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South Africa's coalfields — A 2014 perspective

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ABSTRACT

For well over a century and a half coal has played a vital role in South Africa's economy and currently bituminous coal is the primary energy source for domestic electricity generation, as well as being the feedstock for the production of a substantial percentage of the country's liquid fuels. It furthermore provides a considerable source of foreign revenue from exports.

Based on geographic considerations, and variations in the sedimentation, origin, formation, distribution and quality of the coals, 19 coalfields are generally recognised in South Africa. This paper provides an updated review of their exploration and exploitation histories, general geology, coal seam nomenclature and coal qualities. Within the various coalfields autocyclic variability is the norm rather than the exception, whereas allocyclic variability is much less so, and allows for the correlation of genetically related sequences. During the mid-Jurassic break up of Gondwana most of the coal-bearing successions were intruded by dolerite. These intrusions are important as they may cause devolatilisation and burning of the coal, create structural disturbances and related seam correlation problems, and difficulties in mining operations.

Whilst many of the coalfields have been extensively explored and exploited, those in the north of the country have until recently received much less attention. Four coalfields occur partly or wholly within the Limpopo Province of South Africa and these may contain as much as 70% of South Africa's remaining coal resources. These coalfields in particular have been the focus of recent exploration due to the presence of large coking and thermal coal resources, as well as for their coal bed methane potential, and these resources need to be unlocked with regards to creating maximum benefit and minimal environmental degradation.

South Africa's coals have also been recently addressed as palaeoclimate archives recording Gondwana's postglacial climate amelioration by major changes in land plant communities, and proving high-resolution palynostratigraphy as a crucial tool to decipher climate change during the Permo-Carboniferous. This aspect of the coals of South Africa is also reviewed.

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1. Introduction

Coal was first mined on a commercial basis in South Africa in 1857 and the country is currently the 6th largest coal producer in the world. Whilst in-roads have and are being made into clean energy (including wind and solar power) coal remains the primary energy source in South Africa for domestic power generation, and is set to dominate the energy mix for the foreseeable future. South Africa was one of the first countries in the world to use electricity on a commercial basis and presently Eskom (http://www.eskom.co.za), the state-owned national electricity supply utility, generates 96% of the country's electricity.

Presently South Africa is the only country in the world that operates commercial coal to liquids (CTL) synfuel plants, and coal is the feedstock for the production of a substantial percentage of the country's liquid fuels. Coal is furthermore used extensively in the metallurgical industry (titanium, ferrochrome, ferromanganese and steel industries) and provides a considerable source of foreign revenue from exports.

1.1. The main coal producers in South Africa

South African coal production is dominated by five major companies, these being Anglo American Thermal Coal (http://www.angloamerican.com/), Sasol (http://www.sasol.co.za/), Exxaro (http://www.exxaro.com/), BHP Billiton Energy Coal South Africa (http://www.bhpbilliton.com/) and Glencore Xstrata (http://www.glencorexstrata.com/), with more than 80% of the South African coal market supplied by these companies. Where relevant their individual assets are covered in this review under the applicable coalfield.

1.1.1. Anglo American Thermal Coal (AATC)

AATC is a global coal business with operations in South Africa and Colombia. In South Africa the company wholly owns and operates seven mines, with a 73% stake in two additional mines. Six of the mines collectively supply 23 million tonnes per annum (Mtpa) of thermal coal to both the local and export markets. In addition the company has a 50% interest in the Mafube Colliery and Phola washing plant. They also hold a 24.2% interest in the Richards Bay Coal Terminal (RBCT) through which the bulk of South Africa's coal is exported.

1.1.2. Sasol

The South African Synthetic Oil Limited (Sasol) was established in 1950 and in 1955 produced its first oil from coal. Today Sasol is an international integrated energy and chemical company with its home-base still in South Africa. Coal mined by Sasol feeds into the gasifiers of Sasol Chemical Industries (SCI) at Sasolburg and Sasol Synthetic Fuels (SSF) at Secunda for conversion into crude synthesis gas. At Sasolburg SCI reacts the crude synthesis gas in a low-temperature slurry phase distillate reactor to produce linear-chained hydrocarbon waxes and paraffins. At Secunda SSF reacts the crude synthesis gas in the higher-temperature Sasol advanced reactors to produce, in one step, C1 to C20 hydrocarbons, including synthetic crude oil for downstream refining and fuel production. Gasification also yields essential co-products including ammonia, sulphur, phenolics and pitch for specialty carbon

products. The chemical streams are routed through various downstream processes to produce the likes of ethylene, propylene, solvents and alpha olefins.

1.1.3. Exxaro

Exxaro is one of the largest South African-based diversified resources groups. Its coal assets include eight managed coal mines, from which the company produces some 40 Mtpa of local and export thermal coal, as well as soft and hard coking coal. They operate both the world's largest opencast coal mine and coal beneficiation complex. Exxaro also produces char and related products for the rapidly growing ferroalloy industry.

1.1.4. BHP Billiton Energy Coal South Africa (BECSA)

BECSA is 90% owned by BHP Billiton, a leading global resources company. The company's coal assets include four primary coal mining operations as well as three processing plants, from which it produces thermal coal for the South African domestic and export markets.

1.1.5. Glencore Xstrata

Glencore Xstrata is one of the world's largest global diversified natural resource companies. The company was formed following the merger of Glencore International PLC and Xstrata PLC, which was completed in May 2013. The histories of the two companies have been inextricably linked since March 2002 when Xstrata acquired Australian and South African coal assets of Glencore, the largest shareholder in Xstrata at the time.

1.2. Academic research and previous reviews

Much academic research has been undertaken on South Africa's coal deposits with the hedeys being in the late 1980s and 1990s. The economic aspects of South Africa's coal deposits were last discussed in any real detail in the seminal papers of Volume II of the 1986 Mineral Deposits of Southern Africa (Anhaeusser and Maske, 1986), where the coalfields of South Africa were presented in the order of increasing rank. Following this work a number of review papers were written detailing the coalfields of South Africa, the most important of these being: a review of the coalfields of South Africa in Bulletin 113 (Barker, 1999); a review paper on the Permian coals of southern Africa by Cairncross (2001); and a paper on the characterisation of the coal resources of South Africa by Jeffrey (2005a).

