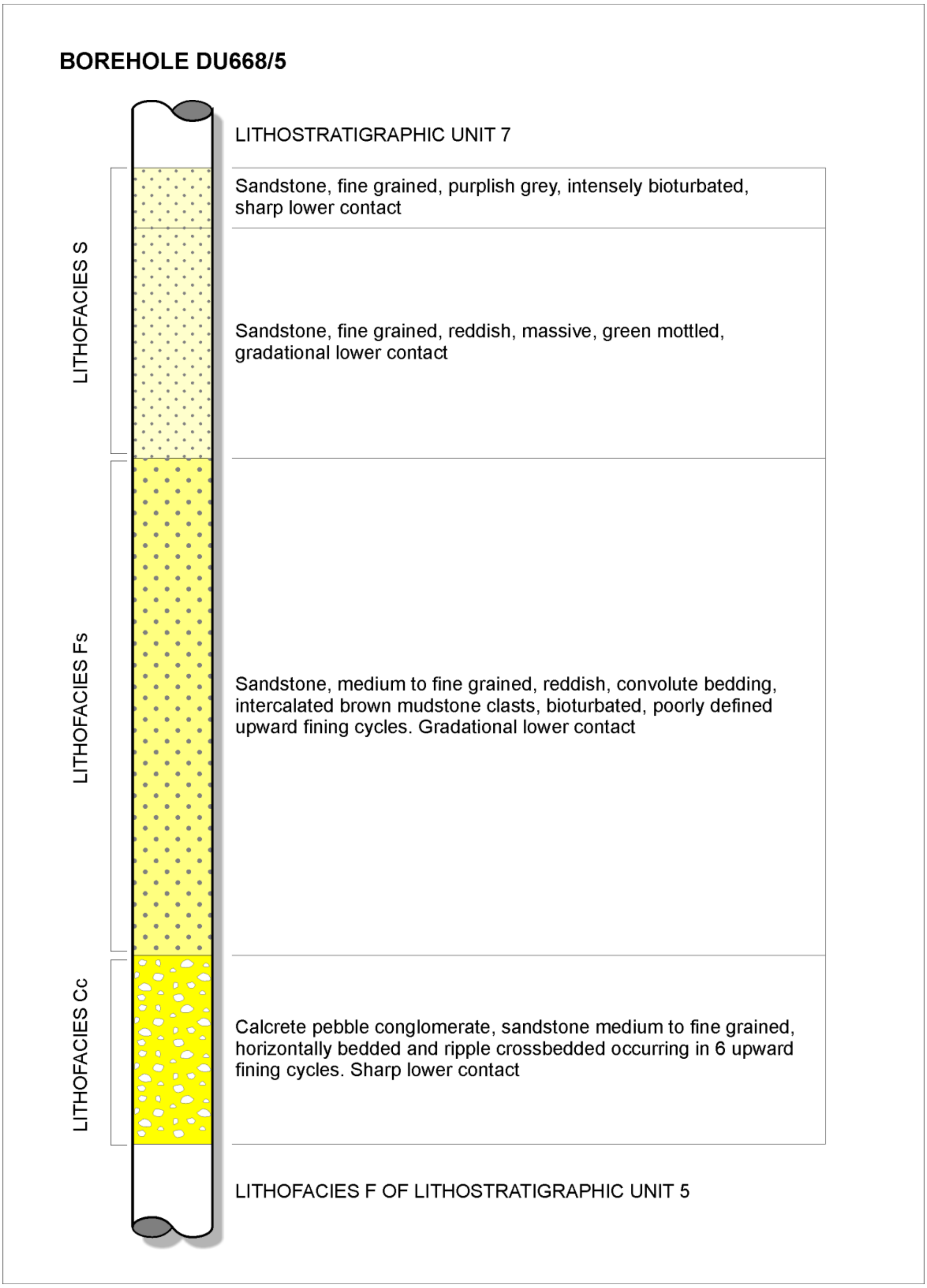


Fig. 7.30. Generalized stratigraphic column: Lithostratigraphic Unit 6.

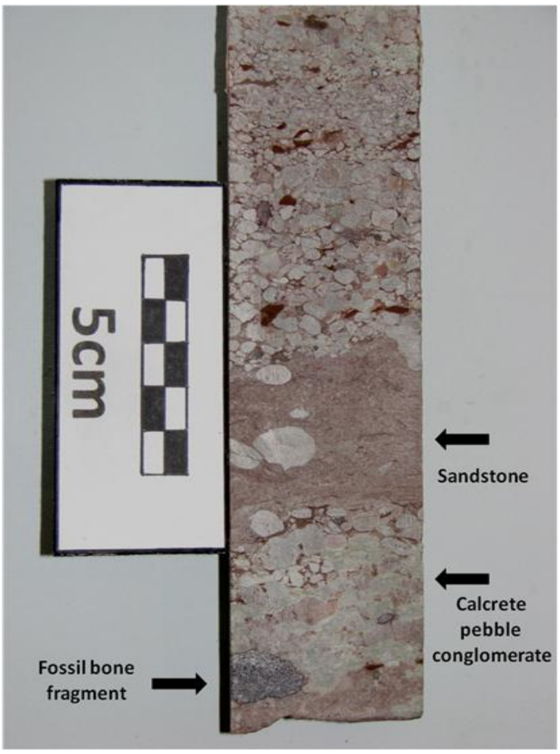


Fig. 7.31. Lithofacies Cc: Lithostratigraphic Unit 6.

Fig. 7.32. Lithofacies Cc depicting matrix supported calcrete pebble conglomerate.

structures i.e. horizontal lamination and ripple crossbedding are present (Fig. 7.33) in the sandstone. The uppermost sedimentary cycles of the Lithofacies Cc do not contain any conglomerates. In these cycles massive or graded bedded medium grained sandstones occur at the base of the upward fining cycles. The basal contacts of the upward fining cycles with underlying cycles are always very sharp (Fig. 7.31 and 7.32).

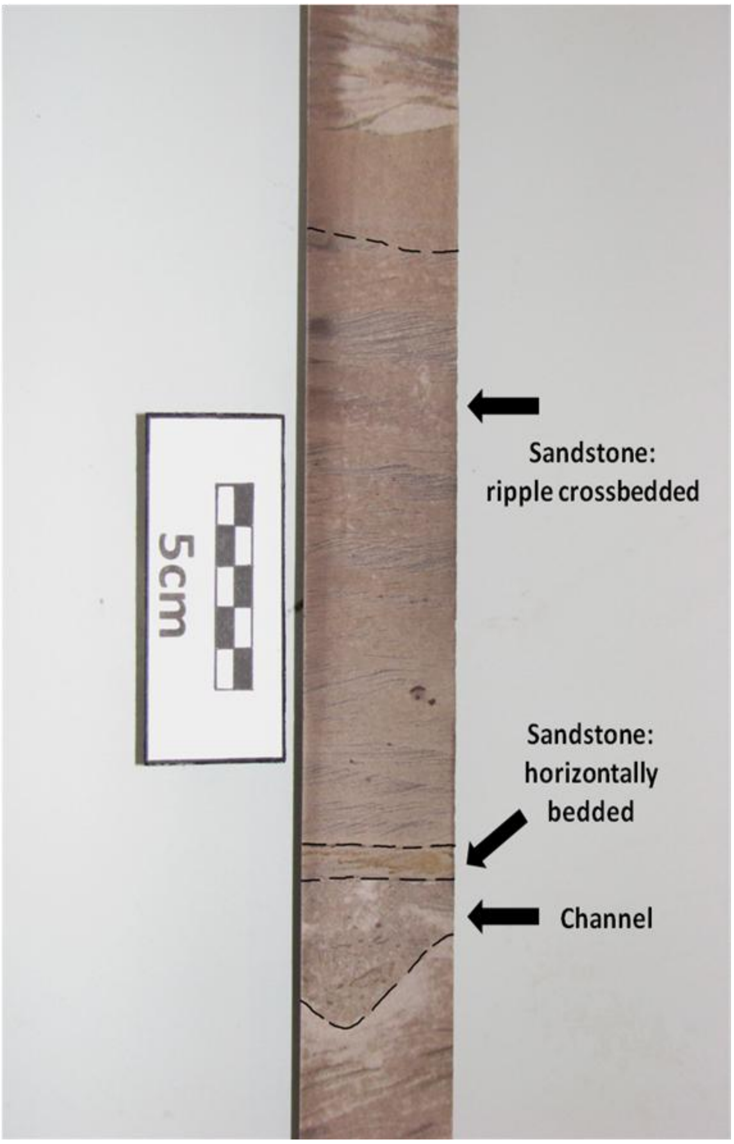


Fig. 7.33. Upward fining cycle: Lithofacies Cc.

The most distinct characteristic of the calcrete pebble conglomerate of Lithofacies Cc is the presence of numerous angular fossil bone fragments. The fragments vary in size between 1.0 mm to 70.0 mm (Fig. 7.31 and 7.32). A large dinosaurian femur designated *Gigantoscelus molengraaffi* was collected by ECN van Hoepen (Du Toit, 1939) in sandstone on the farm Haakdoornbult west of Pienaarsrivier Station. Bone fragments allied to Euskelesaurus were collected at Slypsteendrift and Zebedielas Location in the northeast (Du Toit, 1939). Samples of bone fragments intersected during Ingwe's exploration programme were submitted to the Bernard Price Institute for Palaeontological Research. Due to the size of the bone fragments no positive identification could be made (Fig. 7.34). According to Rubidge (personal communication, 2011) the bone fragments may resemble that of a prosauropod dinosaur that wandered the earth during the very late Triassic or very early Jurassic period of the Mesozoic Era (±206 Ma).

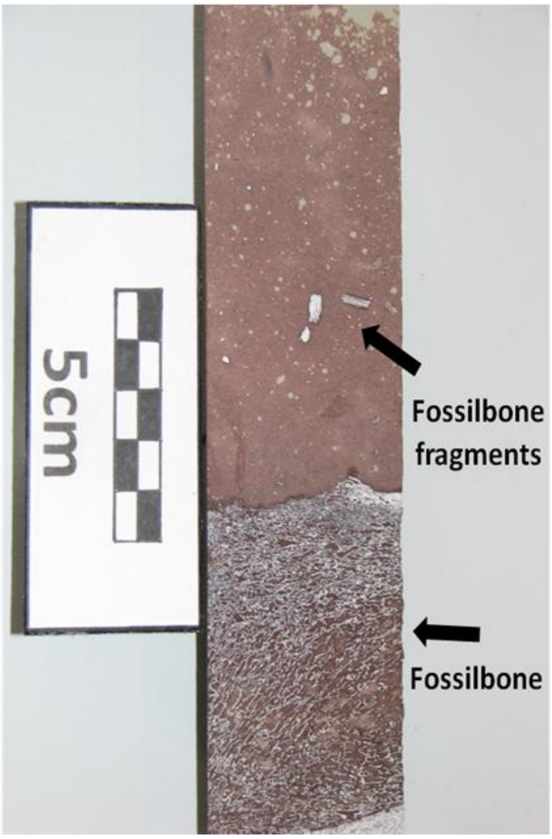


Fig. 7.34. Fossil bone fragments: Lithofacies Cc.

Deformational sedimentary structures (convolute structures) that developed contemporarily with sedimentation include structures such as sandstone dykes and slumping structures. A sandstone dyke, revealing sharp irregular contacts with adjacent sediments of Lithofacies Cc is depicted in Fig. 7.35 and 7.36. Small scale slumping structures occur at the base of some upward fining cycles.

Fig. 7.35. Sandstone dyke in calcrete pebble conglomerate: Lithofacies Cc.

- **Lithofacies Fs**

The lower contact of the Lithofacies Fs was established by the appearance of bioturbated sedimentary beds. A gradual decrease in grain size and the first appearance of sediments revealing real “Red Beds” characteristics define the contact between Lithofacies Cc and Lithofacies Fs. Lithofacies Fs comprises reddish brown green mottled siltstone. Major features of Lithofacies Fs are the total or partial destruction of sedimentary structures and intense bioturbation. Penecontemporaneous deformation and bioturbation are believed to be the agents responsible for this destruction (Fig. 7.37). In undisturbed horizons, massive bedding, horizontal lamination and ripple crossbedding occur in poorly defined upward fining cycles. Ripped up clasts, mainly reddish brown mudstone, occur at the base of the upward fining cycles (Fig. 7.37).

Fig. 7.36. Sandstone dyke in upper part of Lithofacies Cc.

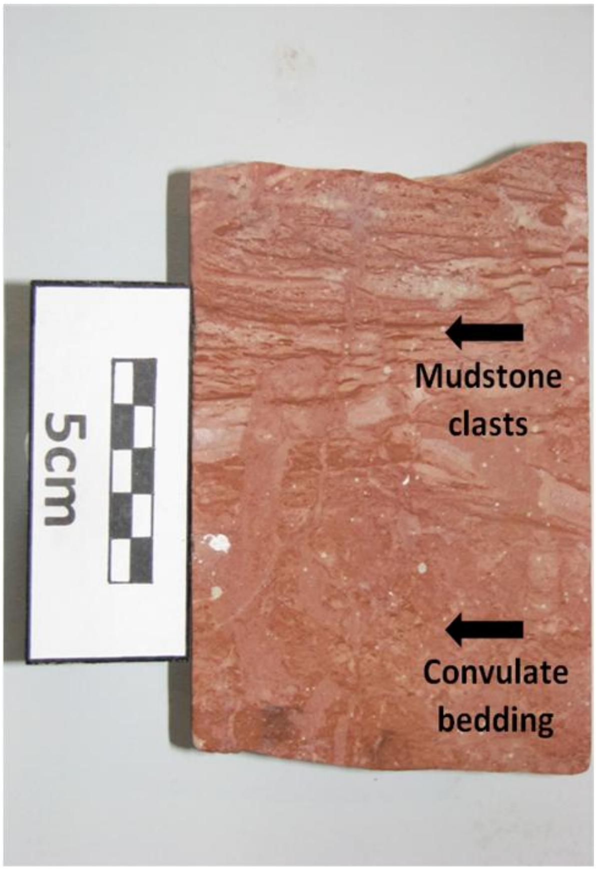


Fig. 7.37. Destruction of sedimentary structures: Lithofacies Fs.

➢ **Lithofacies S**

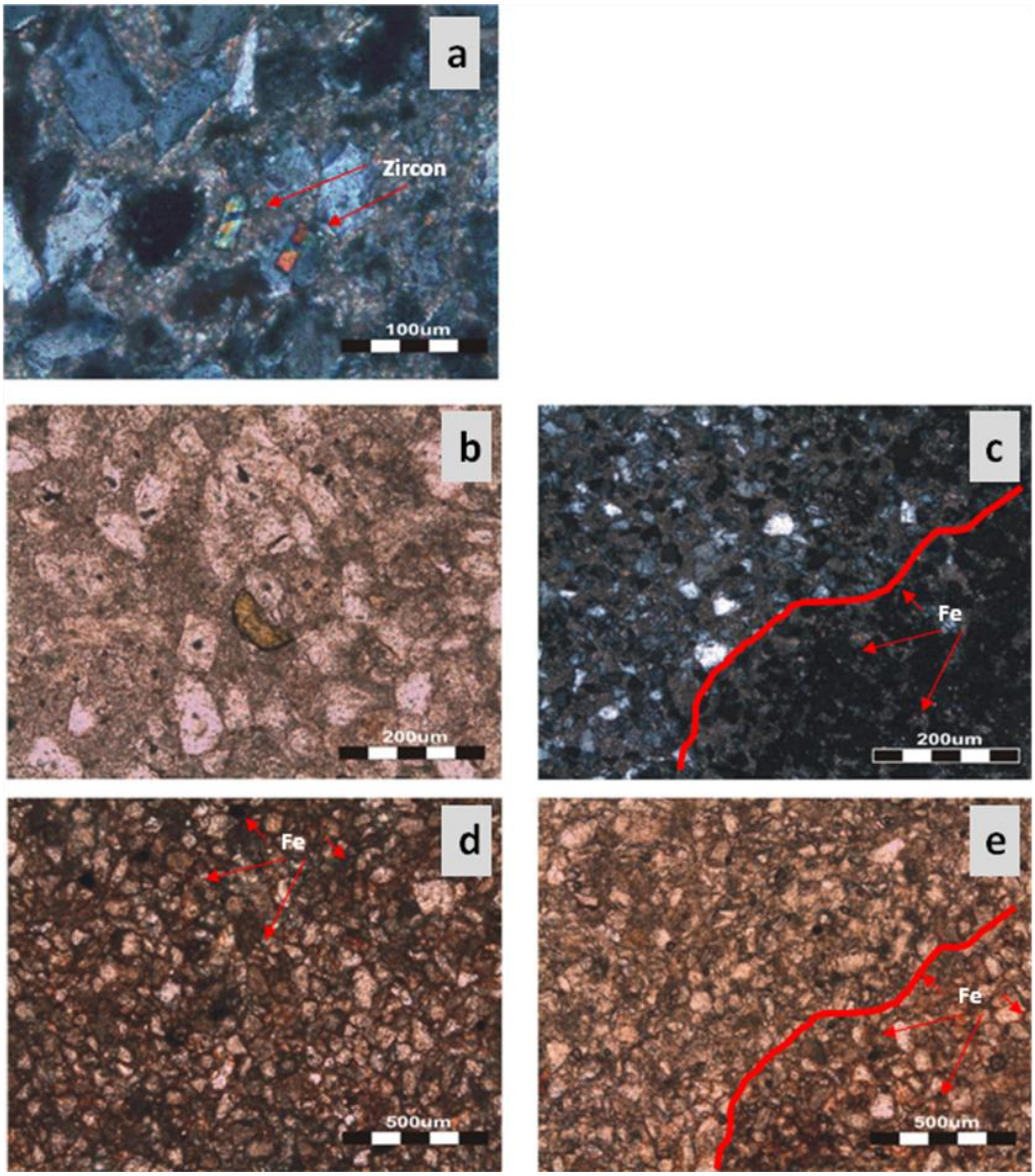
A fine grained (1/8 mm – ¼ mm) reddish brown green mottled, massive bedded sandstone which conformably overlies the Lithofacies Fs, constitutes Lithofacies S (Fig. 7.38). The sandstone is ill sorted and comprise angular to subangular quartz and subordinate feldspar and mica grains.

Thin sections were prepared in order to establish if any mineralogical differences exist between the green mottled sediments and adjacent reddish brown

Fig. 7.38. Green mottled sandstone: Lithofacies S.

sediments. The microscopic analysis revealed that the green mottles do not contain any iron oxides (Fig. 7.39). Leaching of iron oxides, through secondary processes, is believed to be the process responsible for the formation of the green mottles.

Bioturbation occurs in certain horizons in the Lithofacies S. The diameter of these burrows varies from a few millimeters to 1.5 cm. The spatial orientation of these



Legend:

a, b: **zircon grains under plane polarised light and crossed nicols respectively, iron oxides (Fe) have been leached from a and b.**

c: **iron oxides present in the whole sample.**

d, e: **iron oxide partially leached from the sediments.**

Fig. 7.39. Mineralogical differences between green mottles and adjacent sediments: Lithofacies S.

Fig. 7.40. Bioturbation in Lithofacies S.

Fig. 7.41. Bioturbation and change in colour at the top of Lithofacies S.

Fig. 7.42. Concretion horizon at the top of Lithofacies S.

burrows varies from vertical to sub-vertical. The burrows mainly constitute single tubes although complex brancing burrows were also encountered (Fig. 7.40).

The upper 0.5 m to 2.0 m of Lithofacies S is marked by a prominent change in colour from reddish brown to purple grey. This change in colour is accompanied by intense bioturbation (Fig. 7.41) and the presence of irregular shaped septarian like concretions (Fig. 7.42). Where these concretions are developed sedimentary structures are destroyed. These concretions were developed after the deposition of the sediments hence the destruction of sedimentary structures. The preceding description of the upper part of Lithofacies S constitutes a remarkable marker horizon of 2.0 m thick and is considered to be the result of a dramatic change in environmental conditions. This change in environmental conditions, as manifested in the termination of biological activities, constitutes the contact between Lithostratigraphic Unit 6 and overlying Lithostratigraphic Unit 7 (Fig. 7.43).

