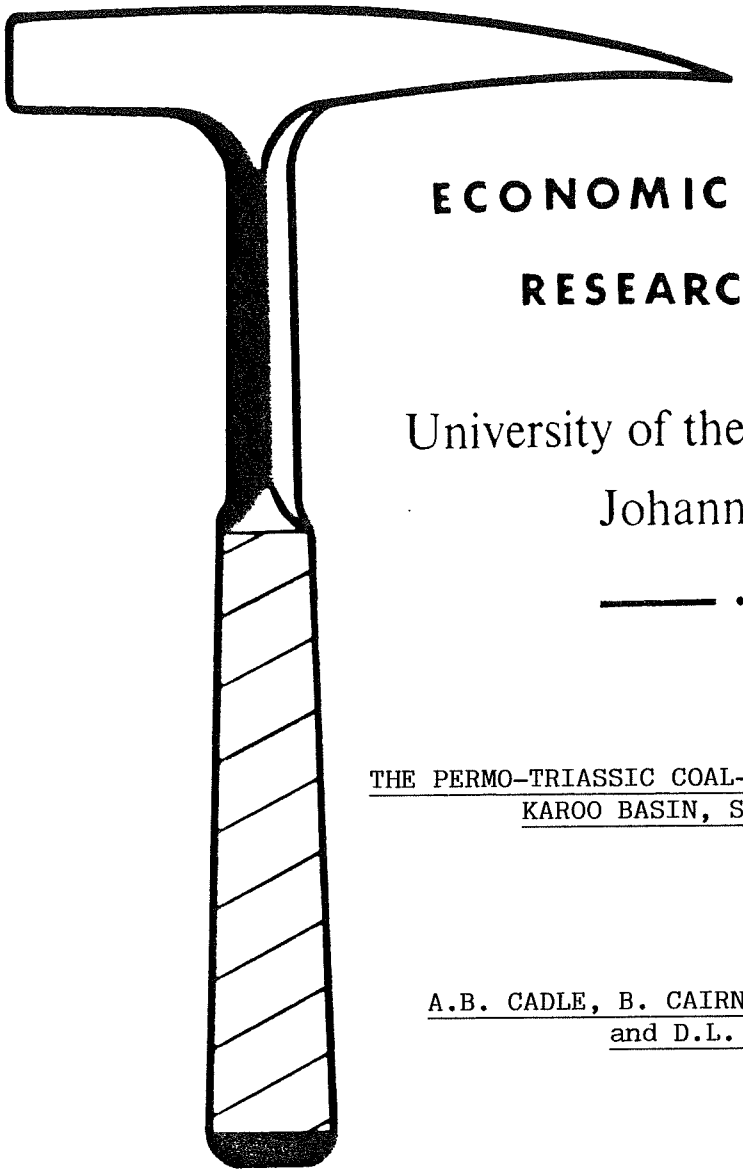

ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
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THE PERMO-TRIASSIC COAL-BEARING DEPOSITS OF THE KAROO BASIN, SOUTHERN AFRICA

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UNIVERSITY OF THE WITWATERSRAND
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THE PERMO-TRIASSIC COAL-BEARING DEPOSITS OF THE KAROO BASIN, SOUTHERN AFRICA

by

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ABSTRACT

The coal-bearing sediments and coal seams of the Karoo Basin, southern Africa are described and discussed. The Karoo Basin is bounded on its southern margin by the Cape Fold Belt, onlaps onto the Kaapvaal Craton in the north, and is classified as a foreland basin. Coal seams are present within the Early Permian Vryheid Formation and the Triassic Molteno Formation.

The peats of the Vryheid Formation accumulated within swamps in a cool temperate climatic regime. Lower, upper delta plain, back-barrier and fluvial environments are associated with peat formation. Thick, laterally extensive coal seams have preferentially accumulated in fluvial environments. The coals are in general inertinite-rich and high in ash, but increasing vitrinite and decreasing ash contents within seams occur from west to east across the coalfields. The Triassic Molteno coal seams accumulated within aerially restricted swamps in fluvial environments. The climate during peat formation was warm temperate. The coals are thin, laterally impersistent, vitrinite-rich, and shaly.

Palaeoclimate, depositional systems, differential subsidence, and basin tectonics influence to varying degrees, the maceral content, thickness, and lateral extent of coal seams. However, the geographic position of peat-forming swamps within a foreland basin coupled with basin tectonics and differential subsidence are envisaged as the primary controls on coal parameters. The Permian coals are situated in proximal positions in the passive margin of the foreland basin. Here, little subsidence took place which promoted oxidation of organic matter and hence the formation of inertinitic coals. The coals in this tectonic setting are also thick and laterally extensive. The Triassic coals are situated within the tectonically active foreland basin margin. Rapid subsidence and sedimentation rates occurred during peat formation which resulted in the preservation of thin, laterally impersistent, high ash, vitrinite-rich, shaly coals.

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THE PERMO-TRIASSIC COAL-BEARING DEPOSITS OF THE KAROO BASIN, SOUTHERN AFRICA

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THE PERMO-TRIASSIC COAL-BEARING DEPOSITS OF THE KAROO BASIN, SOUTHERN AFRICA

INTRODUCTION

The Karoo Basin of southern Africa is unique in Africa as it is the only basin which records the complete late Carboniferous to Jurassic rock record and a change in palaeoclimate from glacial through temperate to dry desert (Fig. 1). The Karoo Basin has an areal extent of some 550,000km^2 and has its greatest sedimentary fill along the southern margin of the basin. The sedimentary succession thins northwards where it pinches out along the northern margin of the basin. The basin is therefore asymmetric in cross-section and is classified as a foreland basin (Allen *et al.*, 1986). At the base of the Karoo Sequence, in the northern part of the basin, extensive coal-bearing deposits are present. The coals are characteristically of Gondwana origin and have a high inertinite and variable semifusinite and vitrinite content and are low in sulphur. The thick economically exploitable coal seams of Permian age are situated above the stable Kaapvaal Craton on the distal or passive margin of the foreland basin (Fig. 2). In this respect these coals formed in tectonic environments similar to the Carboniferous coals in the Illinois and Michigan basins of the U.S.A. (Trask and Palmer, 1986) and the Wolfgang and Blair Athol Basins of Australia (Hunt and Smyth, 1989) . Thin vitrinite-rich seams of Triassic age are present in the southern, tectonically and sedimentologically active portion of the basin. These coal seams are not economically important.

The stratigraphy of the Karoo Basin is tabulated in Figure 1 and comprises the Dwyka, Ecca, Beaufort, and Stormberg Groups. These groups represent sediments deposited in glacial, marine, fluviodeltaic, fluviolacustrine, and dry- and wet-desert environments, respectively. Extensive volcanism, which preceded the break-up of Gondwanaland, terminated sedimentation in the basin.

This paper discusses the stratigraphy, depositional systems, petrography, palaeoclimate, and tectonic setting on the thickness, distribution, and maceral content of the seams and describes the palaeoenvironmental history of the coal-forming stratigraphy.

STRATIGRAPHY AND DEPOSITIONAL SETTING

The Karoo Basin contains an asymmetric fill of sediments and volcanics. The sediments are thickest in the south and thin northwards. The predominant sedimentary transport direction is from south to north with a minor southerly component of fill from the north. Sedimentation commenced in the Carboniferous Period with the deposition of the glaciogenic Dwyka Formation. The Dwyka Formation comprises a widespread fill of subglacial till, glaciolacustrine till, terrestrial moraine, and fluvioglacial outwash (Von Brunn, 1977; Visser, 1986; Visser and Loock 1987). These sediments were deposited from advancing and retreating ice-sheets which bordered the basin (Crowell and Frakes 1972, 1975). At this stage in the depositional history of the basin, its asymmetry was evident as up to 800m of Dwyka Formation is present in the southern basin

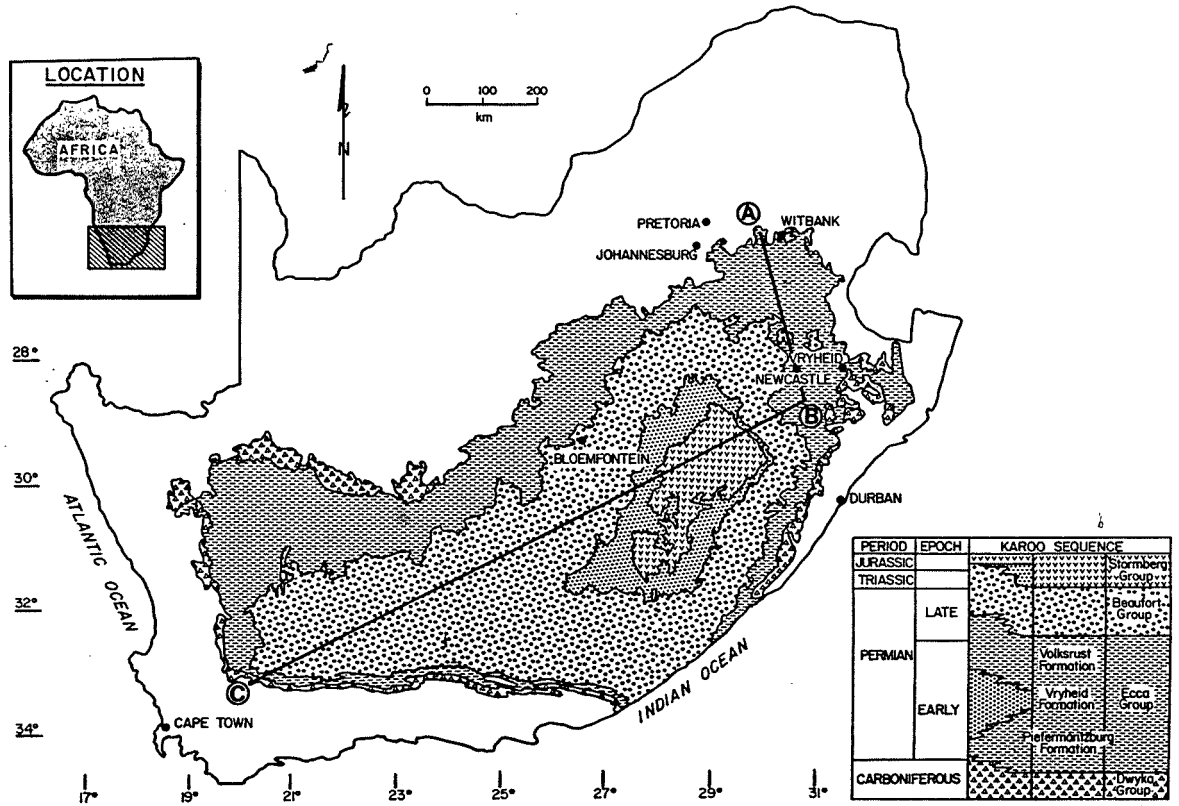


Figure 1: The Karoo Basin illustrating the distribution and stratigraphy of the Karoo Sequence. See Figure 2 for positions A, B, C.

margin. This formation progressively thins and pinches out northward (Fig. 2). Following the retreat of the glaciers the basin was transgressed by the Ecca sea with active sediment fill from the south and north. Deep marine shales, submarine-fan sandstones and shales, and shelf shales characterise the sedimentary styles which operated during the Early Permian along the southern basin margin (Johnston, 1976; Kingsley, 1981). These rocks constitute the Ecca Group. These deep water sediments suggest that the southern margin of the basin was a foredeep, actively being filled by sediments derived from highlands bordering the southern basin margin.

The Ecca Group sediments in the northern part of the basin differ in sedimentary character, reflecting deposition on the stable Kaapvaal Craton. The Ecca Group is divided into three formations; the Pietermaritzburg Formation, Vryheid Formation, and Volksrust Formation (Fig. 2). The Pietermaritzburg and Volksrust Formations represent shelf shales which merge southwards to form the Central Ecca shale facies (Fig. 2, Ryan, 1968). In contrast, the Vryheid Formation constitutes a sequence of alternating conglomerates, sandstones, and shales within which the economically exploitable coal seams are present. These coarser sediments represent a regressive wedge of deltaic, fluvial, and shallow marine sediments which built out into the Ecca sea. The coal seams accumulated in lower and upper delta plain, and fluvial environments. Controls on peat accumulation for these coal seams have been proposed by Le Blanc Smith (1980), Cadle (1982), Roberts (1986), Cairncross and Cadle (1988), and Cairncross (1989).

The Beaufort and Stormberg Groups of sediments reflect the change in basin evolution, depositional systems, and climate during the Late Permian and Triassic Periods. The southern basin margin actively subsided and sediments were transported basinwards from highlands situated to the south. Only the extremely northeastern portion of the basin was influenced by sediments shed into the basin from a northerly source area (Turner, 1975). The basin changed from one dominated by marine and transitional environments to one which became dominated by braided, meandering, lacustrine, and wet- and dry-desert environments (Hobday, 1978; Turner, 1978; Van Dyk *et al.*, 1978; Eriksson, 1981; Stear, 1983). Sedimentation was terminated by the extensive outpouring of the Drakensberg lavas (Figs. 1 and 2) which heralded the onset of rifting and which led, in turn, to the separation of Gondwanaland.

TECTONIC SETTING

The Karoo Basin is classified in this paper as a foreland basin i.e. it is situated in front of a mountain chain, the Cape Fold Belt and an adjoins the Kaapvaal Craton. In terms of tectonic setting the Karoo Basin is similar in tectonic style to the coal-bearing Bowen, Sydney, Galilee, and Cooper Basins of Australia and the Appalachian, Michigan, and Illinois Basins of North America (Tankard, 1986; Hobday, 1987; Hunt and Smyth 1989). In general, these basins form large asymmetric depositories which are bounded by a mountain chain and postulated subduction zone in the east. In the west, these depositories onlap onto cratons.