Two events occurred in the 1990s that had a positive impact on what is known about South African coals. The first of these was the establishment of the Fossil Fuel Foundation (http://www.fossilfuel.co.za/) in late 1994. Since 1995 this organisation has hosted numerous coal technical events, many of which have been region or coalfield focused and at which much new knowledge has been disseminated. The second was the establishment of the Coaltech 2020 Research Programme (http://www.coaltech.co.za/) in 1999. This programme is a state, industry and academia backed collaborative initiative aimed at research and technology advances that will enable the South African coal industry to remain competitive and sustainable to the year 2020 and beyond.

Two major changes have taken place this century in the South African coal industry. The first and most important of these being the implementation of the new Mineral and Petroleum Resources Development Act, 28 of 2002 (MPRDA). The MPRDA defines the State's legislation on mineral rights and mineral transactions in South Africa and entrenches a "use it and keep it" principle, thus preventing the hoarding of mineral rights to the exclusion of new entrants to the mineral industry. The second change, which is partially driven by the former, is the emergence of a number of new junior and mid-tier coal miners, marking a swing away from an industry that was previously dominated by only a few major producers. This in turn has led to much information becoming freely available on various company websites, as well as on the Canadian Stock Exchanges System for Electronic Data Storage and Retrieval (SEDAR, http://www.sedar.com).

This paper draws from all these previous works, especially the papers of the 1986 Mineral deposits of southern Africa (Anhaeusser and Maske, 1986), as well as from an extensive historic literature, numerous personal files and notes provided to the senior author by Dr. Tony Cadle, various open-file reports and company websites, as well as field experience gained by the authors over the past 20 years. Attention is paid to the economically most important coalfields, as well as those that have potential for the future energy mix, and those that have not been covered in much detail elsewhere. Because a lot of data pertaining to the coalfields is of a confidential nature, only publicly available information has been used when discussing coal quality values for each coalfield. A review of this kind has to, by its very nature, be fairly high level and not exhaustive, but it is hoped that sufficient work is referenced that readers can further their individual interests.

As all of the coalfields of South Africa (Fig. 1) occur in rocks of the Main Karoo Basin (MKB) and its associated sub-basins, and because much new work has been undertaken in the past decade on understanding the tectonics and sedimentary fill of these repositories, a brief overview of Karoo aged depocentres of South Africa is critical and is provided below.

2. Karoo Basin overview

The MKB forms part of a major series of Gondwanan basins (Fig. 2) that developed through subduction, compression, collision, and terrane accretion along the southern margin of Gondwana (Catuneanu et al., 1998; Cole, 1992; De Wit and Ransome, 1992; Veevers et al., 1994). These include the Paraná Basin in South America, the Beacon Basin in Antarctica and the Bowen Basin in Australia. These depocentres filled between the Late Carboniferous and Middle Jurassic and their combined stratigraphies represent the best record of non-marine sedimentation of this period anywhere in the world.

The mainly sedimentary fill of these basins is important from a geological and palaeontological perspective in that they contain an almost unbroken record of 120 million years of earth's history, at a period when the Pangaean supercontinent had reached its maximum extent, and during which major evolutionary change was taking place. Their economic significance in terms of energy resources runs to coal and coal bed methane, shale gas, uranium and geothermal energy. Various small oil shows have also been documented, but are believed to be uneconomic (Rowsell and Connan, 1979).

The stratigraphy of the Karoo Supergroup in the MKB preserves markedly different fills between the southern (proximal) and northern (distal) regions of the basin (e.g. Catuneanu et al., 1998; Smith, 1990). North of the MKB, equivalent aged, coal-bearing successions are preserved in isolated extensional intercratonic and intracratonic grabens or half-grabens (Bordy, 2000; Bordy and Catuneanu, 2002a,b,c; Cairncross, 1989; Cairncross, 2001; Hobday, 1986; Johnson et al., 1996; Malaza, 2013; Rust, 1975; Watkeys and Sweeney, 1988) and these are here collectively referred to as the northern basins.

2.1. Regional tectonic framework

Recent interpretations of the basin evolution and tectonic setting of the MKB range from: a retro-arc foreland basin (Catuneanu et al., 1998, 2002; Johnson et al., 2006; Veevers, 2004); a transtensional foreland system created by subsidence and tilting in a strike-slip regime (Tankard et al., 2009); a thin-skinned fold belt that developed from collisional tectonics and distant subduction to the south (Lindeque et al., 2011), to a transient hypothetical mantle plume related model (Turner, 1999). A full review of these individual models is beyond the scope of this paper and the interested reader is referred to the references above as well as Bordy et al. (2005).