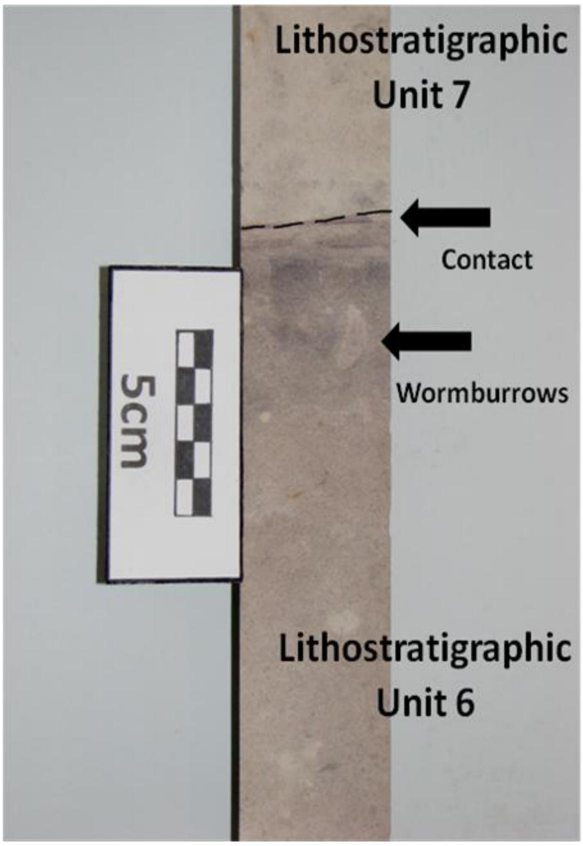


Fig. 7.43. Contact between Lithostratigraphic Units 6 and 7.

7.3.6.2 Depositional environment: Lithostratigraphic Unit 6

A vast flat lying landscape existed prior to the deposition of Lithostratigraphic Unit 6. Several east-west striking cross sections were compiled in order to ascertain the palaeotopography of the base of Lithostratigraphic Unit 6. The maximum variation in relief was encountered along an east-west section from the farm Dandaloo in the east to Gegund in the west, a distance of 40 km. Along this section the palaeotopography varies from 640 m.a.m.s.l. at Dandaloo to 889 m.a.m.s.l at Gegund. Gegund is situated on the southern extension of the anticlinal flexure that separates the Settlers-Tuinplaats and Roedtan Basins respectively. Despite this variance in topography, no substantial changes in the internal architecture of Lithostratigraphic Unit 6 could be ascertained.

➢ Lithofacies Cc

The calcrete pebble conglomerates encountered in Lithofacies Cc constitute intraformational conglomerates. These conglomerates represent pebble channel lag deposits composed of reworked calcrete, sand and silt. The overlying massive and horizontally bedded sandstone is indicative of in-channel sedimentation during upper flow regime conditions. A decrease in energy within the channels resulted in the formation of ripple crossbedded strata in a downstream direction (Cain and Mountney, 2009).

➢ Lithofacies Fs

The fine grained sediments of Lithofacies Fs were probably transported by sluggish, emphemeral, suspension-loaded rivers and deposited in a floodbasin or in lakes occupying low lying areas. Within these environments conditions prevailed that accommodated burrowing terrestrial fauna. Soft sediment deformation and bioturbation resulted in the destruction of sedimentary structures. The climate became progressively drier and warmer during the deposition of Lithofacies Fs and S whilst the prominent red colours are indicative of drier, oxidising conditions that prevailed in the depository.

➢ Lithofacies S

Continental aeolian sands may alternate laterally and vertically with deposits of marginal desert and fluvial environments. Sand dunes, often overlie alluvial fans, fluvial deposits or playa lake sediments frequently pass laterally into such sediments deposited in the interdune or marginal dune areas (Einsele, 2000).

Flooding of the interdune area by fluvial processes can create ephemeral lake deposits. Interfingering of aeolian sands and ephereral lake deposits is ascribed to a change towards a wetter climate. During such an event the sand dunes tend to become eroded by fluvial processes such that the preservation of dunes becomes limited (Einsele, 2000).

It is postulated that a change in climate (wetter environment) developed after the deposition of the Lithofacies Fs. During drier seasonal conditions that developed during the deposition of Lithofacies Fs, desert conditions prevailed causing the development of small scale dune fields (Mountney and Russel, 2009). A succeeding wetter climate caused this dune field to be eroded by fluvial processes and the corresponding deposition in ephemeral lake deposits. Conditions in these lakes were conducive for terrestrial fauna. The bioturbated horizons present in Lithofacies S are evidence that more than one flooding event of the dune field occurred. The termination of bioturbation and the associated formation of concretions at the top of Lithofacies S are indicative of a rather sudden change in climatic conditions with the corresponding termination of preserved terrestrial fauna (Fig. 7.43). The calcareous nodular horizon that occurs at the top of Lithofacies S is interpreted as a palaeosol, heralding a shift to even drier climatic conditions prior the commencement of Lithostratigraphic Unit 7.

7.3.7 Lithostratigraphic Unit 7

7.3.7.1 Lithology

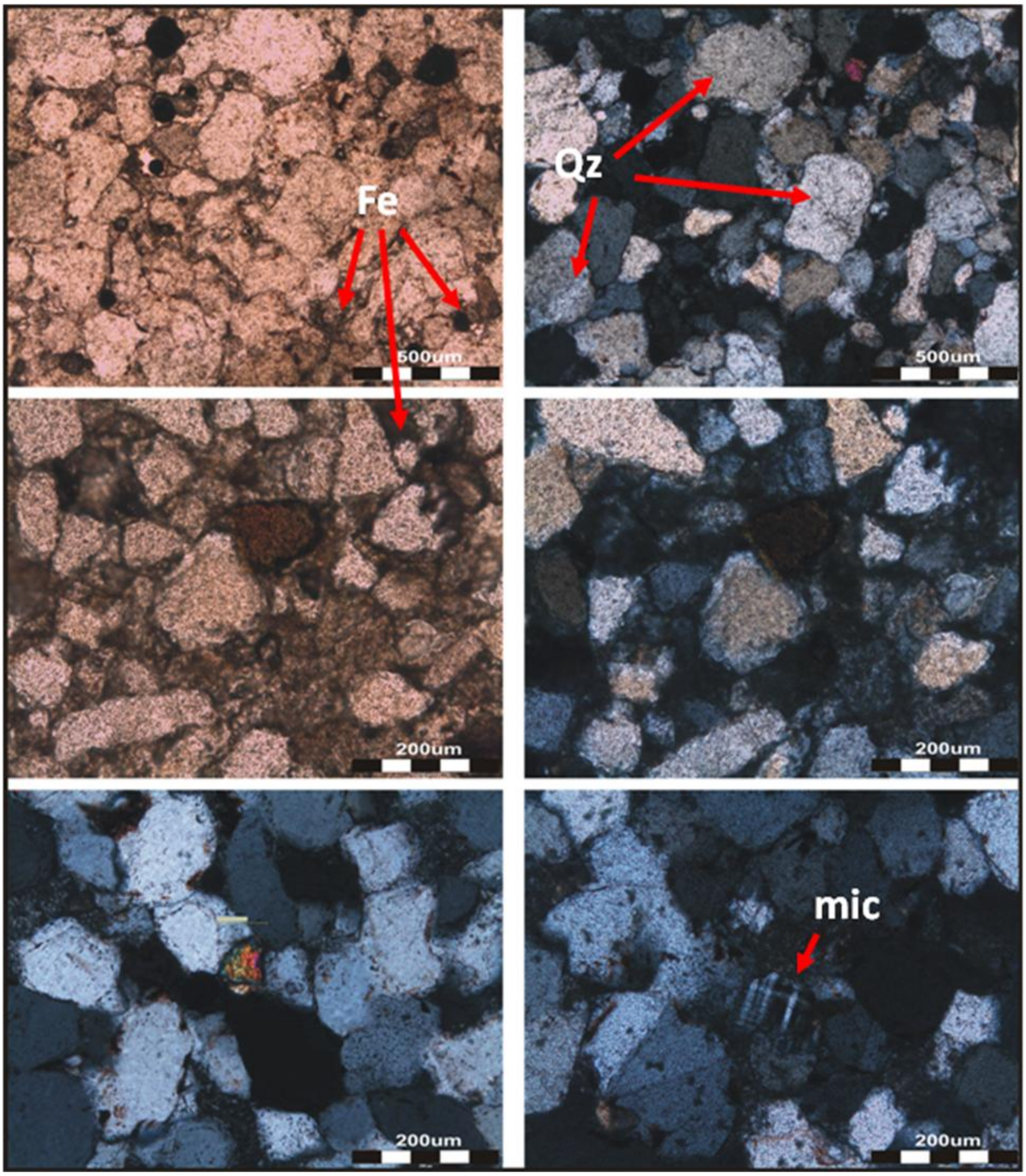
Lithostratigraphic Unit 7 constitutes the uppermost Lithostratigraphic Unit in the SFKB and also marks the end of arenaceous and argillaceous sediments associated with the Karoo Supergroup.

Lithostratigraphic Unit 7 comprises a rather homogeneous succession of sandstone overlain by basalts. Detail pertaining to this Unit is hampered by the fact that the percussion drilling techniques were used to drill through the basalts and Lithostratigraphic Unit 7. It is only in the deeper parts of the SFKB where wireline drilling recovered core samples for detailed description. Due to the homogeneous nature of Lithostratigraphic Unit 7 and the few wireline drilled intersections, no attempt was made to subdivide this Unit into lithofacies.

Lithostratigraphic Unit 7 comprises mainly medium to fine grained quartzitic sandstone, varying in colour from pink below to creamy and orange mottled towards the top. The succession appears to be massively bedded with interbedded upward fining cycles at the base and primarily at the top. The sandstone consists of medium to fine grained (1/4 mm -1/16 mm) rounded to sub-rounded quartz grains. Additional minerals encountered are subordinate K-feldspar and plagioclase grains. The heavy minerals are zircon, epidote, tourmaline and magnetite (Wagner, 1927). Some of the minerals encountered during microscopic investigations are depicted in Fig. 7.44.

A major characteristic of Lithostratigraphic Unit 7 is the absence of pebble or granular size particles. The thickness of this unit is fairly consistent over the entire SFKB and seldom exceeds 120.0 m. Northwest of Naboomspruit remnants of this Unit overlies granitic basement rocks. As this outcrop occurs outside the main SFKB it can be postulated that the aerial extent of Unit 7 was probably much more extensive than the existing SFKB. It is postulated by McCarthy and Rubidge (2005) that by 190 Ma ago the Cargonian Highlands had become totally submerged under a sand sea which extended unbroken for thousands of kilometers suchthat the limits of Lithostratigraphic Unit 7 occurred far beyond the known parameters of the existing SFKB.

Powder XRD analyses were conducted on samples containing orange to light coloured mottles towards the upper part of Lithostratigraphic Unit 7 (Fig. 7.45). These mottles vary in size from 2.0 mm to 1.0 cm. A XRD analysis revealed that the mineral associated with these mottles is laumontite ($CaAl_2Si_4O_{12}4H_2O$). Laumontite is an authogenic mineral that forms due to hydrothermal alteration or very low grade metamorphism. Laumontite possibly originated from volcanic ash that was blown into the depositional environment of Lithostratigraphic Unit 7 (J.C. Loock, personal communication, 2012).



Legend:

a, b:	**Quartz (Qz), secondary iron as mica (Fe)**
c, d, e:	**Tourmaline grains**
e:	**Secondary iron**
f:	**Cross hatched twinning of microcline (mic)**

Fig. 7.44. Minerals encountered in Lithostratigraphic Unit 7.

Fig. 7.45. Orange mottled sandstone: Lithostratigraphic Unit 7.

The upper 5.0 m – 10.0 m of Lithostratigraphic Unit 7 comprises green to grey fine grained sandstone occurring in well defined upward fining cycles. Within these cycles lamination and ripple crosslamination occur respectively. The uppermost cycles are characterized by a greenish colour. The greenish colour is assigned to the presence of chlorite. Associated with the green layer occur numerous fine grained glass shards. In some cases the uppermost cycles are characterized by plant imprints (Fig. 7.46), subordinate thin coal layers (mainly bright coal) and/or layers containing a high percentage of carbonaceous detritus (Fig. 7.47). Hand specimens were submitted to the Bernard Price Institute for Palaeontological Research but no positive identifications regarding the type of plants, due to the small sizes of the samples, could be made (Rubidge, personal communication, 2011).

Fig. 7.46. Plant imprint: Lithostratigraphic Unit 7.

7.3.7.2 Depositional environments

The texture and sedimentary structures (where present) of Lithostratigraphic Unit 7 are compatible with a typical aeolian deposit. The presence of upward fining sequences point to brief wetter interludes giving rise to ephemeral stream deposits in interdune areas. The development of ephemeral lakes, conducive for plant growth, resulted in the preservation of carbonaceous material in some of the upward fining cycles.

The presence of the authigenic mineral laumontite reflects the low grade of metamorphism associated with the overlying flood basalt event. The occurrences of chlorite and glass shards indicate the presence of volcanic rocks in the source area or simultaneous volcanism in the depositional area. The possibility exists that volcanic activity (i.e. volcanic ash), prior to the massive outflow of basalts, influenced sedimentation towards the end of Lithostratigraphic Unit 7.

Fig. 7.47. Carbonaceous detritus in Lithostratigraphic Unit 7.

7.4. Basaltic lavas

The termination of the Karoo Supergroup sedimentation is marked by the presence of amygdaloidal basaltic lavas. The SFKB constitutes a preserved basin resulting in the actual thickness and aerial distribution of lava being uncertain. As previously mentioned, the faults encountered in the SFKB are post-Karoo in age and did not impact on the distribution of the basaltic lavas. In the deeper part of both the Settlers-Tuinplaats and Roedtan Basins lava thicknesses in the excess of 600 m were encountered.

The lavas comprise alternating, fine crystalline dark-grey to greenish and amygdaloidal units respectively (Figs. 7.48 and 7.49). The amygdaloidal units occur at the base of lava flows of which up to 75 different flows were recognized (Roberts, 1992) on Roodedoorn 134 in the Roedtan basin. Thin layers of tuff and agglomerate occur sporadically (Fig. 7.50). Angular fragments of pre-Karoo age rocks i.e. Waterberg Group and Transvaal Supergroup were encountered in the agglomerates.

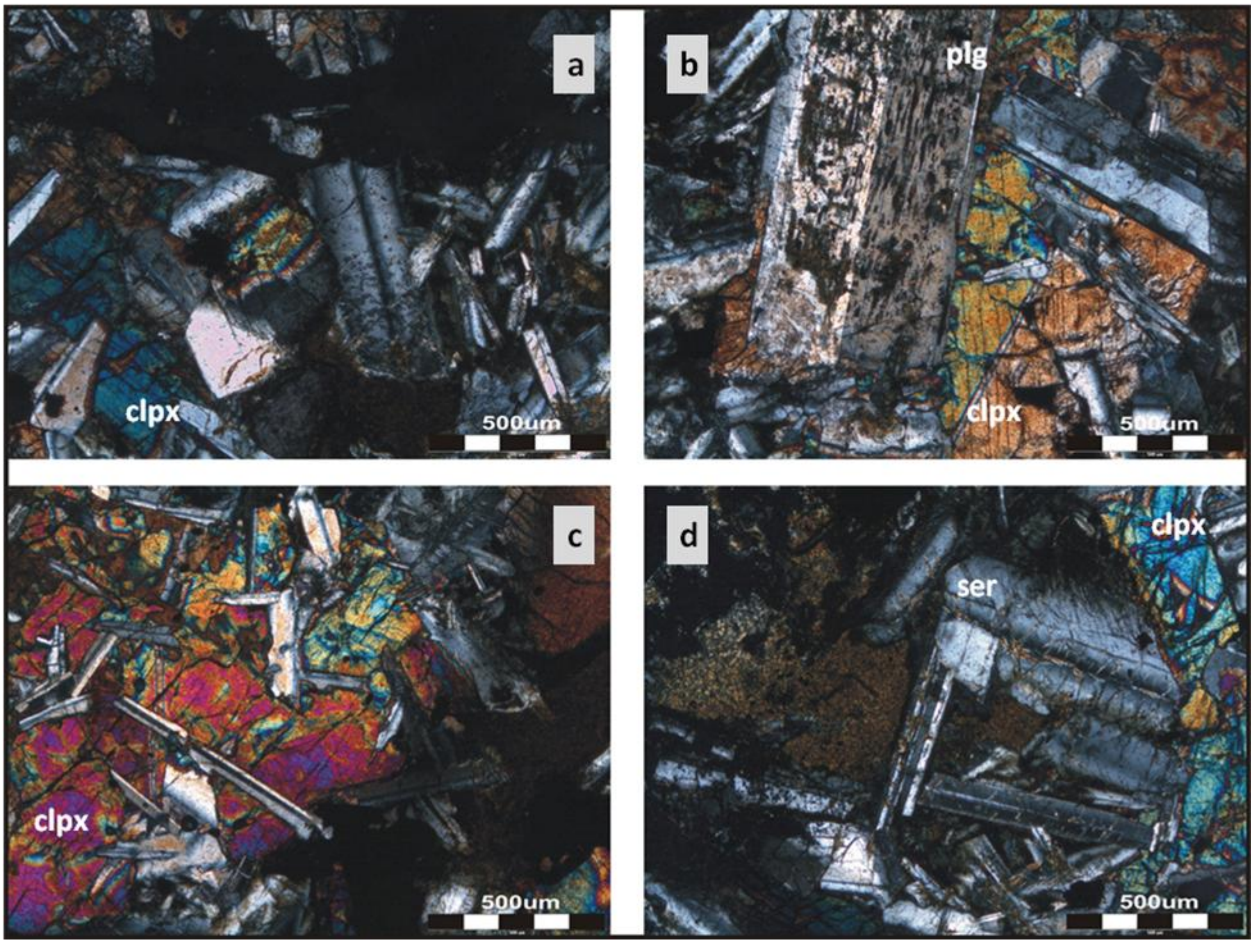
In the lower division of the lavas intercalated sandstone layers occur. The sandstone resembles the sandstone of Lithostratigraphic Unit 7 and differs from it only in being better stratified and composed largely of well rounded quartz grains. The prevalent colour of these sandstone intercalations is reddish brown to light coloured. The underlying Lithostratigraphic Unit 7 has only been visibly indurated for a few centimeters by the lava.

Petrographically the lava comprises primarily plagioclase with polysynthetic twinning (Carlsbad twinning) (Fig. 7.52), pyroxenes, quartz, biotite and calcite. The amygdales comprise chalcedony and round nodules of celadonite.

Fig. 7.48. Fine crystalline basaltic lava.

Fig. 7.49. Amygdaloidal lava.

Fig. 7.50. Agglomerate horizon in basaltic lavas.



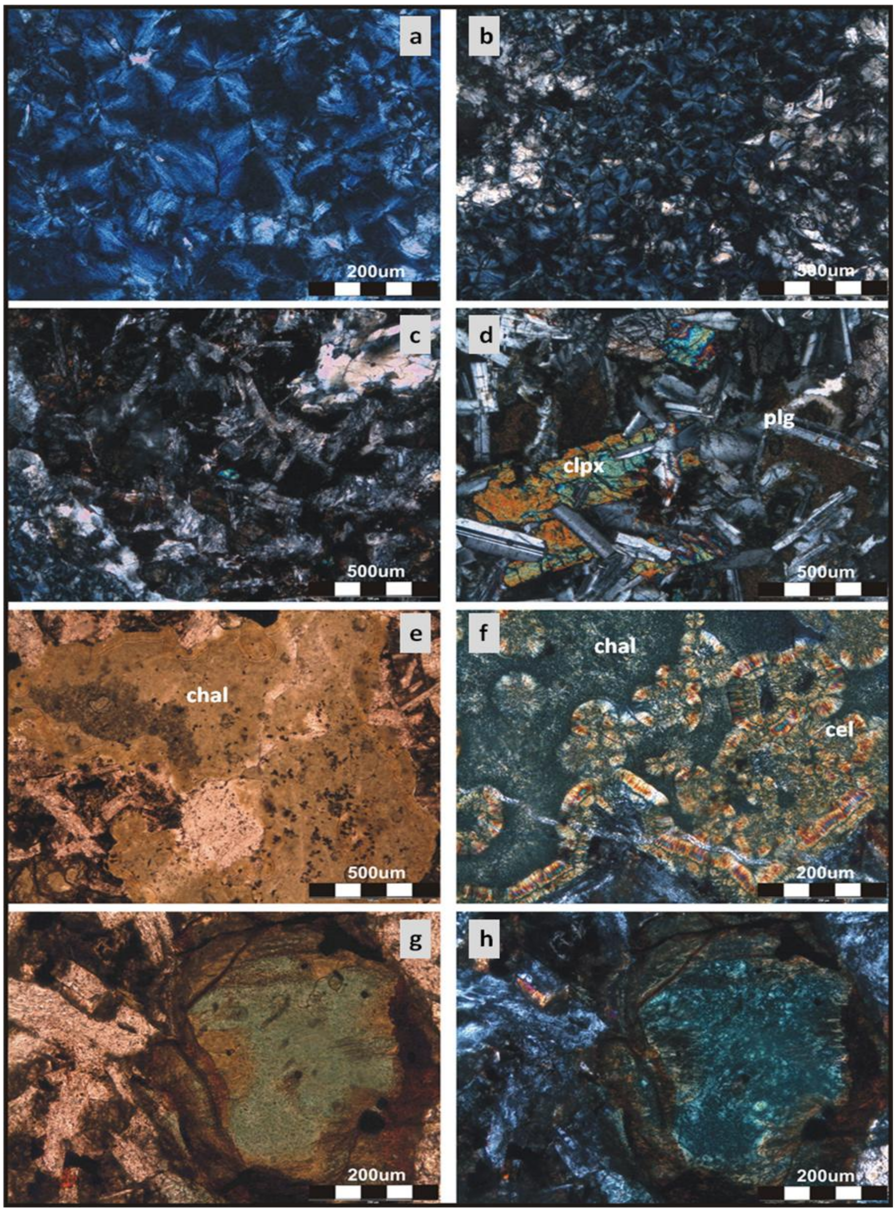
Legend:

a: **Carlsbad twinning in plagioclase (plg).**

b, c: **Epidotised plagioclase and simple twinning in clinopyroxene (clpx).**

d: **Sericitization (ser) in plagioclase.**

Fig. 7.51. Petrographic analysis – basaltic lava.



