The Geological Framework and Depositional Environments of the Coal-Bearing Karoo Strata in the Central Kalahari Karoo Basin, Botswana

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TEBOGO SEGWABE

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ABSTRACT

The investigation of the geological history (i.e., stratigraphy and sedimentology) and the dynamics of coal depositional environments, in particular, the forces responsible for changes in the accommodation space (e.g., subsidence vs. sedimentation rates) in the Permian coal-bearing Karoo strata in the Central Kalahari Karoo Basin (Botswana) revealed new details about the depositional processes and environments.

Detailed review of the temporal and spatial stratigraphic variation of the coal-bearing Ecca Group successions via the analysis of facies changes based on core descriptions, gamma logs, field observations and palaeo-current measurements, lead to the identification of two main informal stratigraphic units, namely the Basal and Upper Units.

The Basal Unit is characterised by an upward-coarsening succession, and it is interpreted as a product of a progradational deltaic setting (i.e., regressive deltaic cycle). This is followed by five sequences of fining-upward successions of sandstones and siltstones in the Upper Unit, interpreted as deposits of distributary channels (the *basal arenaceous member)* capped by finer argillaceous sequences of the deltaic floodplains (the *upper coal-bearing member*). The Upper Unit thus is interpreted as a delta plain facies association which was formed during transgressive phases when conditions for coal-quality peat accumulation (e.g., high water table) were present and the available accommodation space was partly controlled by tectonic uplift (repeated?) at basin margins.

Limited palaeo-current analysis indicates deposition by channels flowing from the east, south-east and north-east. The lack of good quality exposures hampers the reconstruction of the plan form of the channel patterns. However, the little available evidence indicates a high-energy fluvio-deltaic system with irregular discharge and a high proportion of bedload sediments.

Coal-seam thickness in the *upper coal-bearing member* reflect the complex control of the geological processes associated with and following peat formation, such as differential compaction of the underlying lithology, and the erosive or protective nature of the immediately overlying lithology.

1.0 Introduction

Sedimentary rocks throughout the geological record host most of the world's non-renewable fuel and ground water resources as well as other natural resources such as metal ores and fertilizers. Exploration and exploitation of such resources require an understanding of their relationship to the host sedimentary strata. In case of coal-bearing successions, this necessitates the characterization of the host rocks in terms of stratigraphy and sedimentology.

In southern Africa, the Late Paleozoic - Mid-Mesozoic Karoo basins contain the economically most important coal deposits and related resources such as coalbed methane (CBM) which for most countries, including Botswana, form an important source of domestic energy. The sedimentary fill of these basins is also intruded by diamond-bearing rocks, and acts as groundwater aquifers. Currently, thorough understanding of the regional relationships between these coal-bearing basins is hampered by inadequate inter-basinal correlation and limited knowledge of the syn-Karoo regional tectonic activities. The understanding of the Karoo basins in Botswana is particularly incomplete as here large parts of the Karoo rocks are covered by younger sediments.

The Permian coal, the major commodity found in the Karoo basins, has attracted great interest from exploration companies and national geological surveys resulting in the generation of large volumes of mainly subsurface geological data. Because new technologies now allow mining companies to efficiently exploit even deeply seated coal seams, a renewed interest in this mineral commodity is on a rise worldwide. In Botswana, however, coal is not fully utilized as evidenced by the existence of only one operational coal mine at Morupule despite the vast coal resources present in the country. Considering the renewed interest in coal, it can be expected that the Botswana Government will need detailed studies to help manage future coal leases and to regulate mine development in the region. There is therefore a great need for increased knowledge of the sedimentary, tectonic and stratigraphic records of the Karoo basins in order to support and manage future exploration of coal and related resources in Botswana.

To date, the gathering of geological information on coal resources in Botswana has passed the reconnaissance stage, and currently more detailed studies focused on specific locations will better stimulate future coal development in the country. Thus, the undertaking of this study to investigate 1) geological framework of the coal-bearing strata and 2) to work out the dynamics of coal depositional environments, in particular the forces responsible for changes in the accommodation space (e.g., subsidence vs. sedimentation rates) in the Central Kalahari Karoo Basin in Botswana. This study forms part of a larger, regional collaborative project titled the 'Tri-Nations Karoo Basin Correlation Project'. The primary aim of this regional project undertaken by the two national geological surveys (Botswana and Namibia) and the Council for Geoscience (South Africa) is to improve the correlative framework between the Karoo-aged sequences in these three countries.

An in-depth knowledge of depositional framework of an area will enable prediction of coal properties (thickness, geometry, lateral continuity, etc). Furthermore, since coal acts as both source and reservoir for coal gas (coalbed methane), distribution of coal within a basin is critical for establishing coalbed gas resources.

Thus, the main aim of the current study is to investigate the geological history, in particular the sedimentology and stratigraphy of the coal-bearing Karoo strata in the Central Kalahari Karoo Basin. In particular, the project focuses on investigating the influence of the depositional and post-depositional processes on the lateral and vertical distribution of coal seams. Further attempts to work out the dynamics of coal depositional environments, in particular, the forces responsible for changes in the accommodation space (e.g., subsidence vs. sedimentation rates) are also undertaken. Furthermore, by applying modern sedimentary facies analysis techniques to the Karoo succession in the study area, the study is also intended to expand on the achievements of the previous workers (e.g., Green, 1966; Stansfield, 1973; Smith, 1984; Bennett, 1989; Carney *et al*., 1994; Exploration Consultant Ltd (ECL), 1998), which were mainly focused on the (1) identification of the lithologies; (2) subdivision of the sequences into lithostratigraphic units; and (3) classification of the depositional environments but without clear documentation on how these conclusions were reached.

The ultimate objective of the study is to assists with the development of tectonic and depositional models for the Central Kalahari Karoo Basin in order to enhance the correlation with the Karoo strata in South Africa and Namibia.

1.1 Previous Work

The first documentation of the regional lithostragraphy of the Karoo succession in Botswana was by Green (1966) who also attempted correlations with the South African Karoo sequence.

Further knowledge on Karoo stratigraphy of Botswana was enhanced by data from several explorations and groundwater development projects boreholes [e.g., Anglo Botswana Coal (Barnard and Whittaker, 1975); BP Coal Botswana (James, 1976); Shell Coal Botswana (Clarke-Lowes and Yeats, 1977)].

The geophysical investigations, such as the National Gravity Survey (Reeves and Hutchins, 1976) and the Reconnaissance Aeromagnetic Survey (Reeves/Terra Surveys, 1978) have also helped in delineating the Karoo Supergroup in Botswana. These surveys allowed the subsurface mapping of the Karoo rocks and post-Karoo dykes and sills, and their relation to the distribution of Karoo basins in Botswana.

The latest detailed compilation on the lithostratigraphy of the Karoo Supergroup in Botswana was by Smith (1984), based mainly on the results of follow-up drilling to the Aeromagnetic Survey of Botswana and also on coal exploration results.

1.2 Layout

Although the coal-bearing Karoo strata in the Central Kalahari Karoo Basin are confined to the Ecca Group, it is important to describe this group relative to the entire Karoo Supergroup, in terms of basin development, stratigraphy and depositional environment. The regional setting of the Central Kalahari Karoo Basin within Southern Africa also needs to be assessed. The geological background is therefore first described, followed by the tectonic setting, architecture, stratigraphy and depositional environments of the Kalahari Karoo Basin with focus on the Central Kalahari Karoo Basin, a sub-basin of the latter. A review of coal-forming processes and their effects on coal seams in Botswana are then given. This is followed by a description of the study methods used, the results of the study and the interpretation of the depositional environments. The final part of the thesis consists of a discussion, conclusion, acknowledgements and list of references.

2.0 Geology

2.1 Geological Background

Southern Africa is characterized by several distinctive basins (e.g., the main Karoo Basin, the Great Kalahari Basin) which are filled by a Late Carbonaceous – Early Jurassic succession that exhibits near similar lithological characteristics and fossil assemblages (Fig. 2.1) (Rust, 1975; Johnson *et al*., 1996). Among these basins, the main Karoo Basin (South Africa) is considered the type basin as it contains the most complete and best-studied succession.

These southern African Karoo basins preserve a record of a special time in Earth's history, when the Pangea supercontinent reached its maximum extent during the Late Paleozoic-Early Mesozoic interval (Smith *et al*., 1993; Johnson *et al*., 1996; ECL, 1998; Catuneanu *et al*., 2005). Sedimentation in these basins continued to accumulate until it was interrupted and eventually brought to a close by widespread flood basaltic volcanism in the Early Jurassic (ECL, 1998).

The accumulation of the sedimentary fill of these Karoo basins were under the influence of two main controls: 1) tectonism and 2) climate (Catuneanu *et al*., 2005). Climatic fluctuations left a mark on the stratigraphic record, showing evidence of a general shift from cold and semi-arid conditions during the Late Carboniferous-Earliest Permian interval, to warmer and eventually hot climates with fluctuating precipitation until the Early Jurassic (Keyser, 1966; Stavrakis, 1980).

Figure 2.1. The Karoo Supergroup in Southern Africa and Great Kalahari Basin (in yellow) (figure modified after Bordy, 2000 based on Johnson *et al*., 1996).

2.1.1 Great Kalahari Basin

The Great Kalahari Basin (GKB), considered the second largest basin in southern Africa, stretches from Namibia (Aranos Basin) through Botswana (Kalahari Karoo Basin) into Zimbabwe (Mid-Zambezi Basin) and merges southeastward into the Ellisras Basin (Fig. 2.1).

2.1.1.1 Kalahari Karoo Basin

The northeast - southwest trending Kalahari Karoo Basin (KKB) in Botswana (Fig. 2.2) covers over approximately 70% of the country (Carney *et al*., 1994). The basin is filled by Late Carboniferous – Early Jurassic Kalahari Karoo Supergroup which is divided into lower ranking stratigraphic units (e.g., Groups and Formations), most of which have lithological equivalents in the main Karoo Basin of South Africa, as well as in Namibia and Zimbabwe. Sequences established in the various sub-regions of the KKB were given local formation names and correlated across the country (Table 2.1; Smith, 1984). Due to the poor exposure and lack of subsurface data, the KKB and its fill are relatively poorly understood.

The KKB has been divided into four sub-basins: the Central Kalahari (study area), Southwest Botswana, Northeast Botswana, and Northwest Botswana sub-basins, based on geological setting and facies changes (Fig. 2.2; Smith, 1984).

2.1.1.1.1 Central Kalahari Karoo Basin

The Central Kalahari Karoo Basin (CKKB) is bounded by the pre-Karoo rocks in the east and northwest, the Zoetfontein Fault in the south and the Makgadikgadi Line in the north (Fig. 2.3). To the southwest, the CKKB continues into the Southwest Botswana sub-basin, into the so-called Gemsbok sub-basin, whereas to the north, the Karoo strata of the CKKB can be followed into the Northeast Botswana sub-basin.

Because of its large size, CKKB has been subdivided into: ***Western***, ***Southeastern***, ***Southern*** and ***Northern*** Belts (Fig. 2.3; Table 2.1), mainly for descriptive purposes (Smith, 1984).

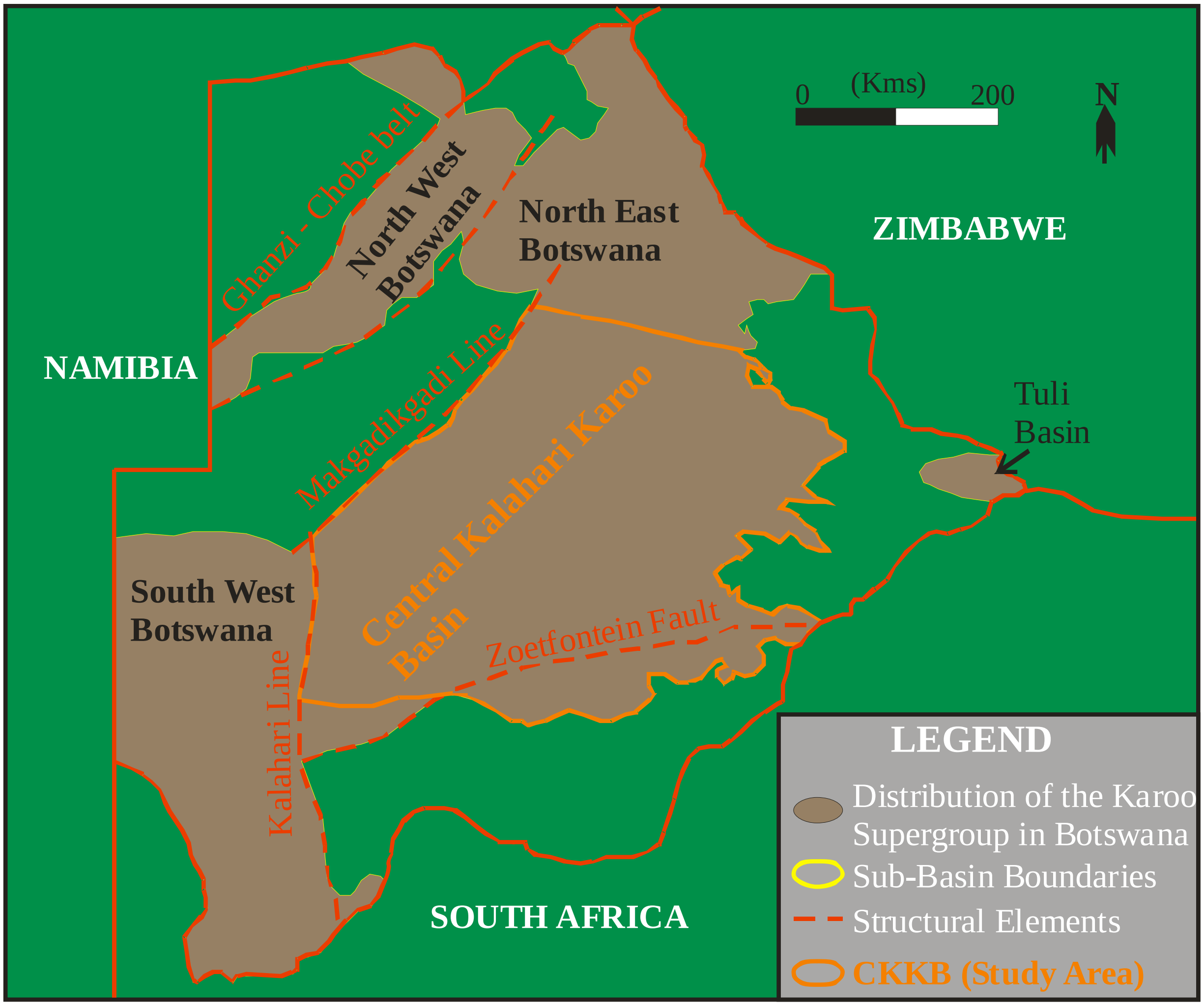


Figure 2.2. Kalahari Karoo Basin outline showing sub-basins (after Smith, 1984), major pre-Karoo structural lines (after Modie, 2007), and outline of the study area (in orange).

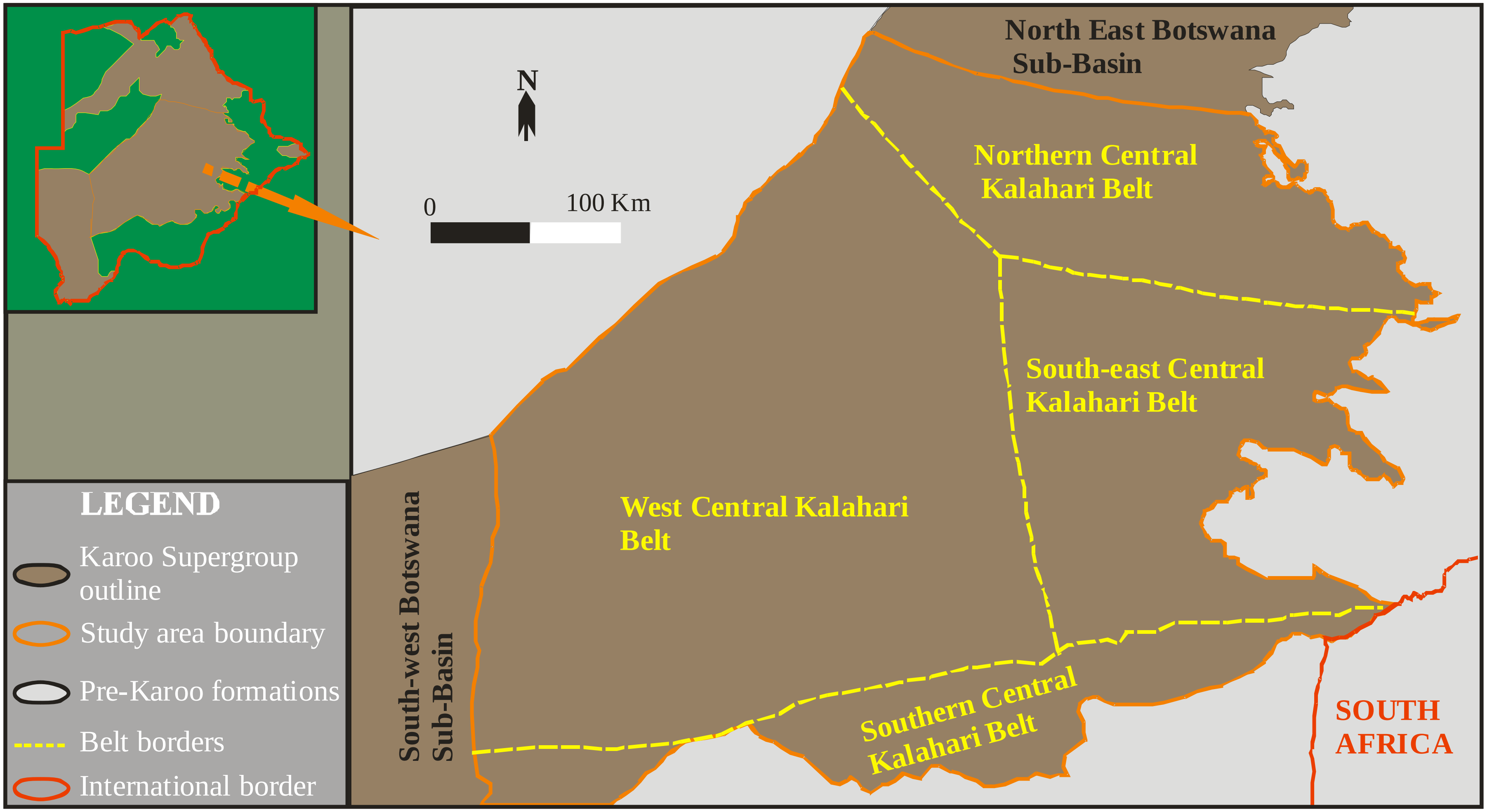


Figure 2.3. Central Kalahari Karoo Basin and its sub-divisions (Belts) (redrawn after Smith, 1984). Insert shows the location of the basin within Botswana.

GROUPS	SOUTH WEST BOTSWANA	KWENENG & WESTERN CENTRAL KALAHARI	MMAMABULA	MORUPULE & SE KALAHARI	NE BOTSWANA & NORTHERN BELT	NORTH WEST BOTSWANA	TULI BASIN
STORMBERG LAVA	STORMBERG LAVA GROUP (Undivided)						Bobonong Lava Formation
LEBUNG	Nakalatlou Sandstone	Ntane Sandstone Formation				Bodibeng Sandstone Fm.	Tsheung Sandstone Formation
	Dondong Fm.	Mosolotsane Formation			Ngwasha Fm.	Savuti Fm.	Thune Formation
					Pandamatenga Fm.		Korebo Formation
BEAUFORT	Kule Fm.	Kwetla Fm.	Tlhabala Formation			?	Seswe Formation
ECCA	Otshe Fm.	Boritse Fm.	Korotlo Fm.	Serowe Fm.	Tlapana Fm.	Marakwena Formation	
			Mmamabula Fm.	Morupule Fm		Tale Formation	
		Kweneng Fm.	Mosomane Fm.	Kamotaka Fm.	Mea Arkose Fm.	?	
	Kobe Fm.	Bori Fm.	Bori Fm.	Makoro Fm.	Tswane Fm.	?	Mofdiamogolo Formation
DWYKA	Middlepits Fm.	Dukwi Formation				?	?
	Khuis Fm.						
	Mmalogong Fm.						

Table 2.1. Lithostratigraphy of the Kalahari Karoo Supergroup in Botswana (Smith, 1984).

2.2 Tectonic Setting of southern African Karoo Basins

The Gondwana Supercontinent was composed of several lithospheric plates which have since parted to form the current Southern Hemisphere continents and India (Fig. 2.4). The southern African remnant of this continents contains Karoo basins such as: main Karoo Basin (MKB) and Great Kalahari Basin (Kalahari Karoo, Aranos, and Mid-Zambezi Basins), as well as a number of small basins in South Africa, Namibia, Zimbabwe and Mozambique (Fig. 2.1).

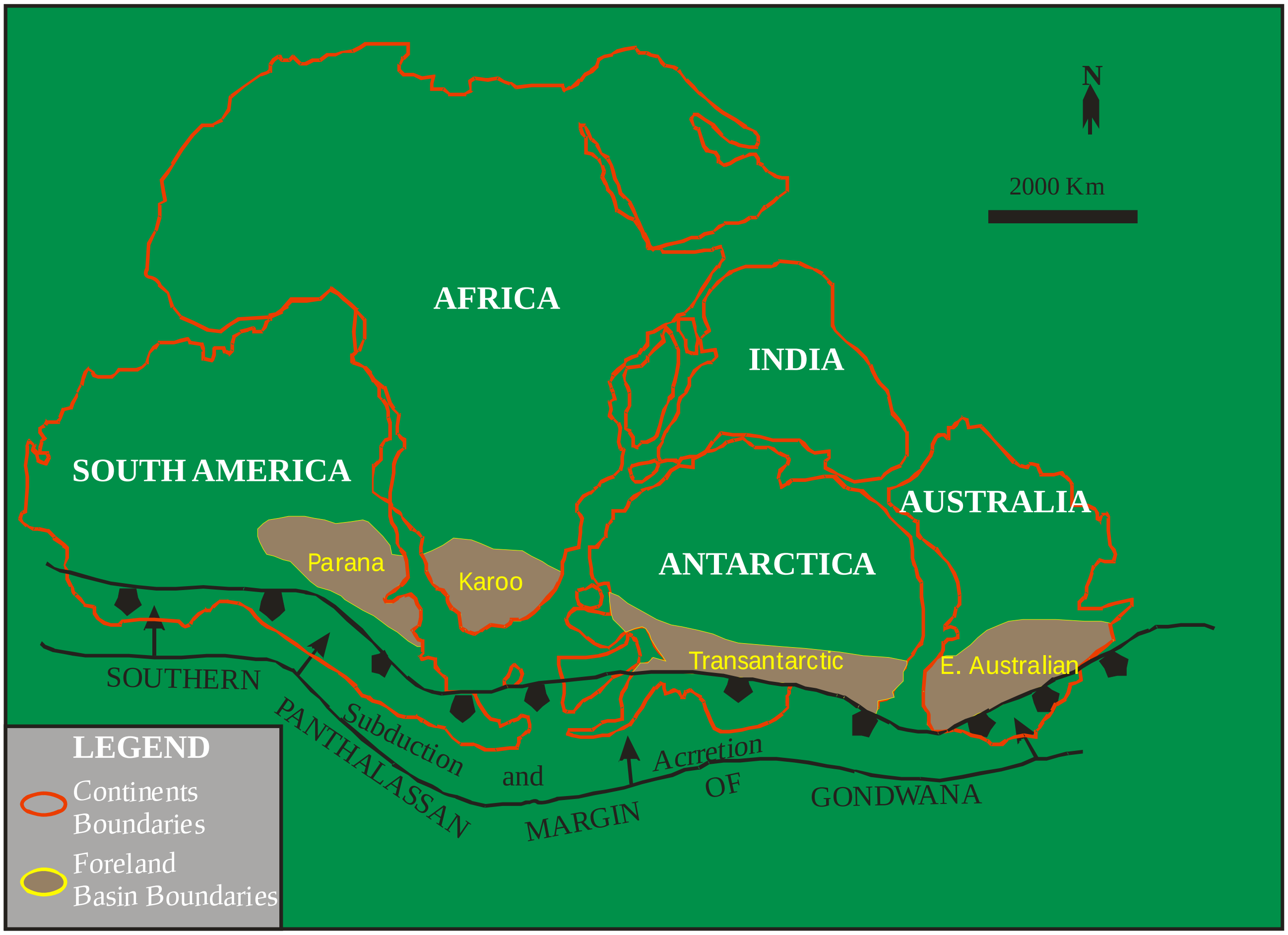


Figure 2.4. Reconstruction of Gondwana during the Late Palaeozoic showing subduction zone and associated foreland basins (Turner, 1999).

The Permian Karoo tectonic framework in most of southern Africa was characterized by a transition from the back-arc basin to a foreland basin setting (Visser, 1995). The change from extensional tectonics to a compressional regime is attributed to a palaeo-eastward migration of compressional stresses as a result of subduction of the palaeo-Pacific plate underneath southern Gondwana (Fig. 2.5) (Turner, 1999). The resultant foreland system basin (e.g., main Karoo Basin) attained its maximum depth at the beginning of the Late Permian (Lock 1978, 1980; Winter, 1984; de Wit *et al*., 1988; Johnson, 1991; Turner, 1999; Smith *et al*., 1993; Visser, 1995; Johnson *et al*., 1996; Catuneanu *et al*., 1998, 2005).

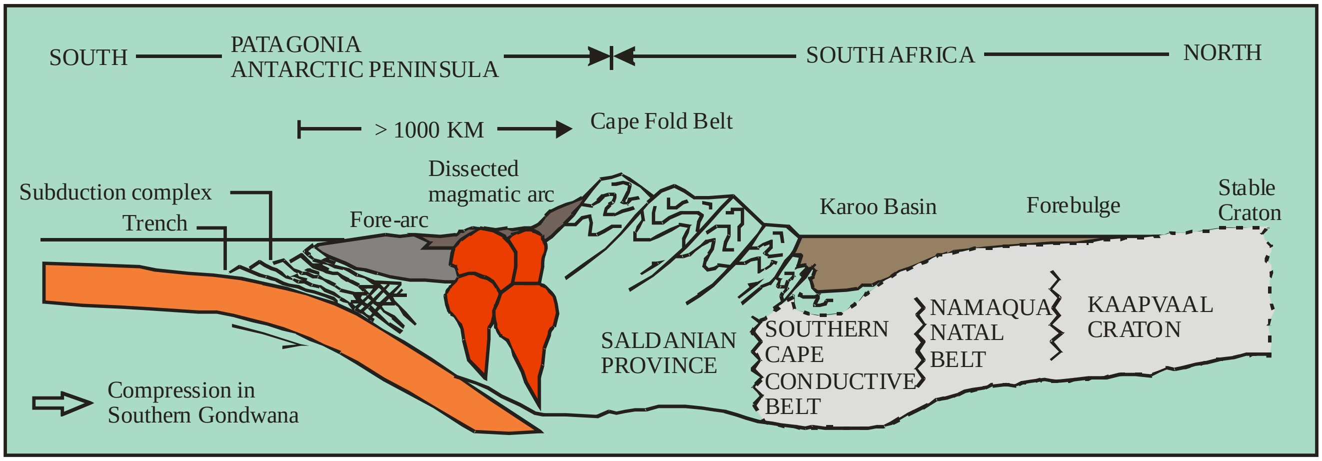


Figure 2.5. Generalised cross-section of the main Karoo Foreland Basin (Turner, 1999).