The southern margin of the Karoo Basin is underlain by rocks of the Cape Supergroup deposited in a possible passive margin setting in shallow to deep marine environments (Rust, 1973; Hobday and Tankard, 1978). These rocks underwent deformation in the Devonian, creating the Karoo

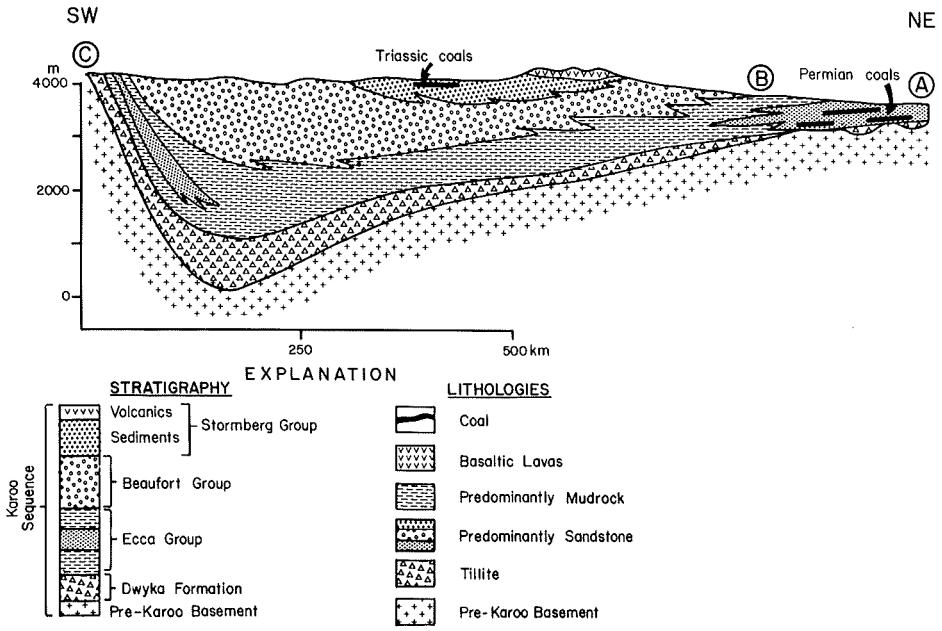


Figure 2: Cross-section through the Karoo Basin illustrating the stratigraphic and geographic positions of coal bearing strata. See Figure 1 for positions of A, B, C.

foredeep. According to the foreland basin model proposed by Quinlan and Beaumont (1984) the foredeep forms due to thrust belt loading and the lithosphere responds elastically by subsiding. De Witt (1977) postulated that south of the Cape Fold Belt an Andean convergent margin existed with a subduction zone located about 1000km south of the Karoo foredeep. This orogenic belt extended across Gondwanaland and is recorded as the early Mesozoic orogen by Craddock (1974). Thus the Karoo Basin and the coal-bearing basins in the eastern part of Australia are situated in tectonically similar settings adjacent to the early Mesozoic orogenic belt. Lock (1980) maintains that the folding and thrusting of the Cape Supergroup rocks probably reached a climax during the Early Triassic. The basinal response to this tectonic activity was the build out of the Beaufort rocks into the basin.

With respect to the foreland basin model proposed, the coal-bearing Ecca Group rocks are sourced from and situated on the northern (tectonically passive) side of the basin. Shoal-water, delta, and fluvial sediments associated with coal seams characterise the sedimentary styles of the tectonically passive margin of the basin. This contrasts significantly

with the submarine-fan sediments and deep water shelf shales that were accumulating in the foredeep along the southern margin of the basin. The change in sedimentary styles is neatly explained in terms of the relaxation phase in foreland basin evolution by Quinlan and Beaumont (1984). During this phase, the lithosphere adjusts viscoelastically, accentuating the forebulge causing the tectonically passive side of the basin to be uplifted and sediments to be sourced into the basin. This tectonic response is believed to have a basin-wide influence on the maceral content of Karoo Basin coals. It is postulated that, in general, the coals accumulated in fresh to brackish mires where low subsidence rates led to oxidation of the peat causing the coals to have high inertinite and ash contents. A similar hypothesis is put forward by Hunt and Smyth (1989) to account for the high inertinite contents in the Wolfgang and Blair Athol Basins (cratonic basins). Higher vitrinite contents in coals are present in the Sydney and Bowen Basins situated in the foredeep area of the foreland basin (Hunt and Smyth, 1989).

PALAEOCLIMATE

Climate is a significant parameter influencing peat formation and accumulation. Temperature and precipitation control plant type, growth rates, and preservation; high wind velocities in high latitudes inhibit plant growth. The marked contrast in characteristics of low-latitude northern hemisphere coals and their sub-polar southern hemisphere counterparts was largely climate-mediated.

The climatic evolution of the main Karoo Basin mirrors the global trends reported by Frakes (1979). The Permo-Carboniferous boundary is marked by a moist, cold phase followed by steadily increasing temperature and aridity up to the Jurassic. Such major trends are mediated by continental drift, atmospheric composition, solar radiation, and attitude of the Earth's axis of rotation (Condie, 1982).

The simplest explanation for the Permo-Carboniferous Gondwana glaciation was the high palaeolatitude (Fig. 3A). Subsequent drift away from the South Pole during the Permian (Fig. 3B) would account for the climatic amelioration which permitted widespread peat deposition in the Vryheid Formation. Fusion of Gondwana with the northern land masses, which formed the supercontinent Pangaea, may have contributed to the global temperature rise since this would have enhanced heat flow to the polar regions by ocean currents (Condie, 1982).

In the main Karoo Basin, the Permo-Carboniferous Gondwana glaciation is recorded in the widespread Dwyka diamictites underlying the Vryheid Formation. Outwash gravels bear testimony to initial temperature rise and glacial melt. Palynological studies of coal seams revealed two distinct and successive climatic regimes during Vryheid Formation deposition (Falcon et al., 1984). The first (Nos. 1 and 2 Seams) relates to the cool periglacial era and the second to a generally milder post-glacial period. Extensive wetlands developed on emergent coastal plains, resulting in widespread peat deposition. In the northern-most part of the basin (Transvaal Coalfield) pre-Karoo relief was appreciable and it is likely that peat deposition was influenced by local microclimates (Fig. 4). Further south (Natal Coalfield), the subdued Karoo floor topography had been buried by argillaceous and sandy sediments prior to peat deposition; here the wetlands were fully exposed to the elements (Fig. 4).

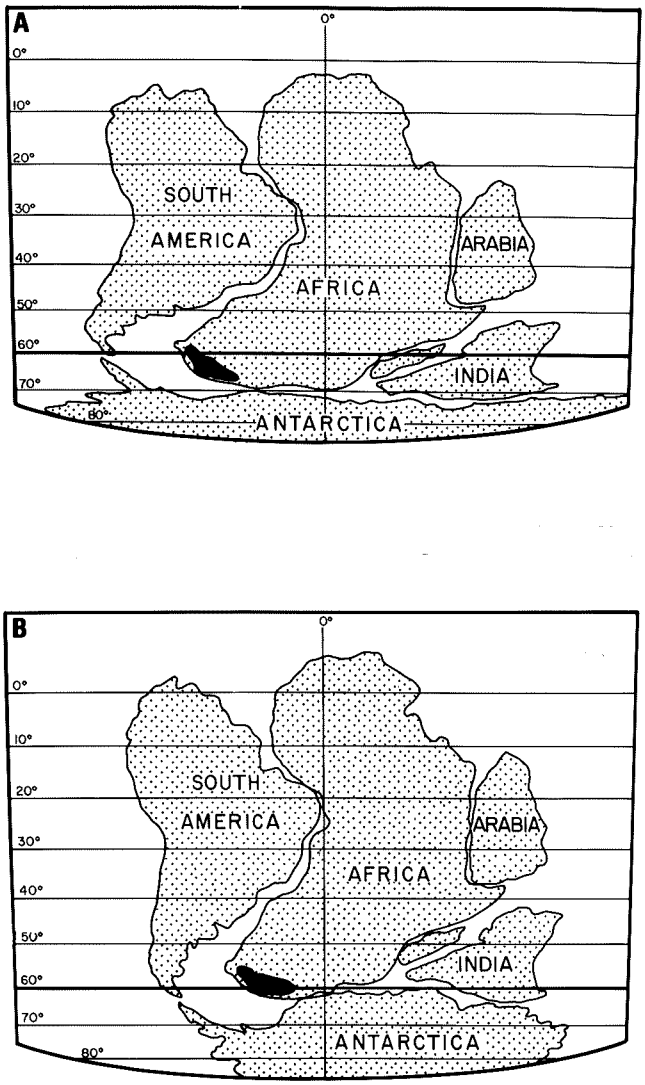


Figure 3: Positions of the Gondwana continents during the Carboniferous and Permian Periods (after Ziegler et al., 1979). A). Position of the Karoo Basin during the Late Carboniferous/Early Permian Periods. B). Position of the Karoo Basin during the Late Permian.

The high palaeolatitude and ample evidence of wave reworking in coastal sands in the Vryheid Formation suggest windy conditions, but not to the degree prevailing on Holocene Icelandic sandurs, where plant growth is minimal (Boothroyd and Nummedal, 1978).

The late Permian Beaufort and Triassic Karoo strata also accord with global climatic trends. Predominant reddish, oxidized sediments reflect hotter and drier conditions, culminating in the aeolian sandstones of the uppermost Stormberg Group sedimentary strata (Figs. 1 and 2). However, during Molteno Formation deposition (upper Triassic) a brief wetter interlude permitted development and accumulation of thin coal seams (Christie, 1981).

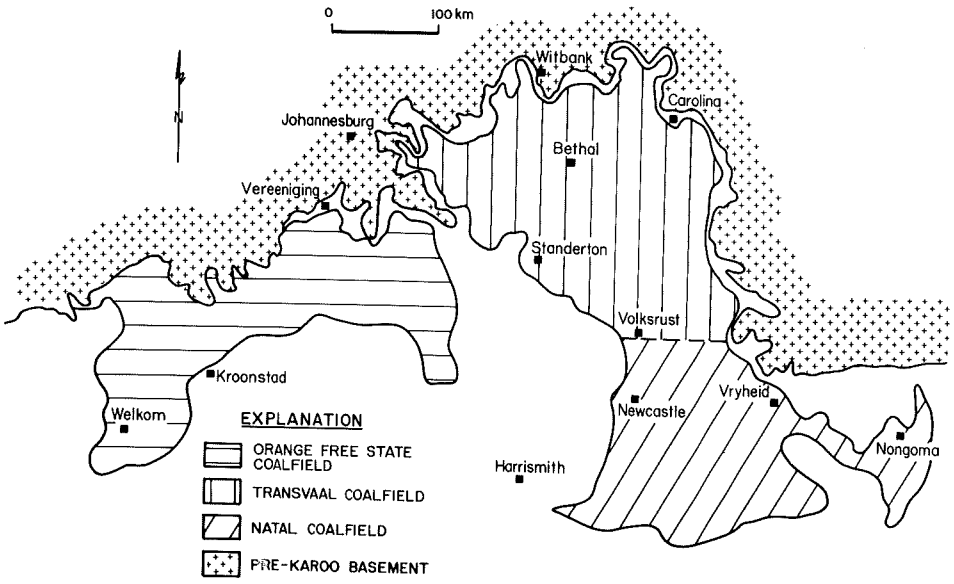


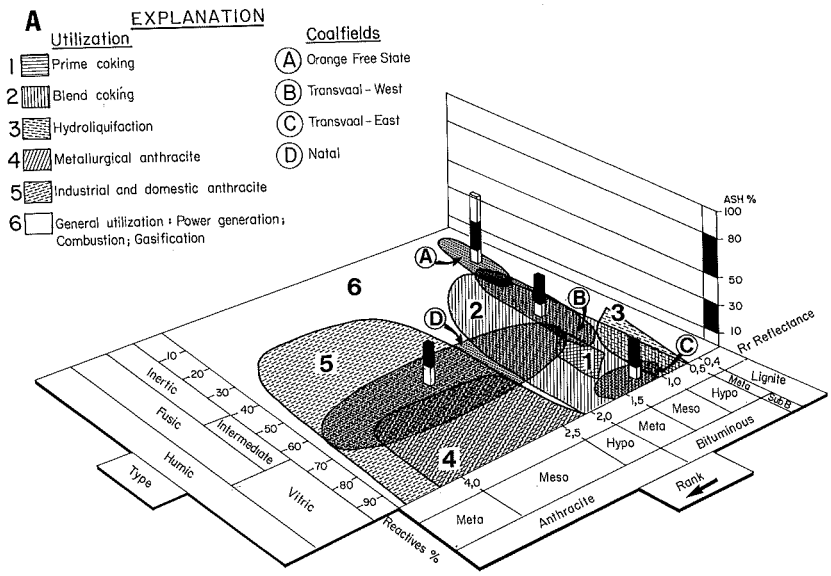
Figure 4: Position of the major Permian coalfields of the Ecca Group in the northern Karoo Basin.

COAL CHARACTERISTICS AND UTILIZATION

Coal Characteristics

In comparison to northern hemisphere (Laurasian) coals, Permian coals of the Karoo Basin are relatively rich in mineral matter and highly variable in type (organic-matter content) (Fig. 5) and rank. Variability in coal type may be ascribed to lateral variations in topographic relief and depositional environment. However, the prime cause was probably vegetational differences (Falcon, 1986a). The coal-forming peat swamps were colonized by vegetation ranging from sub-arctic mosses, through cold-temperate conifers and cool- temperate deciduous forests, typified by the diversified and mixed *Gangamopteris* and *Glossopteris* floras and less dominant lycopods, ferns, cordiatales, early gymnosperms, and reeds. Modern-day temperate deciduous woodlands occur in regions with high summer and low winter temperatures (often below freezing). Forests are characterized by different strata or levels of plant communities: from tall, dominant trees 25 to 50 m high to smaller trees (10 m) and shrubs (3 - 5 m). The floor is covered by herbaceous plants and grasses, bulbs, bracken, mosses, and lichen on fallen logs.