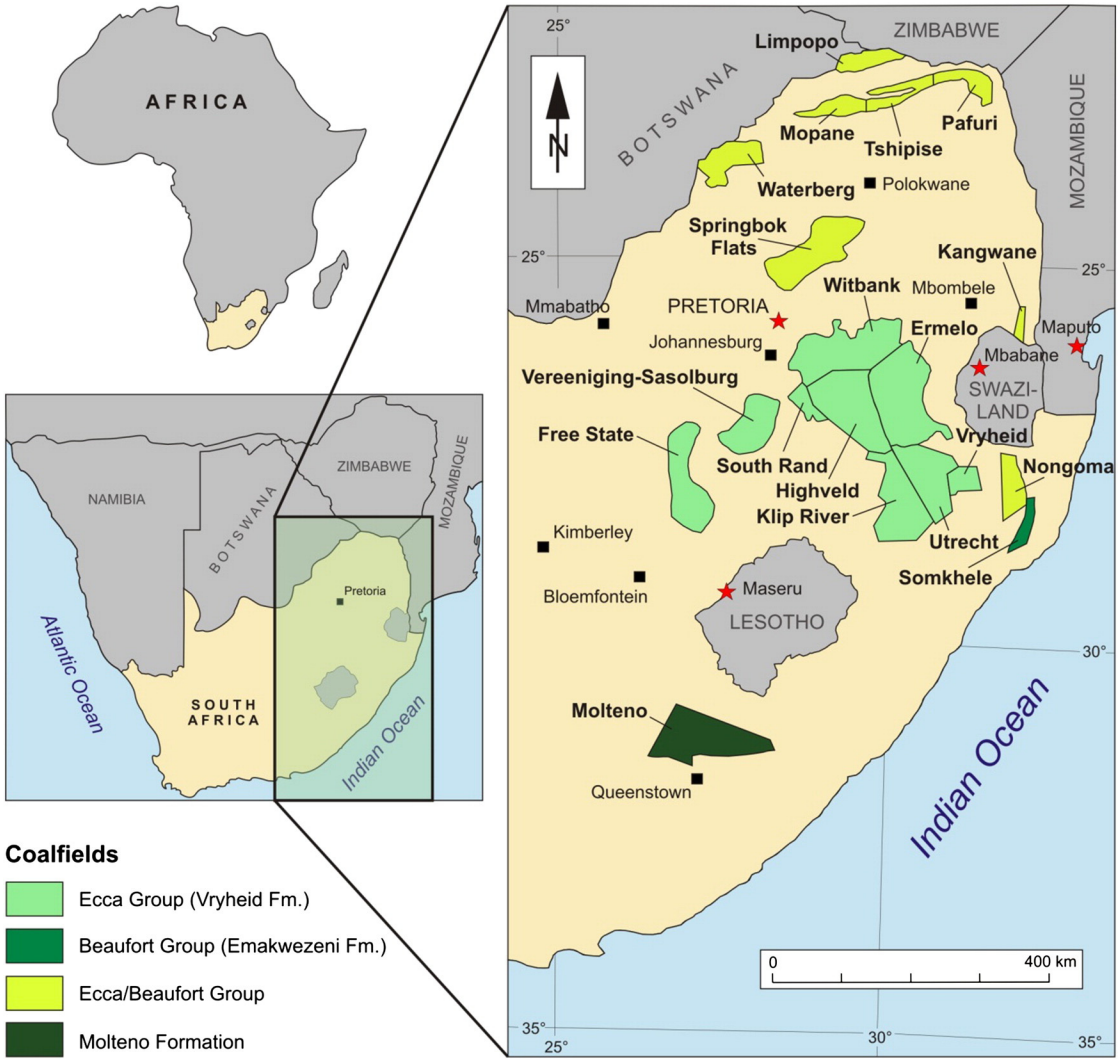

Fig. 1. Coalfields of South Africa. The Mopane, Tshipise and Pafuri coalfields collectively form the Soutpansberg Coalfield. Fm. = Formation. Variously modified after Snyman (1998).

Whilst there is not yet consensus, most authors believe the MKB of South Africa to be a retroarc foreland system (Catuneanu et al., 1998; De Wit et al., 1988; Johnson, 1991; Johnson et al., 2006), which developed in front of the Cape Fold Belt (CFB) section of the Gondwanide Orogeny in response to crustal shortening brought about by the late Palaeozoic–early Mesozoic subduction of the palaeo-Pacific plate beneath the Gondwana plate (Catuneanu et al., 1998; de Wit and Ransome, 1992; Lock, 1980). A combination of supra- and sub-lithospheric loads (Catuneanu et al., 2002; Pysklywec and Mitrovica, 1989) is believed to be responsible for the observed flexural profile and generation of accommodation space.

Whatever their mechanism of formation, Karoo aged depositories in South Africa were formed in two different, yet linked, tectonic settings (Rust, 1975). These are the compression related MKB and the extension or transtension related northern basins.

The Karoo Supergroup of the MKB of South Africa is the best-studied of these fills (Tankard et al., 1982), as well as being the most continuous and best developed of all of the sub-Saharan basins. It is for this reason that the MKB of South Africa is considered as the type locality for southern African coals (Cadle et al., 1993). The extensional, rift related Karoo sub-basins outside of the MKB are often fault bounded, with syn- and post-tectonic rifting. This has resulted in a highly truncated sequence of lithologies that whilst superficially similar, show differences to their correlative counterparts encountered in the MKB.

At group level the general coal bearing stratigraphic succession is similar between the MKB and the northern basins, and as such the overview of the general geology and stratigraphy of the Karoo Supergroup that follows is pertinent to all of South Africa's coalfields. Area specific geology is provided individually for each coalfield.

2.2. General geology and stratigraphy of the Karoo Supergroup

The sedimentary part of the Karoo Supergroup is subdivided into four main lithostratigraphic units, which from the base up are the Dwyka, Ecca, Beaufort and Stormberg (Molteno, Elliot and Clarens formations) groups (Johnson et al., 1996; SACS, 1980; Fig. 3). These are capped by some 1.4 km of basaltic lavas of the Drakensberg Group (Johnson et al., 1996; Veevers et al., 1994), the extrusion of which is related to the break-up of Gondwana (Cox, 1992).