The overall basin geometry of the Great Kalahari Basin is asymmetric as it has a faulted northwestern boundary and a hinged southern flank (Langford, 1991). At the end of Permian, sporadic movement occurred along the boundary faults resulting in the formation of an unconformity at approximately the Permo-Triassic boundary (Drysdall and Kitching, 1963; Drysdall and Weller, 1966 in Langford, 1991). This boundary was a result of both extensional and strike-slip displacements (Daly *et al*., 1991) which produced roughly N-S shortening and E-W extension. These movements were attributed to compressional events taking place along the palaeo-Pacific margin of southwestern Gondwana which included the formation of the Cape Fold Belt (Fig. 2.5).

It is not known to what extent the current southern African Karoo basins were physically connected prior to post-Karoo erosion and some of the present basins could be products of later tectonic movements rather than pre- and syn-depositional downwarping (Johnson *et al*., 1996).

2.2.1 Tectonic Setting of Kalahari Karoo Basin

The Botswana Karoo Supergroup sedimentation is inferred to having taken place in relatively shallow connected basins, reflecting merely the relief of a rigid cratonic area affected by purely tectonic movements (Green *et al*., 1980).

The Kalahari Karoo Basin (KKB) of Botswana and several other subsidiary basins in South Africa, Namibia, Zimbabwe and Mozambique are classified as intracratonic sag basins or rift basins (Orpen *et al*., 1989; Verniers *et al*., 1989; Johnson *et al*., 1996; ECL, 1998).

Sedimentation in the KKB occurred in fault-bounded grabens developed along earlier zones of weaknesses associated with the Waterberg tectonic regime (Green *et al*., 1980; Williamson, 1996). Several faults with E-NE-SW and NW-SE which affected the Botswana Karoo Supergroup distribution appear to involve both syn- and pre-Karoo movements (Green *et al*., 1980; Williamson, 1996). The syn-Karoo faulting provided differential subsidence, which combined with the palaeo-topography, exerted a local influence on the distribution and thickness of Karoo sediments (Smith, 1984).

The use of geophysical data (e.g., seismic, aeromagnetics) in delineating major structural elements, such as faults and lineaments, indicates a rift basin setting for parts of the interior of the KKB (Modie, 2007). The tectonic framework of the KKB appears to have been influenced by pre-Karoo (Archaean, Proterozoic) structural elements as evidenced by the close association of major interpreted geophysical lineaments and the basin boundaries (Fig. 2.2) (ECL, 1998). Such lineaments which include the Kalahari Line, the Makgadikgadi Line, the Zoetfontein Fault, generally parallels major boundaries that defines segments of the KKB (Carney *et al*., 1994; ECL, 1998).

A seismic survey interpretation of the Karoo Supergroup reflects reactivation of the Zoetfontein Fault during Karoo sedimentation and its development as a growth fault (Davison and Steenkamp, 1995 in Modie, 2007). The present structural elements (i.e., open folds, normal faulting, inversion) of the KKB, as interpreted from seismic data, represent several phases of Mid-Late Karoo and post-Karoo compressional or extensional tectonics (ECL, 1998).

Rust (1975) suggested the KKB of Botswana as a miniature of the main Karoo Basin, an idea supported by Catuneanu *et al*. (2005) who stated that the KKB in Botswana might represent the northern limit of flexural deformation that could be attributed to foreland system tectonism. Daly *et al*. (1989) has suggested the KKB and other central African basins as rifts trending N-S, or pull-apart basins along strike-slip zones.

The nature of the boundary between the main Karoo Basin of South Africa and the KKB of Botswana is in some doubt, except that it was an upwarp, the so-called Cargonian Highlands in existence as early as Dwyka times, and still quite evident during Ecca times (Rust, 1975; Scheffler *et al*., 2006). According to Rust (1975), it is not clear whether the two basins were actually disconnected, especially during Ecca and Beaufort times.

2.2.1.1 Tectonic Setting of the Central Kalahari Karoo Basin

Pretorius (1978) described the Central Kalahari Karoo Basin (Fig. 2.3) as a north-westerly plunging synform, with the flanking areas of crystalline basement forming the complementary anticlines. Most of the faults are inferred as post-Karoo in age, but some are believed to be complex structures reactivated at various times since Waterberg Group times (Williamson, 1996). The faults are considered to be the principal structures controlling the graben-like structures in the basin (Williamson, 1996), and some of them are suggested to be part of a NW-SE trending strike-slip splay system of the Zoetfontein Fault (Fig. 2.3) (ECL, 1998).

2.2.2 Architecture of the Kalahari Karoo Basin

The KKB is a shallow, south and southwest-ward thickening succession of clastic sedimentary rocks (Meixner, 1983; Smith, 1984). The basin fill thickens westward up to ~1500 m in the southwest Botswana sub-basin (Fig. 2.2), and thins northward (maximum thickness ~1000 m) (Meixner and Peart, 1984).

The total thickness of Karoo succession in the CKKB is generally in the order of ~1000 m (Revees, 1978; Meixner, 1983) and is widely covered by the sediments of the Cenozoic Kalahari Group, except on the eastern margin, where few exposures have been established (e.g., Smith, 1984; Williamson, 1996).

2.3 Stratigraphy

2.3.1 Great Kalahari Basin

The lithostratigraphy of the Great Kalahari Basin is generally sub-divided into Lower and Upper Karoo by a regional Mid-Karoo unconformity (Smith, 1984; ECL, 1998). The Lower Karoo (Dwyka, Ecca and Beaufort Groups) accumulated sediments during a period of regional sag, while the Upper Karoo (Lebung and Stormberg Groups) was deposited during a period of regional uplift.

2.3.1.1 Kalahari Karoo Basin

The stratigraphic nomenclature of the Kalahari Karoo Basin is largely adopted from the South African Karoo stratigraphy, owing to correlation with the better-exposed and studied main Karoo Basin. In Botswana, the Karoo Supergroup is covered by the Recent Kalahari beds which hamper the understanding of the geology of the Kalahari Karoo Supergroup, as it obscures nearly the entire extent of the KKB. Hence, when compared to the main Karoo Basin where the Karoo Supergroup is well-exposed and well-documented, the stratigraphy of the KKB of Botswana remains largely unknown. The mainly unconsolidated sandy layers of the Kalahari Group vary in thickness from a few metres to locally more than 200 metres, however over most of the Central Kalahari Karoo Basin, the sand thickness is probably less than 100 metres (Clark *et al*., 1986).

Lower part of the Karoo Supergroup (i.e., Lower Karoo) generally commences with a siliciclastic sedimentary sequence ranging from glacial deposits (**Dwyka Group**) to a succession of fluvio-deltaic rocks, intercalated with coal deposits (**Ecca Group**), and succeeded by fluvio-lacustrine succession (**Beaufort Group**). The Upper Karoo, on the other hand contains fluvial and aeolian strata (**Lebung Group**). Widespread continental flood basalts (**Stormberg Lava Group**) commonly succeed the aeolian facies.

I) Dwyka Group

The Dwyka Group is of variable thickness and of discontinuous development. A general subdivision into a lower and an upper part has been proposed (Green, 1957, 1966; Van Straten, 1959; Boocock and Van Straten, 1962; Smith, 1984). The lower part of the Dwyka Group (maximum thickness of ~140 m) is characterized by the occurrence of tillite/diamictite with or without associated fluvio-glacial strata (Boocock and Van Straten, 1962; Green, 1966). The upper part of the Dwyka Group (maximum thickness of ~146 m) consists of argillaceous and silty beds, always in part varved (Green, 1966), but without any tillite/diamictite.

The Group is well-developed in the southwest Botswana sub-basin (Fig. 2.2), where three formations of regional extent can be recognized (Middlepits, Khuis, and Mmalogong Formations) (Table 2.1; Smith, 1984) and is thin in the eastern part of the country (Smith, 1984; Johnson *et al*., 1996).

II) Ecca Group

The Ecca Group has been divided into the lower, middle and upper parts (Van Straten, 1959; Green, 1961, 1966; Williamson, 1996). The lower part of the Ecca Group (maximum thickness of ~107 m) consists of a succession of fine-grained arenaceous to silty beds, invariably dark-coloured, but infrequently carbonaceous. The middle part of the Ecca Group (maximum thickness of ~165 m) is characterized by the development of yellow and white, medium to coarse-grained feldspathic sandstones with numerous developments of coal seams towards the eastern part of Botswana (e.g., Southern and South-east Belts; Fig. 2.3). Westwards across the KKB, it appears that the coal seams diminish, and the arenaceous strata become predominant (Boocock and Van Straten, 1962; Green, 1966). The sandstone bands become thinner up-sequence and eventually disappear completely, leaving an entirely argillaceous and carbonaceous succession which is distinguished as the upper part of the Ecca Group (maximum thickness of ~138 m) (Green, 1962).

III) Beaufort Group

According to Smith (1984), the fluvial Beaufort Group of the KKB (maximum thickness of ~40 m) consisting of pale grey, non-carbonaceous mudstone, thin limestone and rare tonstein is not well-developed in the KKB and is bounded by unconformities. The presence of the Beaufort Group equivalent strata is a controversial issue in the KKB stratigraphy (Green, 1966), as according to some authors (e.g., Rust, 1975), these beds have not developed at least in the western part of the basin, while others (e.g., Smith, 1984) recognized the possible existence of beds equivalent to those of the Beaufort Group in South Africa. Furthermore, certain extensively-developed, grey mudstones reaching thickness of ~134 m were described by Boocock and Van Straten (1962) as a non-carbonaceous facies of the upper part of the Ecca Group, whereas Green (1966) has indicated that a similar succession of non-carbonaceous, argillaceous strata in northern Botswana is the equivalent of the Madumabisa Mudstones (Beaufort Group) in Zimbabwe. According to Scheffler *et al*. (2006), in the eastern KKB, the Beaufort Group is represented by lacustrine mudstones, siltstones, sandstones and limestones.

The above correlations are only tentative, based on lithological and stratigraphical evidence (i.e., the position of the succession within the overall Karoo Supergroup), the only exception being southern Botswana, the Gemsbok sub-basin, where palynology has confirmed the presence of Beaufort Group strata (Key *et al*., 1998). The age of these deposits however remains undetermined, and thus its correlation with the Late Permian

Beaufort Group of the main Karoo Basin (Visser, 1995) is rather tentative. Because of these uncertainties, no local group name has yet been assigned to these beds (Carney *et al*., 1994).

IV) Lebung Group

The fluvial and aeolian Lebung Group includes all the Upper Karoo clastic formations with red bed affinity (Green, 1966; Carney *et al*., 1994) and broadly equates with the Molteno, Eliott and Clarens Formations in South Africa. The ~150 m thick Group consists of red mudstones, sandstones and medium- and coarse-grained, orange to white sandstones which are either massive or cross-bedded and contain sand grains with frosted surfaces, indicating accumulation under aeolian conditions (Smith, 1984).

V) Stormberg Lava Group

The Stormberg Lava Group forms the youngest group in the Karoo Supergroup, and its K-Ar age determination yielded ages in the order of 180 Ma (Coates *et al*., 1979). The maximum ~400 m thick Group is considered to be the stratigraphic equivalent of the Drakensberg Group of South Africa. Throughout Botswana, it is unconformably overlain by the Kalahari Group, considered to be Late Cretaceous to Recent in age (Smith, 1984).

2.4 Ecca Group Stratigraphy

Since the coal-bearing Karoo strata in the Central Kalahari Karoo Basin and the rest of Kalahari Karoo Basin is hosted by the Ecca Group, it is important to describe this group in a separate section.

The rocks of the Ecca Group in southern Africa comprise sequences of mudstone, siltstone, sandstone, minor conglomerate, and in places coal (SACS, 1980; Cairncross, 1987; Johnson *et al*., 1996; 1997). Its maximum thickness of 3000 m is recorded in the southern part of the MKB (the foredeep) (Catuneanu *et al*., 2005), and elsewhere in southern Africa it is considerably thinner (e.g., ~1000 m) (Johnson *et al*., 1996).

Radiometric age determinations are rare for the Ecca Group of southern Africa, however the age of the lowermost Prince Albert Formation in the southern part of the MKB and the underlying Dwyka Group in Namibia have been determined from tuff beds. These ages are 302 +/- 3.0 Ma and 299 +/- 3.2 Ma for the Namibian Dwyka, and 288 +/- 3.0 Ma and 289 +/- 3.8 Ma for the Prince Albert Formation (Bangert *et al.*, 1999). These absolute ages are generally in agreement with the 290 Ma inferred from palynomorphs (Visser, 1990).

Other dated formations are that of the southern Ecca in the MKB, where the coeval gravity flow deposits of the Tanqua, Laingsburg, and Southern sub-basins (i.e., Ripon Formation and its correlatives) are dated as Artinskian, with possible extension into the Kungurian (Visser, 1995; Scott, 1997 in Catuneanu *et al.*, 2002). This age is supported by the dating of the underlying Whitehill pelagic facies as Late Sakmarian (Oelofsen, 1987 in Catuneanu *et al.*, 2002), and also by radiometric dating of the lower Collingham Formation from ash beds as 270 +/- 1 Ma.

Recent U-Pb ages from zircon grains obtained from arc-related volcanic ashes refine time constraints for depositional events of the SW Karoo basin. These give dates for the Collingham Formation as ~275 Ma, while the youngest dated ashes in both the Tanqua and the Laingsburg depocenters are dated as Late Permian (~255 Ma) (Fildani *et al.*, 2007).

In most southern African basins, Ecca Group consists of two or more formations. The most complex sub-division is in the best developed part of the succession in the southern part of the main Karoo Basin in South Africa where up to seven formations are defined (Catuneanu *et al.*, 2005).

In Botswana, the coal-bearing Ecca Group has been subdivided into several local formation names (Table 2.1; Smith, 1984). In the eastern part of the Central Kalahari Karoo Basin, the basal Ecca shales rest on fluvio-glacial and glacio-lacustrine deposits of the Dukwi Formation, the equivalent of the Dwyka Group (Visser, 1995). In the

Northern Belt, the lower formations of the Ecca Group are commonly absent with the upper sequences attenuated (Green, 1966; Smith, 1984). The Ecca Group in the South-east Belt includes the coal measures above the glaciogenic sediments and below the mainly non-carbonaceous silty mudstones of the Tlhabala Formation. In the Southern Belt of the CKKB, the Ecca Group is more widespread than the Dwyka Group (Dukwi Formation) and overlaps onto the pre-Karoo basement (Smith, 1984). The top of the Ecca Group is taken at the top of the youngest persistent non-carbonaceous mudstones of the Tlhabala Formation (Smith, 1984).

2.4.1 Environment of deposition

Palaeo-environmental analysis of the Ecca Group in southern Africa demonstrated that in addition to regional and localized tectonism, the Ecca Group depositional systems were also affected by eustasy as well as climate changes (Smith *et al*., 1993; Catuneanu *et al*., 2002).

The Permian period of southern Africa is characterized by an assemblage of rocks suggestive of climatic conditions suitable for tundra-type peat bog formation caused by northward shift of Africa from polar to sub-polar regions (Smith *et al*., 1993). These organic-rich postglacial sedimentary rocks were deposited in lacustrine, deltaic and fluvial environments (Johnson *et al*., 1996). The prograding and coalescing of the deltas resulted in the formation of extensive coastal plains (Smith *et al.,* 1993) and supported stable *Glossopteris-Equisetalian* vegetation.

2.4.1.1 Kalahari Karoo Basin

The KKB was characterized by the deposition of fluvio-deltaic sands, muds and peat (Smith, 1984; Catuneanu *et al*., 2005). A marine influence during the early stages of the Ecca Group deposition is indicated from the recognition of a shallow marine bivalve (i.e., *Eurydesma*) in the Southwest Botswana sub-basin (Fig. 2.2) of the KKB (Ellis, 1979).

The Ecca Group accumulated during and after the stages of the glacier retreat, where a complex setting of fluvial and delta plain systems with lacustrine swamps were generated (Smith, 1984; Williamson, 1996). This was a period when plants colonized inland sea shores and interdistributary bay areas and eventually resulted in the accumulation of plant debris that formed coal seams (Modie, 2007).

At the beginning of Ecca Group times the region was characterized by a wide spreading body of water that opened to the sea in the west (Smith, 1984). This was gradually infilled at first by pro-delta muds, then increasingly by arenaceous deposits as fluvially-dominated deltas spread across the KKB (Smith 1984), so that towards the end of Ecca Group times, the region was characterized by slowly subsiding, widespread swampy flood-plains (Smith, 1984).

2.5 Provenance of Sediments

2.5.1 Main Karoo Basin

Palaeo-currents and petrology studies of Karoo Supergroup in the main Karoo Basin indicate source areas from the northern cratonic interior of Gondwanaland (including northwestern and northeastern sources); an eastern source; a southern source (comprising Cape Fold Belt and Panthalassan magmatic arc); and a western source (Ryan,1967 in Stratten,1986; Rust, 1975; Turner and Whateley, 1983; Johnson *et al*., 1996).

Deformation of the southern rim of the MKB, caused by the subducting palaeo-Pacific plate, resulted in mountain ranges in the south and material derived from this source, as well as granitic uplands to the west and north-east formed the source for upper Ecca (Smith, 1990). The subsequent folding of Cape Fold Belt caused significant uplift in the south resulting in the Cape Fold Belt becoming a major provenance of sediments for later Ecca Group in the MKB.

2.5.2 Kalahari Karoo Basin

The siliciclastic debris of the eastern part of Kalahari Karoo Basin was predominantly derived from south, from the Cargonian Highlands (Fig. 2.6, Scheffler *et al*., 2006). These occurred during the postglacial phase when drainage channels cut northward into the Cargonian Highlands and transported the weathered debris into a northern depocenter (Scheffler *et al*., 2006).

Smith (1984) suggested the sources of detritus filling the Central Kalahari Karoo Basin as being from the Precambrian basement to the south, as evidenced by cross-bedding orientation from around Letlhakeng area (Western Belt). These is further supported by the presence of angular quartzo-feldspathic nature of the clasts and the garnet and mica content of the sands, indicating the source of the detritus as being derived from Precambrian granite and gneiss complex, with some reworked sediments from the Waterberg Group (Smith, 1984).

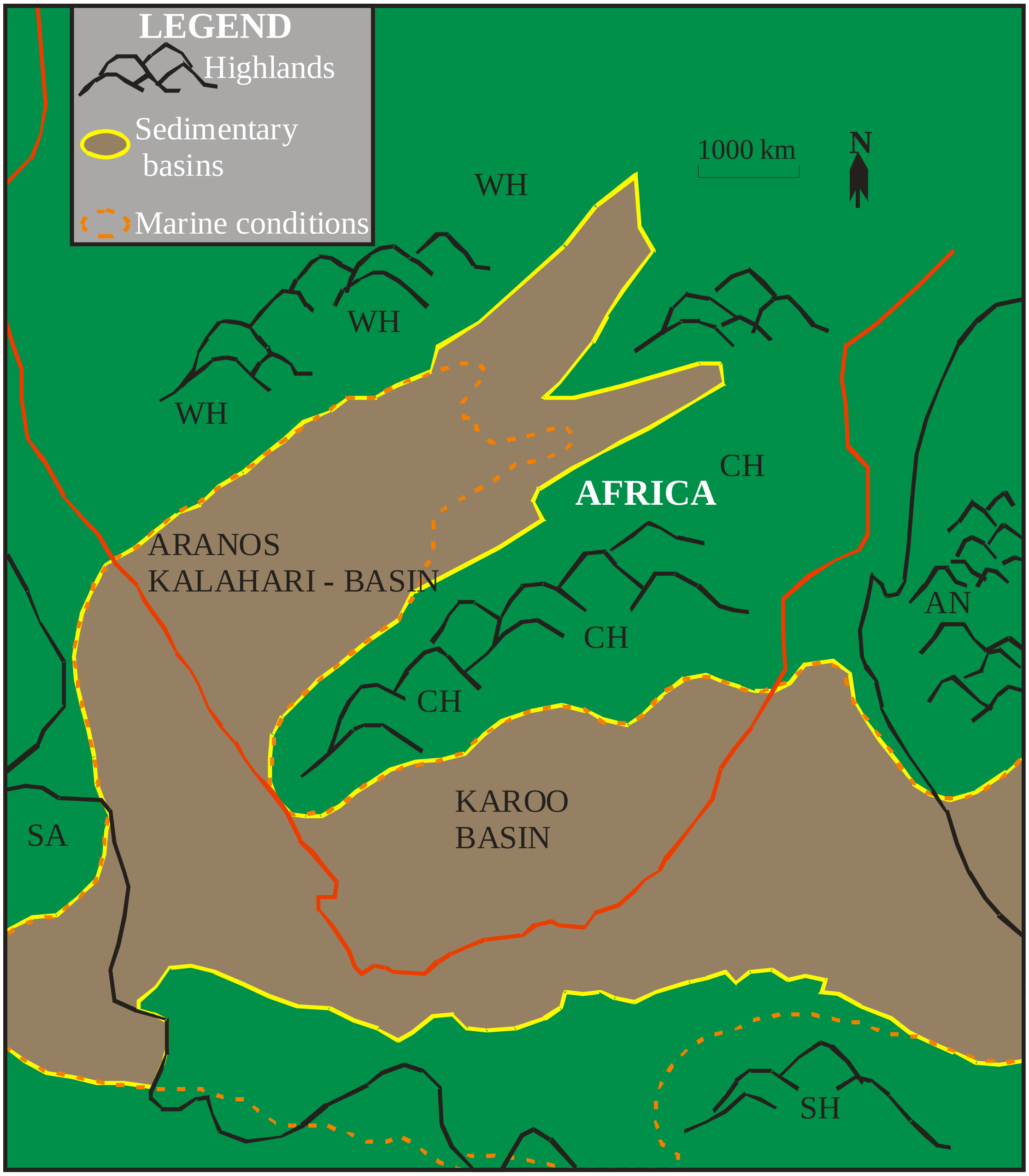


Figure 2.6. Paleogeographic position of the major depocentres of south Gondwana during the Late Palaeozoic (Visser and Prackelt, 1996). WH = Windhoek Highlands, CH = Cargonian Highlands, SH = Southern Highlands, SA = South America, AN = Antartica (Redrawn from Scheffler *et al*., 2006).

Cross-bedding and ripple drift lamination and conglomerate clast imbrication indicates a dominant west direction for the central part of the CKKB (Modie, 2000). Large-scale cross-bedding from foresets in the northern part of the study area shows a westerly direction (Modie, 2000).

Overall, the data indicates the main position of the source areas as been from the east, south-east and north-east.

2.6 Palaeo-environmental setting

The palaeo-environmental settings, including the depositional history and palaeo-climatic conditions which prevailed during the formation of the Karoo Supergroup in Botswana and the other basins to the north of the main Karoo Basin are not well-documented. However, the overall similarity in the vertical lithological sequences in these regions suggest that a progressive shift from glacial to cool, moist conditions to warm, semi-arid and finally hot, arid conditions took place everywhere (Johnson *et al*., 1996).

The Karoo sedimentary sequence was laid down initially under marine conditions, but as the basin developed, and became more terrestrial, the depositional environments sustained an abundant flora and fauna. Of particular interest are the Lower Karoo plants fossils which occur in association with coal deposits and record the evolution and diversification of the *Glossopteris* flora and their eventual replacement by the *Dicroidium* floras of the Triassic (Rayner, 1995).

Permian climate of southern Gondwana is believed to have been influenced by the prolonged Late Palaeozoic glaciations (Plumstead, 1957 in Rayner, 1995), and based on geological and palaeo-botanical evidence, it has been compared to the climate of Siberia or northern Canada today where a strong seasonal climate including very cold winters and temperate summers are common (Rayner, 1995).

Rust (1975) suggested the Early Permian climate having been cold and wet over the eastern half of southern Africa. The Late Permian was characterised by the widespread deposition of red bed facies, indicating a warm climate having a moderate rainfall occurring as a wet season alternating with a dry one (Visser, 1995). Yemane (1993) in Visser (1995) using the distribution of Late Permian climate-sensitive rocks and the presence of fossil flora and fauna, suggested a cool temperate, humid, seasonal climate for southern Africa.

The deposition of the lower part of the Ecca Group occurred in subaqueously reducing, generally moist conditions in marine, lacustrine, deltaic and fluvial environments (Johnson *et al*., 1996).

The Ecca Group in the Kalahari Karoo Basin, belong to the postglacial period which is indicated to have been characterized by a complexity of fluvial and delta plain systems with lacustrine and swampy conditions, in which sandstone, siltstone, mudstone, carbonaceous mudstone and coal beds were accumulated (Smith, 1984; Williamson, 1996).

3.0 Review of coal-forming processes

Peat, the precursor of coal is a sedimentary deposit formed from plant tissues (and their products) and inorganic substances (Cohen *et al*., 1987). Coal is an organic rock derived from chemical and physical transformations of plant biopolymers due to biodegradation during early diagenesis, and by the effects of pressure and temperature acting over long period of time following burial of the peat (Stach *et al*., 1982). Thus, coal is a product of both biological and geological processes acting on plant remains over time, on a specialized environment of deposition (Thomas, 2002).

Coal-quality peat accumulation is primarily dependent on the position of the vegetated swamp surface relative to the water table in the swamp. For optimal peat formation, these two surfaces should coincide, however over time they can move up or down relative to one another and a fixed datum (Fig. 3.1).

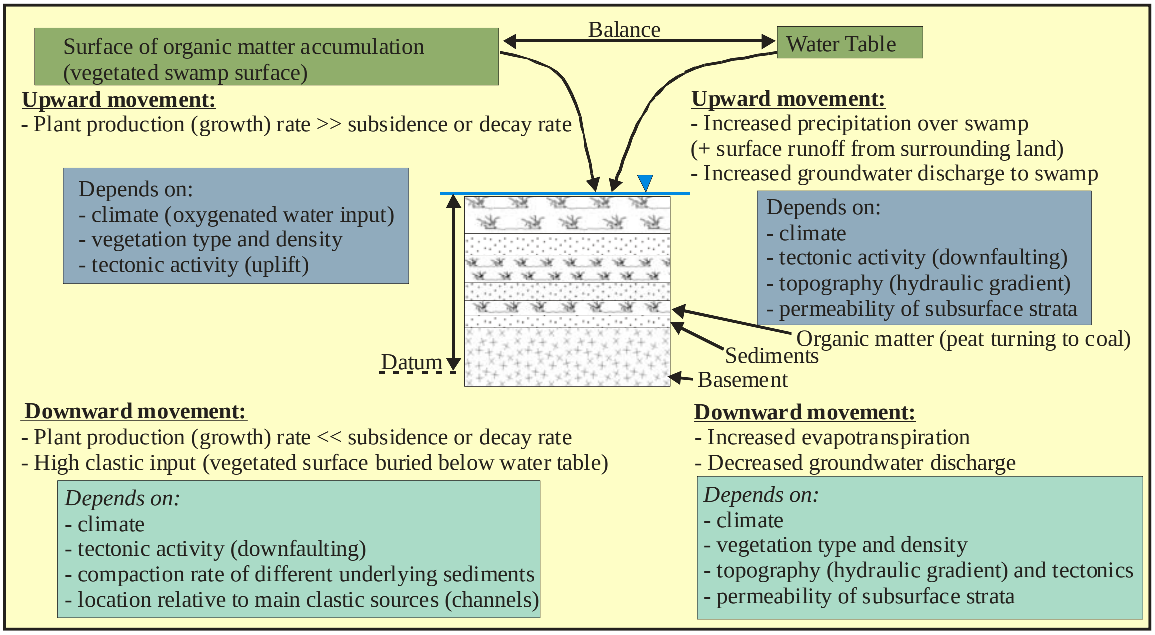


Figure 3.1. Flow chart showing that coal-quality peat accumulation is primarily dependent on the position of the vegetated swamp surface relative to the water table in the swamp (diagram by Bordy and Prevec, 2008).