Legend:

a, b, c:	**Chlorite alteration of pyroxenes.**
d:	**Plagioclase (plg) showing carlsbad twinning and some clinopyroxenes (cpx).**
e, f:	**Amygdales of chalcedony (chal) and round nodules of celadonite under plane polarized light (e) and crossed nicols (f).**
g, h:	**Olivine under plane polarized light (g) and crossed polarized light (h).**

Fig. 7.52. Petrographic analysis: amygdales in basaltic lava.

7.5 Conclusions

Stratigraphic correlation is the demonstration of equivalency of stratigraphic units. The recognition of distinctive features that separate rock stratigraphic units, biostratigraphic and time stratigraphic units makes it apparent that equivalency may be expressed in lithological, palaeontological or chronologic units (Krumbein and Sloss, 1963).

The following discussion is a synopsis of the work of Krumbein and Sloss (1963) and will constitute the basis of stratigraphic correlations in the SFKB.

Lithostratigraphic units as described are bodies of strata identified by objective lithological criteria and are delineated in vertical succession by surfaces representing changes in lithological character or by breaks in the depositional continuity or by marker beds. It has long been the practice in areas of monotonously or excessively heterogeneous stratigraphy to demarcate stratigraphic units by easily recognizable and traceable beds of distinctive lithology, also known as marker beds. Such a marker bed is part of the formal stratigraphy in so far as it maintains a proper degree of consistency of lithological character.

In subsurface stratigraphy as in the SFKB, downhole geophysical surveys provided the means for the identification of marker beds which can be traced over the entire SFKB. These marker beds as identified by geophysical surveys have led to great reliance on these features for the establishment of rock units in subsurface stratigraphy. The closely spaced boreholes in certain areas in the SFKB means that individual lithostratigraphic units can be traced from borehole to borehole by the utilization of lithological data and geophysical surveys. Although fossils/trace fossils are mainly used to delineate and correlate biostratigraphic and time-stratigraphic units, they are also contributors in identifying lithological units. This is particularly applicable where lithological units comprise fossil fragments. True index fossils largely confirm the correlations suggested by the rock unit relationships.

In the SFKB the intercalated calcrete and palaeosol horizons represent conditions which presumably were essentially simultaneous in effect over most of the SFKB. In addition the coal deposits require the coincidence of favorable topographic, tectonic and climatic conditions. These conditions prevailed for relatively short intervals of time and individual coal seams are essentially time-parallel throughout their extent (Krumbein and Sloss, 1963).

Event Stratigraphy refers to the study of sedimentological events which are either depositional or non-depositional. Continental non-depositional events include widespread soil horizons (palaeosols) developed on surfaces of sediment starvation or non-deposition. Paleosols developed in humid areas often display traces of rootlets and an increase in clay minerals and organic matter, whereas palaeosols of semi- arid regions tend to develop various types of nodules and duricrusts. The development of widespread palaeosols in fluvial environments constitutes the best marker horizons in these deposits. Similar to palaeosols, coal seams also represent periods of non-deposition (Einsele, 2000).

The major non-depositional events associated with the Karoo Succession as encountered in the SFKB are listed in Table 7.5.

Table 7.5. Non-depositional events in the SFKB.

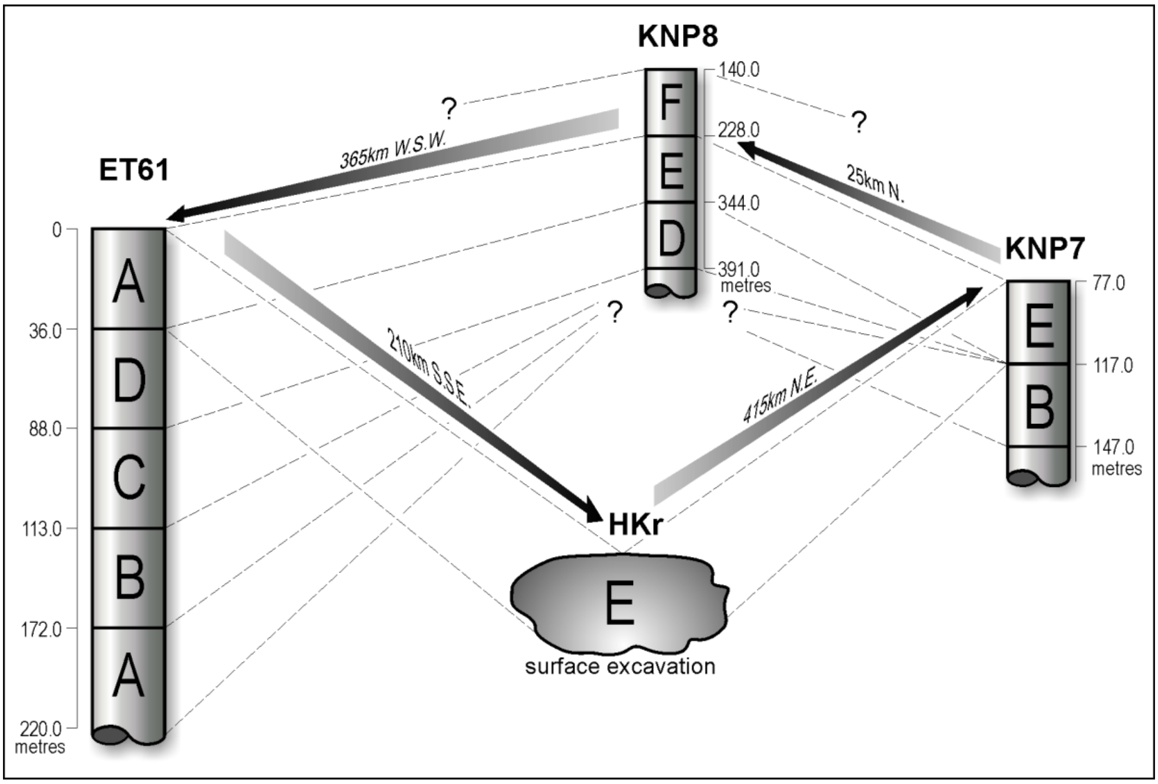
Non-depositional Event	Stratigraphic Position
1. Lowermost Coal Seam	Lithostratigraphic Unit 2
2. Coal Seam	Lithostratigraphic Unit 3
3. Palaeosol (top)	Lithostratigraphic Unit 4
4. Palaeosol (top)	Lithostratigraphic Unit 5
5. Palaeosol (top)	Lithostratigraphic Unit 6
6. Subordinate Coal Development and associated carbonaceous detritus	Lithostratigraphic Unit 7

With the exception of non-depositional events 1 and 6, the remaining events constitute regional non-depositional events developed over the entire SFKB.

The demarcation of a lithostratigraphic units, based on marker beds and the principles of Event Stratigraphy were applied to establish a stratigraphic column for the SFKB.

The basal Lithostratigraphic Unit 1 (diamictite) represents the Dwyka Group in the SFKB. Although, only sporadically developed, the lowermost coal seam is considered to be the first non-depositional event encountered in the SFKB.

Lithostratigraphic Unit 2 is defined as a deltaic succession capped by a coal zone (Lithostratigraphic Unit 3). The coal zone comprises alternating bright coal and carbonaceous shale layers. Within the coal zone each coal layer (upper, middle and lower seams) is considered to be non-depositional events intercalated with depositional events comprising carbonaceous shales. The top of the coal zone is considered to be the occurrence of the uppermost coal band. The coal zone is conformably overlain by Lithostratigraphic Unit 4 of which the sedimentary characteristics resemble that of the interbedded carbonaceous shale layers encountered in the coal zone. The carbonaceous content of Lithostratigraphic Unit 4 decrease upwards, accompanied by a gradual change in argillite colour from dark grey to greyish, purplish and khaki coloured at the top. This colour change is believed to be caused by changes in the climate and depositional environment. Lithostratigraphic Units 3 and 4 comprise a series of beds deposited during a single sedimentary cycle equivalent to deposits associated with a cyclothem (Krumbein and Sloss, 1963). The contact between this cyclothem and Lithostratigraphic Unit 5 is marked by a non-depositional event i.e. palaeosol. A possible link between the SFKB and the Main Karoo Basin was postulated by several researchers in the past. This issue was also addressed and possible thalwegs via the Apies River and along the 29ºE latitute were postulated. Litho- and biostratigraphic subdivisions based on palynostratigraphic correlations by MaCrae (1988) means that the fossil assemblages at Hammanskraal (Biozone E) were correlated with the Grootgeluk Formation in the Waterberg Coal Field (Fig. 7.53). A biostratigraphic correlation between the Waterberg and Witbank Coal Basins revealed a close correlation between the Grootgeluk Formation No. 6 Coal Seam and the No. 5 Coal Seam (Vryheid Formation) of the Witbank Coal Basin (Falcon, 1986). Based on the preceding it is concluded that the coal zone of Lithostratigraphic Unit 3 in the SFKB can be correlated with the No. 5 Coal Seam in the Witbank Coal Basin.



Legend:

(A – C) biozones based on palynostratigraphic correlations.

Exploration boreholes sampled for palynostratigraphic correlations.

ET61	**-**	**Waterberg coalfield**
KNP8 & KNP7	**-**	**Soutpansberg coalfield**
HKr	**-**	**Hammanskraal Fossil Assemblage**

Fig. 7.53. Summary of correlation of the biozones (MacRae, 1988).

Lithostratigraphic Units 2, 3 and 4 represent a succession of sediments identified by objective lithological criteria and are delineated in vertical succession by surfaces representing changes in lithological character and marker beds. Based on the preceding, Lithostratigraphic Units 2, 3 and 4 qualify for formation status.

The classical meandering river and flood plain deposits synonymous with the Beaufort Group of the Main Karoo Basin are not developed in the SFKB. The lack of index fossils in Lithostratigraphic Unit 5 hampers correlation with similar types of deposits in the Main Karoo Basin. However based on the lithological characteristics as described it is recommended that Lithostratigraphic Units 5 obtain formation status. Lithostratigraphic Unit 6 is a typical “red bed” fluvial deposit with the incursion of aeolian conditions in the uppermost part of the Unit. It is recommended that Lithostratigraphic Unit 6 must obtain a formation status in the SFKB.

The correlation of the Bushveld Sandstone (Du Toit, 1954) with the Clarens Formation of the Main Karoo Basin appears to be justified and the use of the latter can be extended to the SFKB.

The stratigraphy of the SFKB, based on observations and research by Roberts (1992), Johnson et al. (2006) and the author of this dissertation are depicted in Table 7.6.

Table 7.6. Stratigraphy of the SFKB (historical vs. revised).

Johnson et al. (2006)	Roberts (1992)	Lithostratigraphic Units (Nel, 2012)
Lebombo Group	Letaba Formation	
Clarens Formation	Clarens Formation	7
	Worthing Formation	6
Irrigasie Formation	Codrington Formation	5
	Lehau Formation	4
Hammanskraal Formation	Warmbad Formation	3
	Turfpan Formation	2
Dwyka Group	Merinovlakte Formation	1

The Hammanskraal Formation as described by Johnson et al. (2006)(Table 7.6) comprises Lithostratigraphic Units 2 and 3. Formal lithostratigraphic names normally comprise a geographic name derived wherever possible from the location of the stratotype or type area (SACS, 1988). If the Hammanskraal Formation refers geographically to the Hammanskraal village towards the south of the SFKB it is misleading as Lithostratigraphic Unit 3 is not developed in the proximity of Hammanskraal and thus does not constitute a stratotype or type area of Lithostratigraphic Unit 3.

The Irrigasie Formation, as described by SACS (1988) and Johnson et al. (2006) is problematic in the sense that well defined lithological units i.e. Lithostratigraphic Unit 4, 5 and 6 were grouped together and statements regarding Lithostratigraphic Unit 5 are incorrect. Lithostratigraphic Unit 5, especially Lithofacies Gm and Sf do not vary considerably in stratigraphic position and thickness from borehole to borehole as quoted by SACS (1988). Based on the descriptions pertaining to Lithostratigraphic Units 4, 5 and 6 it becomes evident that these lithostratigraphic units cannot be considered “as a single argillaceous formation containing one or more arenaceous members or lentils towards the base” (SACS, 1988). Lithostratigraphic Units 5 and 6 qualify as formations irrespective whether of they are equivalent to the Main Karoo Basin Successions.

The change from reducing environments to oxidizing environments occurs after the deposition of Lithostratigraphic Unit 4. Lithostratigraphic Unit 4 is considered to be the end member of a cyclothem comprising Lithostratigraphic Units 3 and 4. Based on the preceding the need becomes evident to exclude Lithostratigraphic Unit 4 from the Irrigasie Formation. In addition, at least 30 Ma had lapsed since the termination of Lithostratigraphic Unit 4 and the commencement of Lithostratigraphic Unit 5 (refer Chapter 8). Lithostratigraphic Units 2, 3 and 4 represent a continuous process of sedimentation and can thus be considered as a formation on a stand alone basis. The stratigraphic nomenclature as presented by Roberts (1992), i.e. Worthing, Codrington, Lehau, Warmbad, Turfpan and Merinovlakte Formations (Table 7.6) refers to farm/town names in the SFKB. Unfortunately, these properties are not representative as stratotypes or type area for the Karoo Supergroup in the SFKB. Type areas with higher drilling densities and more representative geological intersections must therefore be considered as alternatives for the formation nomenclature as defined by Roberts (1992).

A revised stratigraphic column for the SFKB based on the recent research is depicted in Table 7.7.

Table 7.7. Proposed stratigraphic column for the SFKB.

Lithostratigraphic Units	Recommended Stratigraphic Nomenclature
7	Clarens Formation
6	Elliot Formation
5	Settlers Formation
4	
3	Hamburg Formation
2	
1	Dwyka Group

A possible correlation between the stratigraphy of the SFKB and the Main Karoo Basin is depicted in Table 7.8.

Table 7.8. Stratigraphic correlation: SFKB and Main Karoo Basin.

SFKB	Main Karoo Basin
Drakensberg Group	Drakensberg Group
Clarens Formation	Clarens Formation
Elliot Formation	Elliot Formation
Settlers Formation	Molteno Formation
Hamburg Formation	Vryheid Formation
Dwyka Group	Dwyka Group

Chapter 8. Economic Geology

8.1 Coal

The presence of coal in the Springbok Flats Karoo Basin has been known since the beginning of the 1900's. Extensive drilling in the basin commenced in 1952 and culminated in the 1970's with the discovery of uranium resources associated with the coal. Coal is defined as a readily combustible sedimentary rock containing >50% by mass and >70% by volume of carbonaceous material, and is formed by the accumulation, compaction and induration of various altered plant remains (De Jager, 1998). The nature of the organic constituents depends on the relative proportions of the various kinds of plant debris (wood, leaves, bark, spores) in the initial accumulation of peat and on the diagenetic or metamorphic changes that have occurred since the peat was originally deposited (rank of coal). Together with the nature and relative amount of any mineral matter that may be present, this assemblage of organic compounds is reflected by the physical appearance of the coal and will determine the behaviour of the coal when combusted (Ward, 1984). For practical purposes the general nature of the organic compounds can be evaluated by a combination of two sets of analytical data i.e.:

a) proximate analysis
b) ultimate analysis

Proximate analysis gives the relative amount of light organic compounds (volatile matter), as opposed to non-volatile organic matter (fixed carbon). Proximate analysis also gives the amount of moisture and a measure of the inorganic components left as a residue or ash when the coal is combusted.

In addition to the preceding coal qualities the amount of heat liberated from the coal on combustion was also determined (CV, MJ/kg).

8.1.1 Analytical Data

8.1.1.1 Proximate Analysis

Proximate analysis was done as a miscellaneous analysis on all coal samples in the Lithostratigraphic Unit 3. The average proximate analytical values (raw coal) for the major sub-basins in the Springbok Flats Karoo Basin are depicted in Table 8.5.

8.1.1.2 Ultimate analysis

Ultimate analysis reflects the total amount of each of the principle chemical elements in coal i.e.

- Carbon
- Hydrogen
- Oxygen
- Nitrogen
- Sulphur

The average ultimate analysis per coal block is depicted in Table 8.1.

Table 8.1. Ultimate analysis (% mean values).

Coal Resource Blocks	Fraction	C	H	N	S	O
Northern	Raw	50.70	3.60	0.83	1.93	8.06
	F 1.65	63.00	4.30	0.97	1.62	8.39
	F1.75	60.00	4.10	0.95	1.43	8.49
Southern	Raw	50.00	3.50	0.98	2.42	6.88
	F 1.65	60.00	3.90	1.05	1.33	8.25
	F 1.75	59.00	4.10	0.98	1.43	7.80
Tuinplaats	Raw	51.00	3.60	1.00	2.69	6.92
	F 1.65	58.00	3.90	0.90	2.23	7.46
	F 1.75	61.00	4.20	0.87	1.66	7.26

8.1.1.3 Petrographic analysis

Most of the petrographic analysis done, was conducted on samples obtained from the Tuinplaats Sub-Basin due to the inherent coking properties of this coal. Petrographical studies were conducted in order to evaluate the economic potential of the Upper Middle Seam in the Tuinplaats Sub-Basin as well as to understand the geological history of Lithostratigraphic Unit 3. Petrographic analysis conducted on selected 165 mm core samples is summarized in Table 8.2.

Table 8.2. Petrographic analysis.

Maceral	Percentage
Vitrinite	84.00
Exinite	1.80
Reactive Semifusinite	1.60
Inertinite	6.10
Minerals	6.50
Reactives	87.40
Rov (maximum)	0.80

8.1.1.4 Ash analysis

The average values for different compounds encountered in the ash of the coal in the Settlers-Tuinplaats Basin are depicted in Table 8.3.

Table 8.3. Ash analysis: Settlers-Tuinplaats Basin.

Mineral Matter	Percentage
SiO_2	63.20
Al_2O_3	22.00
Fe2O3	3.00
TiO_2	1.12
CaO	4.70
MgO	0.56
Na_2O	0.31
K_2O	1.22
MnO	0.07
P_2O_5	0.16
SO_3	2.83

8.1.1.5 Minerals

The high percentage of sulphur in the coal of Lithostratigraphic Unit 3 constitutes a major environmental hazard especially when coal is combusted in power stations or furnaces. The sulphur content in Lithostratigraphic Unit 3 is on average 1 % higher than the sulphur encountered in the major coal field in the Main Karoo Basin.

Pyrite is a common constituent in Lithostratigraphic Unit 3. Pyrite occurs as euhedral crystals, framboidal aggregates, as veins or on cleat surfaces. Pyrite probably represents the result of bacterial reduction of sulphate-rich peat waters during early diagenesis, but remobilization is also likely under certain conditions (Ward, 1984).