Vryheid Formation coals are, on average, characterized by much higher contents of inertinite than northern hemisphere coals. However, up to 60% of the inertinite group maceral may be classified as semi-reactives (Falcon, 1986b). While vitrinite and inertinite have the same botanical precursors, namely cellulose and lignin from the cell walls of plants



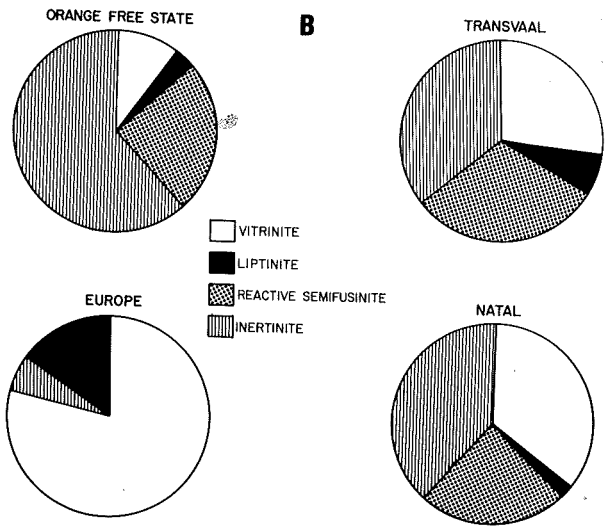


Figure 5: A) Diagram illustrating the variability in type, grade and rank of Vryheid Formation coals and their potential utilization field (after Falcon, 1986b). B). Typical maceral composition of Vryheid Formation coals compared to a typical European coal.

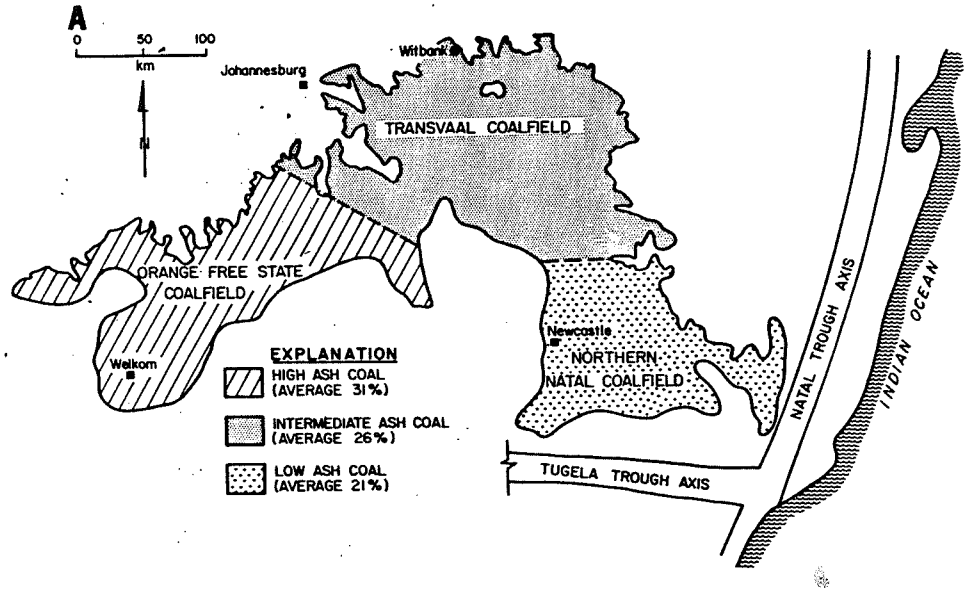
(Stach *et al.*, 1982), inertinite experiences a different geochemical coalification history. The relatively high inertinite content (specifically semi-fusinite, macrinite, inertodetrinite, and micrinite) of Vryheid Formation coals implies that peat were subjected to high rates of oxidation and microbial degradation. This is attributed to the temperate climate (seasonal precipitation), periods of low watertable levels, accumulation of some peats in elevated environments (valley flanks, upper delta plains or alluvial plains), or in swamps frequently inundated by fresh or brackish water (thus increasing pH and Eh levels relative to the levels pertaining to the peat swamps). A further contributory factor was that the coals accumulated on the stable, passive margin of the Karoo Basin which prevented rapid subsidence and burial of the peats. The generally higher vitrinite content of the Natal coals is a function of the more distal setting of the peat swamps and consequently accelerated rates of platform subsidence (sustaining higher watertable levels) brought about by higher rates of differential compaction and proximity to the unstable edge of the Kaapvaal Craton.

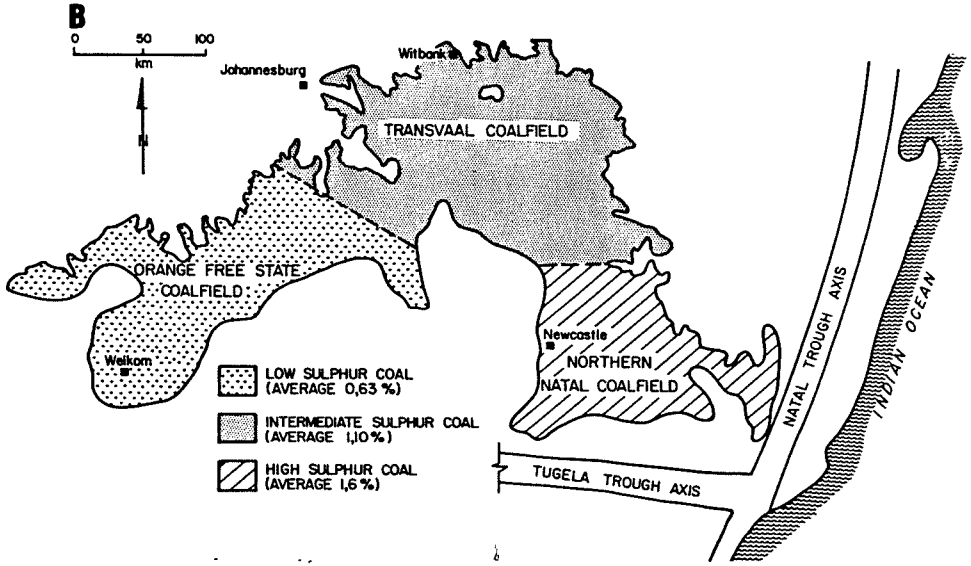
Figure 10 illustrates typical ranges in type, grade and rank of Karoo Basin coals. Coals with vitrinite contents as low as 5- 10% (more typically between 10 and 40%) and high mineral matter contents (30 to 40%) are typical for the detrital or allochthonous, inertinite-rich seams of the Orange Free State Coalfield and portions of the No. 4 Seam in the Transvaal Coalfield (Falcon, 1986b). The No. 2 Seam maceral composition is variable and equal amounts of inertinite and vitrinite may be present. Mostly, however, vitrinite content is between 20 and 40% and mineral matter 10 to 20%. Vitrinite content in the No. 3 and 5 Seams may be up to 60% with mineral matter between 5 and 15%. Exinite content in all seams is generally less than 10%, but may be up to 15%. Natal coals are typically vitric to intermediate in type (60 to 80% vitrinite) and have mineral matter contents up to 40%. Natal coals, although displaying a wide variation in rank, are more similar to Laurasian coals in terms of type and rank than any other Vryheid Formation coals.

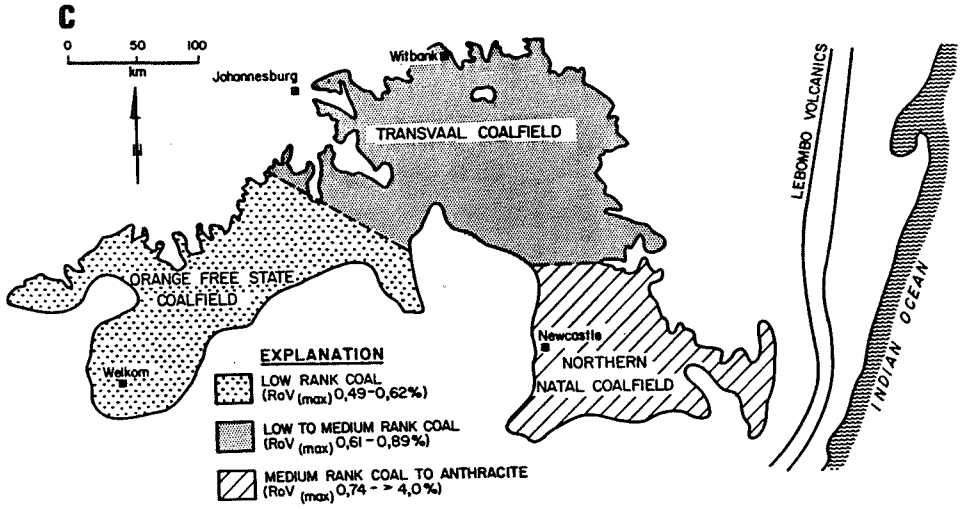
The fact that South African coals, particularly those of the Vryheid Formation, accumulated on a relatively stable continental margin means that they have never been subjected to deep burial, intense tectonic stresses or high geothermal gradients (such as the northern hemisphere coals). Consequently, the coals generally range in rank from sub-bituminous to mid-bituminous, progressing in some regions up to meta-anthracite due to local heating. There is a progressive eastward increase in coal rank across the Karoo Basin coalfields (Figs. 10 and 11C), from sub-bituminous in the Orange Free State, to anthracitic and meso-anthracitic in eastern Natal. Snyman and Barclay (1989) attributed this phenomenon to a regional increase in palaeogeothermal gradient, related to melting of the asthenosphere and consequent large-scale magmatic activity, which culminated in a vast outpouring of lavas during the Jurassic and the break-up of Gondwanaland. Rapid lateral variations in rank are ascribed to Jurassic igneous intrusions (dolerite sills and dykes): contact metamorphism of the coals occurs within a distance of about 0,6 to 2 times the thickness of the intrusion.

Resources and Utilization

The main Karoo Basin is host to the major coal resources of South Africa, though significant deposits are also present in the geographically smaller, contemporaneous basins of the northern Transvaal. Coal is







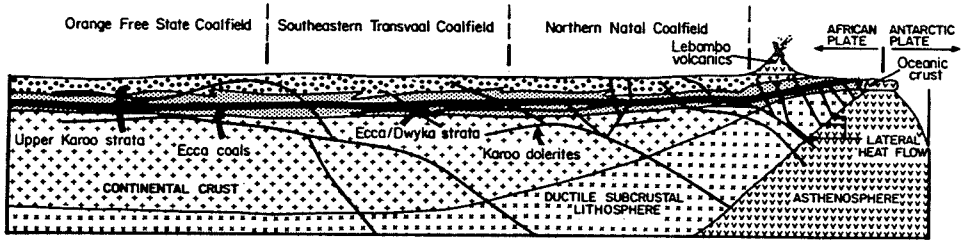


Figure 6: Average values for: A). ash and B). sulphur and C). rank for Ecca coals. The southeasterly increase in coal rank is attributed to the high heat flow and numerous dykes and sills associated with post Gondwana riftigng.

developed at three stratigraphic positions in the Karoo Sequence: the Permian Vryheid and Volksrust Formations and the Middle Triassic Molteno Formation. Coals within the Volksrust Formation have never been exploited and will not be discussed further.

The wide range of depositional settings within which the coal-forming peats accumulated, combined with variations in climatic regimes and plant communities as well as Jurassic dolerite intrusions, impart significant differences in grade, type, and rank between and within coal seams. These differences have important practical implications with respect to mining methods, beneficiation processes, and utilization in the fields of metallurgy, synthetic fuels (oil-from-coal), and power (steam) generation. Figure 6 illustrates the relationship between average type, grade, and rank of coals in the Transvaal, Natal, and Orange Free State coalfields, and their utilization potential. The differences in type, grade, and rank between Gondwanan (more specifically Karoo Basin) and Laurasian coals referred to earlier has necessitated considerable improvements and adaptations in metallurgical and combustion technologies. In terms of combustion performance with respect to boiler design, the inertinite-rich, lower volatile Gondwanan coals burn efficiently with a strong, hot flame, but for optimum ignition and combustion require finer pulverizing (>75% below 75 um), slightly higher secondary-air temperature, and longer furnace-residence times than the more reactive Laurasian coals (Falcon and Ham, 1988). The relatively high ash-fusion temperatures, lower sulphur and chlorine contents, and low sodium, potassium, and iron contents of Karoo Basin coals lessen the need for costly removal of pollutants prior to or after combustion. ESCOM, South Africa's major electricity supplier, burnt 67 m/t of coal to deliver 127 billion kW hr in 1987. In general, the coal used for electricity generation is of poor grade: calorific value averages 21,2 Mj/kg and ash content ranges between 24 and 35%. A recently commissioned power station in the Orange Free State (2472 MW) is designed to burn coal with an ash content of 35 - 36% and calorific value of 16 Mj/kg. In spite of these low coal grades, the average thermal efficiency of power stations is about 33%. South Africa's oil-from-coal industry (SASOL) is based entirely on the Fischer-Tropsch indirect liquefaction process due to the relatively low reactivity (principally a function of low vitrinite content) and high mineral matter content (~20 - 40%) of Karoo Basin coals. All coal used is unbeneficiated, and in 1988 SASOL mined and processed about 35 m/t of coal to produce some 2,5 m/t of liquid fuels in addition to a large quantity and variety of petrochemicals.