Peat forms *in situ* in waterlogged, boggy swamps and marshy regions at all latitudes, where precipitation is greater than evaporation and plant growth outpaces plant decay (Clymo, 1987; Moore, 1987; Cairncross, 2001). The rate of decay is determined by the availability of oxygen and thus the decaying process is slow or stopped where organic matter accumulates below water which is relatively stagnant and deficient in oxygen. For peat to accumulate, the water table must be at or above the sediment surface, there must be a large enough source of plant tissues, and the rate of influx of inorganic sediments (e.g., clastics) must be low (McCabe, 1984; Clymo, 1987; Cohen *et al*., 1987; Moore, 1987).

The accumulation of organic muds and the build up of floating peat mats may infill a lake and transfer into a low lying swamp. Due to the relative impermeability of the peat mats, the growth may progressively impede drainage over wider areas and low lying swamps may become very extensive. With time and annual rainfall exceeding evaporation, the peat may aggrade to produce a raised swamp. These swamps are able to build upwards because they maintain their own water table. This evolution of a peat forming environment from a lake fill or low lying swamp to a mature raised swamp, lead to a vertical zonation of peat facies (McCabe, 1984) and produce different properties (e.g., thickness, quality, lateral extent) of coal.

For example, coal forming in floating swamps is thin due to the exposure of the mats to degradation at both their upper and lower surfaces. The peat thickness is also limited by the shallow water in which floating peat forms (McCabe, 1984). Low-lying swamps, in areas far removed from active clastic deposition are suitable environment for accumulation of thick, high quality peat (McCabe, 1984).

These swamps and marshy regions develop under various environmental conditions, namely back-barrier lagoonal, deltaic, fluvial and alluvial fan settings (Heward, 1978; Horne *et al*., 1978; Flores, 1983; Galloway and Hobday, 1983). Coal-bearing strata have shown peat to be accumulating in close association with active clastic depositional environments (e.g., floodplains, coastal swamps, interdistributary bays, and levees of delta types). For these areas to be suitable sites for peat accumulation, raised swamps have to be developed (McCabe, 1984).

Many swamps have developed in areas distinctly different from the environment in which the underlying sediments were deposited. Some coals and adjacent clastics may have been deposited contemporaneously or the underlying sediments may have been deposited long before the establishment of the swamps. Sediments can also be introduced into low lying swamps by floods, storm or high tides (McCabe, 1984). This calls for the understanding of the type of swamp development and the factors which confined clastic sedimentation, as is not the case that the depositional environment of a coal is the same as the underlying clastics. For all these, detailed studies are required to determine the genetic nature of the association between a coal seam and its associated clastics (McCabe, 1984).

Geological factors such as depositional environment, differential compaction, and basin tectonics are considered important in influencing coal geometry, lateral extent and thickness of coal seams during coal formation. Superimposed on these regional geological factors are equally important criteria such as floral assemblages, palaeo-climate, microbiological processes (determining the degree of organic decomposition), temporal and spatial variations in plant communities, and peat swamp chemistry.

An understanding of the depositional environment of overlying and underlying sediments to a coal seam is important in predicting the coal’s properties. A coal to be considered economic, at least one of the following conditions ought to have been operative during its formation: 1) swamp water chemistry should have prevented the accumulation of clastics in the swamp, 2) peat should have formed in raised or floating swamps protected from clastic deposition, and 3) clastic supply should have been cut off during swamp development (McCabe, 1984).

Through all the stages of coal formation, there are associated gaseous products (e.g., coalbed methane), that have found great usage in modern times. Knowledge of the interplay and relationship between coal distribution, coal rank, gas content, permeability, groundwater flow, depositional and structural settings is critical to the evaluation of coalbed methane.

4.0 Economic Potential of the Karoo Supergroup

It is notable that the Karoo Supergroup in southern Africa is of considerable importance for both scientific and economic reasons. Economically, the Karoo Supergroup is important in that it hosts all of the coal deposits of the subcontinent as well as other resources such as coalbed methane, water and uranium. Scientifically, Karoo Supergroup documents critical events in the tectonic development as well as palaeo-climate and palaeo-biology of the region.

4.1 Coal resources of Botswana

Since the 1970's, interest in the coal resources of Botswana has attracted the attention of several companies, resulting in a significant area of the country been examined at varying scales of detail (Fig. 4.1) (Green, 1957; 1961; Van Straten, 1959; Barnard and Whittaker, 1975; Rust, 1975; James, 1976; Shell Coal Botswana, 1977a/b; 1978; 1979a/c; 1982a/d; 1983a/b; BP Coal Botswana, 1983a/b; King, 1984). At present, very large resources of high ash, medium calorific value, low-medium quality bituminous coal have been confirmed to exist in Botswana (Clark *et al*., 1986).

The thicker and better-quality coal seams are found near the eastern margin of the CKKB (e.g., Mmamabula and Morupule areas) and towards the basin interior, the coals are relatively thin (Table 4.1), with much admixed muddy and silty material (Smith, 1984).

At present, there is only one operational coal mine in Botswana at Morupule, where best quality coal has been reported to occur with good yields of medium ash and calorific value (Clark *et al*., 1986). The Mmamabula area (Fig. 4.1), situated about 130 km south of Morupule has also been reported to contain coal of almost similar grade to that at Morupule, and the area is under intense investigation for development of an operational mine for production of electricity (power station), which is planned to be functional by 2011. Coalfields (Fig. 4.1), in Dutlwe, Serule, Foley, Dukwe, Pandamatenga, Bobonong (Tuli), and Ncojane have been suggested less favourable targets for exploration due to different factors such as Late and post-Karoo intrusions and faulting (Clark *et al*., 1986).

Figure 4.1. Areas prospected for coal (Clark *et al*., 1986) and coalbed methane gas (ECL, 1998).

4.2 Coalbed methane resources

Coalbed methane (CBM) exploration has been confined to the central part of the CKKB (Fig. 4.1), where CBM prospects has been reported (ECL, 1998). Two potential areas has been delineated as Lephephe Low and Mmashoro Low, of which the term “low” refers to structural lows, presumably filled by basalt (ECL, 1998). This Lows were highlighted as petroleum prospects by ECL (1998), based on: 1) the potential source rock of the Ecca Group are thicker than other areas, 2) burial depth was sufficient to generate petroleum, 3) thick basalts provided favourable thermal conditions to facilitate maturation, and 4) basalts also served as a seal.

Coalfields Name	Number of seams		Seam Thickness	Quality	Host Formation
Morupule	3 - Seams	Upper (Serowe Bright)	Avg. 1.8 m	AC(32.3); CV (20.73); SC(6.45)	Top of Serowe Fm
		Middle (Lotsane)	0.6 - 4.5 m	AC (36.3); CV (19.59); SC (2.35)	Top of Morupule Fm
		Lower (Morupule Main)	6.5 - 9.5	AC (25.4); CV (23.08); SC (1.52); VM (24.3)	Bottom of Morupule Fm
Mmamabula	3 - seams	Upper seam	Avg. 2.07 m	AC (19.5 - 34.2); CV (18.94 - 25.10); SC (1.68 - 2.19); VM (25)	
		Middle seam	Avg. 5.39 m		Base of Mmamabula Fm
		Lower seam	Avg. 2.83 m		Mosomane Fm
Letlhakeng	2 - seams	E2b	Avg. 1.45 - 3.16	AC (18.7 - 23.3); CV (22.83 - 28.60); SC (1.41 - 1.86); VM (25.3 - 28.3)	Boritse Fm
		G1			
Dutlwe	Seven seams but only two are mineable		1.5 & 4.0 m	Low - grade, low to medium sulphur content, high ash content	Boritse Fm
Serule	2 seams (basal seam thick)		2.7 - 10.6 m	High ash (>30); medium VM (>20)	Tlapana Fm
Foley			2 .0 m	AC (17.7); cv (24.65); SC (0.7) VM (25); FC (57.3)	Tlapana Fm
Dukwe			2.1 m	AC (22.1); CV (24.8); VM (25.4)	Tlapana Fm

Avg. - Average; AC - ash content (%); CV - Calorific Value (MJ/Kg); SC - Sulphur Content (%); VM - Volatile Matter (%); FC - Fixed Carbon (%)

Table 4.1. Coal seams for Botswana coalfieds (for coalfields location and host formation refer to Figure 4.1 and Table 2.1 respectively) (Clark *et al.*, 1986; Bennett, 1989; Cairncross, 2001).

The most prospective area for development of CBM is the eastern portion of the basin where coal represents about 30% of the total coal/shale section and depths are in the range of 300 m to 500 m, comparable to commercially productive depths in the United States of America (Advanced Resources International, Inc. (ARII), 2003).

5.0 Methods and Processes used in this Study

5.1 The Method

Detailed review of the temporal and spatial stratigraphic variation of the coal-bearing successions, including the analysis of facies changes based on over 800, widely distributed borehole records (e.g., core descriptions, gamma logs), field observations and palaeo-current measurements were performed. Utilizing RockWorks®, the subsurface data was processed and results expressed in form of multi-log plots, cross-sections for correlation purposes and thickness maps.

The above mentioned robust set of borehole data resulted from the extensive coal exploration activities in the study area, but in spite the large numbers of holes, the data has its limitations because majority of the holes end just beneath the lowermost coal seam, resulting in insufficient information regarding the lower part of the Ecca Group and Dwyka Group. The borehole core log descriptions also yield little information on the structure and sedimentary characteristics of the rock sequences. To bridge this information gap, an intensive literature review on reports relevant to the study area was also utilized.

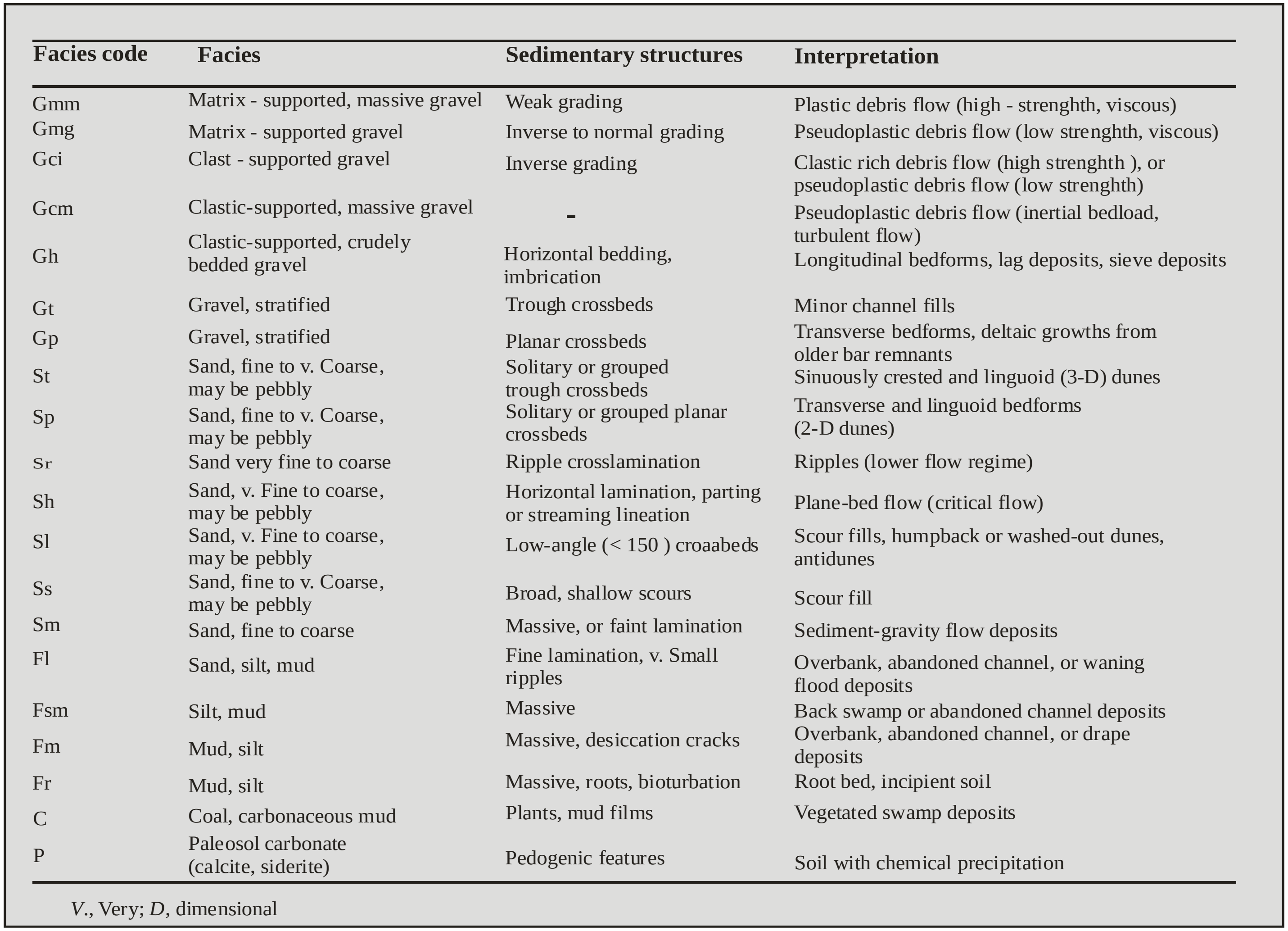
Because of these limitations of the borehole data, priority was given to those boreholes (both water and exploration) that have penetrated the entire lower part of the Karoo Supergroup (i.e., from the Beaufort through to the Dwyka Group and basement).

Since, the boreholes core descriptions were from different companies with different descriptive standards, it was necessary to convert the descriptions to a common format before the data could be used in the lithostratigraphic subdivisions, lithofacies analysis and input into Rockworks® and CorelDraw® for stratigraphic cross-section constructions and correlations.

5.1.1 Lithofacies, facies analysis and facies models

Lithofacies refer to the observable attributes of a sedimentary rock body that can be interpreted in terms of depositional processes (Miall, 2000; Boggs, 2001). These attributes include composition, grain size, textures, bedding characteristics, sedimentary structures, fossils, etc. Each lithofacies represents the physical, chemical and biological parameters of depositional events that generated the rock body itself. Lithofacies can be grouped into lithofacies association or assemblages that are considered the products of a particular depositional environment or sub-environment, and hence characterize the processes that operated in them (Miall, 2000).

The detailed descriptions of all the observable sedimentary features are then used to establish a facies scheme which entails the sub-division of the rock descriptions into descriptive facies (e.g., facies boundaries). A generalized lithofacies scheme (Table 5.1) for describing the deposits of fluvial deposits was erected by Miall (1978). This scheme was modified and now is applied to a wide variety of alluvial deposits, including deltaic successions (Miall, 1990). This lithofacies scheme (Table 5.1) uses codes with two parts, a capital letter for modal grain size (G, gravel; S, sand; F, fines) and lowercase letter for a distinctive texture or structure of each lithofacies. Individual and isolated facies do not have a unique environmental connotation, hence the need for grouping them into facies association which aid in the interpretation of an environment (Miall, 1990).



Facies code	Facies	Sedimentary structures	Interpretation
Gmm	Matrix - supported, massive gravel	Weak grading	Plastic debris flow (high - strenghth, viscous)
Gmg	Matrix - supported gravel	Inverse to normal grading	Pseudoplastic debris flow (low strenghth, viscous)
Gci	Clast - supported gravel	Inverse grading	Clastic rich debris flow (high strenghth), or pseudoplastic debris flow (low strenghth)
Gcm	Clastic-supported, massive gravel	-	Pseudoplastic debris flow (inertial bedload, turbulent flow)
Gh	Clastic-supported, crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits
Gt	Gravel, stratified	Trough crossbeds	Minor channel fills
Gp	Gravel, stratified	Planar crossbeds	Transverse bedforms, deltaic growths from older bar remnants
St	Sand, fine to v. Coarse, may be pebbly	Solitary or grouped trough crossbeds	Sinuously crested and linguoid (3-D) dunes
Sp	Sand, fine to v. Coarse, may be pebbly	Solitary or grouped planar crossbeds	Transverse and linguoid bedforms (2-D dunes)
Sr	Sand very fine to coarse	Ripple crosslamination	Ripples (lower flow regime)
Sh	Sand, v. Fine to coarse, may be pebbly	Horizontal lamination, parting or streaming lineation	Plane-bed flow (critical flow)
Sl	Sand, v. Fine to coarse, may be pebbly	Low-angle (< 150) croaabeds	Scour fills, humpback or washed-out dunes, antidunes
Ss	Sand, fine to v. Coarse, may be pebbly	Broad, shallow scours	Scour fill
Sm	Sand, fine to coarse	Massive, or faint lamination	Sediment-gravity flow deposits
Fl	Sand, silt, mud	Fine lamination, v. Small ripples	Overbank, abandoned channel, or waning flood deposits
Fsm	Silt, mud	Massive	Back swamp or abandoned channel deposits
Fm	Mud, silt	Massive, desiccation cracks	Overbank, abandoned channel, or drape deposits
Fr	Mud, silt	Massive, roots, bioturbation	Root bed, incipient soil
C	Coal, carbonaceous mud	Plants, mud films	Vegetated swamp deposits
P	Paleosol carbonate (calcite, siderite)	Pedogenic features	Soil with chemical precipitation

V., Very; *D*, dimensional

Table 5.1. Facies classification of fluvial deposits (Miall, 1978).

The final stage in the facies analysis is to interpret the sedimentary processes responsible for particular sedimentary features as well as the depositional environments of the objectively described and classified facies associations. This final reconstruction of the palaeo-environment is usually undertaken through the application of an interpretive device, in other words a relevant facies model which is a general summary of a specific sedimentary environment based on many studies of both ancient rocks and recent sediments (Walker, 1984; Miall, 1990; 2000).

Facies models combine the features which may occur within a sedimentary system and therefore can be a powerful tool for the analysis of poorly exposed sedimentary rocks as they act as 1) *norms* for purposes of comparison; 2) *frameworks* to guide future observations; 3) *predictors* in new geological situations; and 4) an *integrated base for interpretation* of the environment or system that they represent (Walker, 1984). However, as with all such summaries and idealizations, rigid following and uncritical use of facies models in any sedimentological research might lead to unnecessary confusion, loss of information or misinterpretation of data primarily caused by the high variability of sedimentary processes (Miall, 1996; 2000).

5.1.2 Subsurface facies analysis

Subsurface data differs from the kinds of data collected from outcrops and modern sediments in many ways. For instance, drill hole data might show a complete section while outcrops rarely do, however no matter how closely spaced the wells may be, they cannot provide as much local information on lateral trends (e.g., thickness and grain size variations) as an outcrop would (Walker, 1984).

Geophysical (petrophysical) well logs are usually applied to supplement the lithological descriptions from core analysis. Well logs are used for correlations between the trace pattern of logs from different wells, so permitting the continuity and relative positions of subsurface formations to be assessed (Wyllie, 1963). Additionally, they can also help in determination of which beds are permeable and thus possibly productive.

There is a variety of such petrophysical logs as they measure different rock properties and hence can be applied for solving diverse geological problems (e.g., identification of lithologies, porous zone, stratigraphic correlation) (Table 5.2) and are described below:

I) SP Log

SP Logs are used for facies analysis and in some cases for correlation. SP log permit correlations in sand-shale sequences, e.g., coals, which are extremely reduced, give a large negative SP deflection or no deflection at all, giving a typical SP log shape. This shapes, in sand-shale sequences, is related to shale abundance, in which, the full SP occurs over clean intervals, and a diminishing SP over shaly zones (Rider, 1996). The SP has now been largely replaced by the gamma ray log for facies identification, and correlation, since the gamma ray log has more advantages (see next section on gamma ray log for the details) (Rider, 1996).

II) Resistivity Log

The resistivity logs are developed for the location of hydrocarbons, facies analysis and for correlation. Through its typical characteristics (i.e., formation's resistivity), information identification on lithology, texture, facies, etc, can be deduced. Resistivity logs do not allow the direct identification of lithologies, but are nonetheless very sensitive lithology indicators, e.g., coal have unusually high, diagnostic resistivities, and therefore easy to identify using resistivity logs (Rider, 1996).

The sensitivity of resistivity logs to subtle lithological changes is the basis for their use in correlation, ideally, logs which correlate well are those which are more sensitive to vertical changes than to lateral variations. Distinctive shapes, trends or peaks over shale zones are related to subtle compositional changes reflecting original pattern of sedimentation and as such can be correlated.

Despite its use in correlation, the resistivity log has its limitations such as: 1) it is influenced by changes in formation pressure and interstitial water salinity which are non-stratigraphic, and 2) post-depositional elements that tend to obliterate the original depositional features.

III) Gamma Ray Log

Gamma ray log can be used for correlation, facies analysis, and to identify lithology (shaliness). Gamma ray log has an inherent advantage for correlation, especially when this concerns shales, since the gamma log values in shales remain constant laterally but changes vertically, an ideal characteristic for correlation. Coals have low gamma ray log values, while shaly coals have a gamma value which depends on the shale (or ash) content.

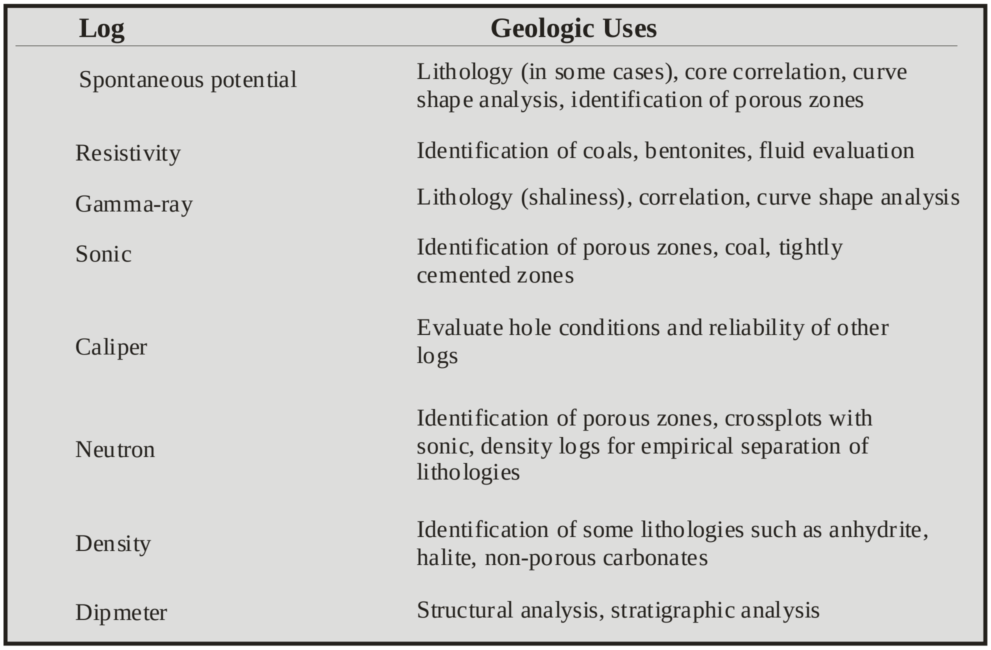
Gamma ray log has many advantages for use in correlation as compared to other well logs such as; 1) it is not affected by depth, 2) it gives some indication of lithology and is simple, and 3) it is repeatable.

IV) Sonic Log

Sonic log helps in identification of lithology, source rocks, and to some extent fractures (Rider, 1996). It is frequently used in correlation. The Sonic log, picks out small variations, probably in texture, carbonate content and sand content, to show a very distinct stratigraphic interval despite the depth differences, a characteristic which makes the sonic log excellent for correlation and even for identification of specific stratigraphic intervals, especially in fine-grained sequences.

V) Density Log

The density log is useful as lithology indicator, assessment of source rock organic matter content, etc. Density log is an excellent indicator of lithology when combined with the neutron log (i.e., neutron-density log combination).



Log	Geologic Uses
Spontaneous potential	Lithology (in some cases), core correlation, curve shape analysis, identification of porous zones
Resistivity	Identification of coals, bentonites, fluid evaluation
Gamma-ray	Lithology (shaliness), correlation, curve shape analysis
Sonic	Identification of porous zones, coal, tightly cemented zones
Caliper	Evaluate hole conditions and reliability of other logs
Neutron	Identification of porous zones, crossplots with sonic, density logs for empirical separation of lithologies
Density	Identification of some lithologies such as anhydrite, halite, non-porous carbonates
Dipmeter	Structural analysis, stratigraphic analysis

Table 5.2. Log types and geological use of the petrophysical well logs (re-drawn from Walker, 1984).

Subsurface facies analysis depends profoundly on the availability of both cores and well logs. Initial environmental interpretations made from cores can be augmented by using, for instance, gamma ray or spontaneous potential well logs, as the analysis of the log curve shapes (Fig. 5.1) is a routine method in interpreting depositional environments.

Features that can be identified from log patterns such as thickness of lithological units, character of bedding contacts, grain-size trend (e.g., fining-upward and coarsening-upward succession) may be used for the: 1) determination of vertical sequence and bedding architecture, 2) recognition and mapping of log facies, and 3) interpretation of depositional environments (Blatt *et al.*, 1991). This analysis when combined with lithological descriptions from outcrops and borehole cores complete the palaeo-geographical and palaeo-geological descriptions of an area.