The basement to the Karoo Supergroup fill in both the MKB and in the northern basins is heterogeneous (Bordy et al., 2004a; Hancox, 1998; Rutherford, 2009) and this heterogeneity plays a significant control on the nature of the fill, particularly during the early phases of the deposition of the Karoo Supergroup. The main crustal scale blocks

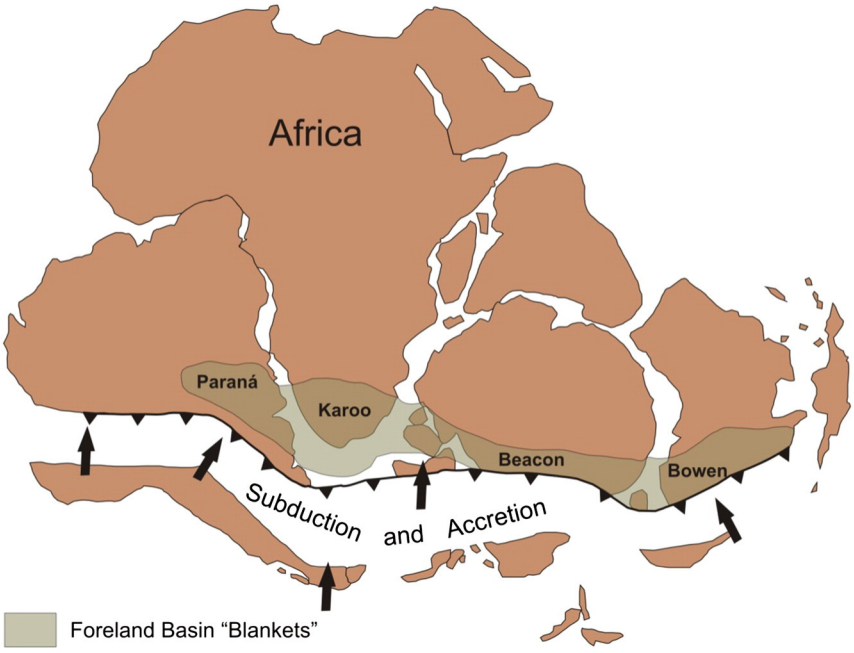

Fig. 2. Position of the Karoo Basin in relation to the other Karoo aged depocentres of south-western Gondwana. Modified from de Wit and Ransome (1992).

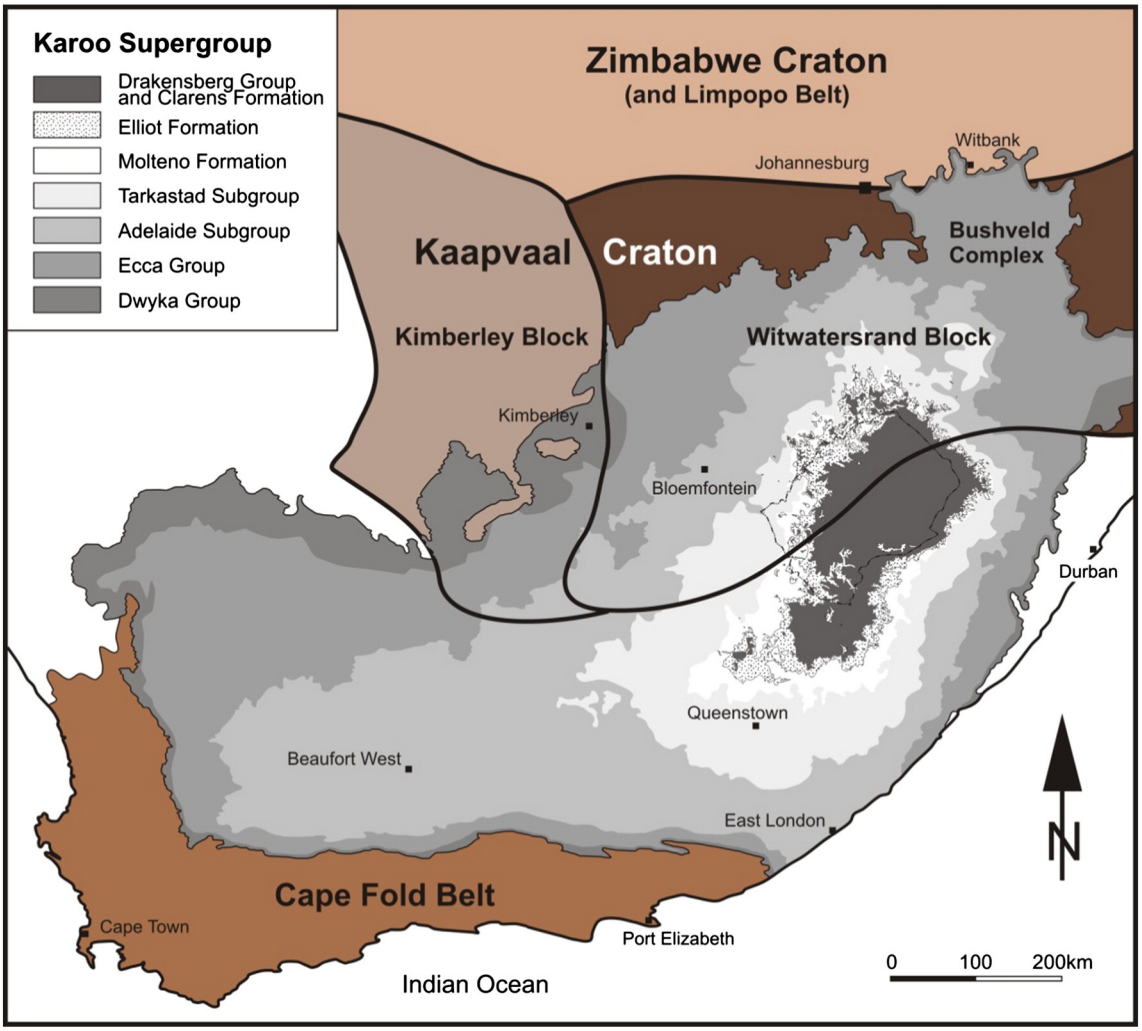

Fig. 3. Geological map of the Main Karoo Basin (after Catuneanu et al., 1998) showing the position of the Kaapvaal Craton boundaries as proposed by Skinner et al. (1992). Modified from Bordy et al. (2004a).

for the MKB are shown in Fig. 3. Most of the coalfields discussed occur on the Wits block of the Kaapvaal Craton. Due to the fact that the coalfields of South Africa occur over such a vast area, the nature of the basement lithologies differ considerably and as such are described below individually for each coalfield. An understanding of the basement lithologies is important for interpreting the nature of pre-conditioning prior to the onset of Dwyka glaciation, which provides an important control on the sedimentary fill of the lower parts of the Karoo Supergroup.