Comprehensive tests pertaining to the sulphur content of the Upper Middle Seam were conducted. The results revealed:

a) a high gaseous sulphur content.
b) a reduction in sulphur can be obtained by reducing the top size of raw coal from 25.0 mm to 12.50 mm. In doing so, a reduction of 10 % in sulphur can be obtained.

c) analysis revealed that 86 % of the sulphur comprises organic sulphur and only 14 % inorganic sulphur.
d) only 7.6 % of the pyrite present in the Upper Middle Seam can be liberated by means of physical processes. The remaining pyrite i.e. 92.4% must be considered as intergrown pyrite and will not be liberated by means of physical processes.

The carbonate minerals encountered are siderite and calcite. Siderite occurs as spheroidal nodules within the coal and was apparently formed by chemical precipitation during early diagenesis. Siderite probably represents the interaction of iron with dissolved CO_2 in peat waters where sulphate concentrations were too low for pyrite formation. Calcite represents late stage accumulation in coals occurring as veins and on cleat surfaces (Ward, 1984).

The high concentration of radioactive minerals associated with Lithostratigraphic Unit 3 will be discussed in Chapter 8.2.

8.1.2 Classification of Springbok Flats Coal

Alpern (quoted by Falcon, 1986b) devised a “Universal Classification for Solid Fossil Fuels” based on grade, type (% reactives) and rank (% RoV rand). According to Alpern the coal of the Springbok Flats can be classified as a humic (vitric), bituminous coal that can be utilised as a low swelling coking coal and/or for power generation or gasification (De Jager, 1998).

8.1.3 Coal Resources

8.1.3.1 Settlers-Tuinplaats Basin

The coal resources for the Springbok Flats Karoo Basin are based on the lithological variations encountered in Lithostratigraphic Unit 3. In order to establish a potentially exploitable mineable horizon the following exercises were conducted:

a) In the Settlers-Tuinplaats basin the Lower Middle Seam was taken as a kernel.
b) In order to extend the potentially mineable width, the in seam parting and the Upper Middle were added, providing that the parting and the Upper Middle Seam complied with the following coal quality constraints at a beneficiation relative density of 1.75 g/cc:

- Float yield % ≥ 60 %, Float ash % ≤ 25 % or
- Float yield % ≥ 50 %, Float ash % ≤ 20 % or
- Float yield % ≥ 40 %, Float ash % ≤ 15 %

By applying these constraints it was possible to demarcate areas where the Total Middle Seam was exploitable. In areas outside the Total Middle Seam resource area either the Upper Middle or Lower Seams become potentially exploitable.

By consistently applying these constraints and a minimum seam thickness of 1.20 m the Settlers-Tuinplaats Basin was subdivided into a Northern, Southern, Warmbath, Tuinplaats and Driefontein coal resource areas.

The coal resources, raw coal qualities and cumulative washed analysis at a wash medium density of 1.75 g/cc are depicted in Fig. 8.1 and Tables 8.4, 8.5 and 8.6.

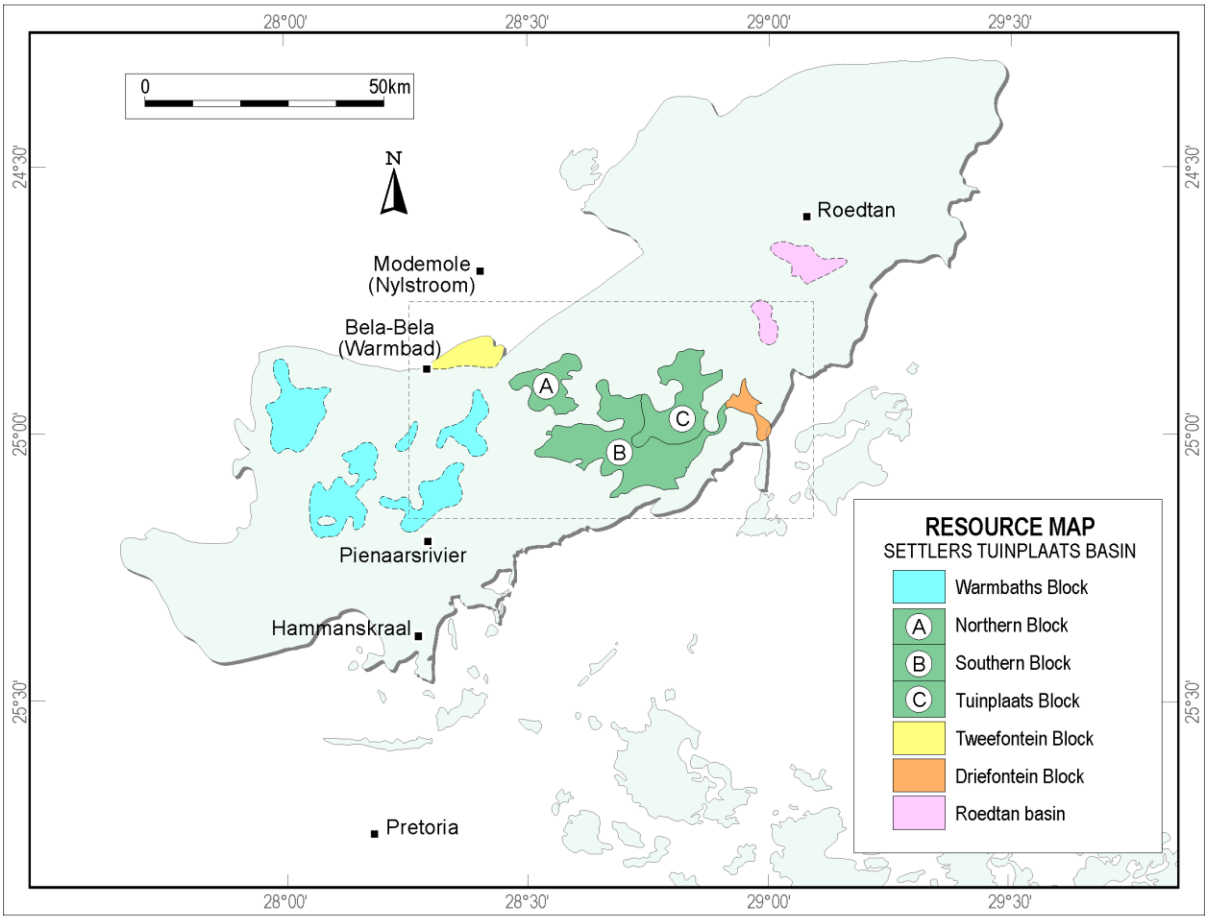


Fig. 8.1. Coal resource map: SFKB

Table 8.4. Coal resources: Settlers-Tuinplaats Basin

Coal Block	Seam Thickness	RD (g/cc)	In Situ resource (t x 10^6)
Northern	1.7 - 3.4	1.57	440.0
Southern	1.6	1.5628	910.0
Tuinplaats	1.45	1.5181	407.0
Driefontein	1.34	1.5181	82.0
Warmbad	3.26	1.5812	1335.0
Tweefontein	2.34	1.509	51.0
		Total:	3225.0

Table 8.5. Raw Coal analysis.

Coal Block	Raw Coal Analysis				
	CV (MJ/kg)	% H2O	% Ash	% Vol	% Total Sulphur
Northern	20.5	2.4	34.9	27.3	2.15
Southern	20.6	2.5	34.6	26.9	2.41
Tuinplaats	23.5	2.1	27.8	30.2	2.86
Driefontein	21.3	2.7	32.7	27.6	2.65
Warmbad	22.2	4.7	28.2	28.6	2.3
Tweefontein	21.2	—	31.3	—	—

Table 8.6. Cumulative washed coal analysis at RD 1.75.

Coal Block		Raw Coal Analysis				
	% Float Yield	CV (MJ/kg)	% H2O	% Ash	% Vol	% Total Sulphur
Northern	73.3	25.4	2.4	21.7	32.4	1.81
Southern	72.7	24.8	2.5	23.4	31.2	1.66
Tuinplaats	82.2	26	2.2	19.2	33.4	1.89
Driefontein	73.3	25.2	2.9	21.1	32.6	1.51
Warmbad	84	—	—	16.8	—	—
Tweefontein	80	—	—	22.3	—	—

8.1.3.2 Roedtan Basin (Fig. 8.1)

In the Roedtan basin, the Upper Seam is the potentially economic seam. It comprises mainly bright coal and has a larger aerial distribution than the Middle and Lower Seams.

For resource calculation purposes, a 0.80 m seam thickness cut-off was used. The coal resources for the Roedtan Coal Basin are summerised in Table 8.7.

Table 8.7. Coal Resources: Roedtan Coal Field.

Seam	Ave. Thickness (m)	Raw Coal RD (g/cc)	Resources (t x 10^6)
Upper	0.98	1.45	98.00
Middle	1.26	1.65	138.00
Lower	1.11	1.65	31.00
Total	1.12	1.563	267.00

8.1.3.3 Mineability of Coal

Most of the coal resources in the SFKB would have to be exploited by underground mining methods, although open cast mining proved to be feasible in the proximity of the southern margin of the Settlers-Tuinplaats Basin. Not sufficient exploration drilling was done in the past to demarcate the potentially exploitable opencast coal resources accurately.

The depth to the floor of the potentially economic coal seams is summarised in Table 8.8.

Table 8.8. Depth to floor of coal seams.

Resource Block	Seam	Min. Depth (m)	Max. Depth (m)
Northern	Total Middle	410	875
Southern	Lower Middle	Sub-outcrop	410
Tuinplaats	Upper Middle	45	385

8.1.4 Coal Utilization

8.1.4.1 Direct liquefaction

The high vitrinite content of coal seams in the coal zone renders these seams ideally suited for direct liquefaction. The best results obtained during bench scale tests were from a beneficiated product with an ash content of ≤ 20 %.

The variations in float yield to obtain a fixed 20 % ash product are summarised in Table 8.9.

Table 8.9. Variation in float yield to obtain a fixed 20 % ash product.

Resource Block	Min. Yield (%)	Max. Yield (%)
Northern	53.4	82.8
Southern	40.2	90.3
Tuinplaats	34.5	95.7

The purpose of direct liquefaction is to produce a hydrocarbon rich liquid, which can be refined by fractional distillation, similar to crude oil, thus yielding automotive fuel and lubricants as final products.

8.1.4.2 Coking Coal

A viable deposit of good quality coking coal has been proved in the Tuinplaats Basin in 1977.

The Upper Middle Seam proved to be the most economically viable seam. The Upper Middle Seam is on average 1.42 m thick with an average float yield of 40% at a RD of 1.40 g/cc. The float fraction has an average ash content of 11.8 % and an average swelling index of 5.5 – 6.0. The average yield of the middling fraction (RD at 1.40 – 1.70 g/cc) is 43.7 % and this product has an average ash content of 24.1 % and a C.V. of 24.8 MJ/kg.

Coking coal analyses revealed an average Roga Index of 74, an average Plastometer Fluidity of 1002 max.

The beneficiated Tuinplaats coal is a high volatile coal with good caking properties, compatible with all blend and coking coals used for the manufacturing of coke. Carbonisation yields a fingery coke with good abrasive properties. The fingery nature of the coke can be overcome by the addition of low or medium volatile coals or by the addition of small portions of coke breeze. The physical properties of known blend coking coal can be considerably improved by the addition of 20% Tuinplaats coke with a resultant increase of only 0.1% sulphur.

The coking coal resources are summarised in Table 8.10.

Table 8.10. Coking coal resources.

Resources (mt)	Average TH (m)	Average borehole yield (%)	Coking Fraction @ RD 1.4 g/cc		
			Average ash %	Average total sulphur	Average swell index
181.2	1.4	40.0	11.8	1.5	5.5 - 6

8.1.4.3 Coal Bed Methane

The Springbok Flats Coal Fields do have coal bed methane potential although the different coal blocks have not been exploited for coal bed methane per se. The suitable rank and depth (certain areas), high vitrinite content and local fracturing due to post Karoo faulting render these coal deposits as a resource for coal bed methane exploitation.

The tectonic structures encountered in the Springbok Flats Karoo Basin relate to pre-Karoo structures i.e. Thabazimbi-Murchison Lineament, that manifested itself as the Zebediele Fault (Roedtan basin) and the Droogekloof Fault Zone (Settlers-Tuinplaats Basin). Fracturing resulted from these tectonic events, depth of burial, rank and vitrinite content of the coal constitute a possible coal bed methane resource in areas in close proximity oto these features.

8.1.4.4 Torbanite

Du Toit (1939) recognised the presence of torbanite layers interbedded in the coal zone on the farm Vangheining south west of Bela Bela. Exploration drilling conducted by Amcoal confirmed the presence of these intercalated layers. No analytical data could however be obtained in order to substantiate this occurrence. Du Toit (1939) mentioned the torbanite layers to be high in ash and volatiles (53%) which correspond to the characteristics of torbanite.

Torbanite is a form of sapropelic coal, characterized by the dominance of the maceral telalginite. Torbanite is formed from algal accumulations in fresh to brackish ponds, lakes and lagoons, usually in close association with peat swamps (Cole et al., 1998). On retorting torbanite yields oil that can vary between a few liters to as much as 500 l/ton.

8.1.4.5 Power generation

The coal resources in the SFKB are ideally suited for power generation through conventional power stations. The uranium associated with the coal does not occur within the coal resource as indicated in Tables 8.4 and 8.7 for the Settlers-Tuinplaats and Roedtan basins respectively. The uranium mineralized coal occurs in close proximity to the palaeotopographical highs. In these areas, no exploitable coal seams occur. Away from the topographical highs more than one coal seam can be present. The uranium is associated with the uppermost coal layer which normally does not form part of the potentially mineable seams.

8.1.4.6 Gasification

Synthesis gas consisting primarily of hydrogen and carbon monosade can be obtained by gasifying coal with steam and oxygen. By means of the Fischer-Tropsch process, the synthesis gas can be converted into either aliphatic hydrocarbons at low pressure or to methanol at high pressure. The synthesis gas can also be allowed to react with excess steam to form more hydrogen, together with carbon dioxide. The latter is removed from the gas by dissolving it in water. Ammonia is made from the purified hydrogen and atmospheric nitrogen by means of the Haber process and is one of the reagents in the manufacturing of fertilizers and explosives (De Jager, 1998).

8.2 Uranium

8.2.1 Introduction

8.2.1.1 Common features of uraniferous coal deposits

A list of certain characteristics of uraniferous coal deposits that seems to be common to most deposits were compiled by Nekrasova (1958b). These characteristics are as follows:

a) Uranium occurs in peat deposits accumulated in continental environments, i.e. in lakes, swamps and ox-bow lakes.
b) Under favourable conditions, uranium occurs associated with severe erosion of the uranium source rock in environments conducive for the dissolution of uranium by groundwater.
c) Uranium in coal deposits is found near granites, metamorphic rocks or overlain by beds of volcanic origin or sedimentary rocks containing abundant pyroclastic material.
d) Most of the uranium in coal is restricted to lower rank coals i.e. lignite and sub-bituminous varieties.
e) Tectonic zones of weakness in sedimentary rocks constitute favourable environments for deposition of uranium.
f) Coarse-grained sediments at either the top or bottom of a coal seam acted as an aquifer by providing passageways for uranium solutions.
g) Fine-grained and/or argillaceous sediments on either side of a coal seam are unfavourable host rocks due to the impermeable nature of these rock types. Tectonic activities might, however, create secondary porosities that will act as passageways for mineral-rich solutions.
h) Uranium mineralisation in coal is not uniformly distributed, but does occur in patches as mineralised areas are separated by barren zones.

8.2.1.2 Uranium in coal

Uranium in coal cannot be attributed to the inherent initial concentration of uranium in plants (Berger, 1974). Three hypotheses for the origin of uranium in coal were proposed by Densen (1956):

a) Uranium was deposited with other detrital minerals in sediments from which uranium was subsequently leached and finally precipitated from solution.
b) Uranium was deposited contemporaneously from surface water by the action of living organisms or other organic matter at the same time as the carbonaceous debris from which the lignite formed, was deposited.
c) Uranium is epigenetic, having been extracted from groundwater by lignite after coalification. It has been postulated that the uranium was derived from sources outside the peat depository.

Microscopic investigations, using α-track methods, conducted by Breger (1974) revealed that uranium solutions penetrated the coal along microscopic fractures and shrinkage. The epigenetic origin of uranium in coal seems to be the most widely accepted mechanism by researchers (Nekrasova, 1958a; Denson and Gill, 1956; Breger and Duel, 1956; King, 1956; Masursky, 1958; Rozhkova *et al.,* 1958 and Breger, 1974: In Hambleton-Jones, 1976) to explain the presence of uranium in coal.

During the epigenetic introduction of uranium solutions into the coal beds, uranium will be adsorbed, providing that the pH is slightly acid. The degree of sorption will be dependent upon the degree of metamorphism (increase in coal rank) or the organic substance. Szalay (1958) described the natural laws which govern the fixing of uranium to organic rich sediments by concluding that the enrichment of uranium in sediments containing fossil plant debris is caused by the humic acid content, which fixed uranium from very dilute solutions in natural waters. This fixation is a reversible cation-exchange process with a geochemical enrichment factor of about 10 000:1. The indigenous humic matter (oxygen-rich plant remains) and redeposited humic extracts (humic acids and humates derived from indigenous organic matter) played independently a major role in the precipitation of uranium. Uranyl humates occur in lignites and are formed by the reaction of humic matter with uranium (Vine, 1958) under Eh and pH conditions that prevailed in the coal swamp at the time.

8.2.1.3 Precipitation of uranium in coal

Three mechanisms that play a role during the precipitation of uranium were defined by Levinson (1974):

a) Reduction.
   The reduction of U^{+6} to U^{+4} resulted in the formation of uraninite or other uranium rich phases. Proposed reduction agents are methane, H_2S, H and other hydrocarbons. The oxidation of ferro- to ferri-iron can contribute to the reduction of uranium in many deposits.
b) Adsorption.
   Adsorption mainly occurs on organic material. The geochemical enrichment factor as calculated by Szalay (1964), equals ± 10 000/1 for $UO^{2+}{}_2$. Adsorption can also take place on clays and iron-oxides.
c) Formation of unsoluble compounds.
   Soluble uranium compounds can precipitate when uranium compounds react with anions such as carbonates, phosphates, silicates, sulphates, organic acids and hydrocarbons. Humic acid polymerizes as large molecules during humification. Due to their size they become unsoluble and carbon exchange takes place between the very soluble $UO^{2+}{}_2$-ion and the unsoluble humic acid resulting in the formation of insoluble uranium compounds. A simplified schematic presentation depicting the movement of uranium in the secondary environment and the enrichment of uranium in organic material (modified after Szalay, 1964) is presented in Fig. 8.2.

<u>Phase I:</u> During phase 1, uranium is leached from the chemically weathered source rock material. The U^{+4} content is ± 4g/t (Clarke-value). Uranium is leached as $(UO_2)^{2+}$ by bicarbonate rich water.

<u>Phase II</u>: Natural water which contains ± 100mg $(UO_2)^{+2}$/t transports the uranium to peat or humic-acid containing sediments.

Phase III: The $(UO_2)^{2+}$-ion combines with humic-acids in the water with an enrichment factor of 10 000/1. The enrichment of $(UO_2)^{2+}$ is 100 – 1000g/t in organic material.

Phase IV: Uranium-rich and humic-rich sediments become buried and the processes of coalification starts. Local migration and enrichment of uranium takes place accompanied by the secondary mineralisation of uranium.

The mechanism whereby uranium becomes concentrated by natural organic matter is described by Breger and Deul (1956). The mechanisms entail the following:

a) Organic matter and anaerobic bacteria reduce uranium to unsoluble uraninite (UO_2).
b) Organic matter adsorbs uranium onto their surfaces.
c) UO_2^{2+}-ions after being in contact with coal, form organo-uranium complexes i.e. uranylhumates. These complexes are unsoluble at pH values higher than 2.18.

8.2.2 Uranium in the Springbok Flats Karoo Basin

The presence of uranium in coal deposits in the RSA was unknown until 1976. It has been stated that the known coal measures in the RSA are unsuitable for uranium deposits (Hamblton-Jones, 1976), but the alternative could also apply namely that the sites that were investigated were potentially unfavourable for uranium deposition. The latter statement proved to be the correct alternative as uranium in coal was discovered in late 1976 on the farm Zamenkomst 635KR in the Settlers-Tuinplaats Basin.

The exploration programme of Ingwe Coal was aimed at outlining potentially economic coal deposits. The discovery of uranium resulted in reject samples from FRI (Fuel Research Institute) being collected and submitted to West Rand Consolidated Laboratories (WRCL) for XRF examinations to determine the uranium grades associated with coal.