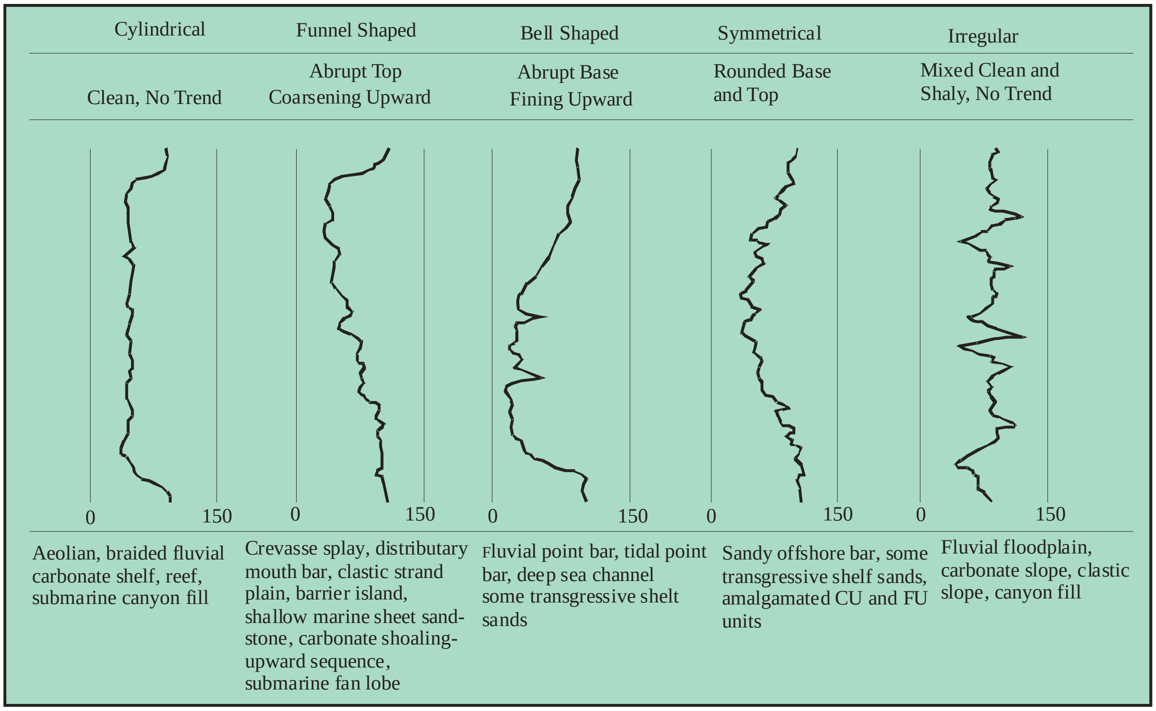


Figure 5.1. Most common idealized log curve shapes and list of some of the depositional settings in which they can originate. Several environments are listed under more than one curve, indicating the logs are not specific to a particular environment (Walker, 1984).

5.1.3 Correlation of logs

In order to achieve a 3-dimensional view of the lateral and vertical trends in any sedimentary basin, correlation of spatially dispersed data is necessary. In the case of well logs or borehole lithologs, this is accomplished by: 1) matching of marker beds i.e., regionally extensive bed or series of beds with distinctive response on any log), 2) the matching of distinctive geophysical log patterns such as the fining- or coarsening-upward sequences. This can also be performed in association with detailed biostratigraphy and sequence stratigraphic (Diessel, 2007).

5.1.4 Sequence stratigraphic approach to coal-bearing strata

Sequence stratigraphic approach permits reinterpretation of well-known coal-bearing strata, solving some of the problems regarding coal seam formation, the stratigraphic record, and cyclicity (Holz *et al*., 2002; Diessel, 2007). The investigation of base level variation and the recognition of key surfaces within the stratigraphic framework of coal-bearing basins provide a clue to a reasonable explanation for the formation of thick, laterally continuous coal seams.

Palynological signatures in the vertical profile of coal seams can aid in distinguishing between transgressive and regressive coal seams. Additionally, petrographic parameters such as vitrinite content and type, vitrinite reflectance, etc., often show significant variations from seam base to top and can be related to the depositional regime (transgressive vs. regressive) under which the precursor peat accumulated (Diessel, 2007).

With a high-resolution sequence stratigraphic framework of a coal basin followed by detailed petrographic analyses of the coal seams, one may predict coal quality and provide guidelines to optimal exploitation.

5.2 Palaeo-current Analysis

Palaeo-current analysis is considered a powerful tool in palaeo-drainage reconstruction. These provide information on the direction of the local and regional palaeo-slope and sediment supply, depositional environment, geometry and trend of lithological units (Potter and Pettijohn, 1977; Miall, 1984; Dasgupta, 2002).

Palaeo-current analysis is dependent of a number of properties found in sedimentary rocks from which current direction can be predicted (e.g., cross-bedding) (Potter and Pettijohn, 1977). The most commonly used measurements for palaeo-current analysis are the dip direction of the foresets (i.e., foresets azimuth) of both planar and trough cross-stratified beds (High and Picard, 1974; Dasgupta, 2002). It has been shown that in most instances, trough cross-stratification is unimodally distributed with small degree of scatter, thus it is a useful, reliable and precise indicator of the channel and main flow direction (High and Picard, 1974; Dasgupta, 2002). Because the scatter in trough cross-stratification is so slight, relatively few measurements of trough cross-stratification are required to yield a good estimate of the palaeoflow as compared to planar cross-stratification which shows a larger degree of scatter.

The main constraints associated with the use of cross-stratification for palaeo-current analysis are: 1) limitation in the variability in local current directions (as observed in recent streams), 2) partial preservation of ancient fluvial deposits, and 3) incomplete outcrop distribution (High and Picard, 1974; Dasgupta, 2002).

In the current study, most of the measurements were obtained from planar cross-bedding in sandstones. Nineteen (19) measurements from the few exposures in the northern and southern parts of the study area were obtained during a field work conducted by the author and seven (7) measurements were from previous unpublished data (Modie, 2000). The western and southeastern parts of the area are poorly exposed and no data was obtained by the author but this gap was bridged by the use of data from previous workers (e.g., Green, 1966; Stansfield, 1973; Smith, 1984; Modie, 2000).

6.0 Presentation and Results

6.1 Stratigraphic subdivision

The stratigraphic subdivision of the lower part (i.e., Dwyka, Ecca and Beaufort Groups) of the Karoo Supergroup in southern Africa is adopted for the Central Kalahari Karoo Basin (CKKB) as part of the Kalahari Karoo Basin (KKB) in Botswana (Smith, 1982a; Smith *et al.*, 1993; Johnson *et al.*, 1996).

The information presented in this thesis regarding the Karoo Supergroup in CKKB is mainly derived from borehole data collected during extensive exploration for coal by various mining companies as well as stratigraphic boreholes drilled by the Department of Geological Survey (DGS) of Botswana over the past 30 years. This subsurface database is augmented by an extensive literature review from previous reports (e.g., Green, 1966; Stansfield, 1973; Smith, 1984; Carney *et al.*, 1994; Williamson, 1996; Modie, 2000) relevant to the study area. All used data (borehole core descriptions, reports, etc.) are kept in the DGS archives.

6.1.1 Dwyka Group

In the CKKB as well as the rest of KKB, the lower boundary of the Dwyka Group is defined by a major unconformity that separates the Karoo succession from the underlying pre-Karoo bedrock (i.e., Archaean suites of the Zimbabwe Craton, Kaapvaal Craton and Limpopo Mobile Belt and the Proterozoic Waterberg Supergroup (Smith, 1984; Bennett, 1989; Williamson, 1996;). The top of the Group is taken at the top of the uppermost bed that shows glacial characteristics such as tillite/diamictite, conglomerate, pebbly sandstones, banded or varved siltstones and mudstones with dropstones (Smith, 1984; Carney *et al.*, 1994; Johnson *et al.*, 1996; Williamson, 1996).

6.1.2 Ecca Group

The base of the Ecca Group is defined at the top of the probable glaciogenic succession of the Dwyka Group (Smith, 1982a) and the appearance of varied sequences of predominantly carbonaceous mudstones, siltstones, sandstones and coals (SACS, 1980; Johnson *et al.*, 1996; Williamson, 1996). In some places the Ecca

Group rests directly on the pre-Karoo surface, indicating a considerable post-Dwyka Group topography and/or localized pre-Ecca erosion (i.e., non-deposition or erosion of the Dwyka Group) (Smith, 1982b, 1984; Williamson, 1996). The top of the Group is taken at the start of the non-carbonaceous, often silty and calcareous mudstones with minor occurrences of fine- to coarse-grained sandstones, siltstones, calcareous nodules and silty limestones of the overlying Beaufort Group.

6.1.3 Beaufort Group

The Beaufort Group in CKKB is characterised by sequences of non-carbonaceous, variegated, siltstones or calcareous mudstones with minor developments of fine- to coarse-grained sandstones, impure micritic limestones, marls and localised breccias (Smith, 1984; Johnson *et al*., 1996; Williamson, 1996). The Group conformably overlies the carbonaceous mudstones and coal-bearing sequences of the Upper Unit (‘*upper coal-bearing member’*) of Ecca Group, and occurs below the regional unconformity at the base of the coarse clastic sedimentary rocks of the Lebung Group.

6.2 Observations

6.2.1 Borehole data analysis

The existing stratigraphic nomenclature for the basin will be reviewed to devise a new simplified scheme with fewer names in order to improve the stratigraphic framework in the area and aid correlation with neighbouring countries (e.g., South Africa and Namibia).

A number of geological cross-sections (Figs. 6.1 & 6.2A - E) were constructed from a total of 114 coal exploration and government borehole log descriptions and 20 geophysical logs (gamma ray). The approach adopted here was the identification of lithologies based on the written and graphical borehole record, subsequent determination of lithofacies and their grouping into environmentally significant genetic units (i.e., lithofacies associations).

The cross-sections were ultimately used to establish the basinal stratigraphic framework in order to understand the spatial and temporal distribution of the different genetic units in the basin, including their three-dimensional geometry and relative proportions (Figs. 6.3 & 6.4).

Furthermore, the analysis of the gamma ray well-logs allowed the identification and confirmation of some distinctive vertical grain size patterns. These curves are mainly cylindrical and rarely bell-shaped both suggestive of upward-fining grain size trends. In addition, a very few upward-coarsening trends have also been recognized. This analysis of the logs helped in fine-tuning the correlation and subdivision of the thicker, undifferentiated sandstone packages of the borehole descriptions.

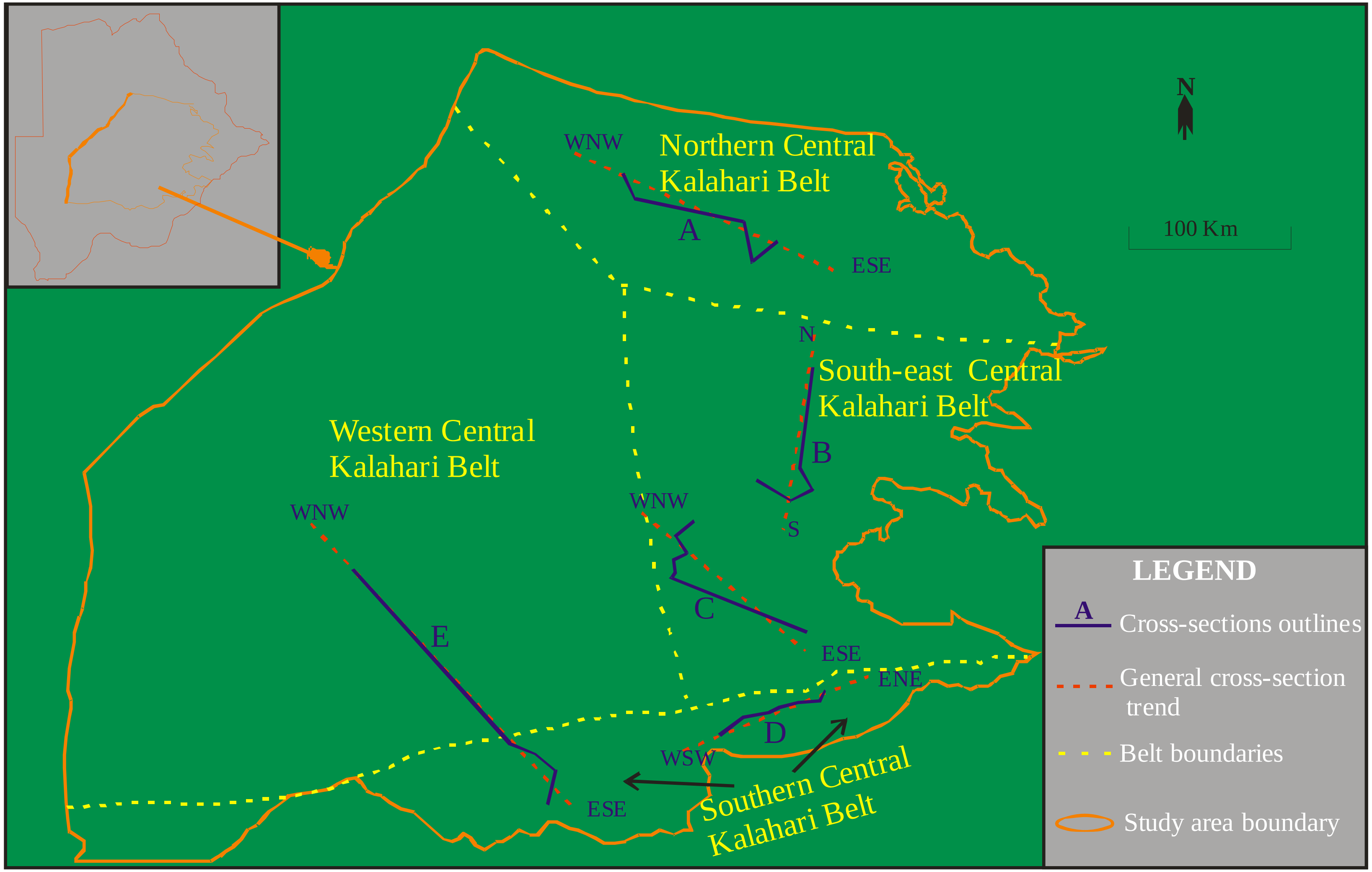


Figure 6.1. Map showing cross-sections constructed in the study area. Insert shows position of the study area within Botswana.

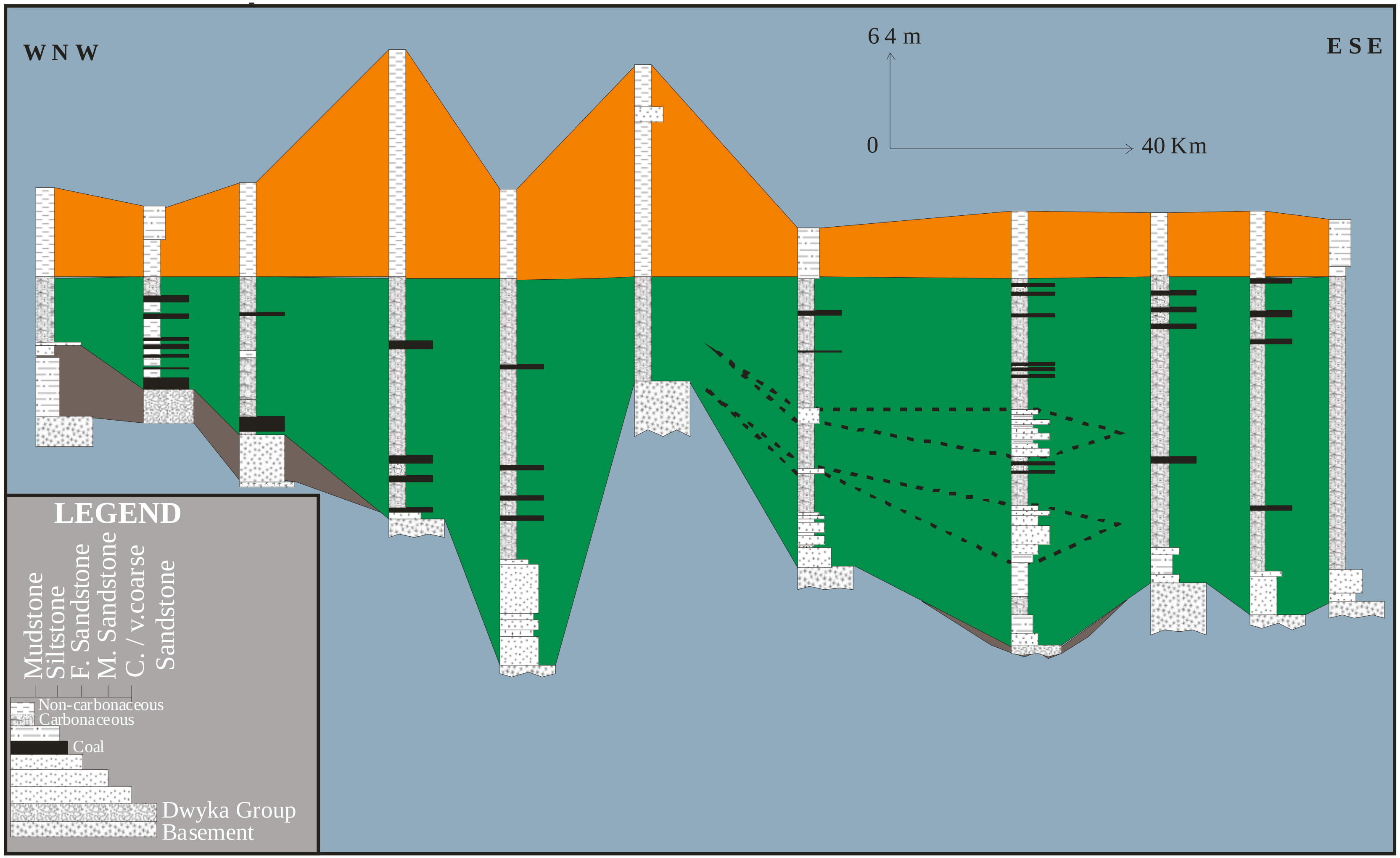


Figure 6.2A. Stratigraphic cross-section A of the Lower Karoo Supergroup in the Northern Belt (for colour codes see Figure 5.3).

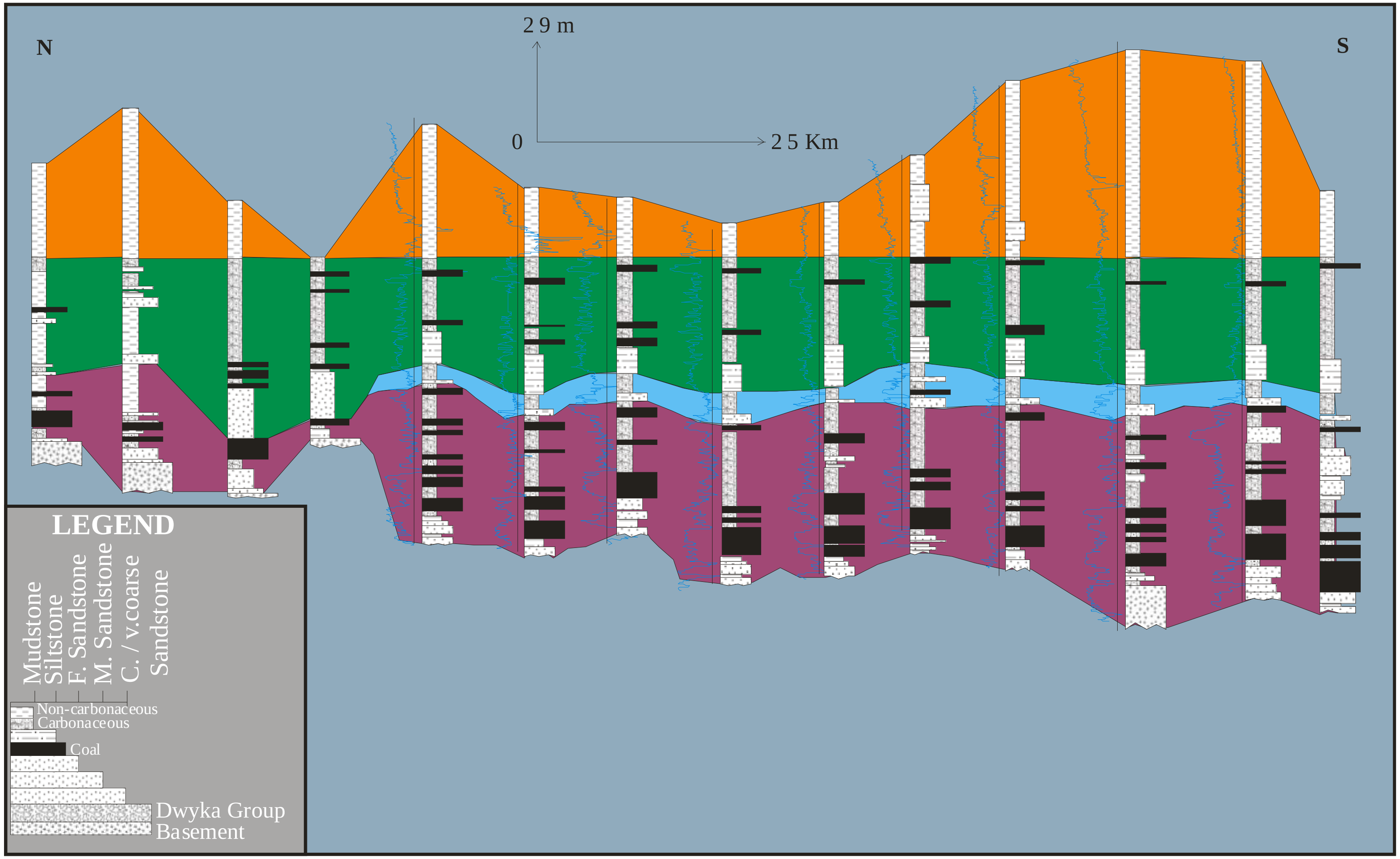


Figure 6.2B. Stratigraphic cross-section B of the Lower Karoo Supergroup in the South-east Belt (for colour codes see Figure 5.3).

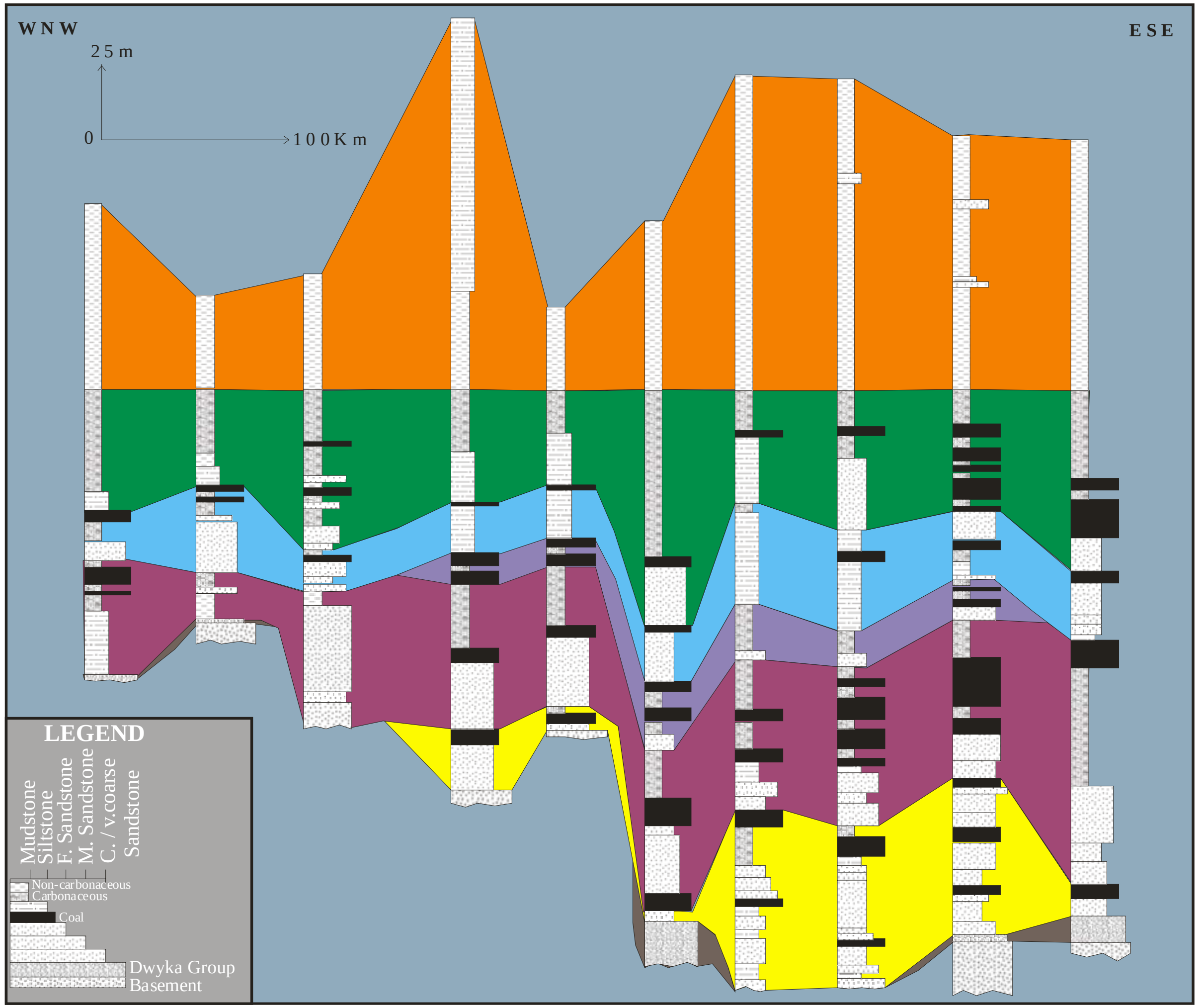


Figure 6.2C. Stratigraphic cross-section C of the Lower Karoo Supergroup in the South-east Belt (for colour codes see Figure 5.3).