Karoo aged depositional environments broadly range from glacial (Dwyka Group), to shallow marine and coastal plain (Ecca Group), to nonmarine fluvial and aeolian (Beaufort and Stormberg groups). Whilst this paper focusses on the Ecca and Beaufort groups and Molteno Formation sedimentary successions, a review of the variable basement lithologies and Dwyka Group is also pertinent, and is therefore included below.

2.2.1. Dwyka Group

Rocks of the Dwyka Group in South Africa are amongst the most important glaciogenic deposits from Gondwana. The Dwyka Group is named for exposures along the Dwyka River east of Laingsburg, and forms the basal succession of the Karoo Supergroup. Sutherland (1870) is credited with ascertaining its glacial origin and Dunn (1875) introduced the term "Dwyka Conglomerate" in the second edition of his "Geological Sketch Map of South Africa". W. Anderson (1901, 1904, 1907) documents various aspects of the Dwyka Group in KwaZulu-Natal (KZN) and felt that it was an important marker horizon in the metalliferous deposits that occurred below it, and coal above it. Dwyka Group lithologies are also well documented by Du Toit (1921) and it was his studies on the Dwyka which led to his thoughts on the wandering of continents, and his documentation of the supercontinent Gondwana (Du Toit, 1937). An excellent review of the state of knowledge of the Dwyka Group in South Africa prior to 1970 is given in Haughton (1969).

Since this time numerous authors have added to our understanding of the Dwyka Group, including aspects of its sedimentology (Crowell and Frakes, 1975; Isbell et al., 2008; Stratten, 1968, 1970; Visser, 1986, 1987a,b, 1989, 1991a,b, 1994, 1995, 1996, 1997; Visser et al., 1987; Von Brunn, 1987, 1996; Von Brunn and Gravenor, 1983; Von Brunn and Stratten, 1981; Von Brunn and Talbot, 1986), palaeontology (A.M. Anderson, 1981; Anderson and McLachlan, 1976) and basinal setting (Catuneanu, 2004; Johnson et al., 1997; Stratten, 1970; Visser, 1993) and it is now widely accepted to be the product of glacio-marine sedimentation, and part of the Late Palaeozoic Ice Age (LPIA) that affected most southern Gondwanan basins (Dineen et al., 2013). Studies of these rocks have also been used to establish the thermal conditions (Visser and Young, 1990) and to estimate the size and duration of the Gondwanan ice sheets (Veevers and Powell, 1987). Despite a long history of study, many questions concerning Dwyka glaciation still however remain (Isbell et al., 2008).

The age of deposition of the Dwyka Group is discussed by Visser (1990). Subsequently the age has been bracketed by two zircon U–Pb sensitive high-resolution ion microprobe (SHRIMP) dates of 302 ± 3 Ma and 288 ± 3 Ma (Bangert et al., 1999). The onset of Dwyka Group sedimentation is therefore believed to occur during the Late Carboniferous, continuing until the Early Permian.

Different proximal (marine facies) and distal (inlet facies glacial, continental) settings have been well documented (Smith, 1990; Visser, 1992), with the proximal foredeep accumulating up to 800–1000 m of marine diamictites, with dropstones derived from floating ice (Visser, 1991a,b; Winter and Venter, 1970). These facies are not however relevant to this review and only the distal northern valley facies are described below in detail. The general direction of ice advance within the distal forebulge area was from north to south (Visser, 1991a,b) and in the northern basins from the east to the west (Catuneanu, 2004). Glacial retreat to the north created a number of glacial palaeovalleys around the northern margin of the MKB, the fill of which have very irregular thicknesses and complex facies relationships. Dwyka Group strata are mostly contained within bedrock valleys incised into Archean to lower Palaeozoic bedrock (Visser, 1990; Visser and Kingsley, 1982; Von Brunn, 1996).

Four localities within the Free State Coalfield (Fig. 1) are listed by Cadle (1974) as having thicknesses greater than 100 m, with a maximum thickness of 317 m recorded to the west of the town of Virginia. Dwyka Group lithologies in the areas underlying the coalfields of South Africa consist of a heterolithic arrangement of massive and stratified polymictic diamictites (Fig. 4), conglomerates, sandstones and dropstone-bearing varved mudstones (Fig. 5). The easily identifiable lithologies form a good marker below the coal bearing Ecca Group.

In the distal sector of the MKB these sedimentary strata accumulated largely as ground moraine associated with continental ice sheets, and is generally composed of basal lodgement and supraglacial tills. These deposits are generally massive, but crude horizontal bedding occurs in places towards the top (Tankard et al., 1982). The difficulty in correlating the Dwyka facies, even between exposures only a few kilometres apart, suggests local development of grounded ice lobes separated by ponds and outwash fans (Catuneanu et al., 2005). The clasts are not imbricated, but some show a weakly developed long-axis alignment parallel to the direction of ice flow as inferred from the subjacent striated pavements (Tankard et al., 1982). At Vereeniging, Dwyka Group lithologies occur as cave fills in the Transvaal Supergroup dolomites.

In the extensional basins north of the MKB, Dwyka Group equivalent deposits occur with thicknesses that range from centimetres to metres. These are often markedly different from their MKB correlatives and include a mixture of colluvial and glacial-outwash alluvial facies (Bordy and Catuneanu, 2002a). Deposition in these environments took place under high-water table conditions, marked by the presence of glacial or periglacial lakes. The presence of lacustrine facies containing angular clasts suspended in a mudstone matrix, similar to the dropstones in the MKB, suggests the presence of floating ice (Bordy and Catuneanu, 2002a).

Palaeontologically the Dwyka Group contains only a sparse fossil record (Anderson, 1981), including disarticulated fish scales and arthropod and fish trace fossils. Bangert et al. (2000) describe the fossil record of Dwyka Group equivalent glacial mudstones in southern Namibia.

A number of coal seams have previously been assigned to the uppermost part of the Dwyka Group in the past (Stavrakis, 1986) and certainly Dwyka aged coals occur in other sub-Saharan Karoo basins, but this aspect of the stratigraphic succession needs to be restudied in detail, with positive seam positions and correlations based on absolute age data, and accurate correlative stratigraphic and palynological studies.