South Africa has limited reserves of coal suitable for coke production due to its low reactivity (vitrinite and reactive semi-fusinite) and high inertinite and mineral matter contents. The introduction of the direct reduction process which does not require coking coal, will increase the life of coking coal reserves and result in the classification of a wide range of non-coking coals as "metallurgical" in future.

Approximately 49% of South Africa's demonstrated coal resources are contained in the Karoo Basin (Bredell, 1987; Table 1).

TABLE 1: DEMONSTRATED COAL RESOURCES - SOUTH AFRICA AND KAROO BASIN

	SOUTH AFRICA (M/t)	KAROO BASIN (M/t)	PER CENT
Demonstrated Resources	121 182	59 925	49
Reserves	55 333	37 625	68

Significantly, the Karoo Basin comprises 68% of total coal reserves and contributed 97% of South Africa's 1988 saleable production. This can be attributed to the generally shallow nature of the coal seams (96% occur at depths less than 200 m), their essentially horizontal attitude, and working thicknesses of between 1,2 and 6 m (Minerals Bureau, 1989). Karoo Basin reserves are, however, predominantly low-grade bituminous coals (77%): only 12% have an ash content below 20%. These contributed the bulk of the 43,3 m/t of beneficiated coal exported in 1988. Coking coal and anthracite account for approximately 4% and 1,5% of Karoo Basin reserves, respectively.

The Molteno coal province, although the site of South Africa's first coal mine and principal coal supplier between 1900 and 1904, essentially ceased production in 1948. Mining on a small scale recommenced in early 1989.

OIL SHALES

Torbanite and cannel coal deposits are characteristically thin (very few seams exceed 1,2 m in thickness) and of restricted areal extent (rarely greater than 25 - 100 km^2,) Christie, (in press). In addition, they are closely associated with and enclosed by coal. Most of the potentially economic torbanite deposits occur towards the top of the Vryheid Formation. A cannel coal is developed in the Triassic Molteno Formation in the Impendhle District, Natal.

Torbanites are black to greenish-black oil shales that contain up to 90% by volume telalginite. Oil yields, depending on grade and degree of maturation, commonly range between 140 and 800 l/t. Minor components include inertinite, vitrinite, sporinite, resinite, and varying amounts of mineral matter. Alginite exhibits intense and spectacular fluorescence under blue and ultraviolet light irradiations with colours ranging from green/yellow through yellow/orange.

Cannel coal, a dull black oil shale, contains very little or no alginite, but is rich in liptinites such as sporinite, resinite, and liptodetrinite (fragmented liptinite) derived from terrestrial vascular plants. Lesser amounts of alginite, vitrinite, and inertinite are present. Cannel coal is not generally recognized as an economic oil-producing commodity, though it may yield between 20 and 260 l/t of shale oil.

The algae present in oil shales (along with other types of organisms) lived in quiescent, aquatic environments. Algae flourished under these conditions which also favoured the accumulation and preservation of organic-rich muds. These algal-based oozes or "gyttjas" are referred to as sapropelic muds. Torbanites within the Vryheid Formation accumulated mainly in ponds and lakes on the No. 5 seam swamp plains. *Reinschia*, an analogue of the extinct *Botryococcus braunii*, was a colonial, planktonic green algae that populated fresh to brackish waters (Hutton, 1986). Modern-day colonies of algae float in surface waters, and frequently aggregate to form extensive rafts. On dying they lose their buoyancy and are deposited in the bottom sediments. The torbanites represent algal accumulation under anoxic, reducing conditions. However, the algae probably lived in oxygenated waters at the centre of lakes and ponds as these areas were beyond contamination by organic substances and peat-derived humic acids. Algal accumulation was invariably terminated by the shallowing of the waters and re-establishment of peat-forming flora.

A torbanite that accumulated in a paralic lake, essentially isolated from detrital influxes, has been identified from above the No. 5 seam in the eastern portion of the Transvaal Coalfield (Christie, 1988). The lake is thought to have formed following the abandonment of a lagoon and progressive progradation of the coastline (Fig. 7). The torbanite, which generally contains between 40 and 80% mineral matter and only up to 30% alginite, overlies a thin back-barrier coal. This torbanite is developed over an area in excess of 200 km^2 and is between 0,9 and 6,8 m thick. Algal accumulation was terminated by the progressive encroachment of bed-load rivers over and into the lake.

The presence of most torbanites near the top of the coal zone was probably in response to a specific and unique set of conditions existing during that period. Furthermore, there is no doubt that basinal subsidence rates, sedimentary processes, and water chemistry played an important role. A warmer climate was most likely the principal determinant in the accumulation of sufficient quantities of algae to form torbanite.

A unique cannel coal seam 3 to 6 m thick, occurring directly above the Indwe Sandstone member (Molteno Formation) in Natal, was documented by Botha (1939). Sedimentary associations suggest that the coal accumulated in channels of an abandoned braided river system over an area of about 180 km^2.

THE COALFIELDS

Introduction

The main economic coal seams of Permian age are confined to the northern and northeastern regions of the Karoo Basin (Fig. 4). Approximately half (50.8%) of the Republic of South Africa's mineable in situ coal resources occur in these areas (Smith and Whittaker, 1986). As such, these coals represent an important energy source for the local as well as the export market.

The critical controlling factor in this restricted geographical as well as geological location of the coal resources was the tectonic framework of the Karoo Basin during the late Palaeozoic. Unlike the rapidly subsiding foredeep in the southern Cape trough (Fig. 2), the northern section of the basin comprised a relatively stable platform. Intermittent subsidence coupled with peat swamp development promoted peat formation, and subsequent burial led to peat preservation. In addition, basinal waters in this portion of the basin were relatively shallow and extended along the arcuate northern palaeoshoreline and this hydrologic feature further enhanced the flourishment of low-lying, paralic peat swamps.

In contrast, the sediments comprising the Natal Coalfield to the east of the Transvaal Coalfield (Fig. 4), accumulated under conditions of greater tectonic instability (Whateley, 1980; Turner and Whateley, 1983; Roberts, 1988). These coals were associated with syn- and post-depositional down-faulting on the flanks of the Kaapvaal Craton. Greater subsidence rates are reflected in the variable thicknesses of the coal-bearing Vryheid Formation from west to east: 80 m on the northern basin margins (Cairncross

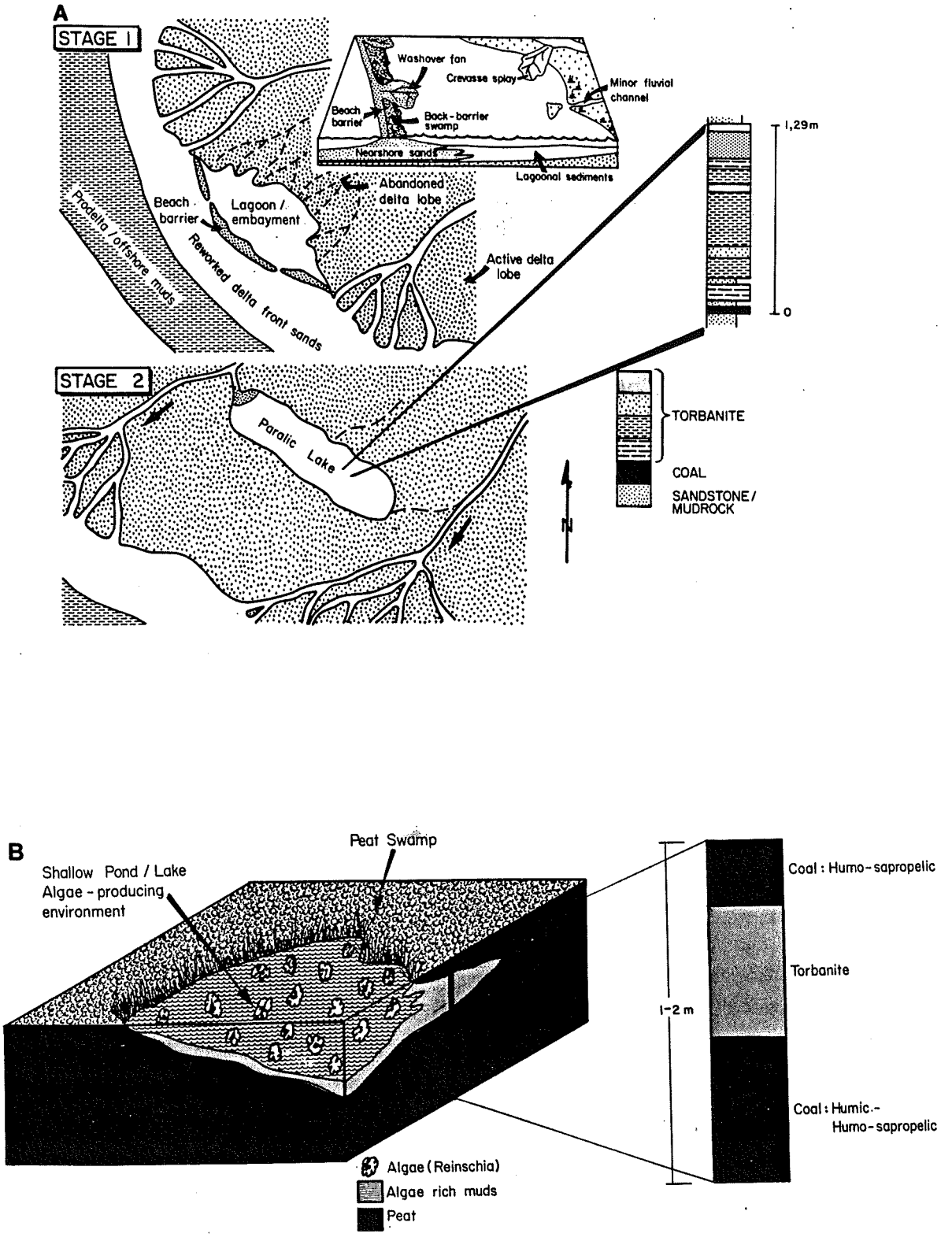


Figure 7: A). Depositional setting and processes leading to the accumulation and preservation of paralic torbanite deposits. B). Depositional environment in which torbanites enclosed by coal are suggested to have formed.

and Cadle, 1987), 180 m in the central Witbank Coalfield (Le Blanc Smith, 1980), 325 m in the central Natal Coalfield (Roberts, 1988) and a maximum thickness of 500 m in the extreme eastern regions (SACS, 1980).

Apart from the west to east change in the tectonic style and subsequent control on total stratigraphic thickness, a north to south component further influenced the distribution of the Vryheid Formation sediments. A deepening of the basin from the northern stable intracratonic platform towards the southern subsiding foreland, was accompanied by a north-to-south pinch out of the Vryheid Formation (Fig. 2). This southerly shale-out (Van Vuuren and Cole, 1979) was source related as sediment was being shed from the northern granitic hinterland by fluviodeltaic systems. Rapid basinward facies migration down the southerly dipping palaeoslope caused the interfingering and shale-out with the deeper water distal shales, approximately 500 km from the present northern basin margin (Fig. 2).

The Transvaal Coalfield

Stratigraphy

A generalized stratigraphy for the Orange Free State, Transvaal, and adjacent Natal Coalfields is illustrated in Fig. 8. Coal-seam nomenclature varies from locality to locality. For example, the Bottom Seam = No. 2 Seam; the Top Seam = No. 5 Seam. However, these coals, and particularly the associated overlying and underlying sedimentary packages can be correlated between the coalfields.

In the Transvaal region, five mineable bituminous seams occur within a sequence seldom exceeding 200 m in thickness (Le Blanc Smith, 1980; Winter et al., 1987; Cairncross, 1989). In proximal basin settings, the Vryheid Formation is reduced to 80m in thickness but nonetheless still contains all five coal seams (Cairncross and Cadle, 1988). The coals are associated with a clastic succession comprising carbonaceous shale/siltstone, fine-to very coarse-grained sandstone and minor conglomerate. The lowermost portions of the stratigraphic column differ significantly from the above-mentioned lithologies. These strata consist of reworked Dwyka tillite, rare varved shales, and pebbly mudstones (Le Blanc Smith and Eriksson, 1979; Cairncross and Hobday, 1985; Winter, 1985).