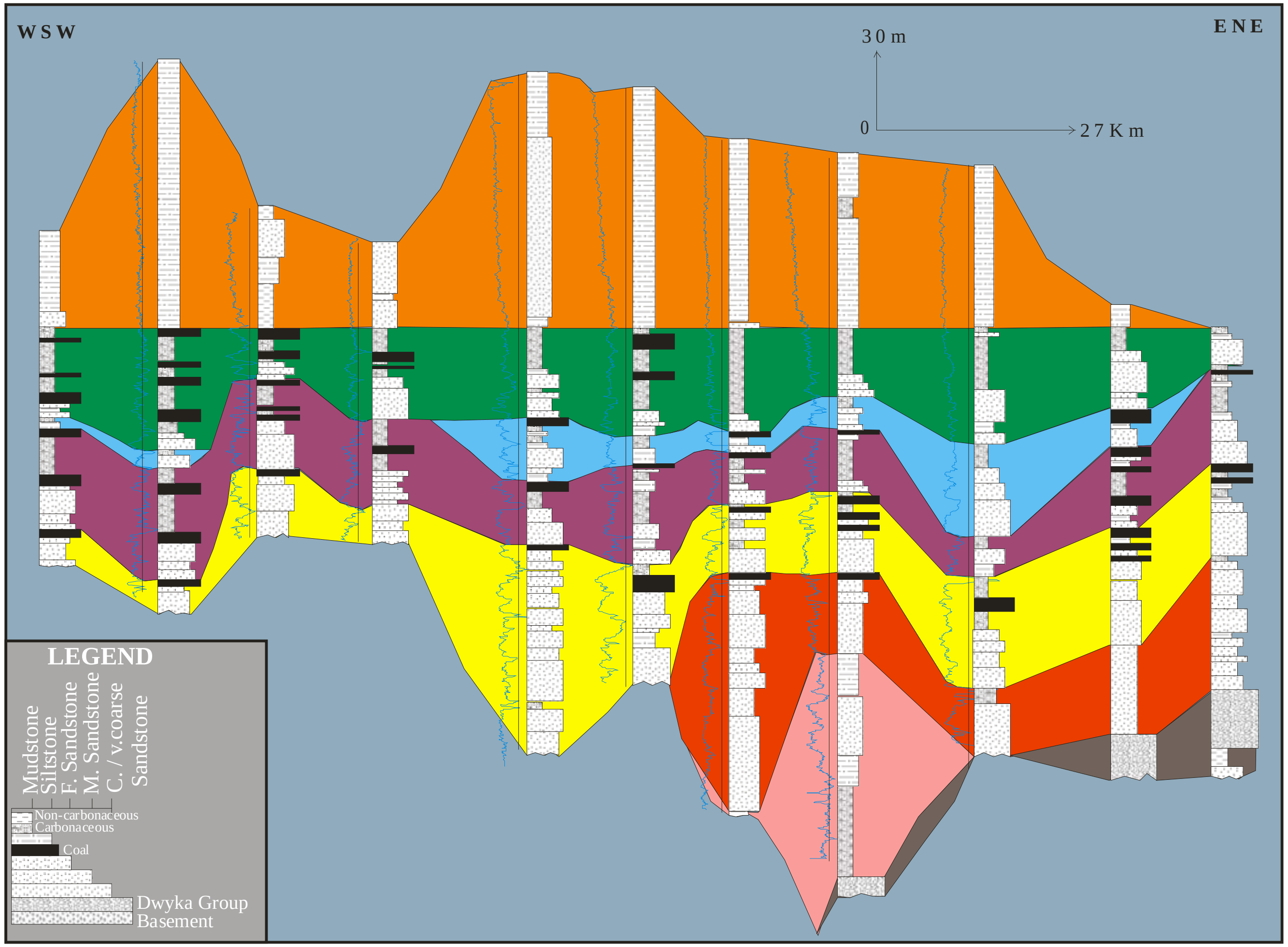


Figure 6.2D. Stratigraphic cross-section D of the Lower Karoo Supergroup in the Southern Belt (for colour codes see Figure 5.3).

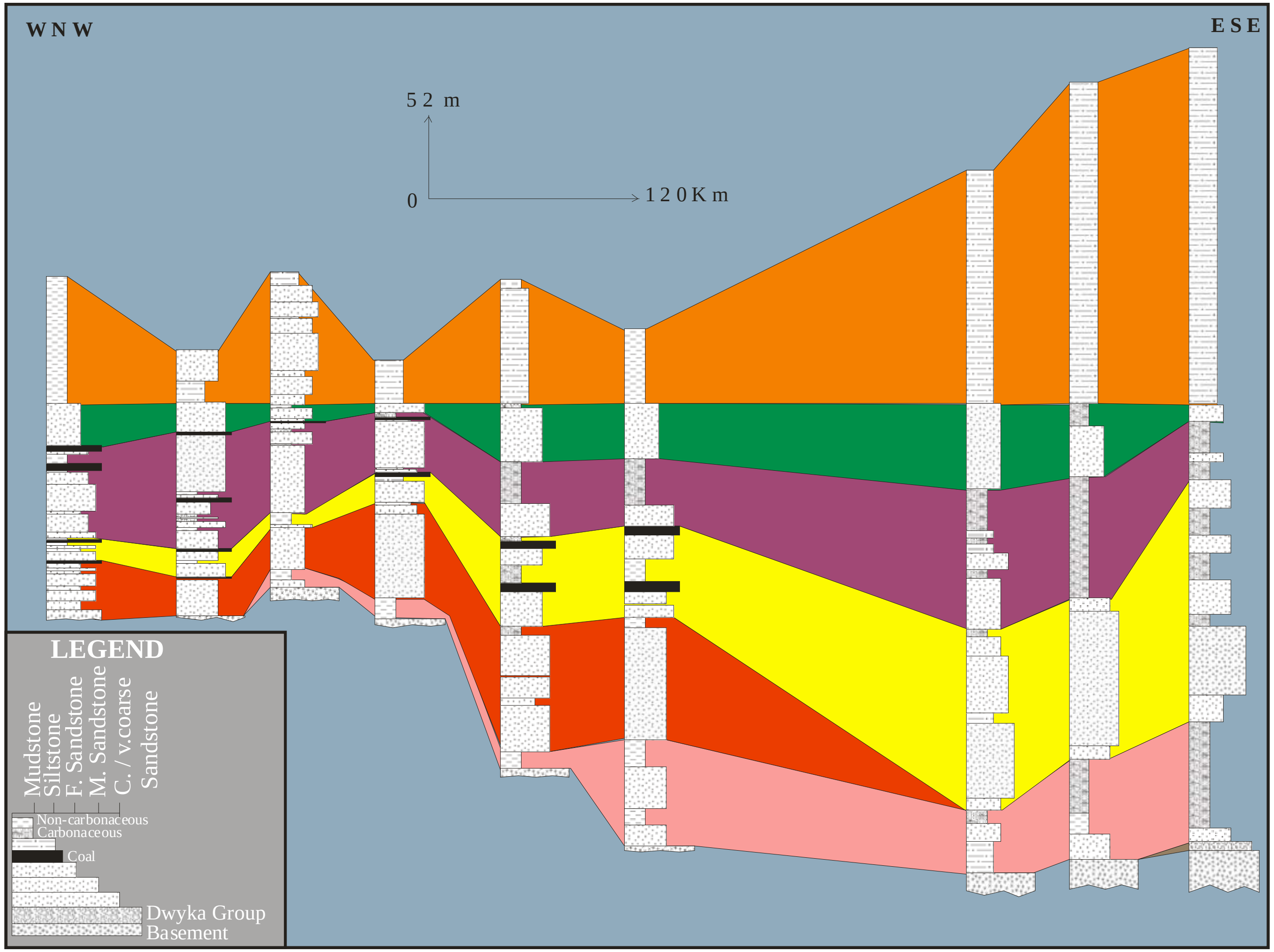


Figure 6.2E. Stratigraphic cross-section E of the Lower Karoo Supergroup in the Western Belt (for colour codes see Figure 5.3).

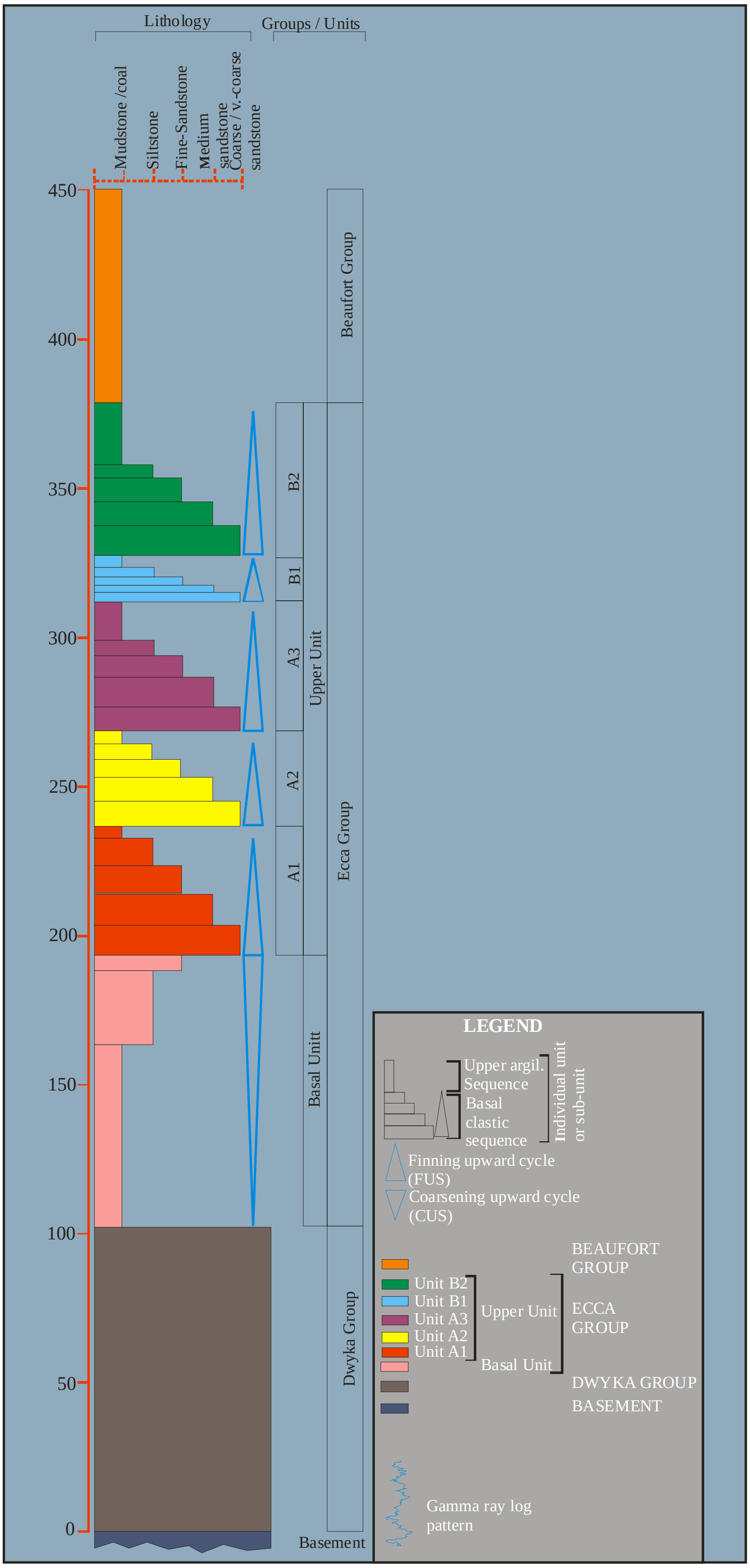


Figure 6.3. Generalised lithostratigraphic sub-division (informal) of the Lower Karoo Supergroup in the Central Kalahari Karoo Basin.

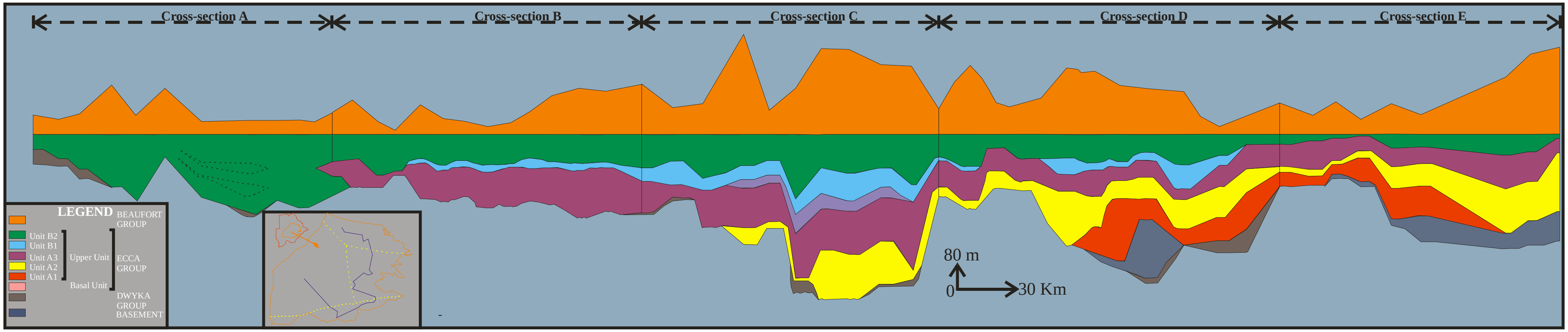


Figure 6.4. Lithostratigraphic section of the Central Kalahari Karoo Basin. Insert shows the position of overall cross-section.

6.2.1.1 Basement Rocks

The basement complex beneath the Karoo Supergroup in the study area consists of mainly high-grade metamorphic and igneous rocks (e.g., gneisses, granites, rhyolites, gabbros, quartzites) from the Archaean suites of the Zimbabwe Craton, Kaapvaal Craton and Limpopo Mobile Belt and the Proterozoic Waterberg Supergroup (Smith, 1984; Bennett, 1989; Williamson, 1996).

This basement complex has a gentle undulating upper surface, rising through the entire fill of the basin forming small isolated basement exposures (e.g., palaeo-highs). Based on the currently available data, it is unclear whether this regional palaeo-morphology has been established prior or during the deposition of the Karoo Supergroup. Because the lowermost two stratigraphic units (i.e., the Dwyka and Basal Unit of the Ecca Groups) show the strongest variation in thickness and pocket-like, sporadic occurrence, it has been suggested that the generation of this palaeo-morphology occurred prior or mainly during the deposition of these units (Smith, 1984; Williamson, 1996).

6.2.1.2 Karoo Sedimentary Units

Detailed analysis of borehole data in the basin confirmed the existence of three distinctive lithostratigraphic units for the lower part of the Karoo Supergroup, namely the Dwyka, Ecca and Beaufort Groups. These are formally recognised units of the Karoo Supergroup in Botswana and the rest of southern Africa (Smith, 1982; Smith *et al.*, 1993; Johnson *et al.*, 1996).

In addition, the current sedimentological investigation of the Ecca Group permitted the division of the Group into informal Basal and Upper Units (Fig. 6.5) based on differences in the abundance of coal horizons as well as upward-coarsening successions (CUS) and upward-fining successions (FUS) as determined by the observed vertical grain size variations. In this way, the Basal Unit is characterised by an upward-coarsening succession of mudstones, siltstones and sandstones, without coal beds whereas the Upper Unit consists of upward-fining successions (FUS) of sandstones, siltstones, carbonaceous and coaly mudstones with coals.

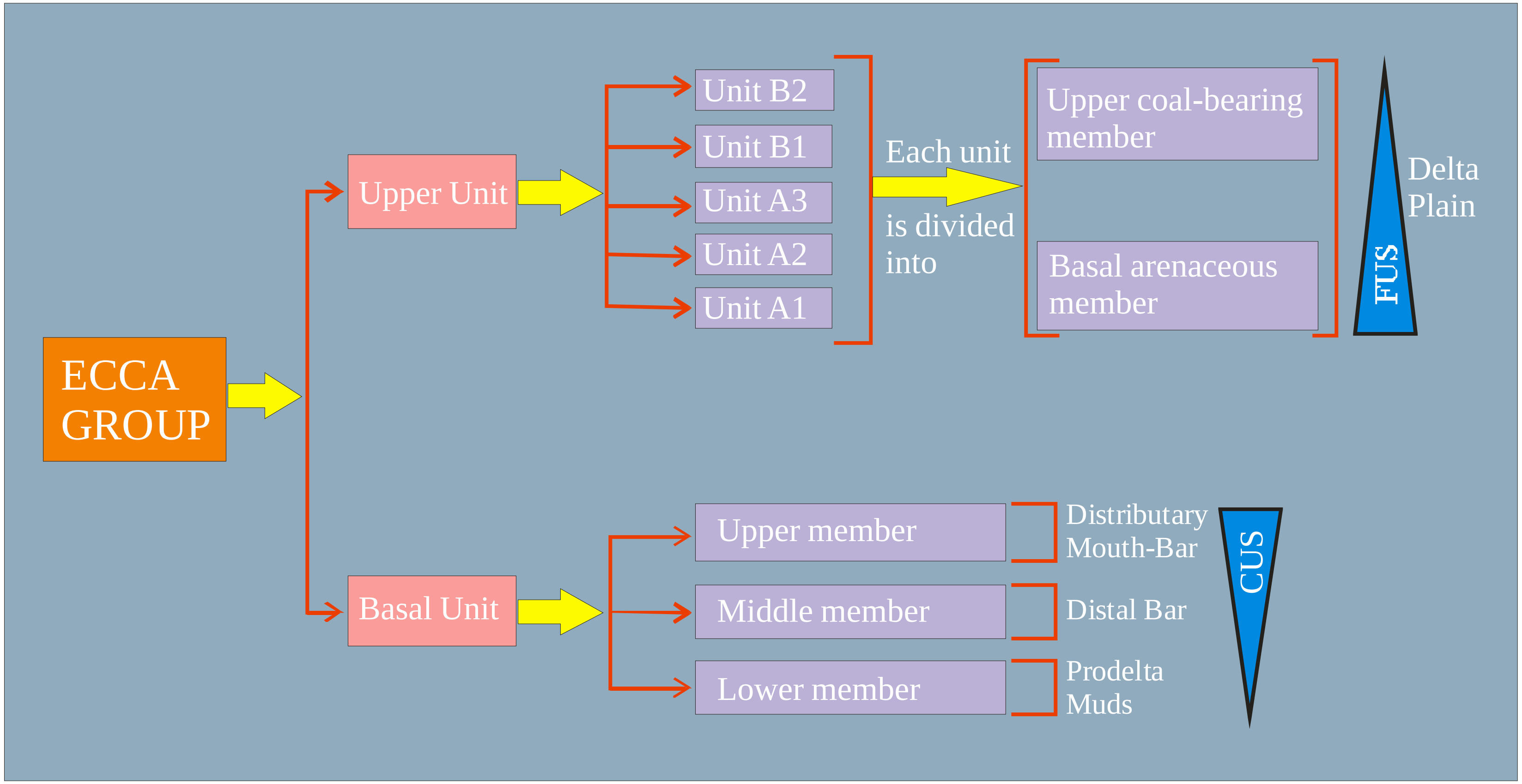


Figure 6.5. Informal sub-division of the Ecca Group in the Central Kalahari Karoo Basin.

Both the Basal and the Upper Units are further sub-divided into members based on facies differences. The Basal Unit consists of *lower, middle* and *upper members*, whereas the Upper Unit has five units, namely Units A1, A2, A3 and B1, B2, each consisting of the *basal arenaceous* and the *upper coal-bearing members*. These divisions and sub-divisions are not recognised in the lithostratigraphic terms of Botswana Karoo Supergroup and therefore are here regarded as informal.

It is noteworthy that because only a few boreholes extend below the economically mineable lower coal zone of the Ecca Group, the stratigraphic architecture for the lower Karoo units is uncertain and thus the current observations had to be augmented by results from previous work in the basin (e.g., Green, 1966; Stansfield, 1973; Smith, 1984; Bennett, 1989; Carney *et al*., 1994; ECL, 1998; Modie, 2000).

6.2.1.2.1 Dwyka Group

The Dwyka Group comprises a broad spectrum of lithologies commencing with the basal tillite, succeeded by conglomerate, sandstone and capped by varvites of siltstone and claystone (i.e., mudstones) (e.g., Green, 1966; Stansfield, 1973; Smith, 1984; Bennett, 1989; Carney *et al*., 1994; ECL, 1998). The Group is mostly absent in the Northern Belt of the CKKB, but locally it may attain a thickness of ~38 m. In the other belts of the CKKB (i.e., Southeast, Southern and Western), the Group shows varying thickness from ~166 m to ~258 m (Smith, 1984; ECL, 1998).

Sedimentary structures associated with this group include slumping and pene-contemporaneous micro-faulting, cross-bedding, sporadic upward fining–successions and dropstones. Cobbles and boulders constituting the conglomerate sequence show striatiations and slickensides in certain areas (Stansfield, 1973; Smith, 1984; ECL, 1998).

6.2.1.2.2 Ecca Group

The Ecca Group in the basin consists of sandstones, coaly and carbonaceous mudstones, siltstones and coals. The thickness of the Group ranges between ~175 m (Northern Belt) and ~300 m (Southern Belt), and its thickness variation in the basin is shown in Figure 6.6.

As previously stated, based on sedimentary facies differences, the Group is subdivided into various units (see section 6.2.1.2) which are presented in the following sections.

I) Basal Unit

The Basal Unit of the Ecca Group forms an overall upward-coarsening succession (CUS) which ranges in thickness between ~40 m (Northern Belt) and ~135 m (Western Belt) (Smith, 1984), with an average thickness of ~90 m.

The *lower member* is a sequence of dark grey, massive or laminated silty mudstones (**Fm, Fsm, Fl**), ranging in thickness between ~20 m (Northern Belt) and ~65 m (Western Belt). Locally, the *lower member* is characterised by the presence of plant fragments as well as pyritic and sideritic bands (Smith, 1984). The member shows a gradual increase in sand upwards into the overlying *middle member*.

The ~50 m thick, upward-coarsening successions of the *middle member* consist interbedded mudstones, laminated, flaser-bedded and ripple cross-laminated siltstones (**Fm**, **Fsm, Fl**) and thin, fine- to coarse-grained, ripple cross-laminated sandstones (**Sr**). The sandstones are characterised by erosive bases, slump structures and bioturbation features (Smith, 1984).

The *upper member* ~10 m thick, consist of massive, sometimes horizontally laminated, fine- to coarse-grained sandstone (**Sh**) that is locally calcareous, micaceous and contains plants fragments (Smith, 1984; Williamson, 1996).

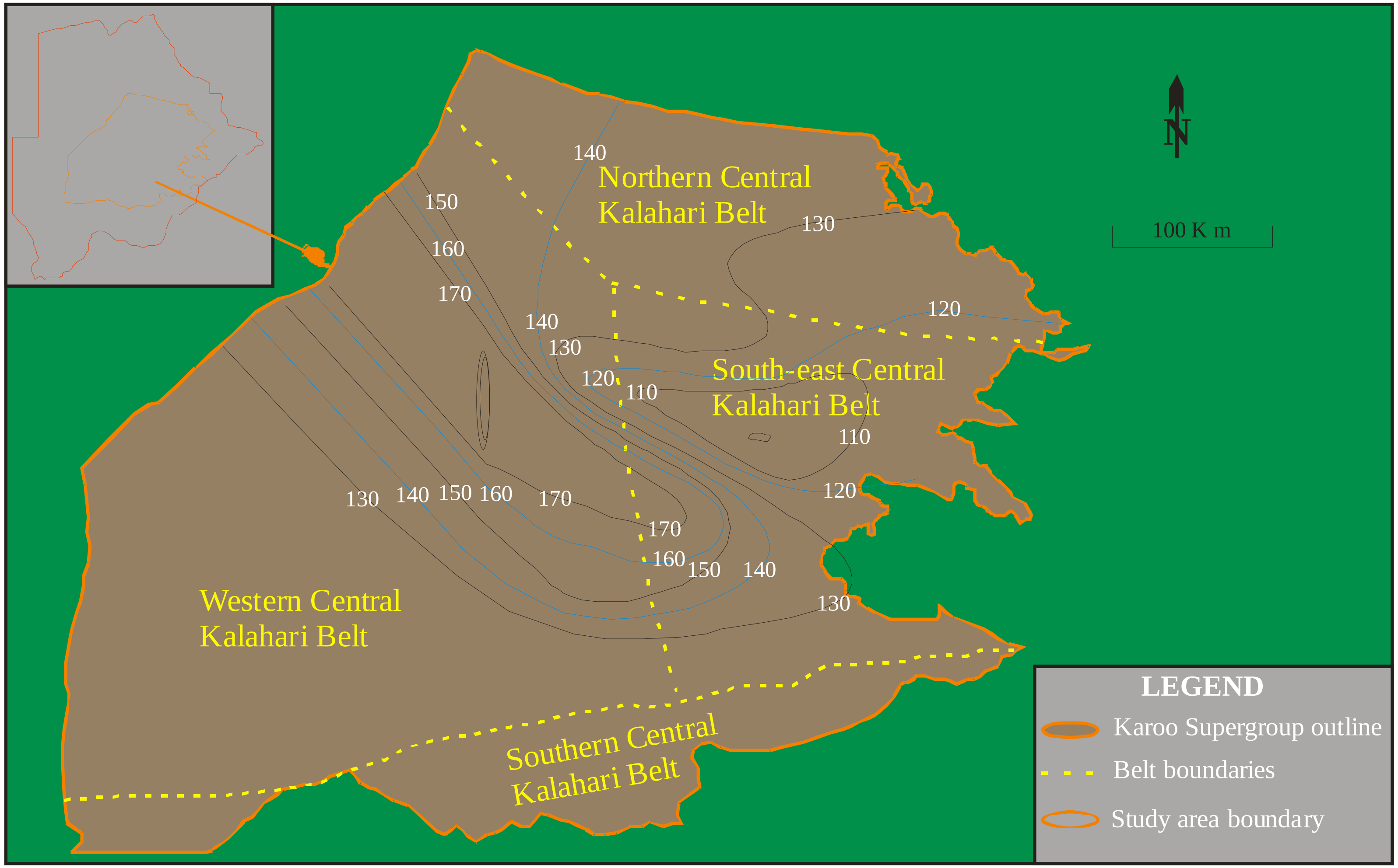


Figure 6.6. Thickness map of Ecca Group in the Central Kalahari Karoo Basin. Contour lines in metres and intervals at every 10 m.

In certain areas (e.g., Mmamabula), this upward-coarsening succession of the Basal Unit is capped by a ~5.0 m thick carbonaceous mudstone (**C**) (Smith, 1984; Williamson, 1996).

The Basal Unit has an uneven distribution in the basin (Fig. 6.7), as it is poorly developed (<40.0 m thick) in the Northern Belt and well-developed (>60.0 m thick) in the Southern Belt. In the Northern Belt, only the *lower* and *middle members* are reported, however in the rest of the basin, all three members are documented (Green, 1966; Stansfield, 1973; Smith, 1984).

II) Upper Unit

The Upper Unit in the study area shows a thickness variation ranging from ~120 m to ~160 m across the basin, with an average thickness of ~140 m. The five informally recognised units (A1 - 3 and B1 - 2) (Fig. 6.4) broadly commence with a *basal arenaceous member* capped by an *upper coal-bearing member* (Figs. 6.2A - E & 6.3).

The *basal arenaceous member* is dominated by massive, medium- to coarse-grained to gritty feldsphatic sandstone with thin interbeds of siltstones, mudstones and coal lenses forming either individual or stacked upward-fining successions (FUS). The *upper coal-bearing member* is characterised by carbonaceous, coaly mudstones and coals with thin upward-coarsening successions (CUS) of sandstone bands or lenses.

Laterally in a southward direction, the *basal arenaceous member* of unit B2 shows gradual change from sandstone (Figs. 6.2A - C) to siltstone (Fig. 6.2D) then back to sandstone (Fig. 6.2E).

Units A3 and B2 are laterally persistent across the basin, but unit B2 is more persistent than unit A3 (Fig. 6.4). Figures 6.8A – D shows the thickness maps for all the units with the exception of Unit A1, which was only intersected in a few boreholes, the remainder stopping higher in the succession. Northward, Unit A3 thins and pinches out, whereas unit B2 thickens and thus represents the entire Upper Unit of Ecca Group in the Northern Belt (Fig. 6.4). The three less persistent units (i.e., A1, A2 and B1) thin and pinch out both to the north and south.