2.2.2. Ecca Group

The Ecca Group strata were first described by Rubidge in 1896 from the Ecca Pass, north of Grahamstown in the Eastern Cape (quoted in Du Toit, 1954). As for the Dwyka Group, significantly different facies assemblages occur in the proximal and distal sectors. The proximal sector has recently been the focus of renewed interest due to the potential for these rocks to host shale gas resources (Geel et al., 2013; Götz, 2014a). Only the distal sector is however covered here.

In the 1970s a number of studies (Cadle, 1974; Hobday, 1973, 1978; Mathew, 1974; Van Vuuren and Cole, 1979) showed that the Ecca Group could be subdivided into several informal units based on the cyclic nature of the sedimentary fills. In 1980 the South African Committee for Stratigraphy (SACS, 1980) introduced a formal lithostratigraphic nomenclature for the Ecca Group in the northern, distal sector of the MKB, which replaced the previously used informal Lower, Middle and Upper subdivisions with the Pietermaritzburg Shale Formation, the Vryheid Formation and the Volksrust Shale Formation.

Fig. 4. Typical diamictite facies of the Dwyka Group overlying basement of the Mozaan Group (Pongola Supergroup). Denny Dalton mine site, KwaZulu-Natal. Heavy red line marks the position of the contact.

Much research was undertaken into the nature of the Ecca Group in the northern part of the MKB in the 1980s. Two separate coal groups were formed at this time, the first, the University of the Witwatersrand group, which was led by Tony Cadle, was established in 1980. The second, based at the University of Natal in Durban, was established in 1981 and was led by Ron Tavener-Smith and Tom Mason. Due to a lack of outcrop, the University of the Witwatersrand group was largely restricted to the study of borehole data, which numbered over 3000 at the time. The Durban group had the added benefit of being able to study the numerous natural sections that are prevalent in KZN.

2.2.2.1. Pietermaritzburg Formation. The name Pietermaritzburg Shale was introduced by Griesbach in 1871 for what later became known as the Lower Ecca Shales. Du Toit (1918) stated that the Lower Ecca Beds (Shales) were the equivalent of the "well-known soft blue Pietermaritzburg shale" and this unit was defined by SACS (1980) as the Pietermaritzburg Shale Formation, but is here referred to as the Pietermaritzburg Formation as SACS has subsequently dropped lithological terms from formal names.

The unit consists almost entirely of dark grey laminated siltstone and mudstone, with subordinate sandstone, and attains a maximum thickness of over 400 m (Du Toit, 1954). Its upper boundary with the overlying Vryheid Formation is gradational and is taken as the horizon above which the sandstone to fines ratio is greater than 0.5 (SACS, 1980). No coal seams occur in the Pietermaritzburg Formation.

2.2.2.2. Vryheid Formation. The majority of the economically extracted coal in South Africa occurs in rocks of the Vryheid Formation, which ranges in thickness in the MKB from less than 70 m to over 500 m (Fig. 6). It is thickest to the south of the towns of Newcastle and Vryheid, where maximum subsidence took place (Cadle, 1974; Cadle, 1982; Du Toit, 1918; Stavrakis, 1989; Whateley, 1980a) and where the basin was the deepest.

According to SACS (1980) the basic concept, distinguishing features and boundaries of the Vryheid Formation are those of the "Middle Ecca"

Fig. 5. Typical varved mudstone lithologies of the Dwyka Group. Note the interbeds of very fine-grained mudstone and coarser sandstone, as well as the presence of soft sediment deformation. Sterkfontein Exploration Project (Borehole SK07-03; 210 m). NQ core diameter (47.6 mm).