Depositional Systems and Controls on Coal Distribution

The high latitude position of the African subcontinent during the early Permian (Fig. 3) produced cool temperate climatic conditions during the initial phases of deposition of the Vryheid Formation (Falcon, 1986). The Ecca Group (Figs. 1 and 2) was preceded by the Permo-Carboniferous Dwyka ice-age during which time large tracts of the subcontinent were covered by continental ice (Tankard et al., 1982, p. 364). These ice sheets were instrumental in sculpturing the rugged basement topography prior to the deposition of the Ecca Group sediments. Glacial retreat, mainly to the north and northeast (Stratten, 1968; Crowell and Frakes, 1975), discharged meltwater which served to rework unconsolidated till as well as introduce coarse, gravelly detritus into the northern basin areas. This flow was channelized via palaeovalleys, and major entry points were located immediately to the west and east of the present day

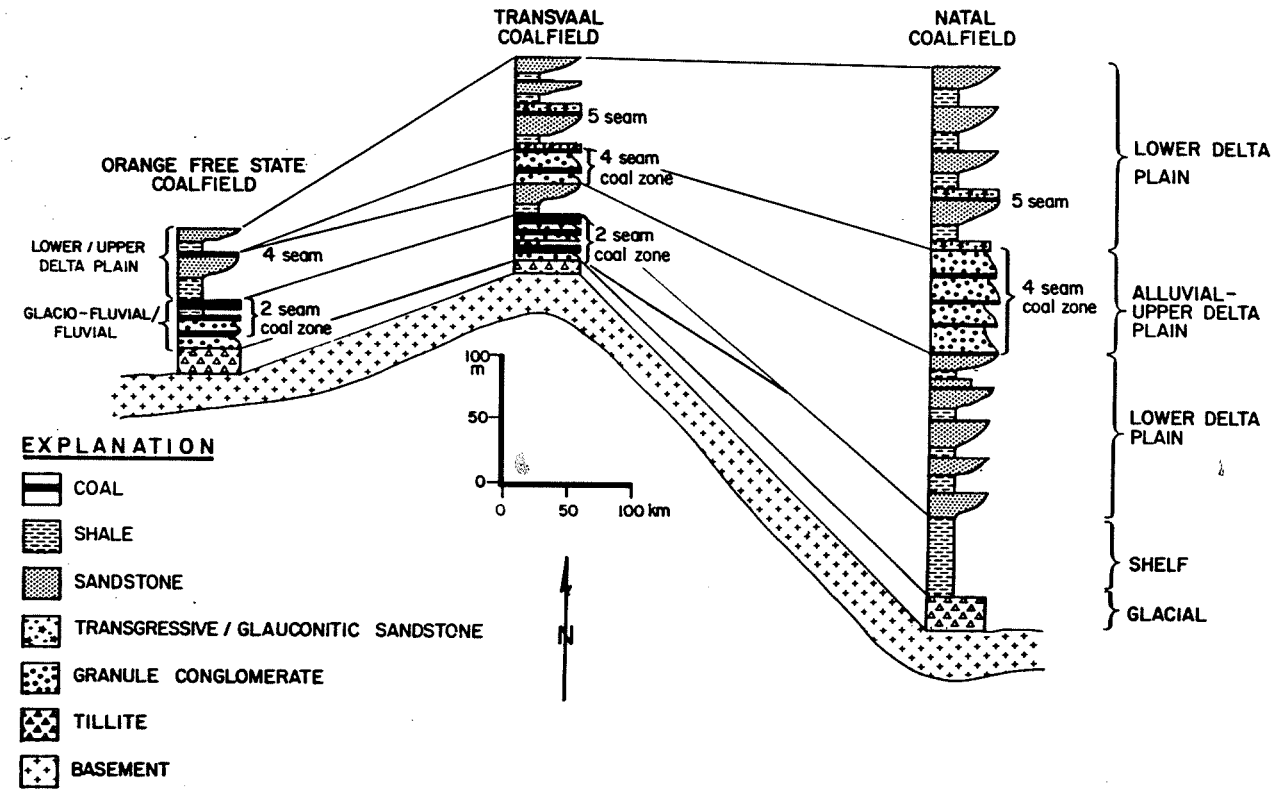


Figure 8: Correlations of depositional systems, lithologies and coal seams between the Orange Free State, Transvaal and Natal Coalfields (after Cadle, 1982). Note the increase in stratigraphic thickness towards the Natal Coalfields illustrating increased subsidence rates in a southeasterly direction.

town of Witbank (Fig. 4). Protected embayments and some palaeolows, which escaped this glaciofluvial influx, were characterized by the deposition of lacustrine muds and restricted glaciodeltaic fill (Le Blanc Smith and Eriksson, 1979). These palaeovalleys had previously been the sites of deposition of isolated pockets of Dwyka tillite. The glacial tillite and overlying glaciogenic strata can, however, be absent, in which case the lowermost coals rest directly on the Precambrian basement (Cairncross and Hobday, 1985). More commonly, the lowermost No. 1 and No. 2 coal seams overlie the glaciogenic sequences, particularly the glaciofluvial braided outwash plain deposits. The coals originated as a direct result of vegetation proliferation and peat swamp encroachment over the moribund alluvial plains. A high water table no doubt enhanced peat accumulation and preservation as the lowermost coals (No. 1 and No. 2 seams) are the thickest and most widespread in the region. In places, minor stream courses persisted across the peat swamp and became entrapped by the resilient flanking vegetation. Furthermore, anastomosed fluvial systems, both fine-grained (Le Blanc Smith and Eriksson, 1979) and coarse-grained varieties (Cairncross, 1980) transected the peat swamp. These channels were typified by vertical aggradation concomitant with peat accumulation, which resulted in narrow, dip-elongate shoestring sand bodies enveloped by the coal. Higher ash, lower calorific value coal, caused by interbedded clastic partings introduced by overbank flooding, parallels these abandoned channel fills. The lower ash, higher calorific value coal is therefore located farthest from the palaeochannel sediments (Cairncross, 1980; Winter, 1985).

The remaining portions of the succession are associated with fluviodeltaic deposits. Coarsening-upward sequences such as above the No. 2 seam (Fig. 8) comprise a basal, highly carbonaceous siltstone overlain by interbedded siltstone and fine-grained sandstone, frequently bioturbated, followed by medium- to coarse- grained arkosic sandstone. The argillitic base of this profile represents gradual drowning of the peat swamp and inundation by transgressive basinal water, from the south, which onlapped onto the continental shoreline. Although the presence of abundant *Glossopteridae* and other comminuted plant debris attest to a continental setting for the argillite, trace fossil assemblages comprising *Rhizocorallium*, *Skolithos*, *Cruziana*, and *Siphonichnus* provide evidence for marine conditions during transgression (Stanistreet et al., 1980). The overlying delta plain facies capped by the No. 3 coal seam include upward-coarsening, bay-fill sequences and crevasse-splay deposits. Coarse-grained channel facies at the top were deposited by the basinward migration of the up-dip fluvial plain over the underlying deltaic platform.

In the Transvaal coalfield, post-depositional fluvial scouring prior to and during No. 4 seam peat accumulation have been well documented (Le Blanc Smith, 1980; Cairncross and Hobday, 1985; Winter, 1985; Cairncross and Cadle, 1988;). Fluvial systems, comprised exclusively of bed-load, braided channels, eroded the underlying coal and deltaic sequences. These fluvial deposits reach 25 m in thickness and consist of coarse-grained to granule-grade, arkosic sandstone, and thin, laterally impersistent lenses of conglomerate, that are structured primarily by planar cross-bedding.

The remaining sequences above the No. 4 seam were deposited by high constructive, lobate delta progradation (Le Blanc Smith, 1980; Cairncross and Winter, 1984). Glauconitic siltstone and cross-laminated fine-grained quartz arenite underlying the deltaic deposits indicate marine

transgression prior to the onset of deltaic sedimentation. To the west, the coals of the Orange Free State (Fig. 8) are associated with regressive deltaic cycles together with multiple-stacked, crevasse-splay sequences (Gilligan, 1986).

Tectono-sedimentary Controls on Coal Distribution

In addition to the overall tectonic control on coal distribution, the topography and lithological diversity of the pre-Karoo basement in the Transvaal and Orange Free State Coalfields were the major controlling factors of sediment and peat distribution. The palaeotopography exercised direct control by initially confining deposition within palaeovalleys. These were sites where peat accumulated on the abandoned alluvial plains and glaciogenic strata. Conversely, the seams pinch-out against palaeovalley margins and are either thin or absent above prominent basement highs (Fig. 9). The intervening valleys therefore contain the thickest coal seams and these, No. 1 and No. 2 seams, are found in the lowermost section of the succession. However, superimposed on the favourable palaeolow settings, were syn- and post-depositional bed-load fluvial systems that flowed from the northern source terrain, transporting sediment down the palaeovalleys into the basin (Winter, 1985, fig. 66). The No. 1 and No. 2 seam peat was therefore partially removed by channel erosion and seam splitting, due to lateral stacking of channel-fill sandstone and minor overbank deposits, is a common feature (Fig. 9). Small-scale overbank deposits are also commonly interbedded within these coal seams.

In proximal basin settings, the bed-load-dominated rivers were large trunk streams up to 10 km in width. As these flowed basinward draining the swamps, channels bifurcated into a network of bank-stabilized anastomosed channels (Le Blanc Smith and Eriksson, 1979; Cairncross, 1980). The anastomosed channel deposits now enclosed by the No. 2 coal seam, and the No. 4 seam above (Winter, 1985), pose several mining and quality problems.

These include:
1) depleted tonnages by scouring and removal of coal;
2) depleted mineable tonnages adjacent and parallel to palaeochannel flanks where the coal interleaves and is split by clastic parting; and
3) downgrade coal quality, i.e, increase the ash content of the coal. Zones of relatively high-ash coal up to 4 km wide parallel the abandoned channel fill tracts.

Fig. 9 graphically summarises these phenomena.

Subtle variations in coal seam thickness were caused by differential compaction affects. In areas where the coal seams closely overlie uncompactable pre-Karoo basement highs, loading and compaction effects have caused thinning of the coal (Fig. 9). Seams situated above channel sandstones can be thinner for similar reasons (Winter, 1985, fig. 81). In areas where significant thicknesses of mud and silt have accumulated, such as some palaeolows, differential compaction of the clays provided depressed areas which favoured peat accumulation and hence thicker coal.

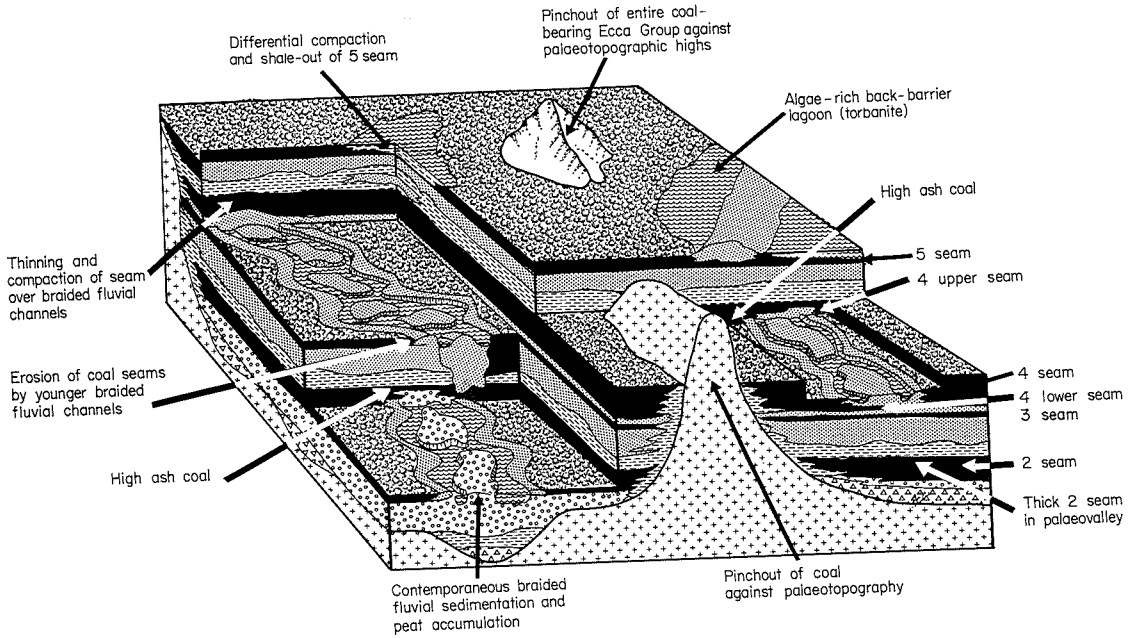


Figure 9: Block diagram illustrating the depositional systems and factors influencing coal thickness, distribution and ash content in the Transvaal Coalfield (Modified after Winter, 1985).

The Natal Coalfield

Stratigraphy

The stratigraphy of the Vryheid Formation in Natal is substantially different from that in the Transvaal. Subsidence rates were higher and the sequence as a whole is thicker, attaining a maximum development of about 500 m in the south near Tugela Ferry (Figs. 8 and 10). Prior to deposition of the Vryheid Formation in Natal, the subdued topography of the pre-Karoo floor had been blanketed by Dwyka Formation diamictites and dark Pietermaritzburg Formation shelf mudrocks. Thus, in sharp contrast to the Transvaal, peat deposition in Natal was little affected by pre-Karoo relief. Coals are largely confined to a stratigraphic interval referred to as the Coal Zone, situated between the Upper and Lower Zones (Fig. 10).

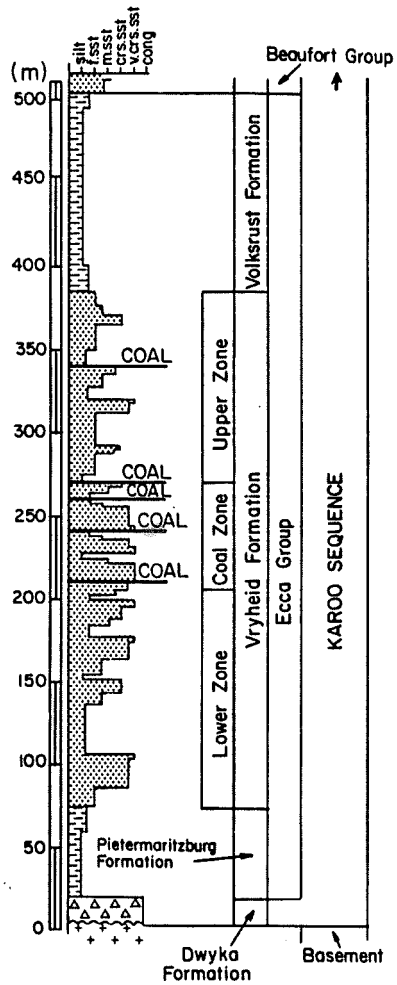


Figure 10: Stratigraphic profile of the Dwyka and Ecca Groups in the Natal Coalfield. The diagram illustrates the grain size variations, positions of coal seams and informal nomenclature of the Vryheid Formation.