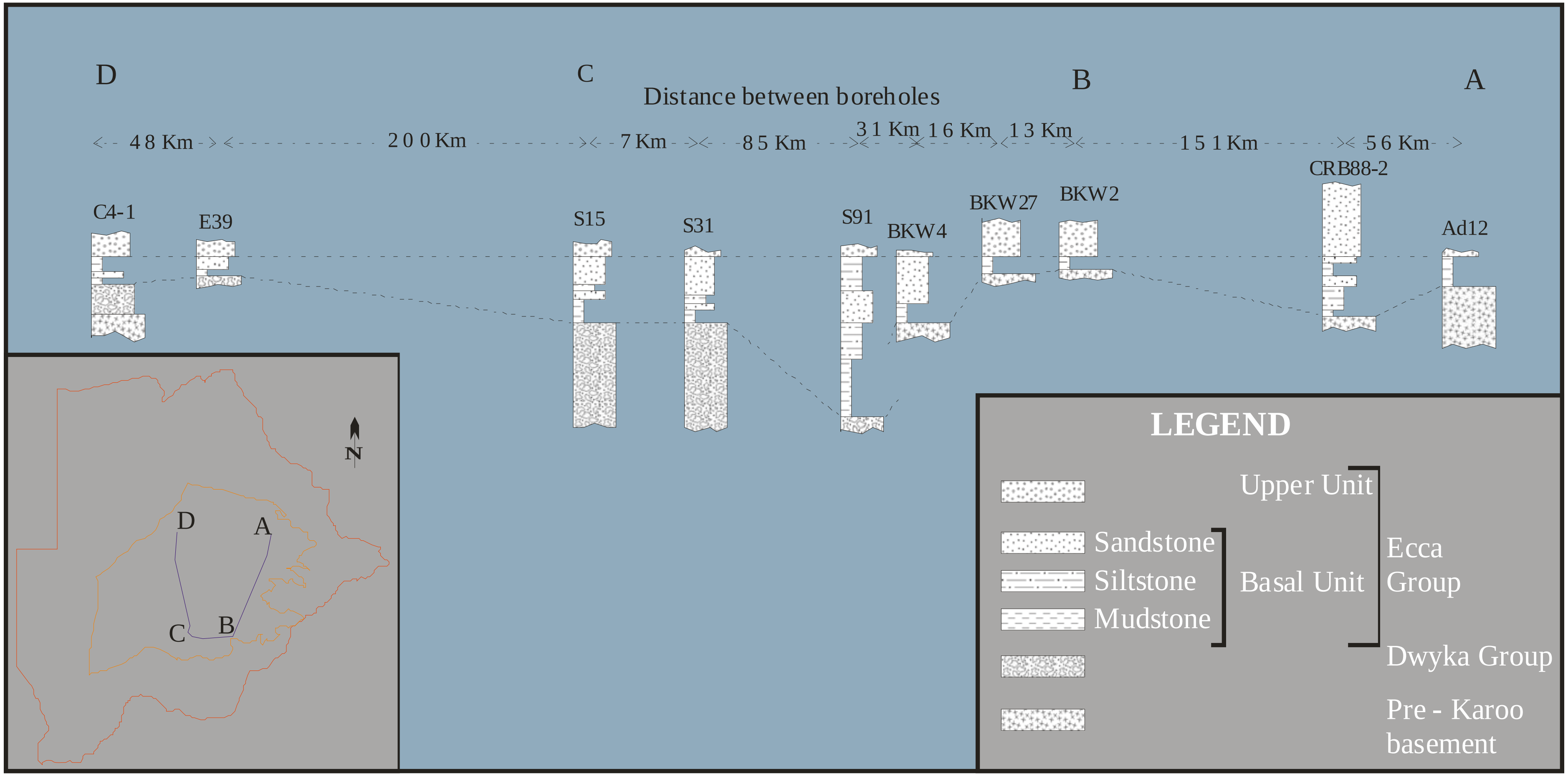


Figure 6.7. Representative boreholes through the Basal Unit of the Ecca Group in the Central Kalahari Karoo Basin.

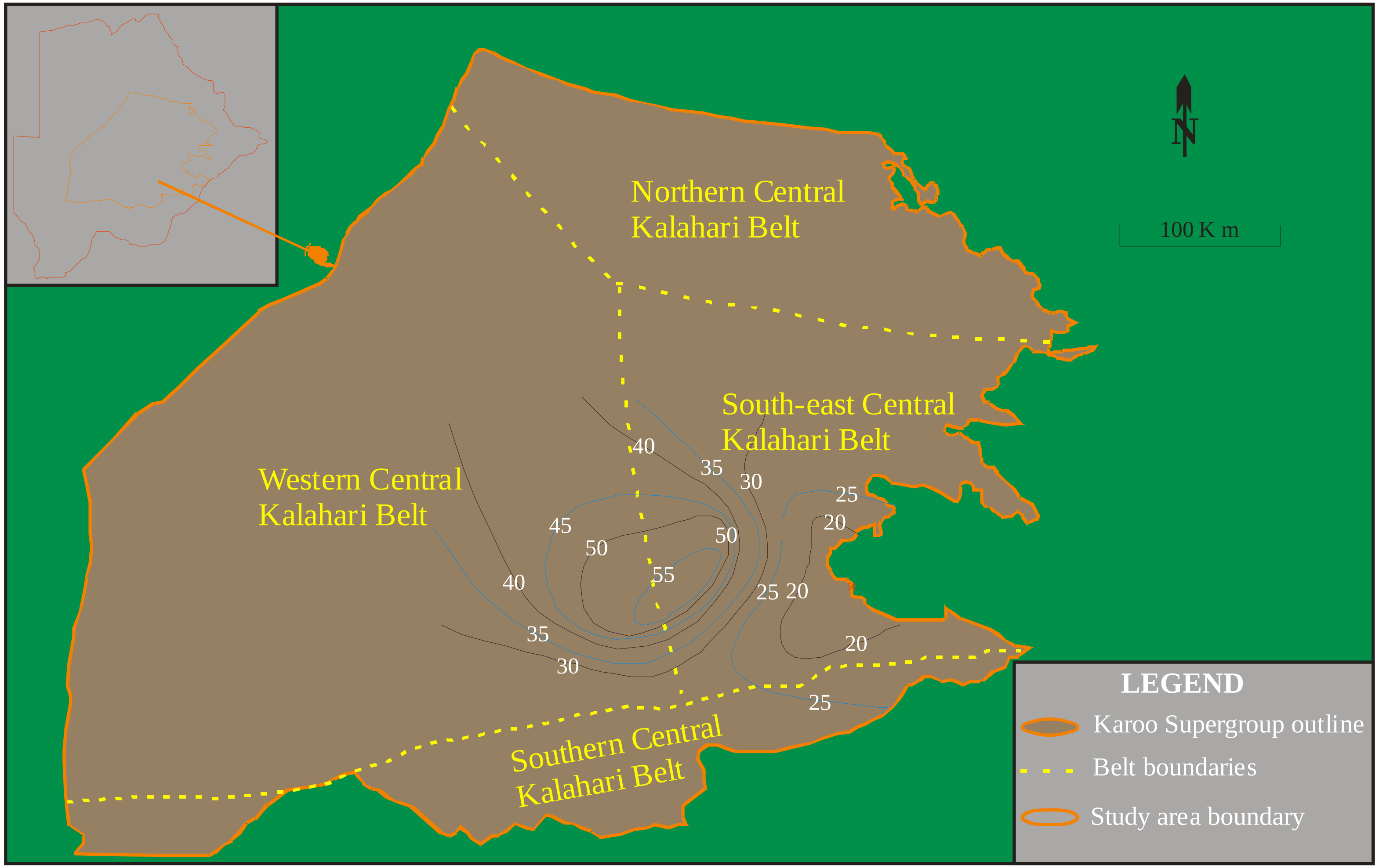


Figure 6.8A. Thickness map of Unit A2 in the Central Kalahari Karoo Basin. Contour lines in metres and intervals at every 5 m.

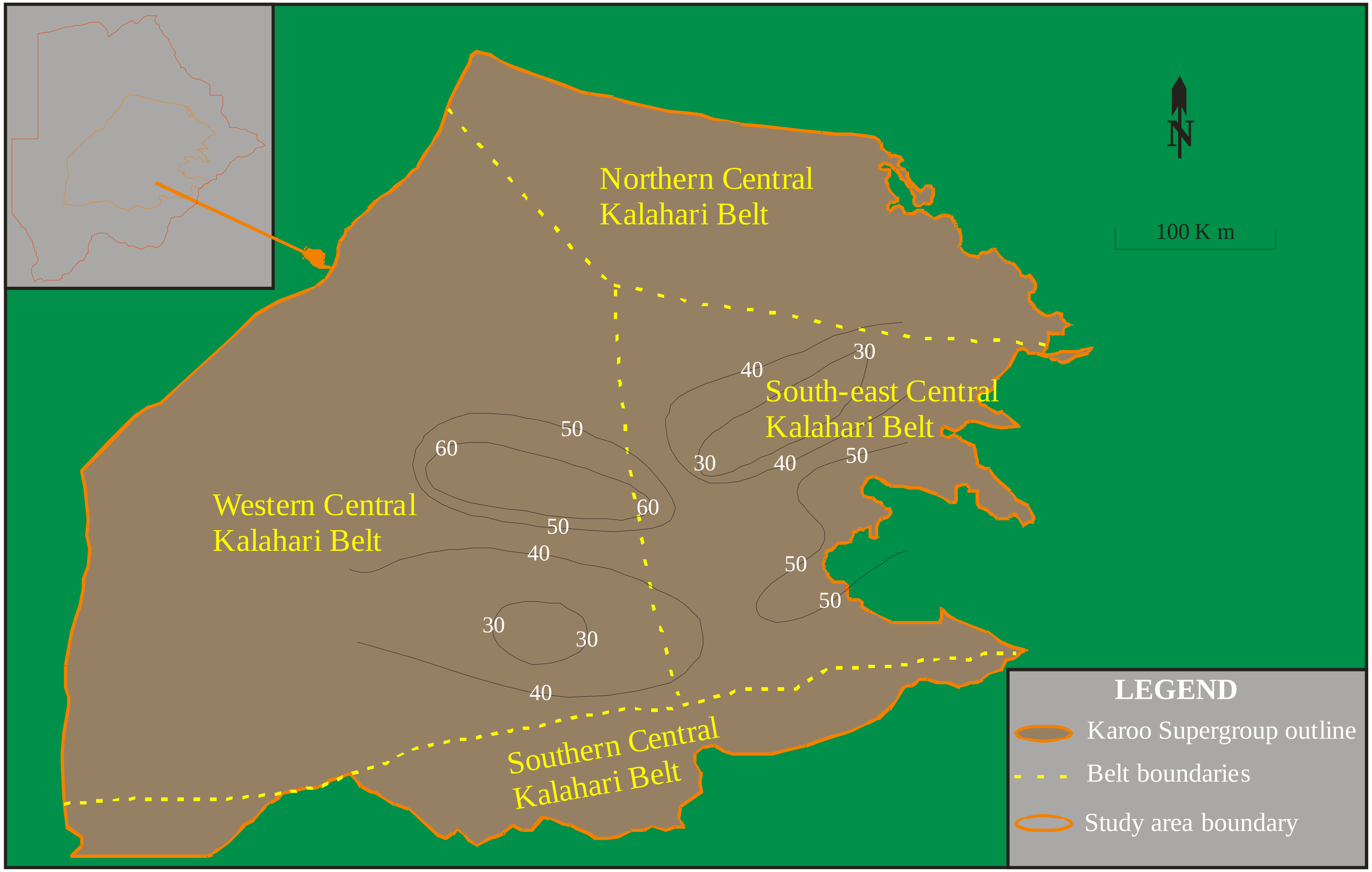


Figure 6.8B. Thickness map of Unit A3 in the Central Kalahari Karoo Basin. Contour lines in metres and intervals at every 10 m.

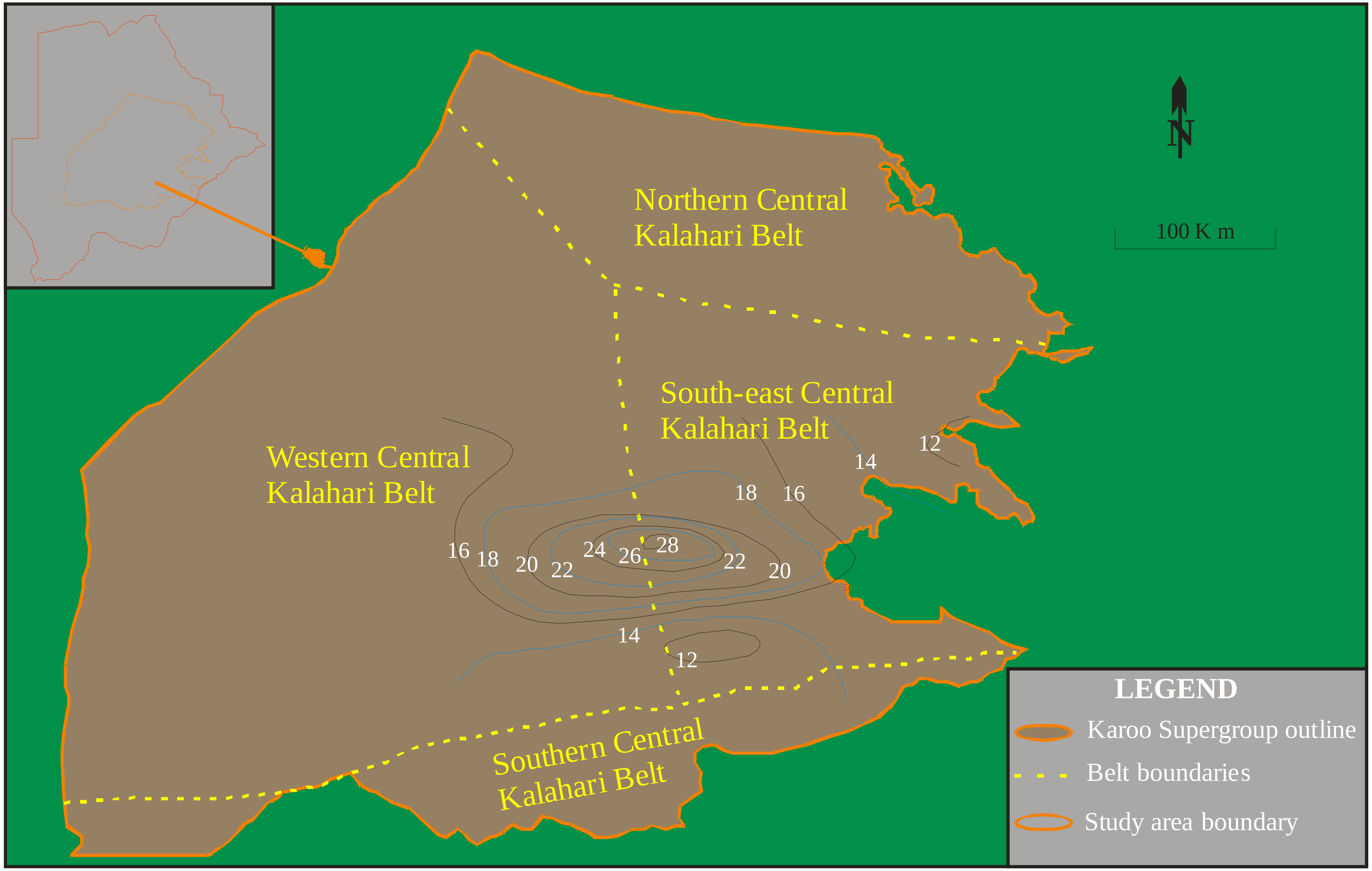


Figure 6.8C. Thickness map of Unit B1 in the Central Kalahari Karoo Basin. Contour lines in metres and intervals at every 2 m.

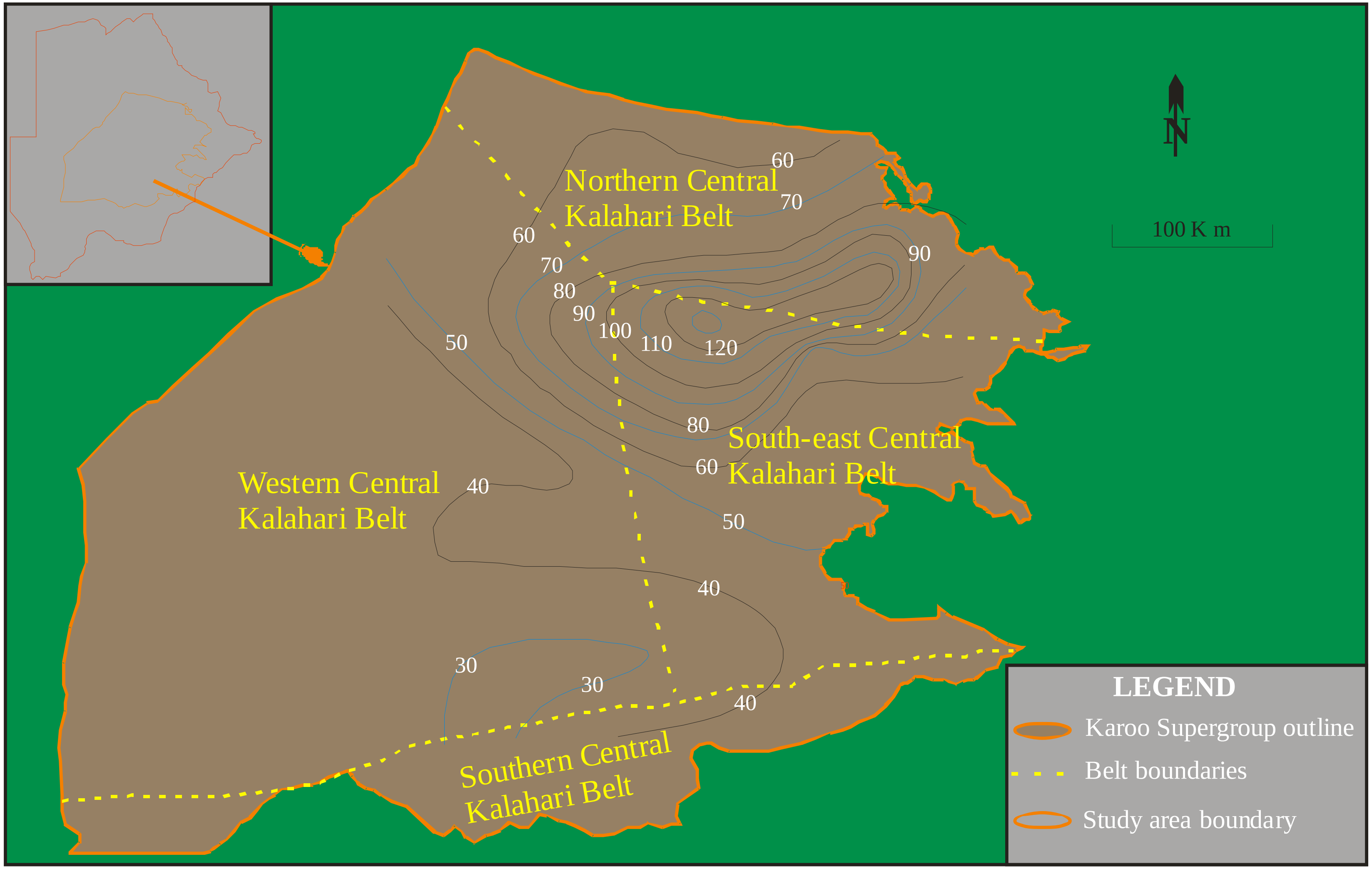


Figure 6.8D. Thickness map of Unit B2 in the Central Kalahari Karoo Basin. Contour lines in metres and intervals at every 10 m.

It is worth noting that the true extent of units A1 and A2 is uncertain northwards as most of the boreholes (Fig. 6.2B) do not penetrate the entire Karoo succession and this might mean that the units extend or even expand in thickness beyond their currently perceived lateral limit.

i) Basal arenaceous member

The *basal arenaceous member* for the five units will be grouped and discussed together as available borehole descriptions are not sufficient enough to warrant separate descriptions.

The member displays an overall upward decrease in grain size from conglomeratic basal lag at the base, to very coarse-grained, to medium- to fine-grained sandstone at the top. In some places, these individual (3 to 12 m thick) or stacked (up to ~40 m thick) upward-fining successions (FUC) are capped by siltstone and carbonaceous mudstones. The sandstones are moderately to poorly sorted, contain gritty to pebbly layers and mudstone rip-up clasts, and have erosional bases.

Sedimentary structures associated with the *basal arenaceous member* include cross-bedding (mainly trough), graded bedding, horizontal lamination, flaser bedding and slumping. The upper parts of some sequences show bioturbation features.

The *basal arenaceous member* is composed of the following sedimentary facies assemblages distinguished on the basis of grain-size and sedimentary structures (e.g., Green, 1966; Stansfield, 1973; Smith, 1984; Williamson, 1996; Modie, 2000):

- Massive or structureless strata (**Sm**)
- Trough cross-bedding with rare low-angle cross-bedding (**St**, **Sl**)
- Planar cross-bedding (**Sp**)
- Ripple cross-lamination (**Sr**)

Thin section analyses revealed high quartz content, low-sphericity and moderate to high angularity of the grains (Stansfield, 1973; Modie, 2000). Sandstones occasionally display micaceous partings and are locally rich in silty to clayey matrix hence the sandstones are often immature. Large-scale, trough cross-bedding (**St**) with set thickness of 20 m were reported around Kweneng area by Modie (2000). Thin (~5.0 m), localized upward-coarsening successions within the assemblage are also reported (e.g., Williamson, 1996). The trace fossil *Siphonichnus eccaensis* was reported at the top of a fine-grained sandstone succession in the Western Belt of the CKKB (Stanistreet *et al*., 1980).

The associated basal lag is mainly a matrix-supported (**Gmm**), rarely a clast-supported conglomerate (**Gcm**) which consists of rounded to sub-rounded pebble- to cobble-sized clasts of ~2 to ~10 cm in diameter. The conglomerate either occurs on erosive surfaces at the base of the upward-fining successions or as bands within the coarse-grained sandstones. In some places, crude planar parallel stratification and poorly developed clast imbrication are displayed (Modie, 2000).

ii) Upper coal-bearing member

The *upper coal-bearing member* normally forms the top part of the units (Figs. 6.2A – E & 6.3). It consists predominantly of coaly, carbonaceous and non-carbonaceous mudstones as well as coals and thin lenses of siltstones and sandstones. The sequence ranges in thickness from ~2 to ~40 m.

The *upper coal-bearing member* is composed of the following sedimentary facies assemblages:

- Massive, non-carbonaceous, coaly and carbonaceous mudstones and coals (**Fm**, **Fsm**, **C**)
- Massive, rippled or laminated siltstones (**Fl**).

The siltstones are mostly non-carbonaceous, and are bioturbated in places. In some parts, the massive mudstones (**Fm**, **Fsm**) are so fine-grained that they display conchoidal fractures (Green, 1966; Smith, 1984).

6.2.1.2.2.1 Coal Development

The coal-bearing zones in the basin are referred to as the *upper coal-bearing members* in the current study. These zones contain many coals, the majority of which are thin (rarely exceed ~1.5 m thickness).

There are few instances where the coals are resting directly on thin (~4.0 m) impermeable strata (e.g., mudstone, siltstone) which in-turn is underlain by thick sandstone (e.g., Southern Belt). In most cases, the lower coal seams are directly underlain by coarse-grained sandstones. Where coals are resting directly on thin impermeable strata or on the sandstones and are overlain by mudstones, the coals are thicker (ranging between ~5.0 and ~14 m), averaging ~9.0 m, but are thinner (up to ~6.0 m thick) where overlain by the sandstones (e.g., Mmamabula area and some parts of Southeast Belt).

The mudrock-hosted coals are relatively thin (~5.0 m) but laterally extensive and in most cases the coals are only about 1.0 m in thickness. The associated inferior coals (as thin as ~0.1 m) usually occur as interbedding and/or alternating with carbonaceous and coaly mudstones.

6.2.1.2.3 Beaufort Group

The Beaufort Group forms the uppermost part of the lower Karoo Supergroup in the study area. The succession consists of silty, non-carbonaceous, and calcareous mudstones with carbonaceous plants fragments at the base (e.g., Northern Belt; Smith, 1984) and siltstones. The mudstones are gently laminated (**Fl**) or massive (**Fsm**) (Williamson, 1996), whereas the siltstones are either finely laminated or thinly bedded (**Fl**) (Modie, 2000). Minor development of ~3 m thick, upward-fining successions (FUS) of fine- to coarse-grained sandstones, siltstones, and limestones occur locally (Smith, 1984; Modie, 2000). The sandstones have erosive bases and are moderately well-sorted, and contain rip-up mudstone clasts (Smith, 1984; Williamson, 1996). The Northern Belt and Southeast Belt of the CKKB are characterised by non-carbonaceous mudstones with partings of coaly streaks and siltstone lenses (Figs. 6.2A - C). In the Southern and Western Belts, the same stratigraphic position is occupied by a sandy, silty succession consisting dominantly of siltstones with sandstones and mudstones (Figs. 6.2D - E).

Sedimentary structures in the sandstones include planar cross-bedding (**Sp**), trough cross-bedding (**St**), horizontal lamination (**Sh**), ripple cross-lamination (**Sr**), graded bedding and desiccation cracks, and bioturbation features (Smith, 1984; Williamson, 1996; ECL, 1998; Modie, 2000). Ripple-drift lamination, convolute lamination and local water escape structures are reported from the siltstones in the Northern Belt (Modie, 2000).

6.2.1.3 Palaeo-current analysis

The palaeo-current measurements obtained by the author and from the literature (e.g., Modie, 2000) are presented in Table 6.1. The study area is characterised by sporadic exposures which greatly limit the recording of the palaeo-current data and their interpretations.

The palaeo-current rose diagrams (Fig. 6.9) were based on the orientation data derived from the foreset dip directions of trough cross-bedded sandstones. A total of 16 measurements were used to produce the diagrams which show a unimodal current pattern. The overall spatial distribution of the mean vectors is as indicated in Figure 6.10.

During the field work around Mosu area (Northern Belt), a west to east palaeo-current trend was observed in the trough cross-bedded sandstone at the north-eastern edge of the Mea Pan. In the vicinity of the area, Modie (2000) reported exposures with large-scale cross-beds with foresets dip orientations towards the east.

	Cross-beading readings											Mean vector
A	358	329	314	245	312	290	310					309
B	165	125	222	155	185	140	175	135	185	200	145	163
C	100	105	78	185	130	105	110	100				112

Table 6.1. Cross-bedding measurements from sandstones in the Central Kalahari Karoo Basin. A – Western Belt (Kweneng area, by Modie, 2000)); B – Northern Belt (Mosu area, by author); C – Southern Belt (Mmamabula area, by author). For localities, see Figure 6.10.