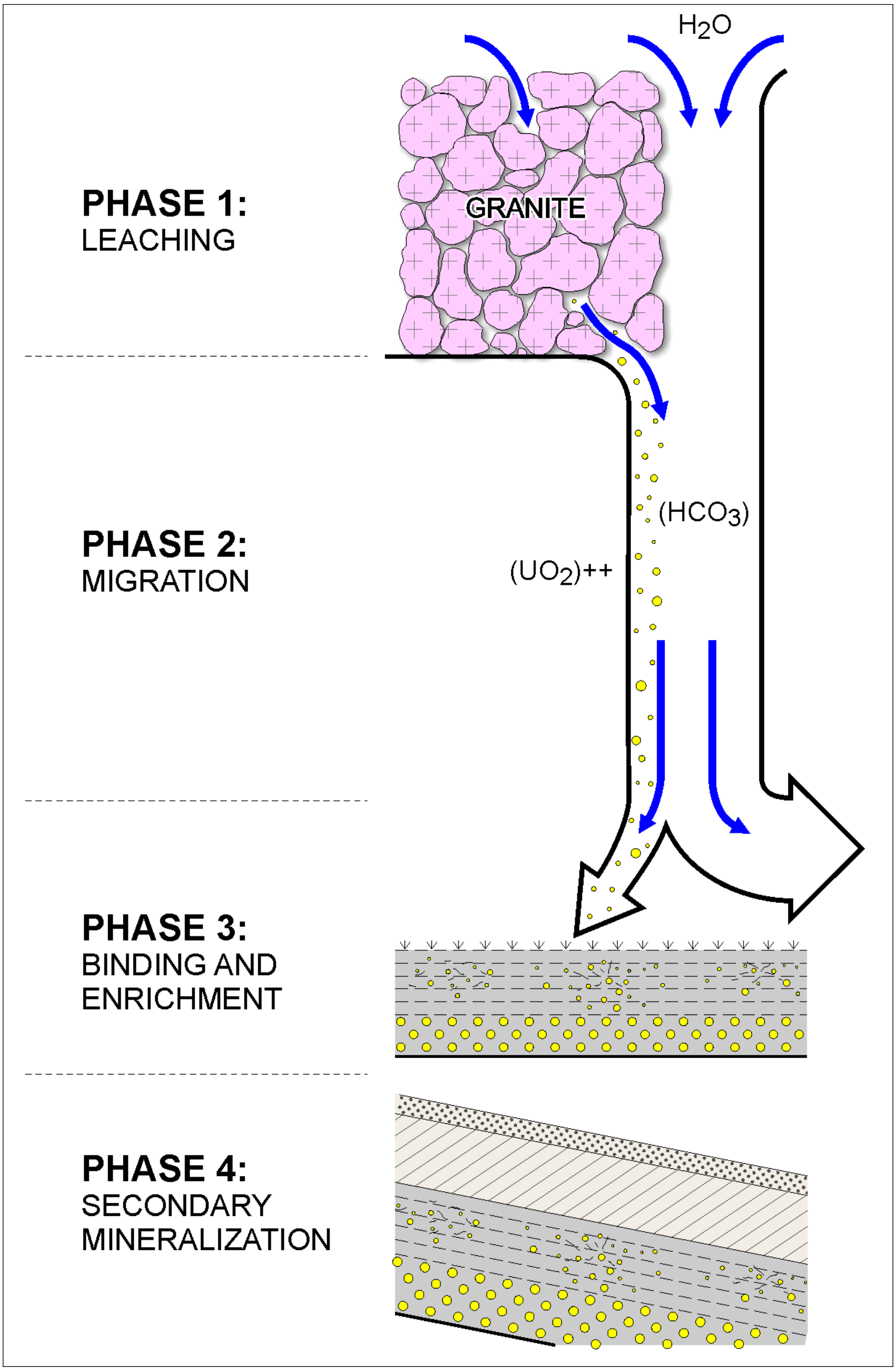


Fig. 8.2. Schematic representation depicting the movement of uranium in the secondary environment and the enrichment in organic material.

To obtain more data regarding the nature of mineralisation, the drilling grid in defined target areas was reduced to 500 x 500 m. The complex nature of uranium mineralisation resulted in a further reduced drilling grid of 200 x 200 m.

This exercise revealed very little additional information concerning the nature of uranium mineralisation. It was subsequently decided, based on previous experiences, to drill newly discovered uranium mineralised areas on a 500 x 1000 m grid.

To outline potentially economic uranium mineralised areas, a 0.2 kg/t grade cut-off over a mineable thickness of 1.0 m was introduced. After the discovery of uranium in the Settlers-Tuinplaats Basin regional exploration concluded in the Settlers-Tuinplaats and Roedtan Basins revealed the presence of uranium associated with the coal in Lithostratigraphic Unit 3. Borehole results from the Settlers-Tuinplaats Basin indicated a potential uranium field, much larger and more continuously mineralised than the Roedtan uranium field.

8.2.3 Exploration Model

The relationship between uranium mineralisation and coal zone lithology are illustrated in Figs. 8.3., 8.4. and 8.5. The following similarities between the three borehole intersections are noticeable:

a) Uranium mineralisation occurs in the uppermost coal layer, irrespective of the lithological thickness of such a layer (Fig. 8.3., 8.4., and 8.5.).
b) More than one coal layer can be mineralised (Fig. 8.3.).
c) The lithology of the immediate roof of the mineralised horizon varies from mudstone assigned to Lithostratigraphic Unit 4 and coarse grained sandstone and conglomerate of Lithostratigraphic Unit 5 (Lithofacies Gm).
d) The X-ray-fluorescence (XRF) spectrometry-grades in kg/t compared to the radiometric grade kg/t varies considerably.
e) Uranium mineralisation in mudstone of Lithostratigraphic Unit 5 (Fig. 8.5.).

Exploration results revealed that the degree of mineralisation is dependant on three major controlling factors:

a) Distance from palaeo-topographic highs;
b) Thickness of Lithostratigraphic Unit 4;
c) Thickness of the Lithofacies Gm (Lithostratigraphic Unit 5).

In close proximity of the palaeo-topographical highs, the coal seams of Lithostratigraphic Unit 3 as well as Lithostratigraphic Unit 4 peter out resulting that Lithostratigraphic Unit 5 is in direct contact with Lithostratigraphic Unit 3. The maximum development of the Gm-lithofacies of Lithostratigraphic Unit 5 coincides with the areas characterized by the subordinate development of Lithostratigraphic Unit 3 and 4 respectively.

A conceptual exploration model based on the preceding variables was created and used for target generation purposes, with great success. Later mineralogical investigation revealed however, that the conceptual exploration model was a handy exploration tool but did not comply with the actual mineralisation processes involved during the precipitation of uranium in the coal of LIthostratigraphic Unit 3.

8.2.4 Mineralogy of the uranium-bearing coal

The first comprehensive mineralogical study on uranium bearing sediments and coal were conducted by G. Smit (Natural Institute of Metallurgy) in 1978. Three sets of samples were submitted. The first set of samples comprised borehole cores of fine-grained sandstone of Lithostratigraphic Unit 2. The second set of samples consisted of carbonaceous shale with bright coal laminae. A third set of samples comprising one sink and two float fractions, bright coal samples and 12 polished sections, obtained from Prof. C.P. Snyman of the University of Pretoria were also submitted.

8.2.4.1 Sample preparation

a) From all the samples in the three sets, thin sections, polished sections, and polished rock slabs were prepared in a vertical as well as in a horizontal direction, and autoradiographs were made of these sections and slabs. This material was used for detailed optical examination.

b) The uranium content of all the samples was determined by X-ray-fluorescence (XRF) spectrometry.

c) Specimens of the carbonaceous shale from the second set and the hand-specimens of bright coal from the third set of samples, were burnt to ash at a temperature of 500˚C.

d) Soluble salts were extracted from a mixture of the float and sink fractions from the third set, and were then identified.

e) Heavy-liquid separation was done in a mixture of methylene iodide and acetone of a relative density of 2.58 g/cc on various sieve fractions of the bright-coal hand-specimen and the 1.7 g/cc sink fraction from the third set.

f) X-ray-diffraction (XRD) traces were run on the samples of borehole core, the ash products, and the soluble salt extractions. XRD photographs were made by the Debye-Scherrer method for the identification of individual grains.

g) Electron-microprobe analyses were done on the haloes observed in the coal macerals and on radioactive spots in the shaly laminae of the coal, which were located by autoradiography.

h) Contact prints were made of the autoradiographs so that these could be compared with photographs of the same size. Photomicrographs were taken of important features in the coal that had been observed in the polished and thin sections.

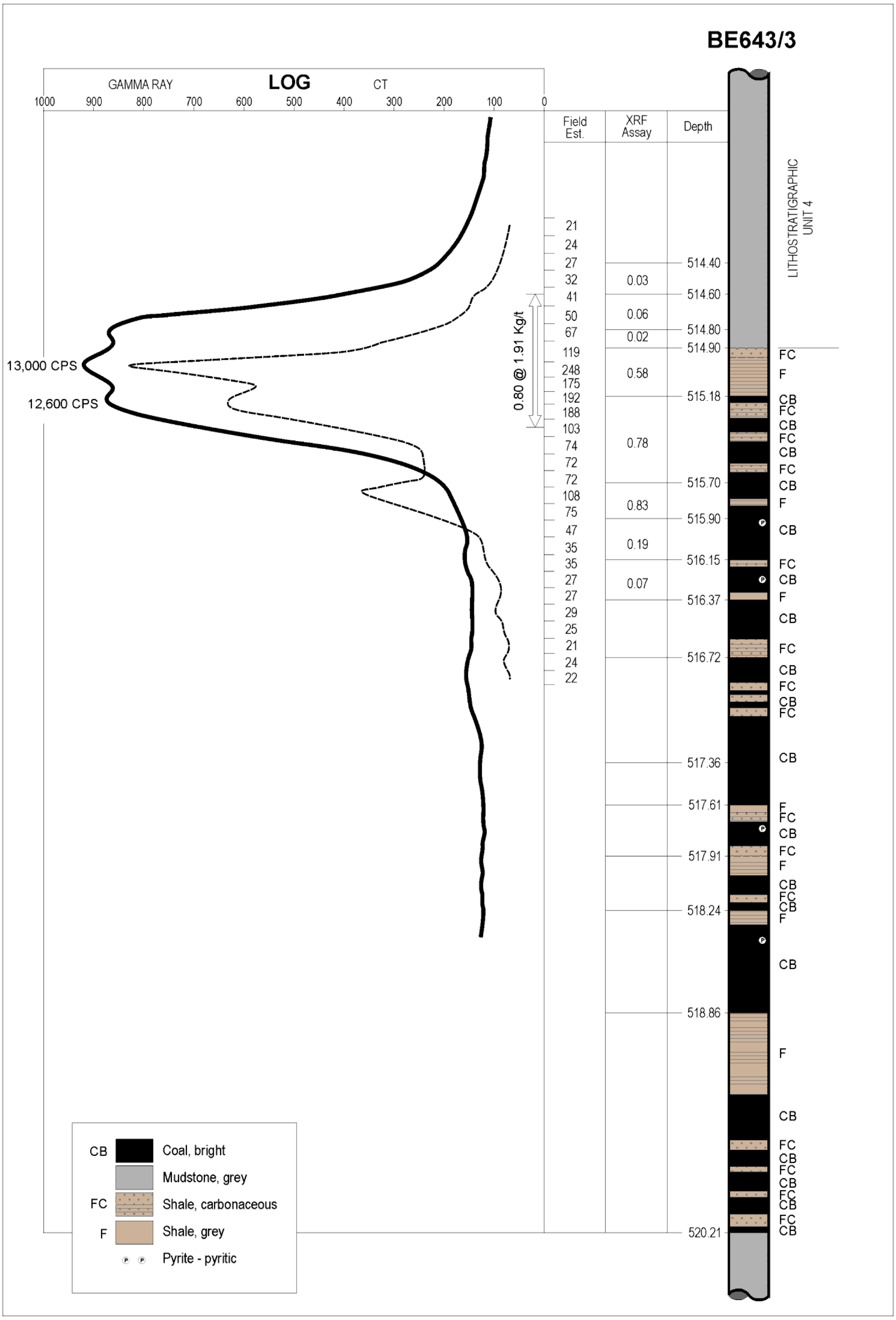


Fig. 8.3. Uranium mineralization and coal lithology: Borehole BE643/3.

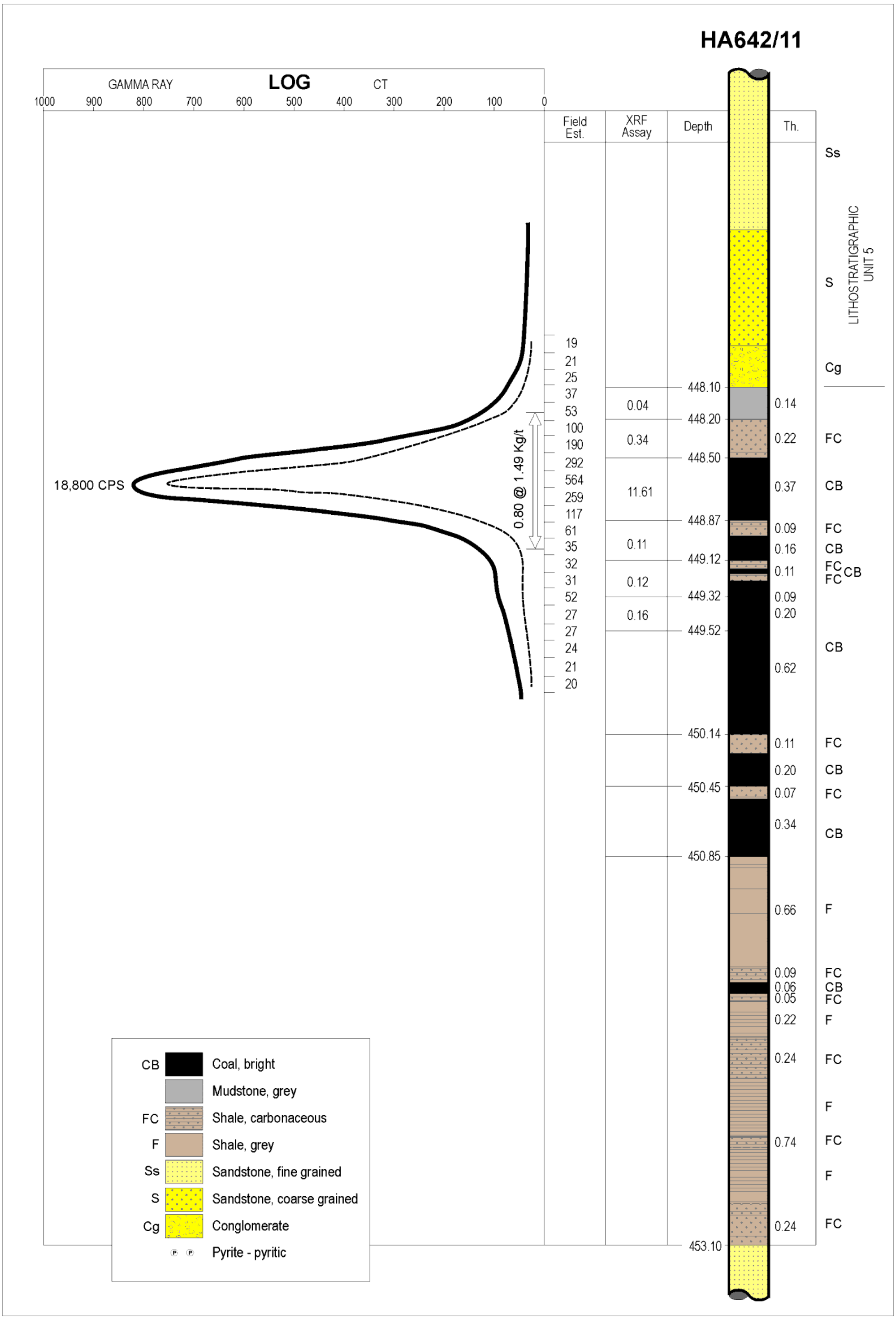


Fig. 8.4. Uranium mineralization and coal lithology: Borehole HA642/11.

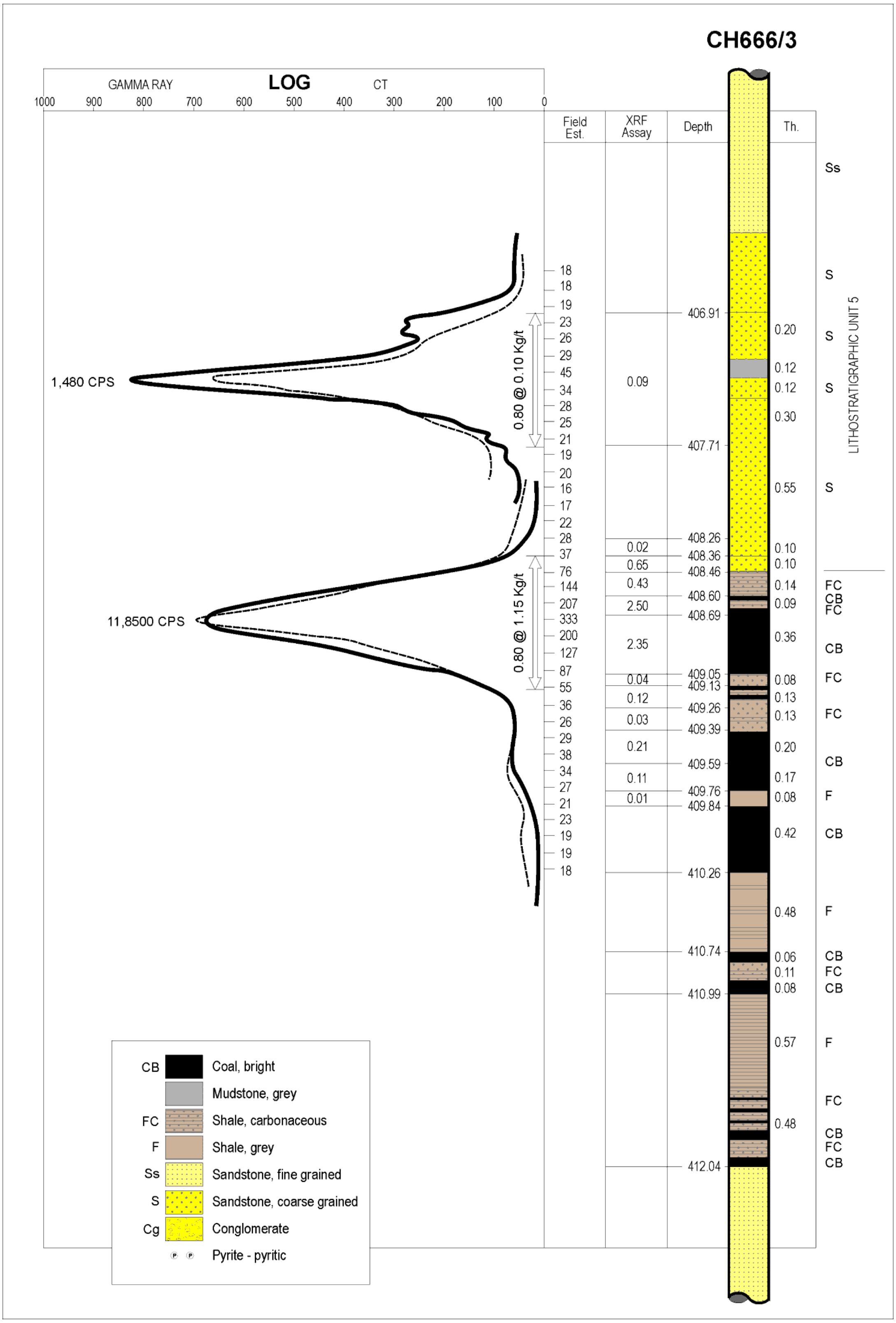


Fig. 8.5. Uranium mineralization and coal lithology: Borehole CH666/3.

8.2.4.2 Description of samples

- **Samples of sandstone from borehole cores**

The first set of samples, consist mainly of pale-grey fine-grained sandstone with grain size ranging between 0.12 and 0.18 mm. The grains are subangular to subrounded, and the sediment shows moderate sorting.

The main constituents of the sediment are quartz, feldspar, mica, rock fragments, grains of iron sulphides, graphite, heavy minerals. Chlorite and calcite occur in subordinate quantities. In some of the samples, calcite is also present interstitially as a chemical cement. The sandstone splits easily along the bedding planes, which display an abundance of mica.