The dominant lithology in the Vryheid Formation of northern Natal comprises light-grey, coarse- to granule-grade arkosic sandstone, which is typically planar or trough cross-stratified (Fig. 10). More mature, fine- to medium- grained arenites form a significant proportion of the Upper and Lower Zones, as do dark-grey to black silty mudstones. Heterolithic facies composed of interbedded arenites and mudrocks are also well developed in the Lower and Upper Zones.

Ichnology also serves as a basis for stratigraphic subdivision of the Vryheid Formation in northern Natal (Roberts, 1986; 1988). The Lower Zone contains an abundant and diverse ichnofauna, including *Siphonichnus*, *Diplocraterion*, *Spirodesmos*, *Rhizocorallium*, *Scolicia* and *Helminthopsis* as the most common ichnogenera. In contrast, the ichnocoenosis of the Upper Zone is typified by small, indistinct vertical and horizontal burrows, while trace fossils in the Coal Zone are rare. The lithologically similar Upper and Lower Zones can only be distinguished by the trace fossil assemblage.

Depositional Framework

The key to the broad controls on peat accumulation in Natal lies in the sedimentary history of the strata beneath the Coal Zone. Lower Zone sedimentation patterns are dominated by upward-coarsening sequences of variable dimensions (Figs. 8 and 10). In many areas, the sandy upper part of the lowermost unit comprises a giant foreset facies association (Fig. 10). These foresets reach 40 m in thickness and are attributed to Gilbertian delta progradation into a body of standing water (Roberts, 1986). Homopycnal conditions, considered necessary for Gilbert-type delta construction, developed via dilution of seawater during fluvial floods (Roberts, 1986). The upper surfaces of these sequences are extensively bioturbated and are overlain by facies suggestive of basinal influence (e.g. herringbone cross-stratification). Transgression of basinal waters over the deltaic sediments resulted from compaction of the underlying sedimentary succession. Occasional coalified plant remains do occur above the delta topsets, but rapid subsidence prevented significant peat deposition (Tavener-Smith, 1989).

Overlying the basal sequence are several upward-coarsening sequences, representing progradation of lobate, wave/fluvial-influenced deltas and, less commonly, wave-dominated coastal sequences (Roberts 1986, 1988; Christie, 1988). Delta and subdelta lobes overlap and interfinger and seldom extend laterally for more than a few kilometres. This sedimentation pattern was caused by delta abandonment and reactivation as slope advantage was alternately lost and regained; the shoreline advanced and retreated in piecemeal fashion. Allocyclic mechanisms have been invoked to explain Vryheid Formation delta cyclicity (Van Vuuren and Cole, 1979), but there is no evidence for this in northern Natal.

Roberts (1986; 1988) and Van Vuuren and Cole (1979) noted the presence of unusually mature sandstones immediately beneath the Coal Zone. These quartz arenites heralded a period of basinal stability; slower sedimentation permitted marginal marine processes to rework coastal sands. At this time, deltas prograded far basinward (towards the southeast), providing stable platforms for peat accumulation (Fig. 11). Braided fluvial sand tracts aggraded and switched in response to diferrential compaction

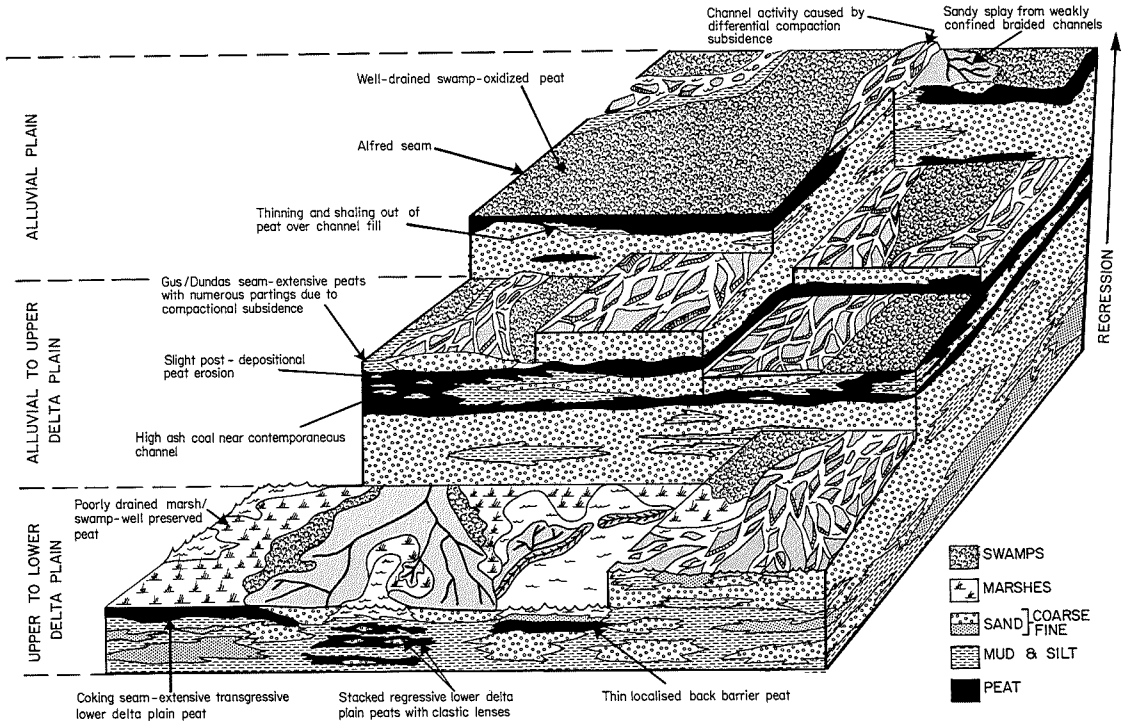


Figure 11: Block diagram of the coal zone in the Natal Coalfields. The diagram highlights the depositional systems operating during peat formation and controls on coal thickness and distribution.

and rapid sedimentation rates. This resulted in the preservation of 25m-thick sandbodies capped by coal. This depositional episode is the equivalent of the No. 4 seam sedimentary package in the Transvaal (Fig. 8), but the strata are diachronous, younging towards the south. Although the Coal Zone can be identified for 150km south of Newcastle (Fig. 4) economic coals are confined to a lobate area situated east, northeast, and 50km south of Newcastle.

Lower Delta Plain Coals

Within lower delta plain environments coals associated with bay-fill (sub-delta) construction are distinguished from those deposited above laterally extensive delta complexes capped by widespread transgressive deposits.

Bay Fill Settings: Laterally impersistent coals cap thin, burrowed, upward-coarsening, bay-fill sequences, which may be vertically repetitive (Fig. 10). These coals rarely exceed a few decimetres in thickness and can seldom be traced for more than a few kilometres. They grade laterally into carbonaceous embayment-fill mudrock (Fig. 10), or pinch out against distributary channel-fill sandstones. The extent of regressive lower delta plain coals is essentially mediated by the surface area of embayments and the proportion of the latter which became emergent. Galloway and Hobday (1983) pointed out that the numerous distributaries which traverse lobate deltas restrict the extent of embayments, hence the lack of continuity of these coals in the Natal Coalfield. Peat deposition was inhibited by sediment influx from distributaries and marine inundation. Splays of coarse carbonaceous sandstone in this environment result in these coals having a high mineral matter content (Fig. 11). Coal type is variable, ranging from bright, laminated, vitrinite-rich coal to dull, inertinitic coals. Sappropelic coals also occur in these settings.

Delta Complex Coals: Coals capping delta complexes are more extensive, thicker, lower in ash, and are more vitrinite-rich than the bay-fill coals. These coals overlie subdeltas including distributary channel-fills. Clastic influx during peat accumulation was reduced, which accounts for the enhanced thickness (up to 2 m) and relatively low mineral matter content of these coals. Owing to low sandstone/mudrock ratios in this distal setting, subsidence rates were sufficient to maintain a high water table. This promoted the preservation of vitrinite peat precursors and many of these coals have metallurgical properties. The thickest of these is referred to as the "Coking Seam" in the Utrecht/Vryheid areas (Fig. 11).

Thin coals occupying the same stratigraphic position as the lower delta plain seams described above, occur sporadically in association with wave-rippled, clean sandstone in the Durban area of Natal (Tavener-Smith, 1982). These coals are high in ash due to incorporation of lenses of reworked arenite. The coals formed in back - barrier settings (Tavener-Smith et al., 1989); where peat deposition was inhibited by washover fans and marine incursions, which collectively account for thin seams of inferior quality and restricted extent.

Upper Delta Plain Coals

The best developed coals in northern Natal are the Gus and Dundas and Alfred seams. These seams equate stratigraphically with the No. 4 seam

in the Transvaal Coalfield (Fig. 8). The coals represent a single peat depositional event, since they merge in some areas to form single thick seam (up to 4 m). They are laterally extensive and can be traced in outcrop and the subsurface for distances exceeding 100 km along strike and dip. Coarse, braided channel-fill sandstones with sheet-like geometries commonly split the coal into subseams (Fig. 8). The peat precursors of the Gus, Dundas, and Alfred seams were deposited on broad, abandoned, braided alluvial and upper delta plains, accounting for their widespread distribution. Periodic reactivation of these abandoned tracts explains the splitting of seams. Areas of rapid subsidence repeatedly favoured channel capture, and several thin seams (up to 8) occur in these localities. Erosion of peats by fluvial scour was minimal, since channel widening rather than stream-bed erosion prevailed (Roberts, 1986). The swamps were better drained than their distal counterparts, but groundwater flow maintained a reasonably high water table. Nevertheless, the Gus, Dundas, and Alfred seams comprise banded, bright vitrinite-rich and dull inertinite-rich coal. Overall, vitrinite contents are lower than the coals present in lower delta plain environments, and are seldom of metallurgical quality.

Coal Zone deposition was terminated by a major transgression caused by accelerated basin subsidence (Fig. 11). Deltaic deposition, similar in style to the Lower Zone, resumed. Coals are present in the Upper Zone, but they are thin and sporadic; once again, basinal instability prevented significant peat deposition. About 60 m above the Coal Zone, the fairly persistent Eland Seam is developed in a lower delta plain environment. It is regarded as the southerly equivalent of the No. 5 seam in the Transvaal Coalfields (Fig. 8), but in Natal it never attains exploitable thickness. The Eland Seam is bright and vitrinite-rich. A major marine incursion, recorded by the Volksrust Formation shelf mudrocks, terminated Vryheid Formation deposition.

The Molteno Coalfield

The Molteno Formation comprises a northward-thinning, wedge of dominantly fluvial sediments deposited during the Upper Triassic. The erosive remnant of the formation is located in the central portion of the Karoo Basin and attains a maximum thickness of approximately 625 m in its southern outcrop area; in the north it is less than 10 m thick. Sediments were deposited by bedload-dominated rivers originating from a tectonically active source area situated to the south and southeast (Turner, 1975; Christie, 1981). This source region represented renewed uplift of the Cape Fold Belt (Tankard *et al.*, 1982).

Stratigraphy and Sedimentology

The lithostratigraphy of the Molteno Formation is depicted in Fig. 12. The commencement of Molteno sedimentation is indicated by the Bamboesberg Member which was deposited by sandy, ephemeral streams which were broad and shallow (Christie, 1981). In contrast to the warm, arid climate prevailing during Beaufort Group sedimentation, the climate was temperate and wet. Peat accumulated in alluvial-plain swamps removed from the locus of fluvial activity. While the Bamboesberg Member is believed to have been the product of an epeirogenic phase of uplift in the source area

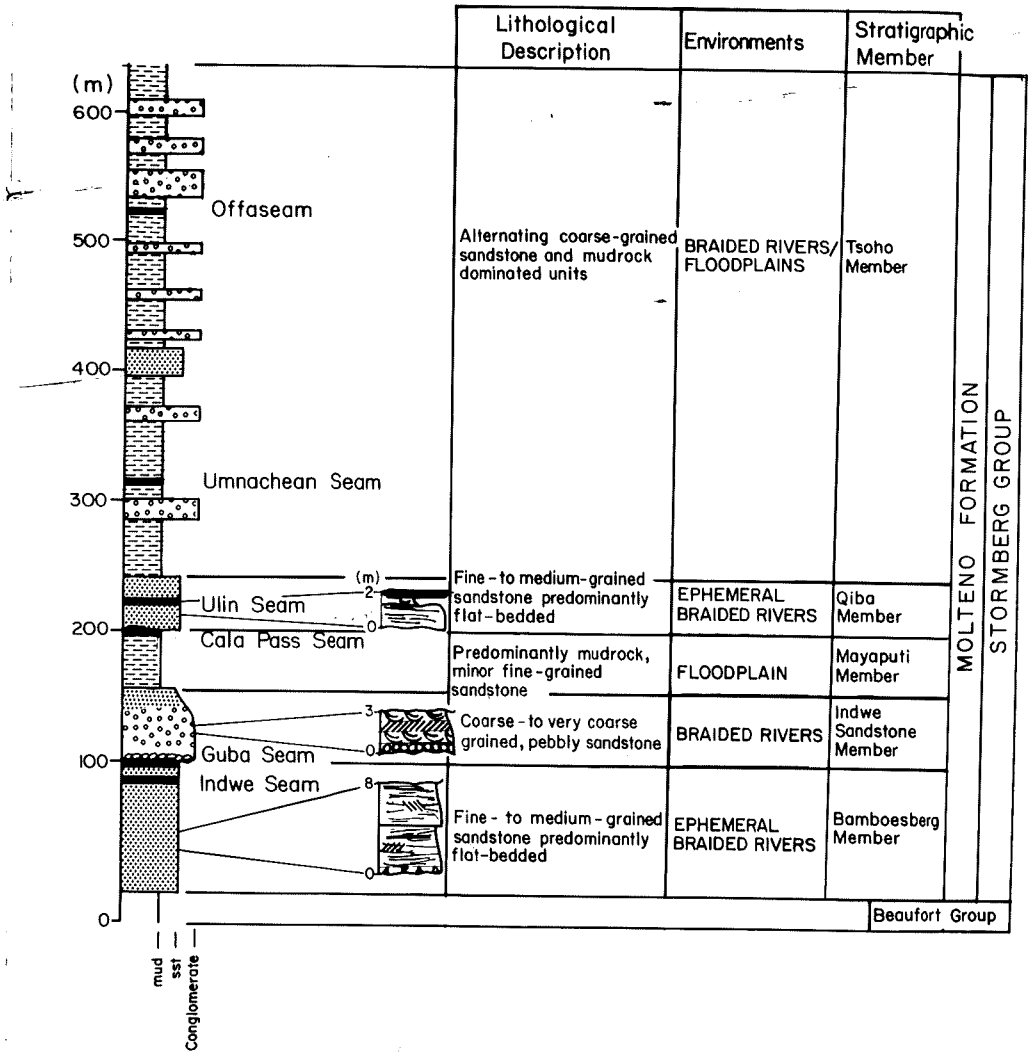


Figure 12: Lithostratigraphy of the Triassic Molteno Formation. Processes dominating during deposition of members are also depicted.