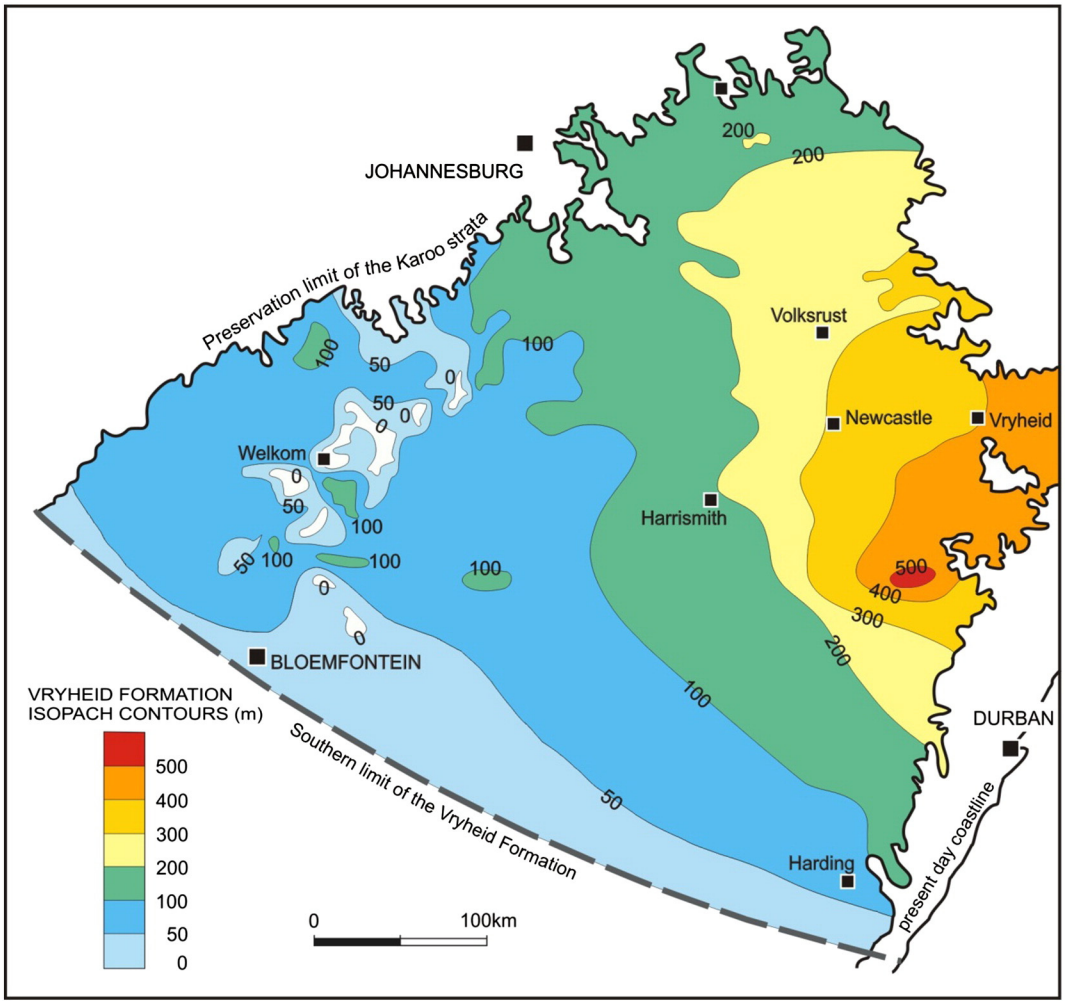

Fig. 6. Isopach map of the Vryheid Formation showing the increase in thickness towards the east. From Cadle (1982).

as described by Du Toit (1954) and others. Prior to 1973 studies of the Vryheid Formation were largely stratigraphic. This situation changed when Hobday (1973) postulated deltaic depositional systems for the Vryheid Formation, and academic studies became more depositionally process orientated.

The rapid sediment transfer into the basin was driven by bedload dominated fluvio-deltaic systems (Cadle, 1974; Hobday, 1973; Ryan, 1968) that prograded south and southwest, and had source areas to the northwest, north, northeast and east of the present-day basin margin (Cadle and Cairncross, 1993).

With the advent of later studies in the Witbank and Highveld coalfields (Cadle, 1982, 1995; Cairncross, 1980, 1995; Cairncross and Winter, 1984; Le Blanc Smith, 1980a,b,c; Winter, 1985) the basic fluvio-deltaic model became refined into greater palaeoenvironmental detail, including the interpretation of beach-barrier deposits (Tavener-Smith, 1983; Vos and Hobday, 1977), bed-load (braided) fluvial deposits (Cairncross, 1979; Le Blanc Smith, 1980a,b,c; Winter, 1985), fine- and coarse-grained anastomosed river deposits (Cairncross, 1980; Le Blanc Smith and Eriksson, 1979) and high-constructive, lobate deltaic complexes (Cairncross and Winter, 1984). It was this array of palaeodepositional environments, and palaeotopographic relief, palaeoclimate and tectonic setting which controlled the distribution and quality of the coal seams (Cadle, 1982; Cairncross, 1989).

Hobday (1973) was the first to refer to the cyclical nature of the upward-fining and upward-coarsening successions that typify the Vryheid Formation, characteristics that are also well-documented by Cadle (1974), Mathew (1974) and Van Vuuren and Cole (1979).

The stratigraphy of the Vryheid Formation is now described as a succession of five coarsening-upward sequences which display a remarkable lateral continuity across the entire distal region of the Karoo Basin (Cadle, 1982). In a complete succession each of the five coarsening-upward sequences starts with fine-grained marine facies, which grade upwards into coarser delta front and delta plain-fluvial facies. Several coal seams occur in the Vryheid Formation and these are associated predominantly with the coarser-grained fluvial facies at the top of each sequence. These coal seams can be traced laterally across the entire area of occurrence of the Vryheid Formation in the MKB; however some disagreement exists as to the exact correlation in the various coalfields. Regional differences allow for the considerable diversity of coal types (organic content), mineral matter composition, and rank (maturity) that is found within the coalfields of South Africa (Falcon, 1986b).

A shifting balance between sedimentation and the rates of base level rise most likely explains the cyclic nature of the Vryheid Formation. The transgressive units which occur at the base of each coarsening-upward sequence are some of the most widespread and laterally continuous beds in the Vryheid Formation in the northern part of the basin (Cadle, 1982, 1993; Cairncross, 1986). Such units form good markers for stratigraphic correlation, and are discussed below for the individual coalfields. Trace fossils have also played a role in the understanding of the palaeoenvironmental history and correlation of the

Vryheid Formation (Christie, 1988; Hobday and Tavener-Smith, 1975; Mason and Christie, 1986; Roberts, 1988b; Stanistreet et al., 1980).

Palaeontologically the Vryheid Formation is best known for the rich fossil plant assemblages of the famous *Glossopteris* flora, which is the source vegetation for most of the Vryheid Formation coals. Detailed palaeobotanical studies based on the well-preserved plant fossils date back to the early 20th century (Etheridge, 1901; Leslie, 1903). Subsequent work was done by the likes of Plumstead (1952, 1956, 1957, 1958, 1969), Lacy et al. (1974), Kovacs-Endröy (1976, 1991), J.M. Anderson and H.M. Anderson (1985), Rayner and Coventry (1985), Adendorff (2005), Bordy and Prevec (2008), Claassen (2008), Prevec et al. (2008, 2009, 2010) and Prevec (2011).

Following continental deglaciation, gymnospermous glossopterids came to dominate both the peat and non-peat accumulating Permian wetlands (Falcon, 1986c; Greb et al., 2006). The associated flora included lycopods, ferns, cordiatales and other early gymnosperms (Falcon, 1986c). No vertebrate fossils have been recorded from the Vryheid Formation. Plant fossils described by Bamford (2011) for the Vryheid Formation are *Azaniodendron fertile*, *Cyclodendron leslii*, *Sphenophyllum hammanskraalensis*, *Annularia* sp., *Raniganjia* sp., *Asterotheca* spp., *Liknopetalon enigmata*, *Glossopteris* >20 species, *Hirsutum* 4 spp., *Scutum* 4 spp., *Ottokaria* 3 spp., *Estcourtia* sp., *Arberia* 4 spp., *Lidgetonnia* sp., *Noeggerathiopsis* sp. and *Podocarpidites* sp.