Marcasite concretions of a diameter between 0.25 and 2.0 mm occur either widely dispersed as isolated particles, or in small clusters. In the latter mode of occurrence the sulphide bodies are embedded in sediment enriched in flaky graphite, mica and carbonaceous matter. The isolated concretions are not associated with organic matter, but are characterized by a sieve texture in which the resistant detritus is occluded by the sulphide. The concretions occurring in the clusters however are massive and exhibit a more of less radiating crystal texture. Their size exceeds that of the detrital grains and the lamellae rich in mica, graphite and carbonaceous matter flow around the concretions, showing that the massive marcasite bodies were formed *in situ* and before compaction was completed.

Discrete round coal particles of a very brittle nature are the only grains that show strong radioactivity. They are about twice the average grain size encountered and are rare.

Primary sedimentary structures in the form of ripples and laminations are accentuated by biotite concentrations along laminations. The planes separating the sandstone and the biotite-rich laminae exhibit a concentration of heavy minerals such as anatase, garnet, zircon, leucoxene, ilmenite, rutile, barite and tourmaline.

➢ Samples of coal from Krugersdorp (West Rand Cons Laboratory)

The samples that were selected at the laboratories in Krugersdorp contain massive or stratified shaly coal, with occasionally intercalated laminations of bright coal. These bright coal laminations are free from quartz grains, but may contain minute specks of an unidentified mineral that acts as a point source of radiation. Haloes of high reflection, which surround the radioactive material, are a common feature in the macerals vitrinite, semifusinite and fusinite (Plate II, Fig. 1 to 4).

One polished section shows folds and faults on a millimetre scale that seem to have influenced the concentration of the radioactive substance, which is fairly common in this section (Plate II, Fig. 1, 2, 3 and Plate 3). Displacement of the vitrite and carbonaceous shale microlithotypes along small faults suggests that the disturbance took place at an advanced stage of coalification, when the organic matter was already solid. The vitrite also displays a microscopic cleat system in a direction vertical to the bedding. The size of the cleats in cross-section is 5 µm by 30 to 50 µm (Plate II, Fig. 5). Local accumulations along the bedding of spheroidal sclerotinite bodies with an average diameter of 0.3 mm are a characteristic feature in the coal (Plate II, Fig. 6). The rank of these bodies varies considerably and despite the fractures that are present it is only rarely observed to contain radioactive material. The thin sections contain flat lenticular bodies of yellow or orange resinite. Textures of collapsed cell walls are common features in the coal (Plate II, Fig. 4).

Syngenetic marcasite concretions occur and may attain dimensions up to 3 mm. The iron sulphide forms at low temperatures in an acid environment and is often precipitated in peat bogs. It may also be inverted from pyrite when the chemical conditions become acid. In one polished section the sulphide is observed to have replaced cell tissue of plant remains. Since the coal macerals flow around the sulphide bodies, they must have formed early in the coalification process, before compaction was completed. Occasionally, small grains of iron sulphide (about 5 mm) are dispersed throughout the vitrinite. No specific relation exists between the pyrite and the radioactive material and these two minerals seldom occur together.

Iron-rich reddish-brown sphalerite is occasionally encountered in the carbonaceous shales. Quartz in the size range 5 to 60 µm, and clay from 60 to 150 µm, probably of colloidal origin, are the main components encountered in the carbonaceous shales.

Thin cracks of less than 1 mm wide, which are filled with calcite of epigenetic origin, traverse the coal mostly in an almost vertical direction. Siderite was not encountered.

- **Samples of coal from the third set**

The coal samples from the third set represent one sink and two float fractions, which are composed of coal chunks varying between 5.0 and 19.0 mm, hand-specimens of bright coal and 12 polished sections prepared from the float and sink fractions. The fractions were obtained by mechanical treatment according to two schemes of crushing, washing and heavy-liquid separation using liquids with relative densities of 1.4 and 1.7 g/cc respectively. The 1.4 g/cc float fraction contains particles of vitrain the 1.7 g/cc sink fraction contains particles of dull shaly coal and the 1.7 g/cc float fraction is a mixture of both constituents.

The hand-specimens of bright coal consist mainly of vitrain, which is interbedded with concretionary iron sulphide or distributed as fine-grained aggregates of anhedral crystals that are aligned parallel to the bedding (Plate II, Fig. 5), or fills small cracks. The latter are often found in combination with calcite-filled fissures, and both are approximately 1 mm or smaller. However, the calcite was introduced at a later date and the pyrite in the cracks probably precipitated from migrating solutions and therefore would be younger than the dispersed and concretionary iron sulphide. Some of this type of pyrite occurs locally in the euhedral form (Plate II, Fig. 8). Marcasite in the second set of samples, as well as the pyrite is not related to the uranium mineralisation.

Some of the fine cracks intersecting the coal are filled with an admixture of quartz, chamosite and calcite. Haloes are absent along the fractures and therefore not connected with the introduction of radioactive material.

Sclerotinite bodies occur abundantly in the carbonaceous shale, but in a more dispersed manner than those encountered in the second set of samples. Here, radioactive matter is only rarely occluded in the fractures within the bodies.

Apart from those around point sources of radiation and minute cracks in the vitrite, radioactive haloes are found only in the semifusinite and fusinite, where they surround cell cavities (Plate II, Fig. 4; Plate 4, Fig. 1).

8.2.4.3 Heavy-liquid separation

Various sieve fractions of the bright-coal hand-specimens and the 1.7 g/cc sink fraction were subjected to heavy-liquid separation in a mixture of methylene iodide and acetone with a relative density of 2.58 g/cc. To facilitate the identification of the components, the sink fractions were subjected to magnetic separation in a Frantz Isodynamic separator at the field strength that is obtained when the electric current is raised to 1,0 A. Table 8.11. lists the minerals encountered in these fractions.

Table 8.11. Detrital minerals in the coal and carbonaceous shale (in approximate order of abundance)

	Bright coal	1.7 g/cc sink fraction
Major components	Calcite Sulphide Magnetite Epidote Quartz	Calcite Sulphide Mica Quartz
Minor components	Feldspar Mica Pyroxene Garnet Rutile Laucoxene Zircon	Sphalerite (some with traces of galena) Feldspar Rutile Pyroxene Magnetite

8.2.4.4 Chemical Analysis

The results of the analyses for uranium by XRF spectrometry on the samples of the three sets are summarized in Table 8.12.

Table 8.12. Analyses for uranium.

Sample	U_3O_8 ppm
Set 1	
Coaly shale	76
Sandstone of pale-grey	126
Sandstone of light-brown	242
Set 2*	
Shaly coal	130
Set 3	
1.4 float fraction (vitrain)	648
1.7 float fraction (vitrain + carbonaceous shale)*	435
1.7 sink fraction (carbonaceous shale)	620
Bright coal (hand-specimen)	547

* The samples were ashed before being analysed by XRF spectrometry.

The analyses on the float and sink fractions of the third set of samples suggest that there is no specific relation between the lithotype of the coal and the uranium content.

8.2.4.5 Electron-Microprobe analyses

Attempts to identify the dark-grey carbonaceous material, which fills open spaces and acts as sources of radiation by XRD were unsuccessful even after the material had been heated to 1000˚C. Electron-microprobe analyses were therefore conducted on the sources of radiation in the hope that this would yield information about their chemical composition. Electron-backscatter and XRD images were made.

The investigation established that uranium is invariably accompanied by yttrium (uraninite is known to incorporate the element in its lattice). The surrouding fine-grained matrix mainly consists of silicon, which may be accompanied by potassium and aluminium, or iron and aluminium (Plate III). This could point to the presence of silica, illite or chlorite. When silicon is detected as occurring on its own, it could represent a cherty product. In one of the thin sections from the second set of samples, the fine cracks are filled with non-radioactive chalcedonic and chloritic material (Plate IX, Fig. 3, 4 and 5). The cryptocrystalline silica could have precipitated from a silica-saturated solution, in which the uranium phase may be loosely retained locally. The following elements were recorded as occurring in trace amounts: titanium, vanadium, calcium and chlorine.

X-ray images of the yttrium-accompanied uranium in the carbonaceous shale demonstrate that the uranium occurs in a way similar to that in the coal i.e. in the form of small specks of between 10 and 60 μm in diameter within the clay matrix (Plate IX). In addition to silicon, aluminium and potassium, the elements sulphur, zinc, calcium, iron and titanium were recorded in the surrounding rock, together with traces of sodium, chlorine and molybdenum. The X-ray-distribution images of sulphur, chlorine and sodium show that these elements are distributed in a homogeneously dispersed manner. Carbonaceous matter is self-evidently an essential component. On two occasions uranium seemed to be associated with minute grains of titanite (20 μm).

8.2.4.6 Autoradiography Analysis

Autoradiographs were prepared from the polished slabs, thin sections and polished sections from all three sets.

➢ Borehole cores of sandstone

Autoradiographs of the sandstone display a faint radioactive intensity of an extremely dispersed nature. A reaction that was only slightly stronger was observed round the concretionary sulphides, which are embedded in coaly shale and which occur rather widely spaced within the sediment. The separation planes outlining the primary sedimentary structures are also faintly marked on the autoradiographs and so is the calcite cement in some of the sandstones, which in that case seem to display a brownish tint. The only particles showing a strong radioactive reaction are the rare brittle and lustrous coal grains of high rank, which are round and amorphous. No discrete uranium-bearing minerals were observed.

➢ Samples of coal

The autoradiographs show the following modes of occurrence for radioactivity in the coal samples from the second and third sets (Plate I):

a) a diffuse homogeneous distribution of weak radioactivity, restricted to the vitrain lithotype (Plate I, Fig. 1, 2 and 3), semifusinite and fusinite macerals and in some of the carbonaceous shales (Plate II, Fig. 2) and;
b) an irregular distribution but stronger radioactivity, which is encountered in the carbonaceous shales and in fractures (Plate I, Fig. 4).

Examination of the polished sections under the microscope revealed that locally the coal macerals contain haloes of a high reflectance. These haloes indicate radiochemical decomposition of the coal, resulting from uranium decay, which in turn has raised the rank of the surrounding coal. Haloe sizes vary between 20 and 200 µm, depending on the amount of uranium-bearing material that is present, and occur in all the coal macerals but are very rare in the sclerotinite bodies. In the structureless vitrain, they may occur in the following manner:

a) around particles of a size below the resolving power of the microscope (Plate II, Fig. 1 and 2; Plate X, Fig. 6);

b) around material that has filled minute cracks traversing the vitrinite (Plate II, Fig. 3; Plate III); or
c) around cell cavities of plant tissue that was coalified to semifusinite and fusinite (Plate II, Fig. 4; Plate IX, Fig. 1).

The distance between the haloes varies considerably. In some parts the distance is as little as 0.05 mm (Plate IX, Fig. 6), but elsewhere, haloes are less abundant, few millimeters apart, or totally absent.

The same pattern of uranium mineralisation occurs in the carbonaceous shale (Plate I, Fig. 4), where the sources of radiation have dimensions between 10 and 60 μm (Plate X). These spots are distributed irregularly throughout the detrital matrix, but have uranium concentrations that are higher than those of the sources of radiation in the vitrinite. Although silicon occasionally accompanies uranium and yttrium, the relative amount of this silicon in relation to the uranium as recorded by the electron microprobe does not seem to justify an assumption that a uranium silicate is present. It is more likely that uranium oxides or hydroxides are disseminated in particles of submicroscopic size in the groundmass of the carbonaceous shale.

Autoradiography shows that the radioactivity in the vitrain is sometimes restricted to the upper or lower part of the seam, but the part concerned cannot be established from the hand-specimen (Plate I, Fig. 1) since the top of the hand-specimen was not indicated.

A thin section of a sample from the second set displays fine cracks that traverse the carbonaceous shale and vitrite. The crack-filling material has entered the coal along the bedding plane and has widened the fracture laterally, producing a ragged contact (Plate IX, Fig. 3, 4 and 5). These cracks contain a mixture of two minerals that exhibit the optic properties of chalcedony and chlorite. This seems to confirm the information obtained on polished sections with the aid of the electron microprobe.

8.2.4.7 Discussion

The radioactivity in the sandstone samples from the first set indicates that uranium is present in very low-grade and non-economic concentrations.

Although the chemical analyses of a mixture of the samples from Krugersdorp also show a uranium content that is below the average of the ore, autoradiography disclosed that, apart from the lean but homogeneously distributed uranium in the vitrain, higher concentrations of the element may occur in carbonaceous shale. In general the radioactive areas in the shaly coal occur parallel to the bedding but, as shown in Fig. 4 of Plate 1, a crack filled by radioactive material crosses the vitrain. Such a crack could have formed only at a later stage when the vitrinite was at least partially solidified. This also applies to the cracks on a millimeter scale that were observed in the polished sections and the exhibited haloes (Plate 2, Fig. 3; Plate 3). On the other hand, the vitrinite is too impervious a maceral for radioactive material to have been introduced after its formation. Therefore, it seems likely that the uranium occurring in this form was concentrated in open spaces in the early stages during the process of coalification. The haloes observed round some of the cleats are considered to have formed during the shrinkage of the coal, when some of the radioactive material could have migrated over a very short distance.

Plate I

Photographs and the corresponding positive contact prints of autoradiographs of polished slabs of hand-specimens from the second and third sets of samples. The photographs of the coal samples were lightened to improve the detail in the coal specimens.

Fig. 1. Vitrain is the main lithotype in this hand-specimen of bright coal from the third set of samples. It is interbedded with some carbonaceous shale, which is faintly accentuated on the left photograph by minute white spots. On the autoradiograph, the carbonaceous shale in general does not show any radioactivity. In the vitrain seam at the bottom of the slabs, there is a radioactive reaction in the lower part, whereas it is absent in the upper part (radioactive areas appear lighter on the autoradiographs).

Fig. 2. This slab from the second set of samples is richer in carbonaceous shale(darker bands), which is non-radioactive, whereas the vitrain produces a general diffuse reaction. The darkest tabular patches in the top part of the autoradiograph correspond to thin light-grey areas occurring in the left-hand photograph. These in general represent pyrite- or carbonate-rich areas.

Fig. 3. As in Fig. 1 and 2, carbonaceous shale and vitrain regularly alternate in this specimen from the second set of samples, again exhibiting a distribution of radioactivity mainly in the vitrain. The darkest patches on the autoradiograph correspond to areas in which carbonates are more abundant.

Fig. 4. This polished slab exhibits not only a weak homogeneously distributed radioactivity in the vitrain, but also a much stronger patch-wise radioactivity in the carbonaceous shale, which shows an orientation parallel to the bedding. A fracture traversing the top vitrain seam continues into the carbonaceous shale before it disappears. Only the part intersecting the vitrain contains radioactive material. When the two photographs are compared closely, it appears that some of the vitrain (e.g. at the left-hand side centre) and some of the carbonaceous shale (lower part of the print) are non-radioactive. The radioactive matter consists of a black very fine-grained substance.

Plate II

Photomicrographs of polished sections of hand-specimens from the second and third sets of samples, taken with incident light in oil.

Fig. 1. Vitrinite (grey) in a polished section from the second set of samples exhibits contamination with very fine-grained material (black), part of which produced haloes of higher reflectance than the coal maceral. Specks of iron sulphide (white) are dispersed throughout the vitrinite, and are in general not related to the haloes produced by alpha radiation.

Fig. 2. Alternating vitrain and carbonaceous shale display spherical haloes of high reflectance round point sources of radiation, which are occluded in inertinite, fusinite,

or vitrinite in a polished section of a sample from the second set. The larger round particles (black) are quartz, feldspar, or clay, the shreds being inertinite (white).

Fig. 3. In a polished section of a sample from the second set, a bright halo formed round fine-grained material of a dark-grey color that has filled microscopic-sized fractures crossing the vitrinite. The crack widens laterally in the direction of the original bedding. The crack-filling material (black) in the righ-hand corner of the photograph above and below the halo has, when observed under the stereoscopic microscope, the same appearance as the radioactive substance. Electron-microprobe analysis indicated uranium, accompanied by yttrium and traces of silicon, iron, and possibly aluminum, in the radioactive part, whereas, in the non-radioactive parts of the crack-filling substance, silicon, aluminum, potassium, and iron are the major elements. The straight crack (black) bordering the left side of the halo and that at the bottom part (black) are filled with calcite.

Fig. 4. Haloes formed round point sources of radiation in fusinite (white), displaying a collapsed cell texture in a sample from the second set. The radioactive substance probably accumulated in cell cavities.

Fig. 5. In a sample of bright coal from the third set, aggregates of anhedral pyrite crystals (white) of diagenetic origin crystallized along the original bedding of the coaly material. Microscopic cleats formed at a later stage in a direction vertical to the bedding.

Fig. 6. Accumulations of sclerotinite bodies are a common feature in the carbonaceous shale of the second set of samples. The average size of these bodies is 0.3 mm. They are embedded in a coaly matrix, which is contaminated by shale, and are of different ranks (different shades of grey). Fractures traverse the bodies, rarely exhibit haloes of high reflection. Some of them show a margin of lower rank at the surface and along the cracks, a feature that is considered to be an oxidation phenomenon.

Fig. 7. The photomicrographs of a polished section from the second set of samples show part of a marcasite concretion (pale grey) that grew in situ during the early

stages in diagenesis, and that in this case, replaced cell walls of plant tissue. The cell cavities are filled with a coal maceral, possibly collinite (black).

Fig. 8. Pyrite (white) occasionally occurs in the form of euhedral crystals. In a polished section from the third set of samples it occurs in a fracture together with calcite, which is of epigenetic origin and was introduced at a later date. The aggregates of anhedral pyrite in the lower right-hand corner of the photograph are orientated parallel to the original bedding of the vitrain.

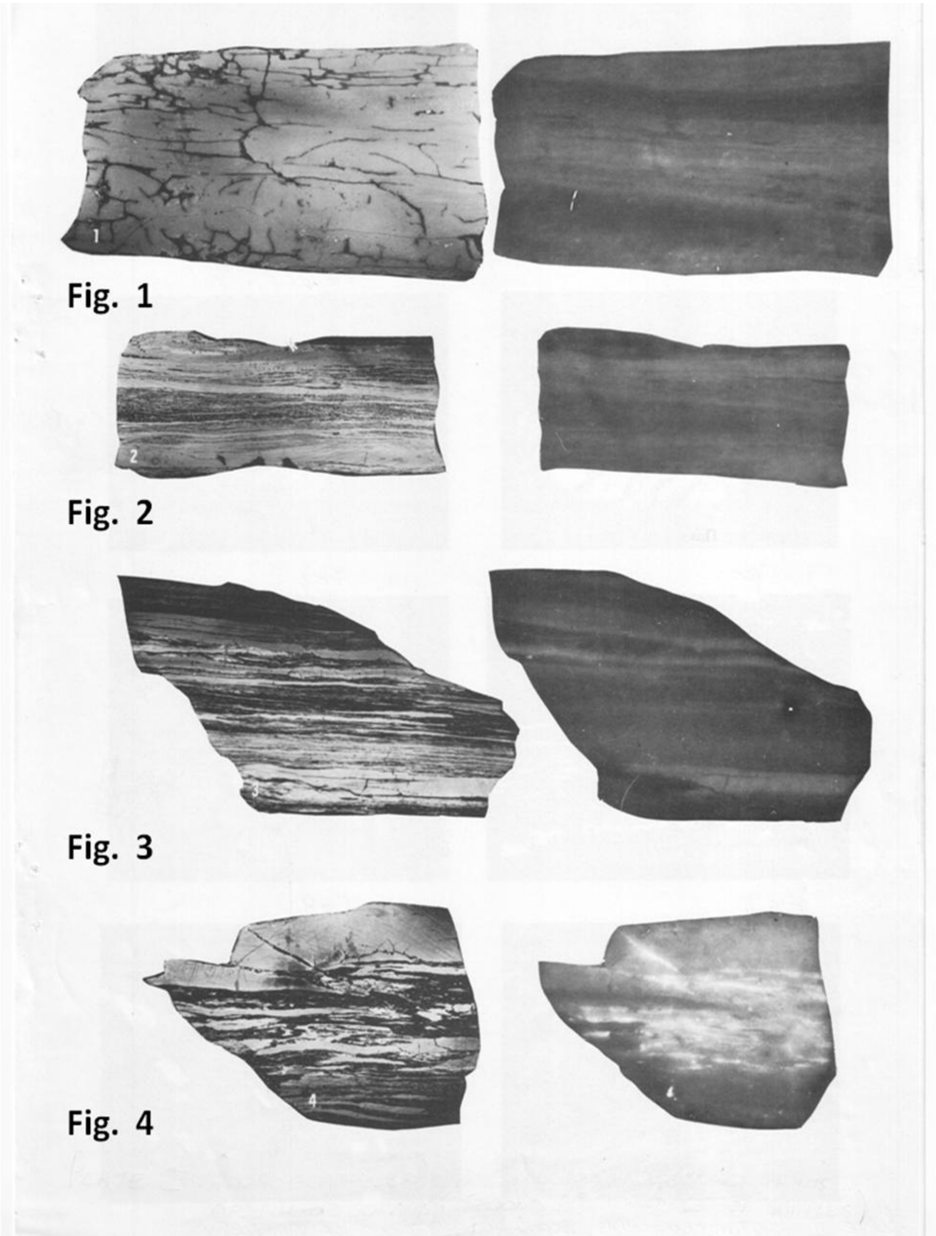


Plate I. Photographs (left) and corresponding contact prints of autoradiographs (second and third set of samples).