(Turner, 1975), Indwe Sandstone deposition was initiated by rapid and significant uplift which resulted in an increase in gradient and competency of streams (Turner, 1975). Large amounts of coarse detritus, including clasts of pebble, cobble and boulder size, were released. Sediment was deposited by high-energy, coalescing bed-load dominated rivers characterized by vertical channel aggradation and rapid channel shifting. The rivers drained an extensive alluvial plain which may have constituted the distal slopes of an alluvial fan complex (Turner, 1975, 1983; Christie, 1981). A decrease in sediment supply and river dimension allowed the development of extensive flood plains in distal parts of the basin where the Mayaputi Member sediments were deposited. In time, these flood plains transgressed southward over the more proximal fluvial deposits. Localized peat swamps ultimately formed the coals at the top of the member.

The Qiba Member was deposited by shallow, high-energy ephemeral streams. A brief hiatus in sedimentation over a restricted part of the alluvial plain coincided with the accumulation of the Ulin Seam peats. The

Tsomo Member reflects periods of intermittent tectonic activity which resulted in the deposition of coarse-grained, braided-river sheet sandstones. These alternated with periods of minor fluvial activity during which extensive lacustrine and floodplain silts and clays were deposited. Maroon and green mudrocks and siltstones in these sequences attest to the increasing aridity. Localised conditions, however, were still conducive for the formation of short-lived peat swamps. It is suggested that the Molteno Formation grades basinward into sediments of the Elliot Formation, deposited within an interior drainage basin (Turner, 1975; Christie, 1981).

The Indwe Seam is widely distributed throughout the western and southern part of the coalfield. It comprises bright and dull shaly coal, intercalated with up to 60% mudrock. Bands of cannel coal up to 20 cm may be present. Although the seam reaches a thickness of 4,5 m in the vicinity of Indwe, it is rarely thicker than 2 m elsewhere in the coalfield. The seam varies both in thickness and composition over short distances due to post-depositional erosion and differential compaction. Both these mechanisms appear to have been controlled by pre-seam channel distribution, which is reflected by the undulatory seam floor (Du Toit, 1905; Ryan 1963).

The Guba Seam is developed at the top of the Bamboesberg Member between 24 and 30 m above the Indwe Seam, but it is rare for both seams to be developed in the same locality. It is similar in composition to the Indwe Seam, but contains less mudrock partings and is sporadically developed. The seam attains a maximum thickness of 2,8 m south of Indwe (where it is currently being mined) and thins southwards and northwards to less than 1,4 m. The upper part of the seam has in many instances been eroded by fluvial channels within the overlying Indwe Sandstone Member. However, the lower part of the seam contains the better grade coal. The Cala Pass and Ulin Seams comprise predominantly dull, shaly coal intercalated with up to 80% mudrock. Neither are thicker than 1,8 m, and are mostly between 15 and 80cm.

The Molteno coals range in rank from low-volatile bituminous to anthracite. The most striking feature of the coals is their high mineral matter content which is between 25 and 35% for coal washed at R.D. 1,80. The average sulphur content is generally less than 0,6%, but chlorine content is up to 6% in some areas (Turner, 1969).

The characteristics of the Molteno coals were controlled by peat accumulation in an alluvial setting, and climatic conditions that were only marginally suitable for peat preservation. Sedimentary associations suggest that the peat swamps were regularly inundated by sediment-laden waters, which would have deleteriously affected Eh and pH balances (Christie, 1981). Low subsidence rates due to minimal compaction of a predominantly sandy substrate possibly resulted in high rates of peat oxidation and degradation.

DEPOSITIONAL HISTORY AND PALAEOGEOGRAPHY OF THE COALFIELDS

The palaeogeography preceding and during the deposition of the Ecca coal seams is summarised through a series of block diagrams (Figs. 13 and 14). Sedimentation in the northern portion of the Karoo Basin began during the Late Carboniferous with the deposition of subglacial, glacio-lacustrine and fluvio-glacial sediments. As the ice sheets retreated northwards to highlying terrain much of the sediment was deposited subglacially into the Ecca sea which formed over a large geographic area in front of the ice sheets (Fig. 13A). Only in the topographically elevated areas such as the Orange Free State Coalfield and the northernmost area of the Transvaal Coalfield did the icesheets deposit their sediment load subaerially. In these areas high velocity stream systems emanating from the snouts of glaciers reworked the sediment to form a glaciofluvial outwash plain. Palaeotopography played an important role in funnelling sediment around palaeotopographically high areas into palaeotopographic low lying areas. This period of active sedimentation was shortlived and, immediately thereafter, peat began accumulating over the glacio-fluvial sedimentary platform. Periodically, the peat swamps were traversed by braided and anastomosed streams which today form seam splits (Le Blanc Smith, 1980; Cairncross, 1981; Cadle, 1982; Winter, 1984) .

This outbuilding of a glaciofluvial outwash plain was restricted to the northern and northwestern rim of the Orange Free State and Transvaal Coalfields. It is therefore only in these areas that the No. 2 coal seam is present (Figs. 2 and 13B). South and southwestwards of these areas the glaciofluvial outwash plain merged into glacio-deltaic and shallow shelf shale deposits. Consequently, in Natal, no equivalent coal seam is preserved due to the shallow marine setting which prevailed at that time. In the Transvaal Coalfield the conditions for peat accumulation and preservation were favourable as the No. 2 seam forms the basic export product for power generation. Subtle basin geometry and subsidence rates account for the difference in vitrinite and inertinite contents for the No. 2 seam from the two coalfields. The No. 2 seam coal from the Orange Free State has a high inertinite and ash content (Figs. 5 and 6). The elevated and stable position of the coalfield probably caused slow subsidence of the peat swamps resulting in oxidation of organic matter forming high inertinite contents in the coal. Within the Transvaal Coalfield a sub-basin formed south of Witbank where sufficient subsidence took place to allow the organic matter to accumulate in the reducing zone of the mire and promote the formation of the comparatively vitrinite-rich No. 2 seam (Fig.5).

Following the accumulation of the No. 2 seam peat a basinwide transgression took place drowning the peat swamp and terminating any further peat accumulation. This transgression probably resulted from uplift of the southern basin margin (Quinlan and Beaumont, 1984) causing deepening of the basin. In response to this deepening, shallow water deltas prograded into the basin and formed the relatively stable platform upon which the No. 4 seam peats accumulated (Fig. 14A). The relative stability of the basin dictated sedimentary fill. The Orange Free State and Transvaal Coalfields record one major delta pulse whereas the Natal Coalfield records up to five regressive delta pulses (Fig. 8). Thus the influence of differential compaction and basin subsidence increases in a southeasterly direction. The coal seams associated with this period of sedimentation are thin, usually $<$50cm thick and are vitrinite rich (Holland

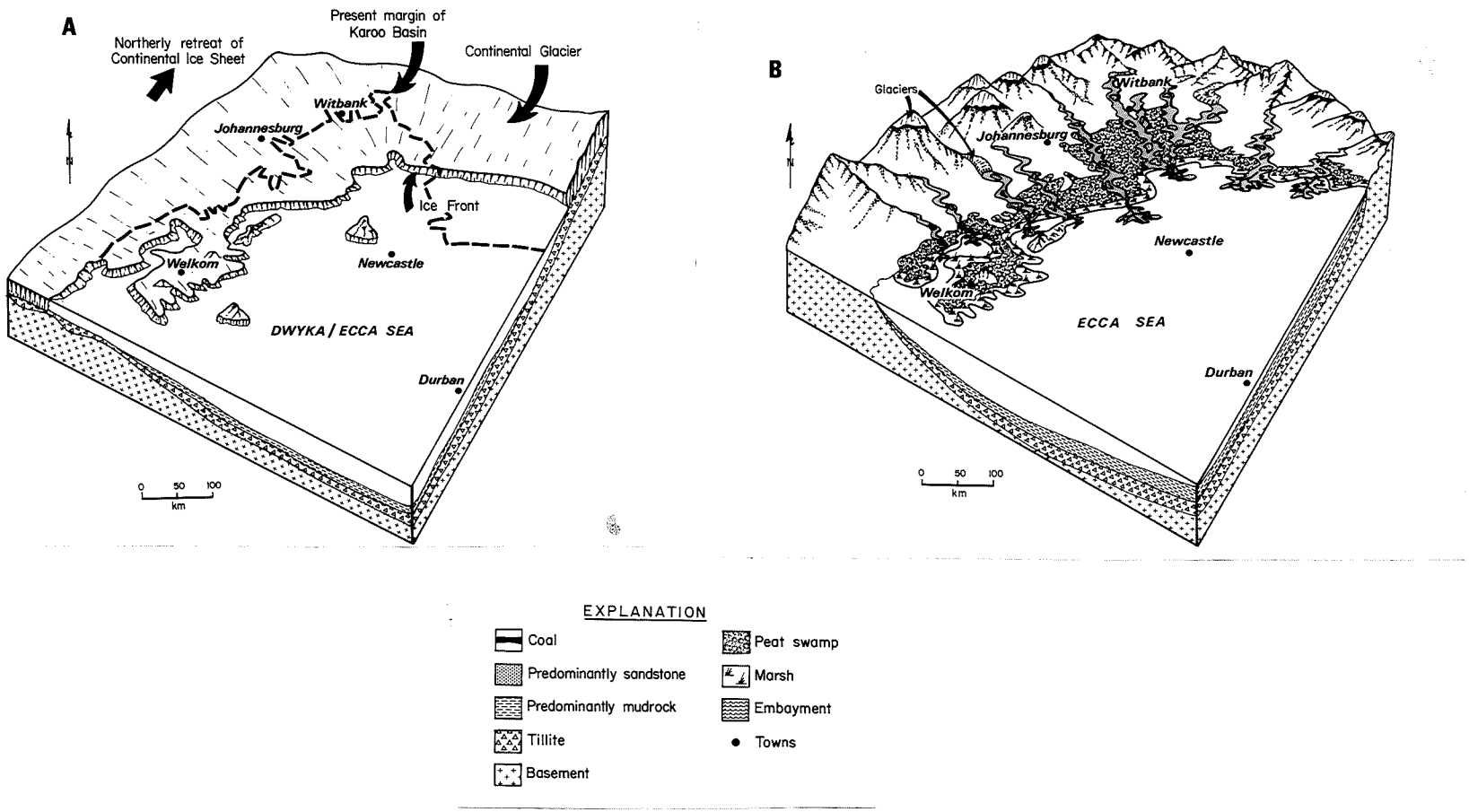


Figure 13: Palaeogeographical reconstruction of the Coalfields during the Late Carboniferous, Early Permian Periods. A). Dwyka Group/Pietermaritzburg Formation palaeogeography illustrating the Southern African landmass partly covered by a retreating continental ice-sheet. The ice front demarcates the position between the subaerial landmass and the sea. B). No. 2 coal seam palaeogeography. Following continental glacial retreat, sediment was shed basinward by fluvial and deltaic systems. This sediment provided the platform upon which the No. 2 seam peat accumulated.