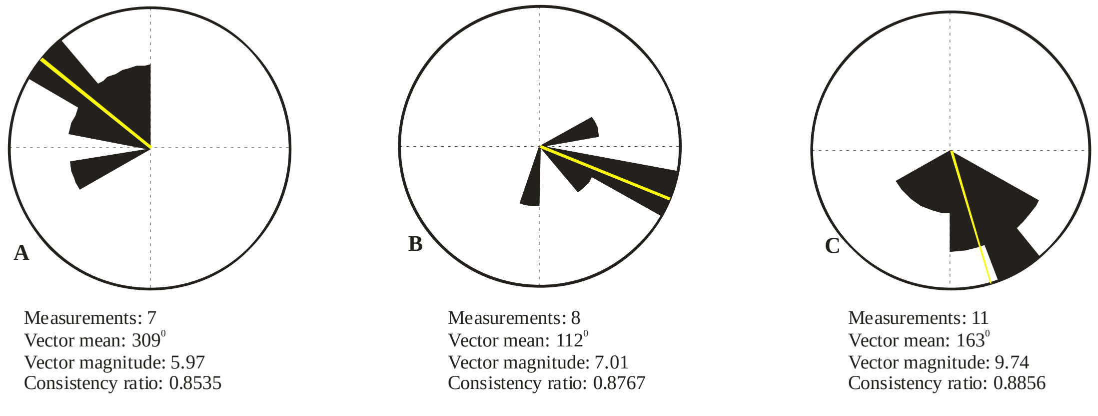


Figure 6.9. Palaeo-current rose diagrams for cross-bedded sandstones in the Upper Unit of Ecca Group. A – Kweneng area (from Modie, 2000); B – Mmamabula area (by the author); C – Mosu area (by the author).

From Mmamabula area (Southern Belt), Modie (2000) recorded a north-south trend from straight and sinuous-crested ripple crest-lines suggesting currents in an east-west direction.

The plotted seven palaeo-currents readings (Fig. 6.9) from trough cross-bedded sandstones in the Western Belt (Kweneng) displayed a dominant palaeo-current trend to the northwest (Modie, 2000).

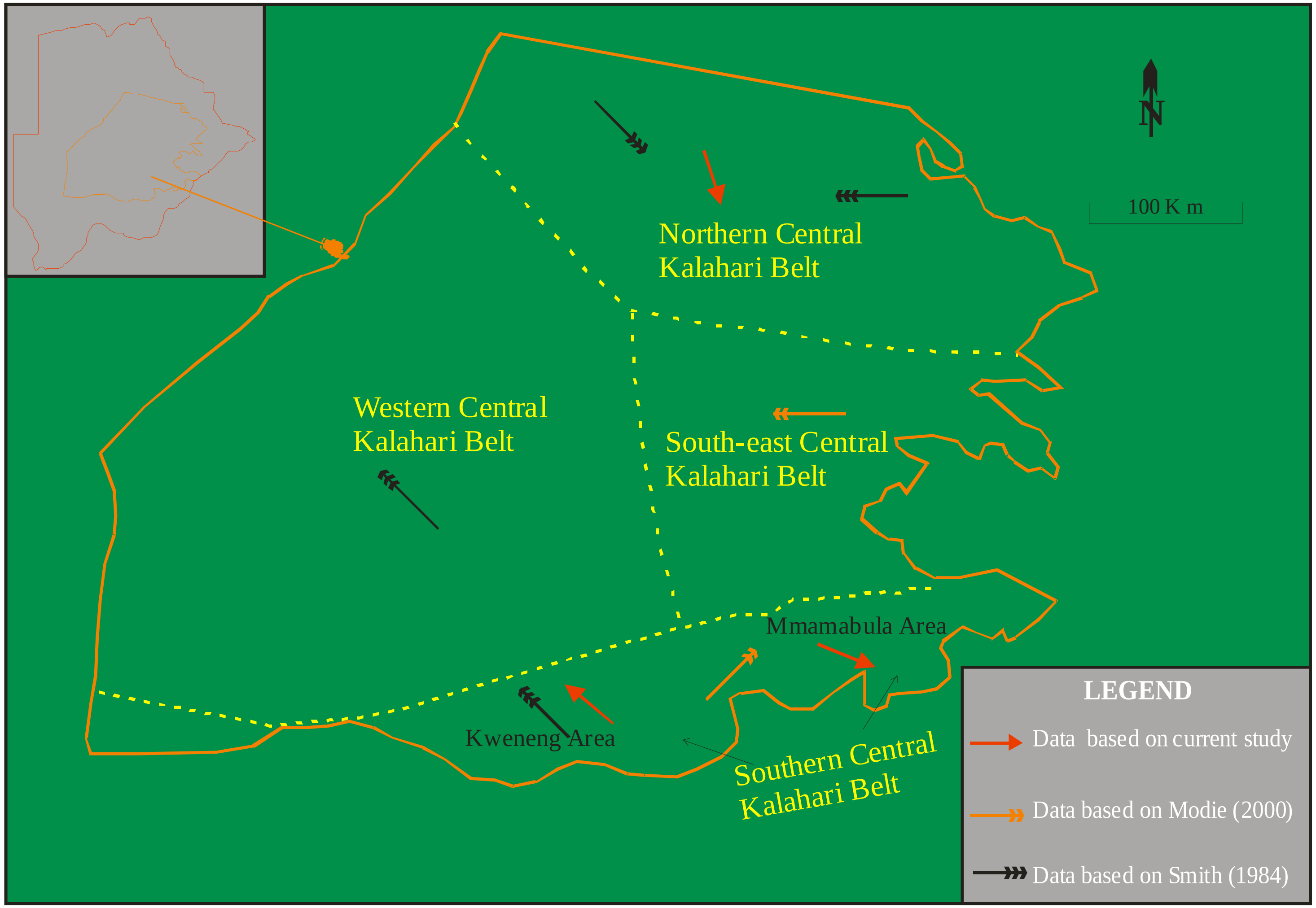


Figure 6.10. Palaeo-current orientation map inferred from foresets dip direction of cross-bedded sandstones in the Upper Unit of Ecca Group in the Central Kalahari Karoo Basin.

7.0 Interpretation of Depositional Environments

Detailed analysis of lithofacies types and facies assemblages in the Central Kalahari Karoo Basin suggests a deltaic depositional environment. A brief review of the different delta types and morphology is given first, followed by a summary of the characteristics of the different sub-environments of a deltaic system. The final part of the section interprets the various deltaic units of the Ecca Group in the study area.

7.1 Delta types

A delta forms when a river deposits its transported sediments near the entry point as it enters a sea or large lake (Fig. 7.1) (Coleman, 1976). Delta morphology reflects the interaction between fluvial, tidal, and wave processes, as well as gradient and sediment supply (Fig. 7.2) and are characterized as: 1) **River-dominated deltas**, occurring in microtidal settings with limited wave energy, where delta-lobe progradation is significant and redistribution of mouth bars is limited, 2) **Wave-dominated deltas**, characterized by mouth bars reworked into shore-parallel sand bodies and beach ridges, and 3) **Tide-dominated deltas** which exhibits tidal mudflats and mouth bars that are reworked into elongate sand bodies perpendicular to the shoreline (Coleman and Wright, 1975; Galloway, 1975; Leeder, 1982; Orton and Reading, 1993).

The amount, mode of transport and grain size of the sediment load delivered to a delta front have a considerable effect on the facies, formative physical processes, related depositional environments and morphology of the deltaic depositional system (Orton and Reading, 1993).

Figure 7.1. The Modern analog of a river-dominated deltaic system (Milia, 2002: http//www.cosis.net/abstract/).

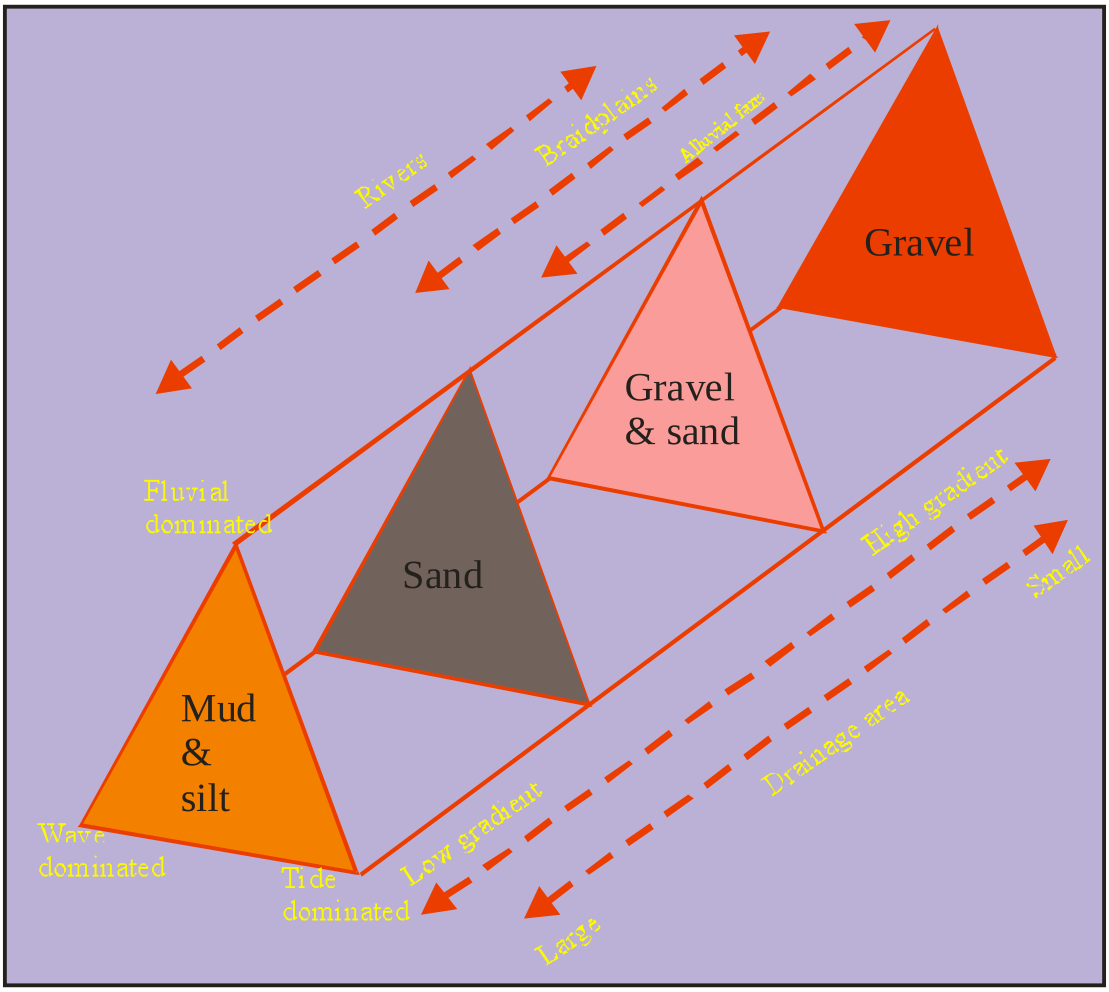


Figure 7.2. Delta classification based on feeder system, depth ratio and river-mouth processes (after Coleman and Wright, 1975; Galloway, 1975; Leeder, 1982; Orton and Reading, 1993).

7.2 Deltaic depositional environments and facies

When a delta forms, the flow of a river into a body of water produces a distinctive pattern of channel bifurcations (Olariu and Bhattacharya, 2006) that scale directly with the width and depth of the channel entry point and can be modelled accurately from the theory of turbulent jets (Slingerland *et al.*, 1994; Olariu and Bhattacharya, 2006).

As the river deposits more and more sediments, the delta progresses seawards with the main river channel splitting into several distributary channels, forming a branching pattern (Fig. 7.3). These distributaries will spread their sediments on a plain-like delta surface (**delta plain**), as well as on the delta slope (**delta front**). Further offshore, coupled with decrease in energy, the fine clays and silts are carried in suspension to deeper, quiet parts of the sea/lake and settle to the bottom (**prodelta**).

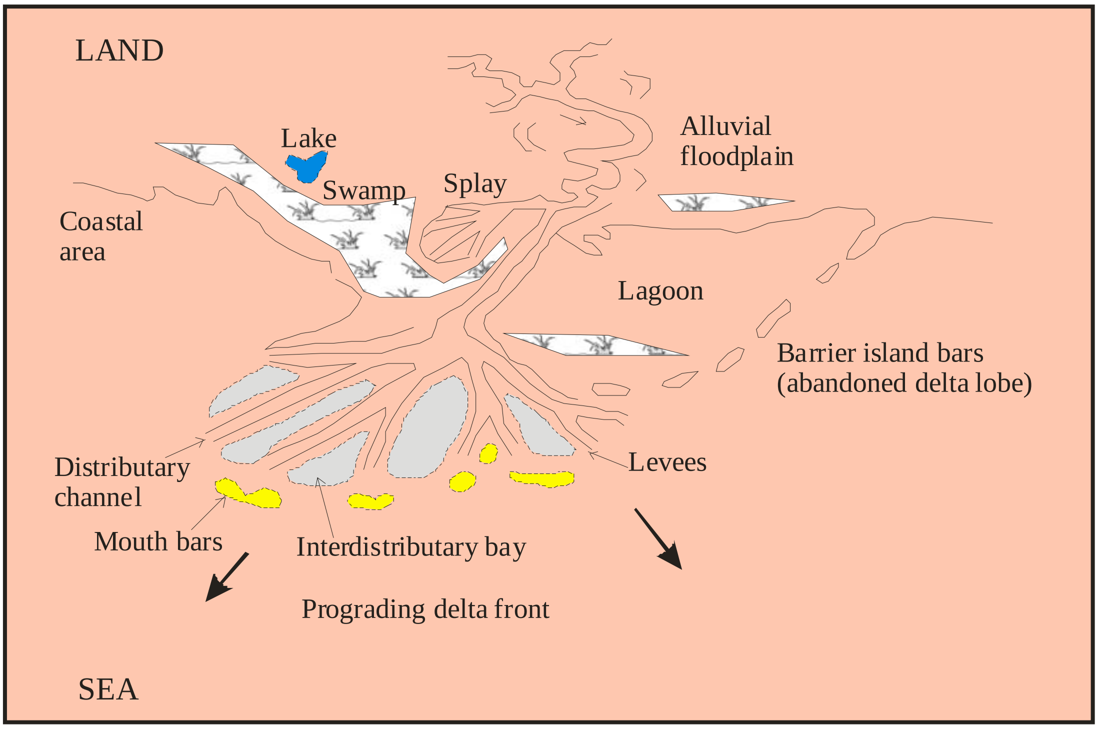


Figure 7.3. Simplified diagram showing delta morphology (redrawn after Williamson, 1996).

Because delta-plain gradients are small and sedimentation rates are high, the direction of distributary channels can be changed easily by aggradation or differential subsidence and compaction, such that the gradient will be steeper in other directions and might capture part of the flow, resulting in uneven discharge distribution among the distributary channels (Olariu and Bhattacharya, 2006). For a large delta system, distributaries can rejoin, forming a delta pattern similar to braided or anastomosed rivers (Morisawa, 1985 in Olariu and Bhattacharya, 2006). Usually the number of distributary channels increases from the delta apex to the shoreline (Olariu and Bhattacharya, 2006).

The energy of the river is reduced at the entry point resulting in gradual loss of sediment transporting ability and thus deposition. Rapid deposition of coarser material occurs immediately after the point of entry, whereas finer material travels further seaward, and as a consequence, a progressive seaward decrease in sediment grain-size develops**.**

With time and as the delta progresses seaward, the coarser sediments will be deposited over the previously deposited finer ones resulting in the typical upward-coarsening successions associated with deltaic systems.

These upward-coarsening succession from bottom upwards consists of bottomset beds (silts, clays) succeeded by foreset beds (sand, silts), and these are usually capped by the deposits of interdistributary bay fill (silts and muds). This is succeeded by the upward-fining successions of the distributary channel deposits (topset beds – gravel, sands) (Coleman, 1976, 1980; Reineck and Singh, 1980). This idealised stratigraphic profile of a deltaic succession is referred to as a progradational sequence, showing that the river supplied clastic sediments to the sea/lake more rapidly than can be removed by wave processes (Coleman, 1976).

The vertical sequence of tide-dominated delta consists of the basal muds of the prodelta, tidal sandbodies of the delta front, and a delta plain of tidal mudflats cut by two-way tidal channel sands overlain by tidal flats and mangrove swamps (Leeder, 1982; Reading, 1986, 1996). Whereas, the vertical sequence for wave-dominated delta show basal prodelta muds and delta front sands interbedded with mud. Delta plain, however, may show lateral intertonguing of distal bars overlain by channel or more likely, the prograding delta plain beach ridges, coastal barrier, and dune complex (Leeder, 1982; Reading, 1986, 1996).

Although delta morphology and processes are varied, three broad sub-environments on deltaic system can be distinguished as discussed below, with more focus on fluvially-dominated delta.

7.2.1 Delta plain sub-environment

This is a zone far removed from marine processes and is characterised by fluvial processes (Coleman, 1976; Galloway and Hobday, 1996). It is covered by a mosaic of high and low depositional energy settings which consist of a network of active and abandoned distributary channels, and inter-channel areas (floodplains) (e.g., interdistributary bays, marshes and numerous overbank crevasse splays) (Fig. 7.3).

Distributary channel fill: Most river channels that feed into deltas (e.g., Mississippi river) scour through their previously deposited sediments resulting in more stable, distributary channels. These prevent lateral migration of channels and the formation of point bars or meander belts, but in high-bedload channels, migration does occur forming similar channel deposits as that of meandering alluvial systems (Coleman and Prior, 1980; Smith, 1980).

During channel abandonment, the basal part of the channel is filled with poorly sorted sands and silts, succeeded by organic debris, primarily peats (Coleman and Prior, 1980) with the uppermost part commonly containing organic-rich clays showing root burrowing and / or silt-infilled animal burrows (Coleman and Prior, 1980).

The distributary channels have many characteristics pertinent to fluvial channels (Reading, 1996). Their deposits are mostly characterised by erosively based sandstones with basal lags and display an upward-fining succession. The associated sedimentary structures from the base upwards consist of cross-bedded sandstones into ripple-laminated finer sandstones with silts and clay alternations and usually topped by rootlets as indicative of emergence (Reading, 1996).

Marshes: These are low energy, flat lying areas dominated by plant life resulting in high production and preservation of organic material (e.g., coaly / carbonaceous mudstones and coals). Marshy areas are dominated by horizontally laminated deposits which are often disturbed (bioturbated) by organisms living in these areas, and thus leading to massive mudstones. Furthermore, lenticular, wavy and flaser bedding may occur in the sediments.

Interdistributary bay: These are low to intermediate energy regions found between distributary channels and opening into the sea (Fig. 7.3). Deposits of this environment are normally brought-in during high floods and are usually fine-grained. The associated sedimentary structures are lenticular bedding, horizontal laminations with alternating zones of fine silts and silty muds. Bioturbation from burrowing organisms is extremely common in this area and in most cases destroys all the sedimentary structures, hence leading to the formation of massive mudstones.

Crevasse splay / bay-fill deposits: These are low to intermediate energy regions found between or adjacent to major distributary channels, extending seaward as a radial bifurcating channels similar to the veins of a leaf (Coleman, 1976). Their deposits are characterised by upward-coarsening successions of alternating silts and silty muds and organic debris at the base upwards into well-sorted sandstones with graded bedding and small-scale climbing ripples (Smith, 1980).

7.2.2 Delta front sub-environment

The delta front sub-environment is dominated by both river and basinal processes. These form the sloping part of the delta that leads into the deeper waters and is the most active depositional area in the whole deltaic system. The sub-environment is generally characterised by gradual seaward decrease in sediment transport energy reflected in fining of sediments in offshore direction. This way, coarser (gravel, sands) material is deposited near the channel mouth (**distributary-mouth bar**), and silts and some clays (**distal bar**) further offshore. With continued decrease in energy seaward, finally the finest sediments eventually settle at the outskirts of the delta (see next section on **prodelta** setting).

Distributary mouth bar: These form at the distributary channel mouths in the proximal part of the delta front as a result of the decrease in velocity in river currents as it enters the sea/lake. Rapid deposition of coarser, sand size sediments occurs immediately at the entry point (Coleman, 1976). Due to the variation in turbulence at the channel mouth, silts and clays can also be deposited but further re-working by marine processes results in cleaning and sorting of the sediments, hence the well-washed and well-sorted sandstones of the distributary mouth bars which are often trough cross-bedded and climbing ripple laminated.

Distal bar: These form the seaward sloping (distal) margin of the delta front and consist of interbedded, laminated mudstones, siltstones and sandstones in upward-coarsening successions (CUS). The units show scour and fill, erosion surfaces overlain by cross-bedding, ripple marks and occasional bioturbation which may disturb the lamination. The associated trace fossil assemblages are of low diversity as few organisms live in this area due to the continuous sediment supply and fluctuation in water salinity (Reading, 1996).

7.2.3 Prodelta sub-environment

Prodelta sub-environment forms the zone seaward to the delta front sub-environment and is dominated by basinal processes. This is a low energy sub-environment dominated by very low rate suspension settling. It is commonly characterised by laminated mudstones and silty mudstones, becoming more silty upwards towards the delta front deposits. Ripple cross-lamination and small-scale graded bedding are common sedimentary structures associated with this sub-environment (Coleman, 1976; Galloway and Hobday, 1996). Sediment burrowing organisms are common due to the quietness and slow deposition in the area, and this high rate of burrowing (bioturbation) usually destroys the primary structures (Coleman, 1976).

7.3 Depositional environments for Ecca Group

The facies associations identified in the Central Kalahari Karoo Basin resemble those of a fluvially-dominated delta plain, delta front and prodelta environment as described below:

7.3.1 Basal Unit

The three identified informal members (*lower*, *middle* and *upper*) of the Basal Unit of the Ecca Group resemble characteristics of the prodelta and delta front facies association in a prograding deltaic depositional environment. The evidence for this comes from the upward increase in grain size in the sequence as shown by the succession of interbedded mudstones, siltstones and fine sandstone grading upward into a predominately sandy unit.

The massive and laminated, grey and black silty to shaly mudstone facies (**Fm**, **Fsm**, **Fl**) forming the *basal member* and resting on pre-Karoo rocks or Dwyka Group are interpreted as deposits of the prodelta setting. They display lamination and bioturbation characteristics of a quiet, low energy setting, dominated by slow suspension settling.

The interbedded mudstones, siltstones and sandstones (**Fm**, **Fsm**, **Fl**) in an upward-coarsening succession in the *middle member* are interpreted as deposits of distal bars. The fine- to medium-grained, cross-bedded and ripple-cross laminated sandstones (**St**, **Sl**, **Sp**, **Sr**) of the *upper member* are interpreted here to represent deposits of the distributary mouth bar. The distal bars and distributary mouth bar deposits form the delta front depositional setting.

The overall transition from massive or laminated mudstones through interbeds of mudstones, siltstones and sandstones to upper fine- to medium-grained sandstones, capped by erosively based coarser clastics is typical features of a prograding deltaic depositional environment (Whateley, 1980; Cairncross and Cadle, 1987; Tavener-Smith *et al*., 1988; Holland *et al*., 1989).

In the Northern Belt of the CKKB, mostly the uppermost part of the distributary mouth bar is absent and this is usually caused by 'cannibalization' (erosion) by the distributary channels on the prograding delta plain (cf. Reading, 1996).

7.3.2 Upper Unit

The observed features (e.g., erosive bases, associated sedimentary structures (**Sm, St**, **Sl, Sp** and **Sr**), the upward-fining successions) of the Upper Unit of the Ecca Group as well as its stratigraphic position, immediately overlying what is inferred as delta front depositional setting, imply that this unit is likely to represent the delta plain depositional setting. The sandstone facies assemblage represents deposits of the distributary channels and the fine-grained facies assemblage represents the floodplain deposits on a delta plain.

7.3.2.1 Sandstone facies assemblage

The observed characteristics of the sandstone facies assemblage, from erosive bases with sporadic basal lag conglomerates, mudstone rip-up clasts, the associated sedimentary structures (**Sm, St**, **Sl, Sp** and **Sr**), the upward-fining successions (FUS), all resemble those of the alluvial or distributary channel fill deposits of delta plain settings. The coarse clastics ranging in grain size from medium- to coarse sandstone to grit and pebble, the variable, but usually poor sorting and sub-rounded to rounded pebbles of the basal lag conglomerates collectively suggest a high energy depositional environment. The occasional occurrence of thin siltstone and mudstone lenses in the sandstones indicates change in flow condition (i.e., fluctuating energy levels).

Crude horizontal layering and minor clast imbrication displayed by the basal lag conglomerate suggest deposition by traction currents and a high discharge (Reading, 1996). Matrix- and clast-supported basal lag conglomerates (**Gmm**, **Gsm**) are indicative of deposition in gravity flows resulting from the collapse of channel banks (Collinson, 1996). The generally poor-sorting of the pebbles in the basal lag conglomerates indicates little or no reworking of sediments by channel waters, and hence short transportation as well as rapid deposition and burial (Smith, 1980). The associated mudstone rip-up clasts and mudstone flakes relate to channel migration as well as erosion and reworking of floodplain sediments (Smith, 1980; Reading, 1996).
Massive (structureless) sandstone facies (**Sm**) may be taken as further indication of gravity flows resulting from the collapse of channel banks (Collinson, 1996). In particular, this massive facies may indicate liquefaction induced by slope instability or sudden shock on saturated soft sediments (Tavener-Smith *et al.*, 1988). In addition, this facies may also indicate rapid deposition during floods (Reading, 1996).

Trough cross-bedded sandstones (**St**) are taken as evidence for downcurrent migration of sinuous-crested dune bedforms in strong currents (Allen, 1963), whereas planar cross-bedded sandstones (**Sp**) are interpreted as straight-crested dune bedforms in somewhat weaker currents (Allen, 1963). Rippled sandstone (**Sr**) is evidence for deposition of gentle, tractional currents in relatively shallow-waters.

The upward-fining successions in this facies assemblage indicate gradual decrease in current energy from upper flow to lower flow regime conditions (Reading, 1986, 1996). The multiple stacking of the upward-fining successions is interpreted as evidence of cyclic sedimentation where successive flooding events resulted in erosion, channel aggradation followed by abandonment or channel re-occupation (Miall, 1978). The occasional capping of the fining-upward successions by siltstone may be an indication of channel abandonment (Wright, 1985; Cairncross and Cadle, 1988).

7.3.2.2 Fine-grained facies assemblage

The siltstones and mudstones (**Fm**, **Fsm**, **Fl**) of the fine-grained facies assemblage were deposited from suspension during and after the decline phase of flooding in relatively quiet, low energy waters of the delta plain environment (Reading, 1996). Such fine-grained facies are usually products of overbank levees, interdistributary bays, crevasse splays, embayments, lagoons or lakes as well as marshes and swamps (Hobday, 1973). The coaly, carbonaceous mudstones and coal facies (**C**) generally form in swamps marginal to shallow lakes and bays (for details on formation of coal see section 3).

In particular, the thin, upward-coarsening clastic sequences found associated with this facies assemblage reflects an overbank deposition in levees or crevasse splays during floods. The preservation of fine horizontal laminae, ripple cross-lamination and bioturbation suggest slow deposition in a low energy environment where various sediment dwelling organisms existed. The usual lack in structure of the siltstone may be a result of either rapid deposition by flood or homogenization by bioturbation (Reading, 1996).