Fig. 1

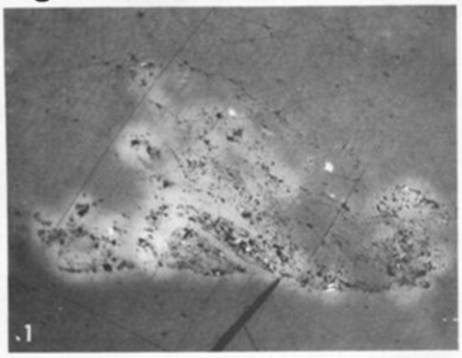


Fig. 2

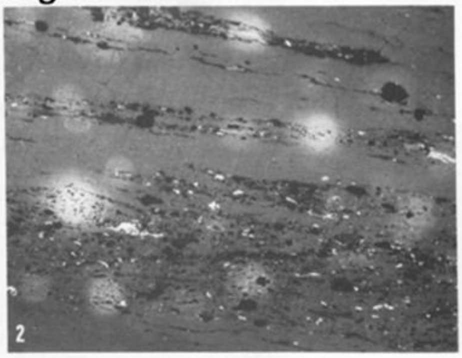


Fig. 3

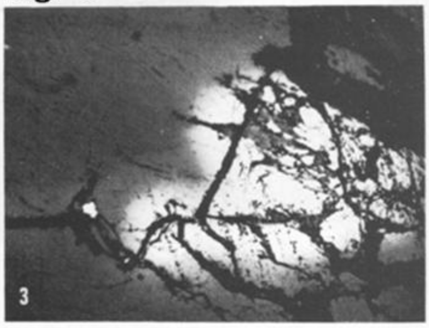


Fig. 4

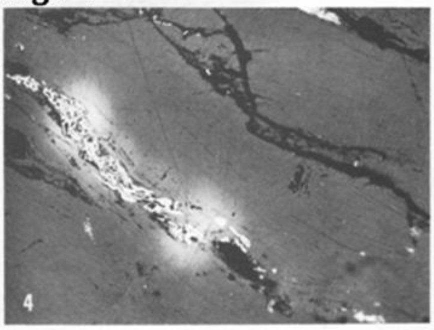


Fig. 5

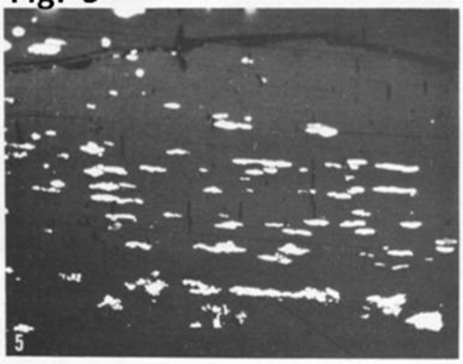


Fig. 6

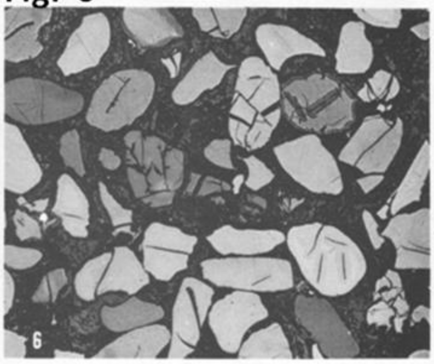


Fig. 7

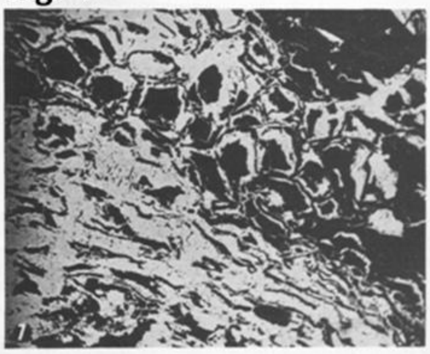


Fig. 8

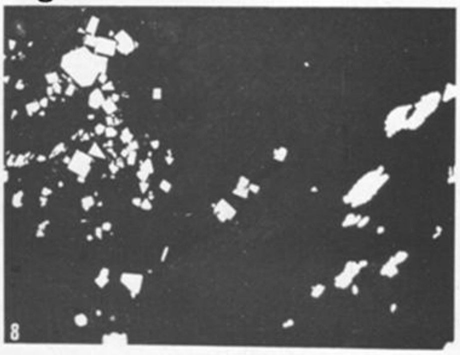


Plate II. Photomicrographs (second and third set of samples).

8.2.5 Uranium minerals

A mineralogical investigation on coal and coal ash on 17 samples submitted by Ingwe Coal (Pty) Ltd was compiled by S.A. de Waal (1980). The only uranium mineral detected in untreated coal samples was coffinite. Six distinct forms of coffinite were observed and are described in Table 8.13 as types 1 – 6 (also refer to Plate III).

Table 8.13. Types of coffinite observed in untreated coal samples.

Type	Description	Size µm
1	Fills cell cavities of original plant material in coal with a fusinite structure (Plate III, A to C)	< 15
2	Irregular grains along early dislocation planes in vitrinitic coal (Plate III, B and C)	< 20
3	Irregular gains interstitial to detritus of inorganic nature (Plate III, D)	< 10
4	Very finely divided and dispersed in detrital coal grains (Plate III, D)	
5	Aggregates (predating compaction stage in coal formation) of irregular grains with fusinite fragments or pyrite, or both (Plate III, E to H)	< 20
6	Minute specks and grains in vitrinite coal (Plate III, H)	< 3

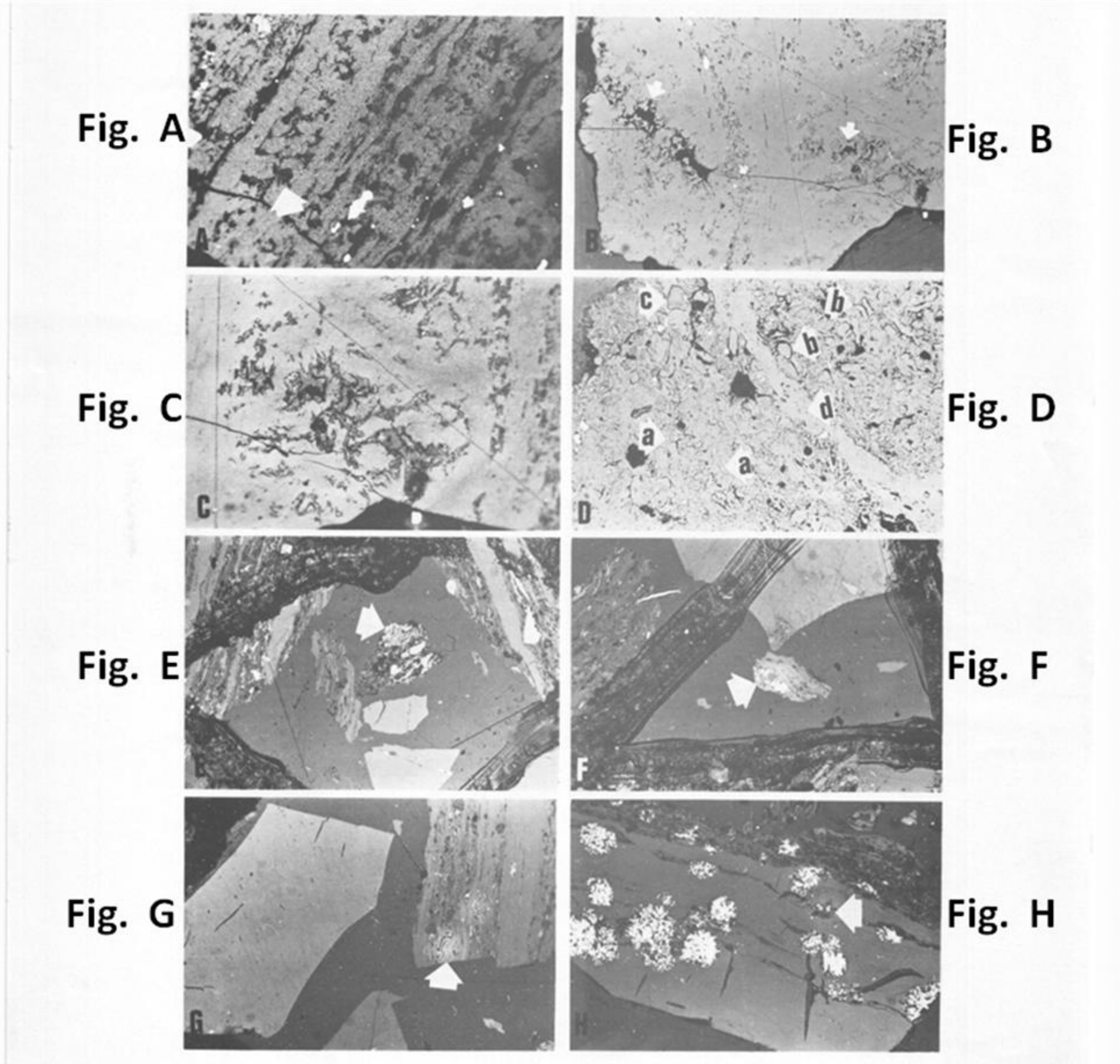


Plate III. Photomicrographs of coffinite types in untreated coal samples.

8.2.6 Conclusions

The main uranium-bearing mineral in the coal samples investigated is coffinite, which is chemically associated with yttrium, calcium and phosphorus. It occurs in a wide variety of physical forms in carbonaceous shale and in massive vitrinitic and fusinitic coal. Pyrite is often closely associated with the coffinite.

8.2.7 Mineralization Model

The exploration model that was created, was based on the assumption that the uranium-bearing fluids were introduced to the coal depositional environment during the deposition of Lithostratigraphic Unit 5. The problem encountered using this hypothesis was the time that had lapsed between the deposition of the coal and the deposition of Lithostratigraphic Unit 5.

The Hammanskraal fossil assemblage, that was investigated in an open pit towards the southern peripheries of the Springbok Flats, contains palynostratigraphic data that was used by Macrae (1988) for correlation purposes. The Hammanskraal fossil assemblage in Lithostratigraphic Unit 2 was correlated with bio-zone E in the Waterberg coal field (Macrae, 1988). The age of this fossil assemblage is of late Permian Epoch, ± 260 ma. Although this fossil assemblage is older than the coal deposits of Lithostratigraphic Unit 3 it will be used to establish a relative time frame to calculate the time lapsed between Lithostratigraphic Units 3 and 5. Prosauropod dinosaur remains encountered in the basal part Lithostratigraphic Unit 6 are dated to be very late Triassic to early Jurassic i.e. ± 200 Ma (Rubidge, personal communication, 2011). It is postulated that ± 60 Ma had lapsed from the deposition of Lithostratigraphic Unit 2 to the end of Lithostratigraphic Unit 5. No plant fossils were encountered in borehole cores from Lithostratigraphic Unit 5 meaning that the actual duration of sedimentation could not be determined.

The Beaufort Group of the Karoo Supergroup as encountered in the Main Karoo Basin was not developed in the Springbok Flats Karoo Basin. The Beaufort Group of the Main Karoo Basin was deposited during the late Palaeozoic to early Mesosoic era, over a period of ± 30 ma (Plumstead, 1969). If it is assumed that Lithostratigraphic Unit 5 in the Springbok Flats Karoo Basin is an equivalent of the Molteno Formation of the Main Karoo Basin, it can also be concluded that ± 30 Ma had lapsed since the end of the coal formation period to the start of the deposition of Lithostratigraphic Unit 5. This hiatus manifested itself as a distinct palaeosol that was developed between Lithostratigraphic Units 4 and 5. In the absence of Lithostratigraphic Unit 4 i.e. in areas adjacent to palaeo-topographical highs, coal clasts occur in the Lithofacies Gm of Lithostratigraphic Unit 5. These clasts were transported, as the original layering of the coal clasts show a random spatial orientation within the Lithofacies Gm.

Based on the preceding, it is concluded that the process of coal formation was completed and that the rank of the coal was probably that of bituminous coal prior to the deposition of Lithostratigraphic Unit 5. In addition it was observed that most of the embedded coal clasts encountered in Lithostratigraphic Unit 5 were also radioactive. These clasts comprise either bright coal or bright coal and carbonaceous shale. The impermeable nature of the vitrinite coal and associated carbonaceous shale layers add to the conclusion, based on geological observations, that the uranium was introduced during the early stages of coal formation, possibly during the peat stage and that no relationship exists between uranium mineralisation in the coal and the deposition of Lithostratigraphic Unit 5. The high grade uranium encountered in areas where Lithostratigraphic Unit 5 constitutes the immediate roof of the coal can be ascribed to palaeo-topography and the sedimentary processes that prevailed during the deposition of the Lithofacies Gm of Lithostratigraphic Unit 5 in close proximity of palaeo-topographical highs.

Despite the preceding geological observations, the actual uranium mineralization model is based on the work done by Smit (1978) and de Waal (1980). Research results obtained from investigations conducted by the above mentioned researchers reveal that apart from the lean but homogeneously distributed uranium in the vitrinite, higher concentrations of the element may occur in the carbonaceous shales. Radioactive areas in the more carbonaceous shale type coal occur parallel to the bedding, but, as indicated in Fig. 4 of Plate I, a crack filled by radioactive material was observed transgressing the vitrinite. Such a crack could only have formed at a stage when the vitrinite was at least partially solidified. The same is applicable to the cracks observed in the polished sections that exhibited radioactive haloes (Plate II, Fig. 3; Plate III). The uranium associated with these structures was introduced after the formation of the coal and was concentrated in open spaces in the early stages of the coalification processes. The radioactive haloes associated with cleats are considered to have formed during a process of shrinkage in the coal implying that some of the radioactive material could have migrated over a very short distance.

In conclusion the following sequence of events could have contributed to the concentration of uranium in the coal of Lithostratigraphic Unit 3. Initially, surface and groundwater carrying uranyl ions in solution or in an adsorbed state had access to accumulations of plant debris, and thus came into contact with stagnant water, where reducing conditions prevailed. On entering this environment, characterized by different physio-chemical conditions, the hexavalent uranium was reduced to the tetravalent state. The co-precipitation of pyrite and tetravalent uranium is expected in this type of environment and iron sulphate was indeed observed in various forms in the vitrinite and carbonaceous shales. During peatrification, the uranium was removed from solution and fixed in the peat. Humic acids might have played a role in the withdrawal of uranium from solution in the form of uranyl humates which could have been precipitated, for example in cell cavities. In the range of solid organic matter, peat and low rank coals are the most efficient collectors of uranium and this process is irreversible. The homogeneous distribution of uranium in the vitrinitic coal as indicated on the autoradiographs suggests that such a sequence of events early in the process of coalification could indeed have taken place. The carbonaceous shale was probably deposited during an influx of argillaceous material into the coal depositional environment. Uranyl ions had likely been transported in the adsorbed state on clay and other fine-grained particles, which precipitated in the form of microscopic sized uranium oxides, hydroxides or silicates in the shale matrix.

The dispersed occurrence of point sources of radiation in the coal and carbonaceous shale suggests that no change in distribution took place during the coalification process. The occurrence of uranium as crack-filling material can be indicative of the remobilization of the uranium in solution or colloidal suspension within the coal deposit, possibly aided by the process of compaction. It is therefore assumed that the crack filling radioactive material is of a different origin and that it probably precipitated from uranium-bearing colloidal solutions at a later stage. The cracks, which formed when the organic matter was already in an advanced state of coalification, controlled the permeability of coal. Fine fractures, younger in age than the cracks are filled with calcite, quartz or secondary pyrite and do not contain any radioactive compounds.

The maximum concentration of uranium in coal in the Springbok Flats Basin occurs in close proximity of the palaeo-topographical highs especially where these highs comprise granites of the Lebowa Suite of the Bushveld Igneous Complex. The concentration of uranium in the coal is too high to account for a direct origin from granitic rocks. However, the geochemical enrichment factor of Szalay (1958) is ± 10 000:1 in peat. This enrichment factor represents the ratio of the concentrations of bivalent uranium oxide in peat to that in water. The humic acids are considered to be responsible for the accumulation of uranium in organic matter resulting in the association of uranium and peat.

A depositional model similar to that depicted in Fig. 8.2. is postulated for the uranium concentrations in the coal in the SFKB. The association of uranium occurrences and palaeo-topographical highs comprising granites is assigned to the fact that solutions, derived from the granitic resource, carrying uranyl ions entered an environment of low energy, resulting that the dispersion of uranium were restricted primarily to the area adjacent to palaeo-highs.

8.2.8 Uranium Resources: Settlers Tuinplaats and Roedtan Basins

8.2.8.1 Grade determination

- **Radiometric Grade**

The radiometric grade over the uraniferous horizon was determined by wireline logging techniques i.e. Chemtron and BPB down-hole geophysical instruments. This grade was expressed in terms of kilogram per ton over widths of 0.80 m, 1.00 m and 1.20 m respectively. To arrive at an acceptable grade for resource calculations, the mean grade between the Chemtron-analogue and BPB analogue value over the best 1.00 m was taken, provided a discrepancy of not more than 10% between the two values existed. In cases where the discrepancy was more than 10%, the BPB-analogue value was accepted.

In cases where the grade over the best 1.00 m was in excess of 0.20 kg/t, the borehole was deflected to obtain a second set of values over the same uraniferous horizon. For resource purposes the arithmetic mean value of the original borehole and the deflection was used.

In addition to the radiometric grade determinations, the mineralised horizon was sampled and submitted to WRC Laboratories for X-ray fluorescence analyses. The XRF uranium grade was determined for the float fractions at R.D's 1.55; 1.65 and 1.75 and the sink fraction at R.D. 1.75 for samples comprising mainly bright coal. On shale samples, only the raw ash, total sulphur, R.D. and uranium grades were determined.

When comparing the radiometric uranium grades determined in the original borehole with that of the deflection, differences between the two values were found. In subdividing the radiometric uranium grades of 156 boreholes and their deflections in three grade categories i.e.

> 1.00 kg/t,
1.00 kg/t – 0.50 kg/t
< 0.50 kg/t

it was found that in the category > 1.00 kg/t, 86% of the original boreholes yielded a higher radiometric uranium grade than their deflections. In the category 1,00 kg/t to 0,50 kg/t, only 51% of the original boreholes yielded a higher grade whilst in the category < 0,50 kg/t, only 31% of the original boreholes yielded a higher uranium grade than the deflection.

- **XRF versus radiometric grade of original boreholes (deflections not analysed by means of XRF)**

In Table 8.14. a comparison between the mean radiometric and XRF uranium grades from 75 boreholes in five different grade categories is drawn.

Table 8.14. XRF uranium grades versus mean radiometric uranium grades.

Grade categories	XRF	Radiometric	% difference
> 1.00 kg/t	1,83	1,53	20% XRF
1.00 – 0.80 kg/t	1,09	0,88	24% XRF
0.80 – 0.60 kg/t	0,76	0,70	09% XRF
0.60 – 0.40 kg/t	0,52	0,48	08% XRF
0.40 – 0.20 kg/t	0,20	0,27	35% XRF

Table 8.14. illustrates that in the categories higher than 0.40 kg/t, the XRF grades are higher than the radiometric grades. This phenomena is ascribed to the nugget effect which manifests itself in the fact that a large random sample will on average give a value closer to the mean value of the area represented by a specific borehole. In general terms, the effective sample analysed by the radiometric probe in the borehole is some 15 times greater than the NQ-core sample. The gamma ray counts are influenced by uranium at a distance as far as 50 cm into the sidewall of the borehole. Hence, it was decided to use the radiometrically determined values for resource calculation purposes instead of values obtained by means of XRF determination.