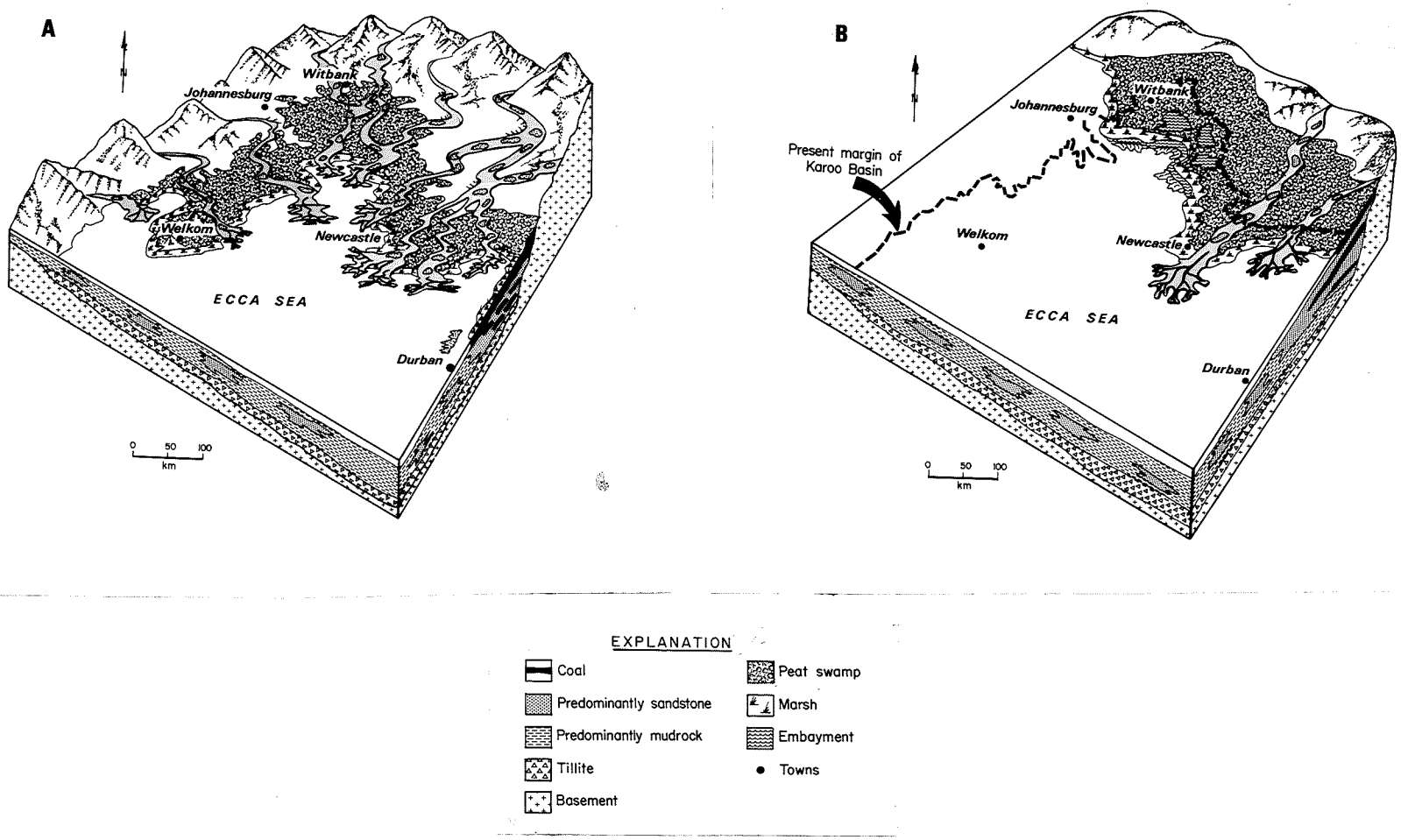


Figure 14: Palaeogeographic reconstruction at the time of No. 4 seam and No. 5 seam peat accumulation. A). No. 4 seam palaeogeography. Maximum regression of the coastline took place prior to and during peat accumulation. Rapid deposition and subsidence in the east took place while in the west peat accumulated in a stable tectonic environment. B). No. 5 seam palaeogeography. The aerial extent of the peat swamp and fluviodeltaic plain had become reduced and the topography of the hinterland reduced. Embayments, lakes and ponds were filled with algal material which formed torbanites.

et al., 1989). Following this period of deltaic sedimentation an upper delta plain environment prevailed and the No. 4 seam peats accumulated. During No. 4 seam accumulation greater subsidence and sedimentation rates in the area of the Natal Coalfields resulted in the seam splitting into 4 or 5 relatively thin subseams (Fig. 8, Roberts, 1988). In the Transvaal and Orange Free State Coalfields the No. 4 seam usually comprises one or two subseams illustrating that in these coalfields limited subsidence and sedimentation during peat accumulation took place.

The clastic partings separating the seams of the No. 4 coal zone are interpreted as braided fluvial channel sandstones and interchannel sandstones and shales (Winter, 1985; Holland et al., 1989). The highest ash and lowest volatile coals are situated at the position of merger of the No. 4 Lower and Upper seams and deleteriously influence the coal up to 9km away from the channels (Fig. 9; Winter, 1985). In the area of the Natal Coalfields the more rapid subsidence rates during the period of No. 4 seam accumulation is reflected in the higher sulphur and vitrinite contents of these coals (Figs. 5 and 6). The coals have average vitrinite and sulphur contents of 35% and 1,6% respectively. This contrasts with the No. 4 seam coals in the Transvaal and Orange Free State where the vitrinite and sulphur contents are 10-25% and 0,6-1,1%, respectively. The thickness of the No. 4 seam coals in Natal is influenced by the proximity of the source area and subsidence. This led to abundant clastic deposition during No. 4 seam peat accumulation. Consequently, the individual seam thicknesses of about 2m is less than the average seam thickness of 4m in the Transvaal and Orange Free State Coalfields. The increase in rank of the seam from the northwest (Orange Free State Coalfield) towards the southeast (Natal Coalfield) is due to the proximity of the Natal Coalfield to the Post-Karoo rift margin situated off the Natal Coast (Fig. 6C). A high geothermal gradient together with more abundant dolerite dykes and sills have increased the coal rank from a high volatile bituminous coal, present in the Transvaal Coalfield to a low volatile bituminous to anthracitic coal in the Natal Coalfield.

The peat swamps reached a maximum basinward position during No. 4 seam accumulation (Fig. 14A). This was achieved through the progradation of the underlying delta systems which formed a stable platform for peat accumulation. The most active area of sedimentation remained the east whereas in the west (Orange Free State) a more passive sedimentary regime prevailed and shoreline systems prevailed (Fig. 14A; Vos and Hobday 1977). Once again, as in No. 2 seam times, transgression terminated No. 4 seam peat accumulation. Reworked shoreline, deltaic and fluvial sediments typify destructional facies which spread over the peat swamps as laterally extensive, thin glauconitic sandstones (Cadle, 1982). The glauconitic sandstones suggest that the transgressing water body was brackish (Burst, 1958; Selley, 1976). These thin glauconitic sandstones further provide an excellent stratigraphic marker horizon documenting this basinwide transgressive event.

Following this transgressive event shallow-water deltas again prograded into the Ecca sea forming the last laterally extensive area for peat accumulation. During this period of peat accumulation differential compaction and transgression of the peat swamp by basinal waters caused low-lying embayments to form. The bodies of water formed as isolated embayments within the peat swamp or as back-barrier embayments (Fig. 14B).

The proliferation of algae in these embayments led to the formation of torbanite deposits within and above the No. 5 seam (Fig. 7, Christie, 1988).

Figure 14B illustrates the geographic extent of the No. 5 seam peat swamp which is reduced in areal extent when compared with the No. 4 seam peat swamp. The No. 5 coal seam is in general thin i.e. < 1m thick and vitrinite-rich compared with the underlying No. 2 and 4 seams. The thinness of the seam suggests that the peat accumulation period was short lived, although, a favourable peat reducing environment did prevail (Falcon, 1986a). Tectonic instability of the basin caused a further transgression of basinal water over the No. 5 seam terminating peat accumulation. At this point in the depositional history of the Vryheid Formation the basin became tectonically active as is reflected by the build out of three to four delta pulses capped by laterally impersistent thin coals (Fig. 8). This sedimentary sequence reflects that with time basin instability increased to such a degree that the depositional systems migrated landward. Ultimately, the distal shelf shales of the Volksrust Shale Formation transgressed over the coal-bearing Vryheid Formation (Fig. 2).

The Triassic Molteno coals formed in ponded embayments which were inundated periodically by flood water from adjoining ephemeral braided streams. The peat swamps were situated within the active sedimentary margin of the Karoo foreland basin. Unlike the wet post-glacial and cool-temperate climates under which the Ecca peats accumulated the Molteno peats formed in a warm temperate climate with seasonal rainfall distribution (Falcon, 1986a). Periodic flooding of backswamp environments coupled with sedimentation and subsidence in the foreland basin setting preserved peat as thin discontinuous seams with high ash, vitrinite and shale contents. In terms of maceral content, these seams are comparable to coals formed in foreland basin settings such as the Sydney and Bowen Basins of Australia (Hunt and Smyth, 1989).

CONCLUSIONS

A number of factors are considered important in influencing coal type (maceral content), grade (mineral matter content), lateral extent, and thickness within the Karoo Basin. These factors are: palaeoclimate, depositional systems, subsidence rates, and basin tectonics, the latter being, the most important criteria controlling coal characteristics.

Palaeoclimate

In terms of the maceral content of any individual Karoo Basin coal seam palaeoclimate is not considered an important factor. As has been mentioned previously, the Ecca coals accumulated in a post-glacial and cool temperate climate (Falcon, 1986a). This deduction of palaeoclimate is based upon monosaccate and disaccate pollens (Falcon, 1986a) and *Gangamopteris* and *Glossopteris* flora (Plumstead, 1957). Palaeoclimate is questioned as a factor influencing coal type because within a single coal seam such as the No. 2 coal seam, which must have experienced a similar regional palaeoclimate, coal type varies dramatically. For example, within the No. 2 seam the vitrinite content increases from 10 to 27% between the Orange Free and Transvaal Coalfields. A similar increase in vitrinite content is present within the Transvaal Coalfield and between the Transvaal and Natal Coalfields (Fig. 5B). However, as a general statement the Ecca coals can be classified as inertinitic.

Contrasting with these coals are the Molteno coals which accumulated in a warm temperate climatic setting experiencing seasonal rainfall (Falcon, 1986a). These vitrinite-rich, shaly coals have formed from the maturation of dicrodium (fern-like flora). One argument that could be put forward for the influence of palaeoclimate on coal type is that cool temperate climates promote inertinitic coals while warmer temperate palaeoclimates promote the preservation of vitrinitic coals.

Depositional Systems

The association of depositional systems influencing coal type, grade, and thickness is well documented within the Transvaal and Natal Coalfields (Le Blanc Smith, 1980; Cadle, 1982; Cairncross and Cadle 1988; Christie, 1988; Roberts 1988). Summarising, peats forming in lower delta plain environments are generally thin $<$1m thick, laterally impersistent (10km in width) and relatively high in vitrinite. The rapid subsidence of the organic matter into the reducing environments within the peat swamp prevents severe oxidation thereby promoting the vitrinite content of the coal.

The coal seams associated with upper delta plain and fluvial settings are thick (2-20m), laterally extensive (10-150km) and have higher inertinite and lower vitrinite contents than coals deposited within lower delta plain environments (Holland et al., 1989). This association of fluvial systems and thick laterally persistent coal seams does not apply to the Triassic Molteno coals. These coals are laterally impersistent, thin shaly and vitrinite rich. With reference to the Karoo Basin no definitive statement can be made concerning fluvial depositional systems and coal thickness and maceral content.

Differential Compaction

Differential compaction of the underlying sediments is considered an important factor in determining the maceral content and thickness of seams. Areas of subsidence can occur over several km^2 or over hundreds of km^2 thus influencing coal properties over a small or large area. Excess subsidence of the peat swamp causes drowning of the swamp and termination of peat formation resulting in the preservation of thin coal seams. For example, the lower delta pain coal seams of the Natal Coalfields are thin ($<$ 50cm) and vitrinite rich (Fig. 10).

The influence of differential compaction on coal type for the No. 2 and 4 seams in the Orange Free State and Transvaal Coalfields is marked. The Orange Free State coals are generally high in inertinite and situated on an elevated stable basement undergoing very little subsidence. Consequently, the swamps were probably well drained, which led to the oxidation of the organic material, thus promoting the formation of inertinite-rich coals. Tracing the coal seams eastwards and southeastwards from the Orange Free State through the Transvaal Coalfield to the Natal Coalfields (Figs. 5 and 10) the coal seams become thinner and higher in vitrinite. This is attributed to greater differential compaction of the peat swamp over thicker underlying sediments, leading to the greater preservation potential of organic material.

Basin Tectonics

Basin tectonics, in association with a wet climatic regime, is the primary control on coal type (maceral content) and thickness. The Ecca coals are inertinite rich suggesting that organic matter was exposed to oxidising conditions during peat formation.

The Permian peat swamps accumulated on the passive cratonic side of the Karoo foreland basin. This tectonic setting promoted comparatively little subsidence of peat swamps and hence, on a regional scale, these coals are inertinite rich. Variations in inertinite and vitrinite contents of the coals are attributed to subtle differential subsidence of the peat swamps. In every instance, transgressive deposits of either regional or local extent overlie the coal seams and terminate coal accumulation.

In the Transvaal Coalfield the coal seams thin stratigraphically upwards reflecting that the basin became progressively more unstable with time (Cadle, 1982). Consequently, the more frequently basin subsidence took place the thinner the coal seams. Examples illustrating this contention are: the No. 2 seam present at the base of the Vryheid Formation is over >12m thick in places, the overlying No. 4 seam is about 4m thick and the No. 5 seam, the uppermost laterally persistent seam, is about 1m thick.

In summary, basin tectonics i.e. drowning of the peat swamps by basinal waters due to excessive subsidence is postulated as the primary regional control on coal thickness. The geographic location of the peat swamps on the stable craton undergoing slow subsidence is considered the regional control promoting the formation of high inertinitic coals.

The influence of basin tectonics during the Triassic is also envisaged as controlling the occurrence of thin, high ash, vitrinite-rich Molteno coal seams interbedded with shale. The coal seams are located in the tectonically active portion of the basin where rapid subsidence and sedimentation occurred. Consequently, rapid subsidence of the basin promoted the preservation of organic material as vitrinite-rich coal and deposition of silt and mud to form shale beds. Rapid rates of sedimentation by braided fluvial systems advancing into the basin from the tectonically active highland source area situated south of the present basin margin terminated peat accumulation. Thus the coals are thin, laterally impersistent, high in ash, shaly, and vitrinite-rich.

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