7.4 Influence of associated strata on coal seam thickness

Important controlling factors in lateral continuity and thickness of coal seams are thought to be variations in the compatibility of the platform beneath the peat, as well as subsequent erosion, most commonly by fluvial channels (Tavener-Smith *et al.*, 1988; Cairncross, 1989). Accumulation of peat on thin impermeable strata (e.g., mudstone, siltstone), which in-turn is underlain by thick fluvial channel sandstone and capped by mudstone will result in thick coal seams. Also peats that accumulate directly on thick sandstones and capped by mudstone achieve great thickness. The thickening of the coal seam where underlain by thin impermeable strata or thick sandstone is due to the foundation stability of the underlying strata which cause less subsidence, less drowning, hence thicker peats accumulation. In the above two scenarios, thin coal seams will result where the peat is overlain by sandstone. These thinning of the coals where overlain by coarse-grained sandstones may be attributed to erosion, but where overlain by mudrock, coals are thicker because the mudrock might have provided a protective layer from subsequent erosion by channel activity (Tavener-Smith *et al*., 1988).

The coals of the study area display characteristics of the influence of the overlying and underlying strata on seam thickness, for example, those coals resting on thin (~ 4.0 m) argillaceous sequences (e.g., mudstone or siltstone) which in-turn are underlain by thicker sandstone or are directly resting on thicker sandstones, are thicker (up to ~14 m), but are thinner (up to ~4 m thick) where overlain and underlain by the sandstones.

Coal seams underlain by thick argillaceous strata (e.g., mudstone, siltstone) are subject to a higher rate of subsidence and mostly experience inundation before peat had achieved great thickness and thus result in thin coals (Tavener-Smith *et al*., 1988). Most of the coal seams within the basin seem to have formed under similar conditions as evidenced by the fact that the mudrock-hosted coals are relatively thin (~5 m), suggesting that inundation of the peat might have taken place due to a higher rate of subsidence of the mudrocks.

The repetitions of inferior coals (as thin as ~0.1 m) which usually occur as interbedding and/or alternating with carbonaceous and coaly mudstones are postulated as a reflection of either an accelerated rate of subsidence leading to drowning of peat or suggest retarded subsidence causing desiccation of the peat at the surface and destruction by oxidation (Tavener-Smith *et al*., 1988).

Petrographically, the coals show a high inertinite and mineral matter content (Bennett, 1989; Williamson, 1996), a characteristic of upper delta plain coals (Holland *et al*., 1989). Furthermore, coal thickness (usually ~5 m), lateral extensiveness, the less splitting by carbonaceous / coaly mudstones and rare thin siltstones and sandstones partings (~0.2 to 0.7 m thickness) in coals, are all characteristics typical of upper delta plain coals (Tavener-Smith *et al.*, 1988; Holland *et al*., 1989).

8.0 Discussion

The succession of the stratigraphic sequences is a record of sea-level fluctuations, mainly expressed as changes in accommodation, and environmental changes that exert control via sediment supply. The driving forces behind these environmental changes are brought about by: 1) tectonics (e.g. changes of relief and drainage in the hinterland, basin subsidence), 2) climate, 3) the physics and chemistry of the ocean and organic evolution (Wagner, 1993; Catuneanu, 2006).

Thus, the changes in depositional trends reflect interplay between the space available for sediments to fill (i.e., accommodation space) and the amount of sediment influx. This space is in turn modified by the basin-scale influence of allogenic controls (Fig. 8.1), which thus provide the common thread that links the depositional trends across a sedimentary basin from its fluvial to its marine reaches (Catuneanu, 2006). For example, a combination of tectonics and eustatic processes would control the relative changes of sea-level which will in turn control the accommodation space. Tectonics and climate would control the type and amount of sediment supply. On the other hand, the supplied sediments will determine how much of the accommodation space is consumed.

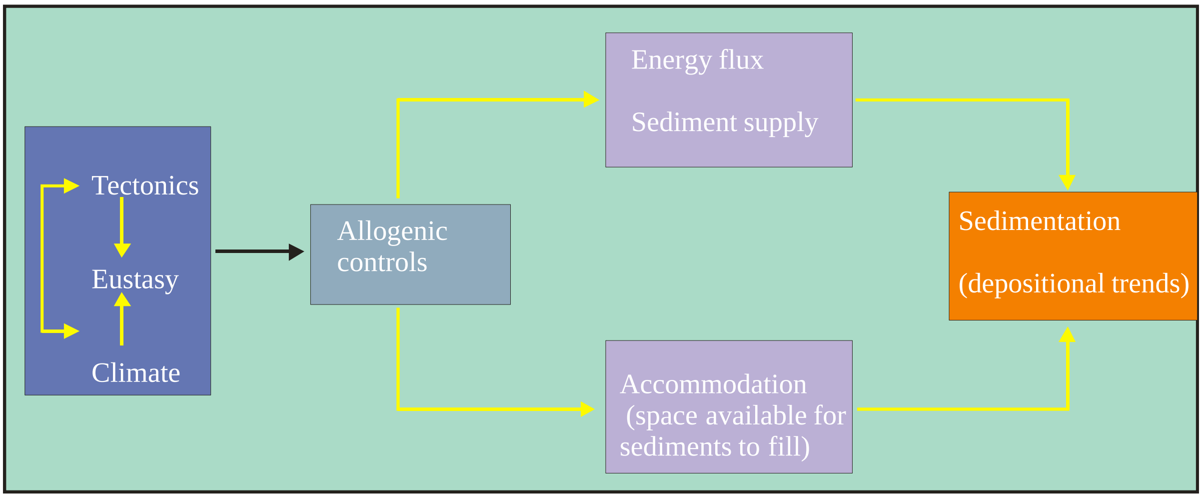


Figure 8.1. Allogenic controls on sedimentation, and their relationship to environmental energy flux, sediment supply, accommodation and depositional trends (Catuneanu, 2006).

These processes (i.e., tectonics, eustatic, climate) may change independently of each other, for instance, the tectonic movement can affect the slope gradient in the delta plain, which will determine the channel pattern (e.g., meandering or braided). This will further affect the resulting sediment supply, energy flux, etc. Climate change or river diversion will affect the discharge, sediment volume and grain size.

In addition, at the limit between non-marine and marine environments, the shoreline trajectory (i.e., position of shoreline through time) is also determined by transgressions and regressions. It can be reconstructed by looking at the distribution of transgressive and regressive packages.

Transgression is characterised by the deepening of the marine waters in the vicinity of the shoreline. This is the stage where creation of accommodation space is greater than the consumption of accommodation space by sedimentation, i.e., rates of base level rise is greater than rates of sedimentation (Catuneanu, 2002; 2006). The resulting pattern is that of retrogradation of facies, with the scoured surfaces cut by waves during the shoreline transgression being overlapped by the aggrading and retrograding shoreface deposits (Fig. 8.2).

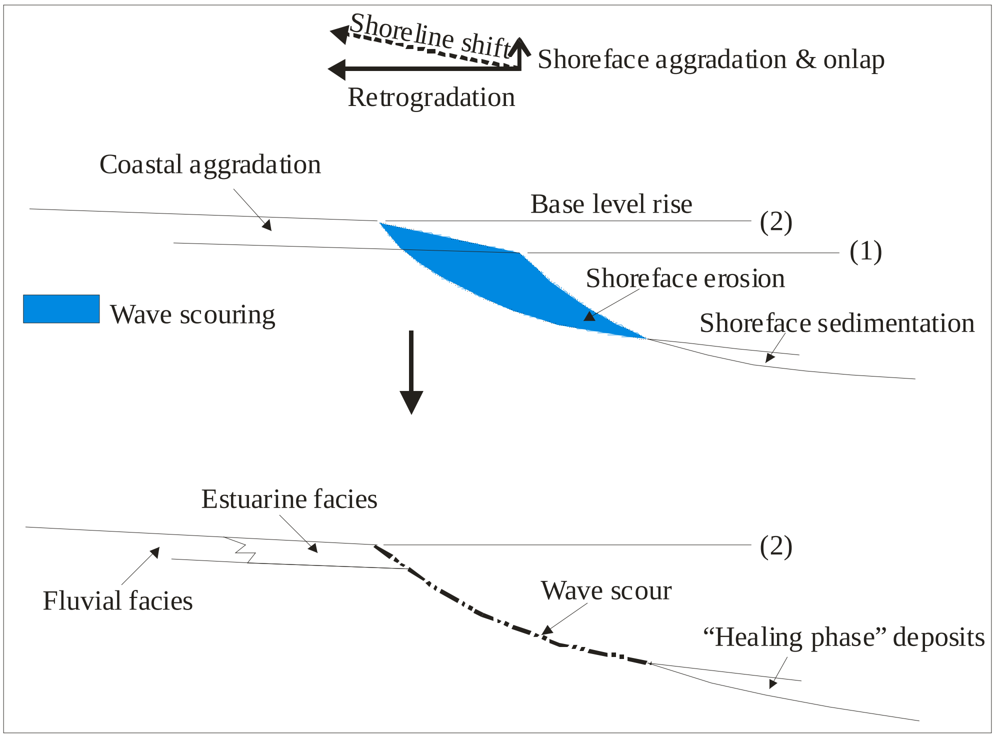


Figure 8.2. Transgressions: driven by base-level rise, where the rates of base level rise outpaces the sedimentation. The two opposing forces in operation here are: 1) sedimentation in the estuary (i.e., coastal aggradation), followed by 2) wave (ravinement) erosion in the upper shoreface. The balance between these two forces decides the preservation of the estuary facies (Catuneanu, 2002, 2006).

Forced regression is characterised by destruction of accommodation space by base level fall (Fig. 8.3), irrespective of the sediment supply (Catuneanu, 2002, 2006). These result in progradation of facies, accompanied by erosion in both the nonmarine (fluvial incision) and shallow marine environments and offlap of the prograding shoreface deposits. Forced regressive deltas are characterised by offlapping prograding lobes. Sediment bypasses fluvial and delta plain systems. Additional sediment is supplied by fluvial and marine erosion, providing high sediment to the shallow and deep marine systems (Catuneanu, 2002; 2006).

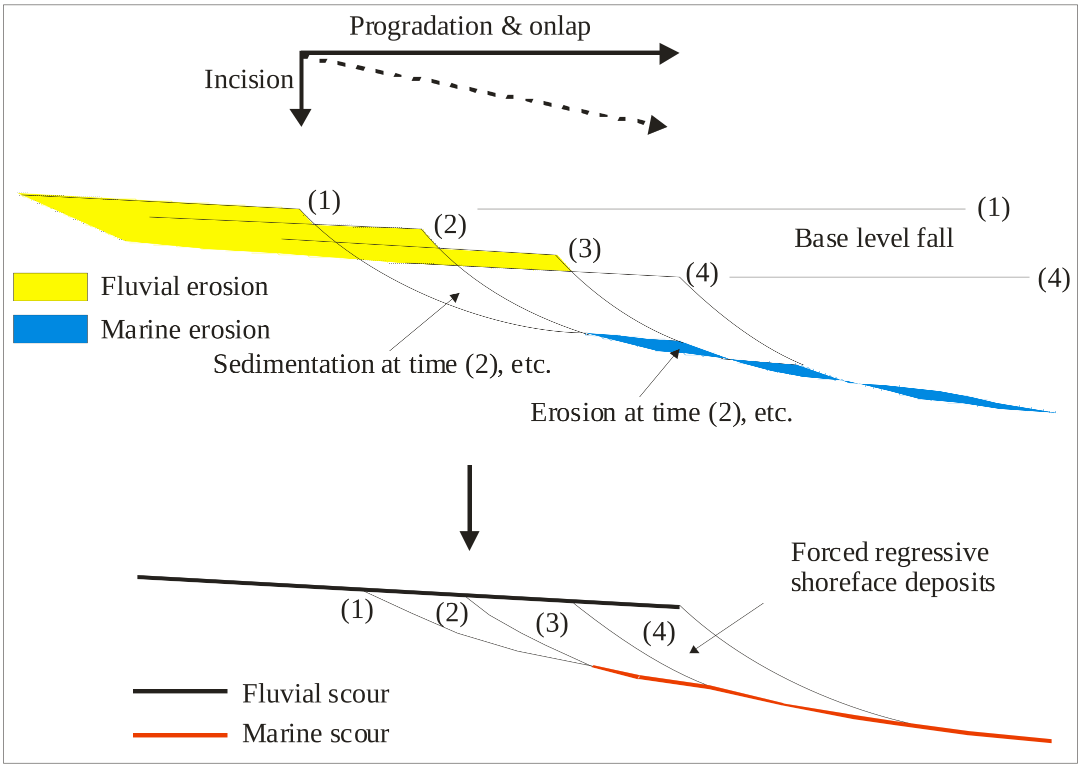


Figure 8.3. Forced regressions: driven by base level fall. Irrespective of sediment supply, the shoreline is forced to regress by the fall in base level. The rates of progradation are generally high (Catuneanu, 2002; 2006). .

Normal regression occur when the consumption of accommodation space by sedimentation is greater than the creation of accommodation space, i.e., rates of sediment supply is greater than rates of base level rise (during the early and late stages of base level rise). This results in aggradation (i.e., newly created accommodation space being filled), sediment bypass and progradation of facies (Fig. 8.4). Normal regression can be regarded as a sediment supply-driven process.

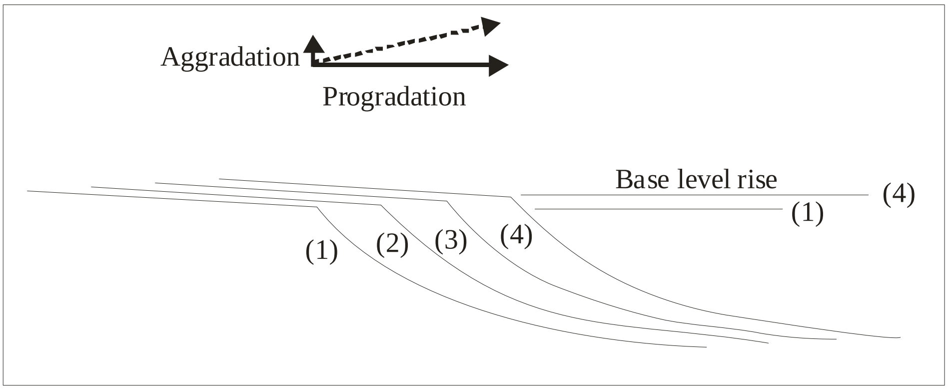


Figure 8.4. Normal regressions: driven by sediment supply, where the rates of base level rise are outpaced by the sedimentation rates (Catuneanu, 2002; 2006).

8.1 The role of accommodation in coal formation

The fundamental control on coal formation and preservation is the accommodation rate in relation to peat production (Bohacs and Suter, 1997). The most important coal formation (in regard to thickness and regional extent) occurs within the transgressive systems tract, where creation of accommodation space is large and this is depicted in Figure 8.5.

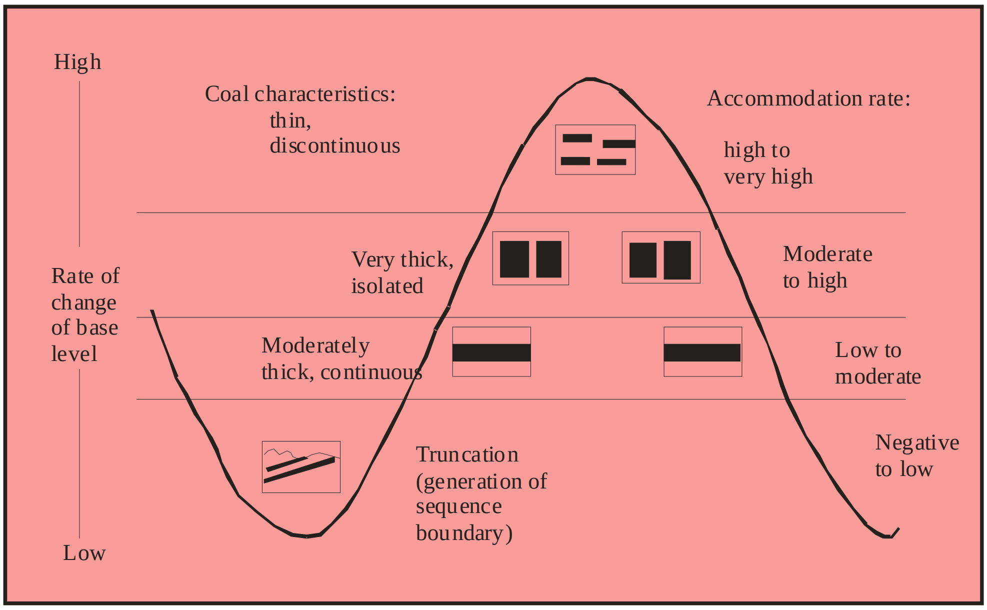


Figure 8.5. The predictive model of coal thickness and geometry (from Bohacs and Suter, 1997).

Within the limits imposed on the rate of peat accumulation by climate and plant physiology, high-accommodation settings produce well spaced, and often thin coal seams, whereas moderately low-accommodation settings generate thick, compound seams that may span several parasequences and/or sequences (Bohacs and Suter, 1997; Holz, *et al*., 2002; Diessel, 2007;). High-accommodation settings produce coals with a comparatively simple internal organisation, often in the form of an upward high-to-low vitrinite succession.

On the other hand, in the low-accommodation settings, compound coals are more complex, continuous with a dulling upwards trend, and commonly characterised by erosion surfaces (Holz, *et al*., 2002). Their preservation potential is low, so that frequently only lowstand and the basal portions of transgressive systems tract deposits are retained (Holz, *et al*., 2002; Diessel, 2007).

8.2 Controls of cyclothem formation in coal-bearing strata

Cyclothems are regular, repeated successions of strata deposited as a result of cyclic or rhythmic sedimentation (Hampson *et al*., 2001). The observed cyclothems/cycles in coal-bearing strata are as a result of the interaction of a number of factors, e.g., tectonic, eustatic, sedimentation, and climatic processes. These factors operate concurrently, with different intensities to produce the great variety of cyclothems observed in different regions and at different times (Einsele *et al*., 1991). These controls are defined in the following sub-sections:

I) Sedimentary control

The vertical stacking of cyclic sequences depends on the palaeotopography and tectonic stability of the region, i.e., ratio between sediment supply and subsidence rates (Einsele *et al*., 1991). For example; 1) where supply slightly exceeds subsidence rates, e.g. Mississippi delta, this will result in thick sequences with off-lapping successions, 2) where supply kept pace with subsidence, this results in facies units which are stacked more or less vertically, with thin cyclothems (Einsele *et al*., 1991).

The cyclicity can also be accomplished under constant rates of basin subsidence or base level rise by periodic shifts in sediments transport, e.g., in fluvial-dominated deltas where relatively high rates of delta progradation and delta top accretion lead to instabilities between the topographically raised active delta plain and the adjacent sediment-starved bays (Einsele *et al*., 1991). The most widely accepted examples of supply control on sequences are short-term variations in supply by the switching of feeder channels in deltas and submarine fans, leading to delta lobe switching (Schlager, 1993).

On the other hand, continued gradual basin subsidence can also result in repeated many times of channel avulsion and lobe switching, i.e., vertical stacking of cyclic sequences.

II) Climatic control

Drier climate causes deterioration of the vegetation cover and increased erosion and sediment transport leading to deposition of sand in coastal regions. On the other hand, humid climate promote plant growth in depositional environments as well as in the source area, by so doing reducing clastic input and enhancing peat formation and due to sediment starvation the sea transgresses. Also humid climate can result in increased runoff resulting in deposition of coarser clastics (Einsele *et al.*, 1991).

III) Eustatic control

Eustatic sea level fluctuations in the earth history are referred to be caused by; 1) fixing of sea water on the continents by glacial build-ups or other climatic processes and later release of water by melting glaciers, 2) varying volumes of ocean water displaced by rising mid-oceanic ridges due to changes in spreading rates.

IV) Tectonic control

Deposition of coarse clastics is considered as the sedimentary response to rapid uplift along boundary faults.

8.3 Facies association, Processes and Depositional environments of Ecca Group

The review of the characteristics of Ecca Group facies associations and the final characterisation of the processes and depositional environments that took place during Ecca Group times (e.g., subsidence *vs*. sedimentation) are presented below.

The observed overall upward increase in grain-size (CUS) characteristic of the prodelta and delta front facies association suggest progradation in a deltaic depositional environment, i.e., regressive setting. However, the limitations in the currently used data to afford the separation between the different genetic types of regressive settings (i.e., the normal and forced regression) calls for another way of subdividing the rock record, i.e., the amalgamation of different genetic types of deposits (normal and forced regressions) into one single unit, the regressive systems tract (e.g., Catuneanu, 2006). This includes all strata that accumulated during shoreline regression (i.e., the entire succession of undifferentiated highstand, falling-stage and lowstand deposits) which define the progradational stacking patterns within the marine portion of the basin.

As a general practice when the deposits of the regressive phase are amalgamated, the directly overlying sequence is assigned to a transgressive setting (Catuneanu, 2006), thus the delta plain facies association (current study) in the basin will be postulated to be that of a transgressive phase.

In practice, simplified versions of stratigraphic cyclicity may also be encountered, such as: repetitive successions of transgressive facies where continuous base level rise in the basin outpaces sedimentation in a cyclic manner (Catuneanu, 2006). Thus, the vertical stacking of the transgressive facies (i.e., Unit A1, A2, A3 and B1, B2), may be an indication of a repeated (?) pulses of transgressions accompanied by short-lived regressions which formed relatively thin deposits which in most cases are likely to be completely eroded by subsequent transgressive wave scouring (e.g., Catuneanu, 2006).

Sediment yield is dependent on local relief of the drainage basin, and thus the higher the relief, the greater the sediment yield. In addition, high relief is normally associated with high-order stream patterns characterised by highly variable and extremely erratic discharge (Coleman, 1976). These types of conditions result in braided channels, where the erratic discharging channels display relatively coarse and poorly-sorted sediments with considerable grain-size variation both laterally and vertically. Commonly, the sandstone bodies from braided channels are characterised by multiple upward-fining sequences stacked one upon another (Coleman, 1976; McLean and Jerzykiewicz, 1978).

The grain-size difference of the delta plain sediments is related to the distance between headwaters and the delta (Flores, 1975). Thus, a short distance between headwaters and the delta results in coarser, sometimes pebbly sediments (e.g., Niger, Rhone rivers) whereas, a longer distance between headwaters and the delta results in finer grained sediments (e.g., Mississippi river).

The abundance, vertical multiple-stacking of sandstones and locally coarse- to pebbly grain-size of the *basal arenaceous members* of Units A1, A2, A3 and B1, B2 throughout the basin might suggest a relative uplift (repeated?) of pre-Karoo formations around the basin margins which created a higher energy environment with the consequent deposition of highly arenaceous units. The poor-sorting, coarse- to pebbly grain-size, and scoured bases of these arenaceous sequences suggest extremely erratic discharge and high-bedload sediment yield which are usually characteristics of braided distributary channels. In addition, the sub-angular to sub-rounded nature of quartz and feldspar grains might imply short transport from a nearby source area.

The observed strongest thickness variation and pocket-like sporadic occurrence of the Dwyka Group and the Basal Unit of Ecca Group (e.g., in the Northern Belt, where the Basal Unit is frequently absent or poorly developed (< 40 m thick) and sometimes resting directly on pre-Karoo strata) might suggest deposition on a basement ridge that formed during pre-Karoo times and persisted at least until early Karoo times.

9.0 Conclusions

The review of the characteristics of Ecca Group facies associations in the Central Kalahari Karoo Basin revealed information about the depositional environments and the geological processes that took place during Ecca Group times.

The Ecca Group succession in the basin is composed of two informal stratigraphic units, namely the Basal and Upper Units with the Basal Unit consisting of *lower, middle* and *upper members,* whereas the Upper Unit consists of five (5) successions, each with a *basal arenaceous* and an *upper coal-bearing member*.

The Basal Unit is characterised by an upward-coarsening succession from prodelta facies (*basal member*) into distal bar (*middle member*) and capped by the distributary mouth bar facies (*upper member*). This is a characteristic of a fluvially-dominated prograding deltaic depositional environment (i.e., regressive deltaic system).

Directly overlying this regressive cycle are deposits of the Upper Unit interpreted as those of a delta plain depositional setting. These are deposits of the distributary channels and floodplain, postulated to be deposited during a transgressive phase as they are directly overlying what is inferred to be deposits of a regressive systems tract.

During deposition of the Upper Unit, the basin was characterised by uplift (repeated?) at the margins which caused a high relief and high energy, fluvially influenced environments. Evidence such as the poor sorting and sub-angular to sub-rounded quartz and feldspar grains suggest short transport distance of sediments.

The swampy areas supported flourishing vegetation resulting in the accumulation of good-quality peat. This was restricted to the transgression phase as this is the stage: 1) when the water table is at its highest level relative to the landscape profile, 2) characterised by a high accommodation to sediment supply ratio, thus provide suitable conditions for peat accumulation.

From this, it shows that timing of the shoreline trajectories is important for coal exploration and exploitation, as a general trend of peat accumulation is affected by the various stages of a base level cycle, in response to changes such as accommodation, sedimentation, etc. For example, forced regression is unfavourable for peat accumulation and subsequent coal development because accommodation is negative and the non-marine portion is generally subjected to fluvial incision and/or palaeosol development. Whilst, transgression is the best phase of a stratigraphic cycle for coal formation as it marks the peak for peat accumulation.

In order to properly document the sequence stratigraphic history of the study area (e.g., the difference between forced and normal regressions), much work and data is still needed in the form of:

I) High resolution seismic surveys where stratal terminations can be defined, as these would allow the inference of the type of shoreline shifts, helping in the recognition of the stacking patterns defined by shifts of the shoreline.

II) Dating to establish the temporal relationship between the delta plain as well as prodelta and delta fronts deposits.

The erosive and protective nature of the overlying strata had an influence on seam thickness, e.g.:

I) Coals overlain by sandstones are thinner due to erosion by distributary channel activity.
II) Coals overlain by mudrock are thicker because the overlying mudrock might have protected the coals from subsequent possible erosion.

Differential compaction of underlying strata to coal modified seam thicknesses, e.g.:

I) Coals resting on thin impermeable strata (i.e., mudstone, siltstone) which in turn is underlain by sandstone are thicker
II) Coal resting directly on sandstones are also thicker

This is because sandstone compaction is less leading to little subsidence and less drowning, thus thicker peat accumulation.

III) Coal resting directly on thick mudrock is thin as a result of more compaction, causing more subsidence and as a result more drowning, hence thinner peat accumulation.

The second scenario (i.e., the differential compaction of underlying strata) shows that much can be gained by extending a hole a few metres below the base of any coal seam, as this might allow the assessment of the pre-peat depositional environment and enable useful predictions concerning the characteristics of the coal seams elsewhere in the region to be made.

The current study has contributed to the advancement of the knowledge base on the Kalahari Karoo of Botswana by applying sedimentary facies analysis to the Karoo succession in the study area. In this regard, the project has determined new lithofacies, and identified lithofacies associations by grouping of the lithofacies into environmentally significant genetic units in order to better categorize the types of depositional processes as well as to improve the prediction of coal characteristics (e.g., lateral extent, thickness). Finally, the application of facies models, in other words the comparison of the identified lithofacies associations with modern and ancient examples, helped the better characterisation of the processes and depositional environments during Ecca times.

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