- **Grade distribution in floats and sinks**

A total of 179 boreholes in the Settlers – Tuinplaats Basin area with XRF uranium grades greater than 0.30 kg/t were used to determine the distribution differences of uranium in organic material (floats) and inorganic material (sinks) of the coal. The proportions of uranium reported in the float and sink fractions at R.D. 1.75 are summarized in Table 8.15.

Table 8.15. Uranium grade distribution.

Number of boreholes used	Proportions of U_3O_8 in floats at R.D. 1.75	Proportion of U_3O_8 in sinks at R.D. 1.75
179	48%	52%

From this it is evident that the uranium is virtually equally distributed in the float and sink fractions of the 179 boreholes. However, the average float yield is 35.6% (average yield of 179 boreholes) and therefore the grade of the floats is 0.57 kg/t compared to the 0.50 kg/t of the sinks (average grade of 179 boreholes).

8.2.8.2 Uranium resources

In areas where Lithostratigraphic Unit 5 directly overlies Lithostratigraphic Unit 3 abundant carbonaceous detritus and coal clasts occur in the lower 0.50 – 1.00 m of Lithostratigraphic Unit 5. In these areas the lower portions of Lithostratigraphic Unit 5 are also uraniferous. For resource calculation purposes the enriched Lithostratigraphic Unit 5 sediments were excluded from the resources.

The thickness of the mineralised horizon is dependent on the distance from the palaeo-high and therefore on the thickness of Lithostratigraphic Unit 3. In close proximity of palaeo-topographical highs, only single coal bands, ranging in thicknesses from 0.10 m to 0.50 m were mineralised. Despite the variation in thicknesses, a radiometric grade (kg/t) over the best 1,0 m of the mineralised horizon was calculated and used for resource calculations.

The aerial distribution of potentially exploitable uranium resources associated with Lithostratigraphic Unit 3 for both the Settlers – Tuinplaats and Roedtan Basins is depicted in Fig. 8.6. The uranium resources were calculated by multiplying

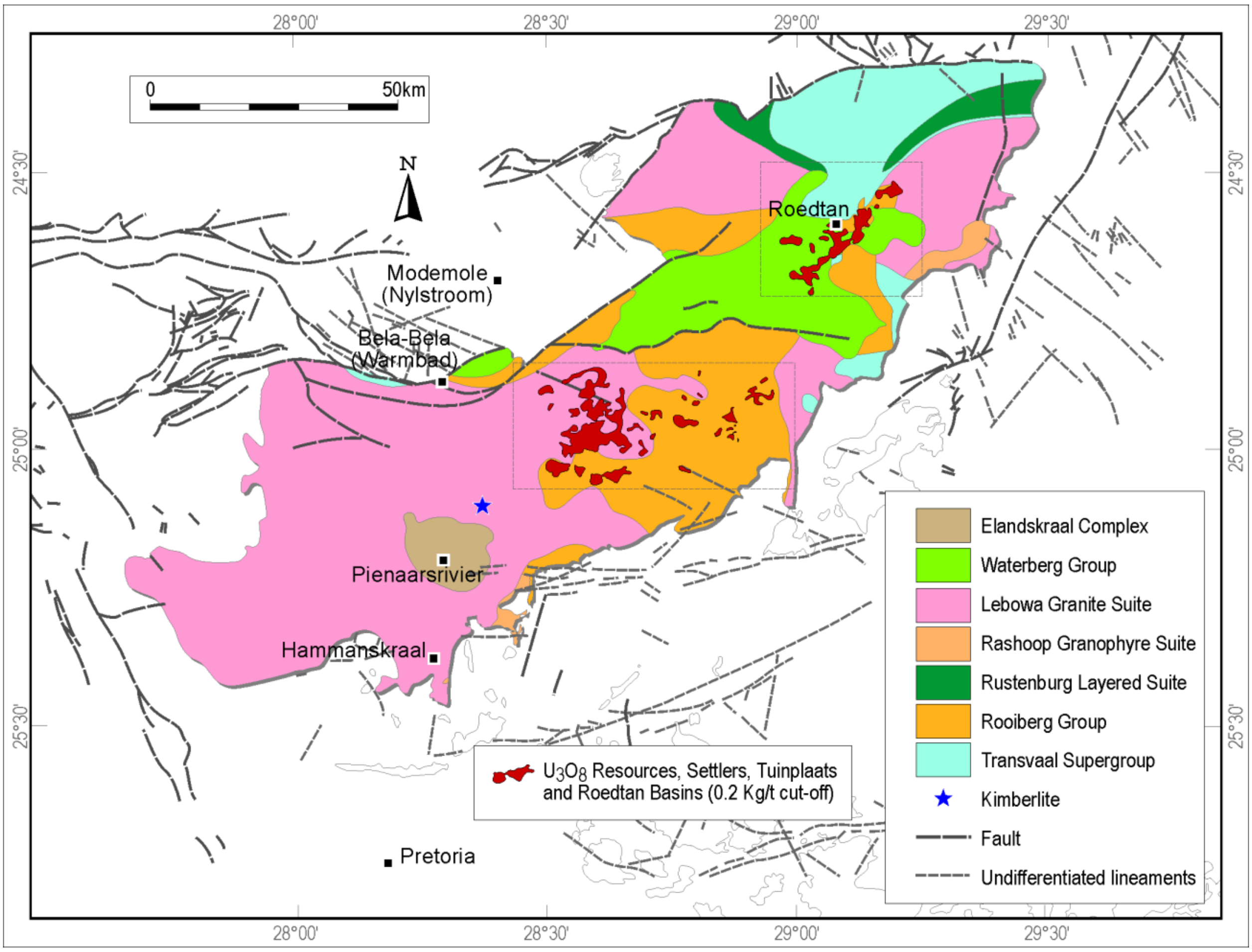


Fig. 8.6. Uranium resource map: SFKB.

the area underlain by uraniferous coal by 1.0 m (mineralised horizon thickness) and a R.D. of 1.71 g/cc. A radiometric cut-off grade ≥ 0.20 kg/t was used to demarcate the resource areas. The in situ uranium resources (cumulative breakdown) are given in Table 8.16.

8.3 Uranium occurrence other than in Lithostratigraphic Unit 3

During the course of the exploration programme in the Springbok Flats Karoo Basin, uranium mineralisation was intersected in varying quantities in virtually each of the lithostratigraphic units of the Karoo Supergroup.

Table 8.16. Uranium resources for the Settlers – Tuinplaats and Roedtan Basins.

Basin	Resource categories (kg/t)								
	>1	1 - 0.90	0.90 - 0.80	0.80 - 0.70	0.70 - 0.60	0.60 - 0.50	0.50 - 0.40	0.40 - 0.30	0.30 - 0.20
Settlers – Tuinplaats									
Total Inferred resources (mt)	6.43	5.42	5.43	8.03	16.04	16.98	29.55	48.86	105.78
Cumulative: t x 10^6	6.43	11.85	17.28	25.31	41.35	58.33	87.88	136.74	242.52
*Grade (kg/t)	1	0.98	0.94	0.88	0.79	0.72	0.63	0.53	0.41
Roedtan									
Total Inferred (mt)	1.38	1.22	2.49	3.41	3.82	8.69	10.93	19.86	68.85
Cumulative: t x 10^6	1.38	2.6	5.09	8.5	12.32	21.01	31.94	51.8	120.65
*Grade (kg/t)	1	0.98	0.91	0.85	0.79	0.69	0.61	0.51	0.36

* Weighted averages

8.3.1 Lithostratigraphic Unit 7

Uraniferous mineralisation occurring in Lithostratigraphic Unit 7 was intersected on two farms in the Roedtan Basin. The uraniferous horizon occurs near the contact of Lithostratigraphic Unit 7 with the overlying basaltic lavas. Volcanic ash resulted from the outflow of the lava was considered to be the source of the uranium. Due to the erratic occurrence of this mineralization, no follow-up work was done.

8.3.2 Lithostratigraphic Unit 6

The calcrete pebble conglomerate that constitutes the base of Lithostratigraphic Unit 6 contains numerous fossil-bone fragments. Interbedded with these conglomerates are tuffaceous mudstones probably related to volcanic activities that prevailed during the deposition of these mudstones. In most instances it was found that the bone-fragments are also uraniferous.

8.3.3 Lithostratigraphic Unit 5

Samples with a uranium mineralization grade in excess of 1.0 kg/t was intersected on the farms Chester 666 KR and Benwell 663 KR in Lithostratigraphic Unit 5.

The uraniferous horizon on Chester 666 KR occurs in a sandstone layer. The sandstone comprises mainly angular quartz, subordinate perthite, volcanic ash fragments and felsite. Associated with above mentioned grains, several heavy minerals like rutile, zircon and tourmaline were identified. The sandstone is poorly sorted and immature. Samples of this sandstone were submitted to Prof. C.P Snyman (University of Pretoria) for a mineralogical investigation. The samples were crushed and the heavy minerals separated at a R.D. of 2.90 g/cc.

The float fraction of R.D. 2.90 g/cc yielded uranium at a grade of 1.27 kg/t (XRF), indicating that the uranium minerals occur in a very fine disseminated form.

Spectrographic analyses of the sink fraction at R.D. 2.90 g/cc revealed the presence of U, Mn, V, Ti, P, Fe, Mg, Si and Zr. This corresponds to the following identified minerals: zircon, rutile, pyrite, chalcopyrite, tourmaline and braunerite, a yellowish-brown colloidal uranium mineral rich in titanium. According to Prof. C.P Snyman (personal communication, 1979) braunerite formed from the titanium minerals by the addition of uranium in solution.

The presence of volcanic ash fragments associated with the sandstone could be indicative of volcanic activities during the deposition of the mineralised sandstone. A possible volcanic origin for the uranium occurrence can therefore not be excluded. Due to the localised occurrence of uranium mineralisation in Lithostratigraphic Unit 5, no further detailed investigations were conducted.

8.3.4 Lithostratigraphic Unit 4

The uranium mineralisation encountered in Lithostratigraphic Unit 4 is not associated with the pre-Karoo topographical highs as in the case of the uraniferous coal. The uranium mineralisation in this unit occurs in the deeper part of the basin where Lithostratigraphic Unit 4 obtains its maximum thickness. The impermeable nature of Lithostratigraphic Unit 4 prevented the downward migration of uraniferous solutions. Based on the preceding, it is postulated that the uranium associated with Lithostratigraphic Unit 4 is a younger event than the event resulting in the mineralisation of the coal.

8.3.5 Lithostratigraphic Unit 2

A relatively high uranium grade was intersected in a borehole drilled in the north-western corner of Zebediela’s Location 123 KS. The uranium mineralisation occurs in a coarse grained arkosic sandstone approximately 2.0 m below Lithostratigraphic Unit 3. In addition, uranium mineralisation was also encountered in a subordinate coal seam sporadically developed in Lithostratigraphic Unit 2.

A detailed resistivity survey conducted revealed a WNW-ESE trending trough with subsidiary channel trending NW-SE. This trough possibly represents a proximal fluvial distribution channel during the early stages of deposition of Lithostratigraphic Unit 2. Follow-up drilling revealed erratic low grade mineralisation assigned to a low percentage of carbonaceous material associated with the sandstone. The area was considered unsuitable for economic uranium mineralisation.

8.3.6 Lithostratigraphic Unit 1

No uranium mineralisation was encountered in any of the exploration boreholes that intersected the glacial derived sediments of Lithostratigraphic Unit 1.

8.4 Diamondiferous kimberlites

8.4.1 Klipspringer kimberlite field

According to Ehlers and Du Toit (2002) kimberlite fissures intruded into tensional fissures and weak zones created by the TML. Discoveries of kimberlite fissures and pipes in the Klipspringer Field to date indicate that these intrusions are distributed over ± 25 km along an elongated zone parallel to the TML.

The Zebediela Kimberlites (Fig. 8.7.) form part of the Klipspringer Kimberlite Field and occur on the farm Rusland 93 KS. The main fissure exploited is on average 1.0 m thick and yielded a diamond grade of 90 cpht (Southern Era 2nd Quarterly Report, 1996).

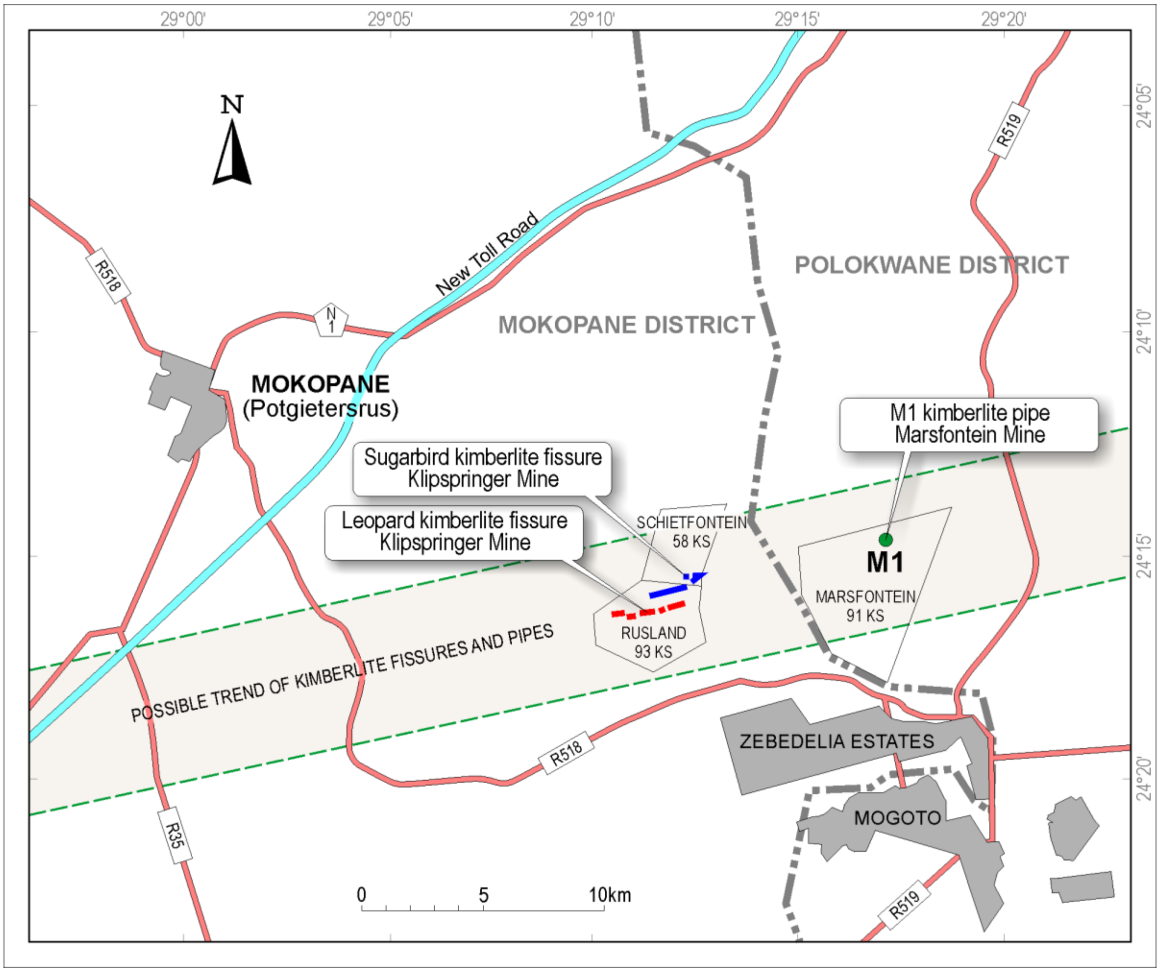


Fig. 8.7. The Klipspringer kimberlite field.

8.4.2 Palmietgat kimberlites

A diamondiferous kimberlite fissure and pipe system was discovered by De Beers on the farm Palmietgat 34 JR, ± 7 km east of the railway siding at Radium and approximately 15 km south southeast of Bela Bela. They dyke and pipe (blows) system is approximately 4 km long and includes six small pipes (blows) totaling about 4.8 ha (Lynn et al., 1998).

Three of these blows were exploited by North American Mining Corporation (Pty) Ltd during 2005. An average of 16 cpht was recovered (personal communication N. Claassens, 2010).

8.5 Economic deposits of the secondary environment

The following economic deposits associated with the secondary environment constitute brief summaries based on research by Ehlers and Du Toit (2002).

8.5.1 Dolomitic limestone

The best known dolomitic limestone deposits in the SFKB are situated near both the Immerpan and Zebediela railway stations. The various operating and dormant dolomitic limestone quarries within the Immerpan limestone field are depicted in Fig. 8.8. The actual resources of these deposits are unknown.

8.5.2 Gypsum

One of the most prominent gypsum deposits discovered so far is situated on the farms Klippan 555 KS and Uitzichtspunt 553 KS. The gypsum resources are estimated to be in the order of 500 000 t at an average grade of 20% gypsum (Coertze, 1961). A similar sized deposit is known on the farm Klavervalley 616 KS.

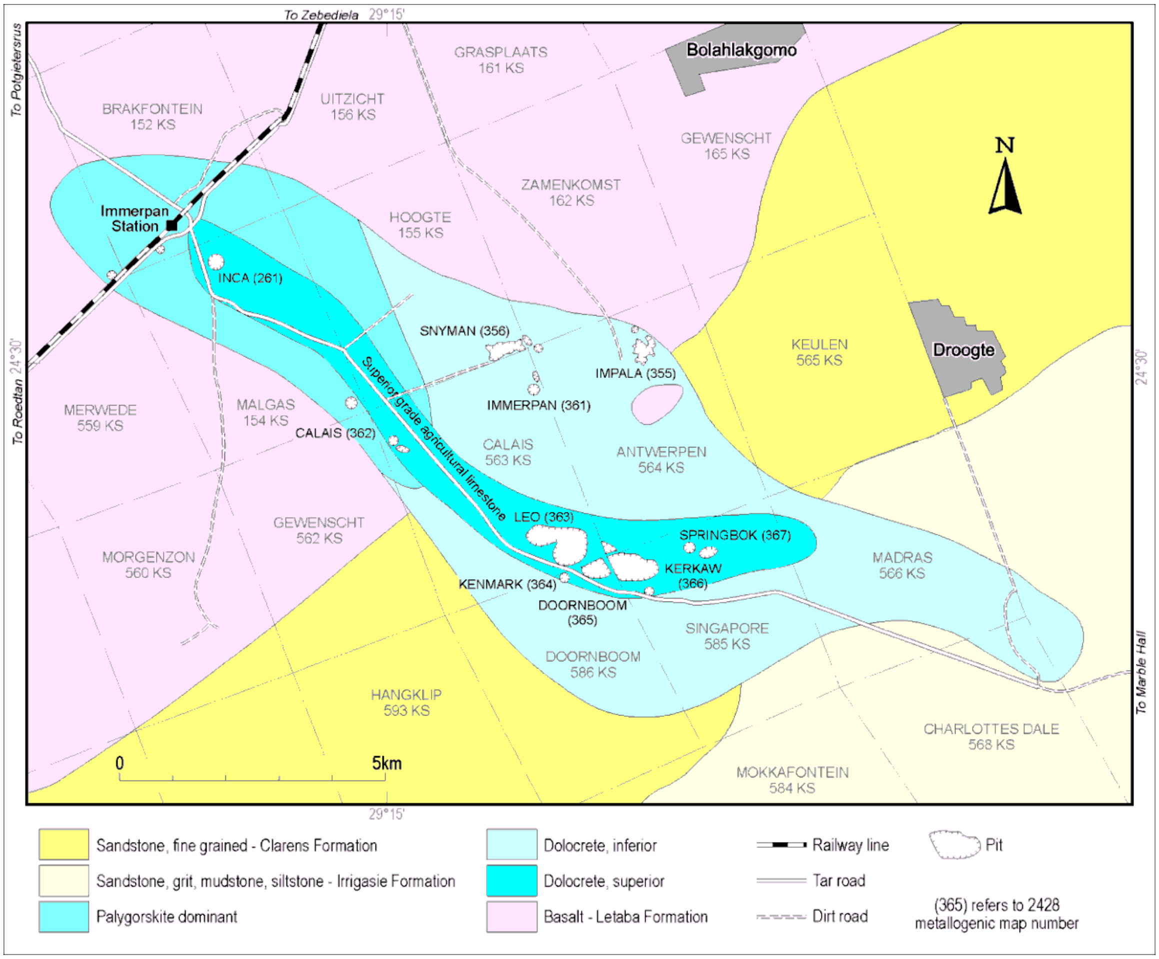


Fig. 8.8. The Immerpan limestone field.

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