Various palynological studies have also focused on the coal bearing successions of the Vryheid Formation. Aitken (1993, 1994, 1998) worked on the Vryheid Formation in the Witbank and Highveld coalfields, as well as at Lindley in the Free State Coalfield. Millsteed (1994, 1999) reported on the Early Permian palynomorph assemblages from the Vryheid Formation of the Sasolburg–Vereeniging Coalfield. Recent studies focus on the Witbank Coalfield (Götz and Ruckwied, 2014).

2.2.2.3. Volksrust Formation. SACS (1980) applied the name Volksrust Shale Formation to the old "Upper Ecca Beds", with the choice of name based on a description given by Blignaut et al. (1952). The general thickness of the unit is between 150 and 250 m and it is dominated by dark grey-green siltstones and mudstones, with phosphatic/carbonate/sideritic concretions. Cadle (1974) documents that the Volksrust Formation shows an overall coarsening-upward trend. Coals occur interbedded with the mudstones in places. The Volksrust Formation is postulated to have formed in shallow to deep water basinal conditions.

Palaeontologically the Volksrust Formation is probably best known for its low diversity trace fossil assemblage (Tavener-Smith et al., 1988) and various organic microfossils. Macrofaunal remains include only various insects (Van Dijk, 1981) and a rare bivalve assemblage (Cairncross et al., 2005). Plant remains and fossilised wood are also known.

2.2.3. Beaufort Group

The Beaufort Group represents the transition from subaqueous (Ecca Group) to fully subaerial deposition (Rubidge et al., 2000) with predominantly fluvial sedimentation. Rogers and Schwarz (1902) introduced the term Beaufort "Series" and Johnson (1966) suggested the use of the "Group" designation. The Beaufort Group consists of two subgroups, the lower Adelaide and upper Tarkastad subgroups (Fig. 3). Lithologically the Beaufort Group consists of alternating fine-grained lithofeldspathic sandstone and mudstone, normally forming fining-upward cycles and displaying features generally considered to be characteristic of fluviatile deposition (Johnson, 1976). Few lithostratigraphic marker horizons exist. Coal is restricted to the Adelaide Subgroup and its equivalents.

The Beaufort Group is a palaeontological superlative, containing probably the best documented succession of Permo-Triassic vertebrate fossils in the world. Hancox and Rubidge (1997) discuss the role of these fossils in the interpretation of the development of the Karoo Basin. Overviews of the palaeontology of the Beaufort Group are given in Hancox (2000), Hancox and Rubidge (2001) and Rubidge (2000, 2005) and references contained therein. The abundance of tetrapod fossils has allowed biostratigraphic subdivision of the Beaufort Group into eight biozones (Kitching, 1977; Rubidge, 1995, 2005). A biozonation based on fossil wood has also been erected for the Beaufort Group (Bamford, 1999) and various rich plant fossil localities are also known (Bordy and Prevec, 2008; Claassen, 2008). Correlations based on the fossil occurrences were previously utilised for age assignations, however more recently a number of volcanic ash beds from the Beaufort Group have been dated (Coney et al., 2007; Rubidge et al., 2013), which has for the first time allowed for the establishment of a precise temporal framework for this interval based on absolute ages.

The contact between the Beaufort and Stormberg groups is covered in detail by Hancox (1998) and is not repeated here other than to note that it represents the largest magnitude unconformity within the Karoo Supergroup of the MKB.

2.2.4. Stormberg Group

The Molteno, Elliot and Clarens formations were previously regarded as belonging to part of the Stormberg "Series" (see Du Toit, 1954; Rogers and Schwarz, 1902), which became collectively referred to as the Stormberg Group. In 1975 SACS decided that the continued use of "Stormberg" as a group designation in a formal lithostratigraphic scheme could not be justified. Recently however SACS have reversed this position and the group status has been re-instated (Cole pers. comm.).

2.2.4.1. Molteno Formation. The Molteno Formation forms the basal unit of the Stormberg Group and comprises a northward thinning wedge of dominantly clastic sedimentary rocks (Christie, 1981; Hancox, 1998; Turner, 1975). Geographically, the Formation crops out over an area of some 25,000 km^2 (Turner, 1983), forming a roughly oval-shaped feature in the MKB extending from the Eastern Cape Province northward into Lesotho, KZN and the Free State.

The Molteno Formation has previously been subdivided into a lower Bamboesberg and Indwe Sandstone members, and an upper unit that has been variously grouped and named by previous authors (Bordy et al., 2005; Christie, 1981; Hancox, 1998; MacDonald, 1993; Turner, 1975). Except for the Bamboesberg and Indwe members this terminology has not been accepted by SACS.

As economic coal seams occur only in the Bamboesberg Member, this is the only unit covered here in any detail. Lithologically, the Bamboesberg Member is composed of up to five stacked fining-upward sequences between 5 and 50 m thick. These sequences are composed of laterally extensive sandstones, capped by thin lenticular siltstones and mudstones, and for the uppermost three cycles, rare coal. Three coal seams have previously been recognised within the Bamboesberg Member (Christie, 1981; Du Toit, 1905; Hancox, 1998; MacDonald, 1993).

Palaeontologically the Molteno Formation contains a remarkably rich assemblage of plant and insect fossils (J.M. Anderson and H.M. Anderson, 1983, 1984, 1989, 1995, 1998, 2008; Anderson et al., 1998; H.M. Anderson, 1974, 1976a,b, 1978; J.M. Anderson, 1979, 1984, 1989; Scott et al., 2004) as well as rare fish (Jubb, 1973). The upper parts of the Formation contain some of the world's oldest dinosaur trackways (Raath et al., 1990). Given the rich invertebrate palaeofauna, trace fossils attributable to these forms are suprisingly rare in the Molteno Formation (Hancox, 1998; Turner, 1978).

Whilst no absolute dates exist for the Molteno Formation, most authors now follow Du Toit (1954) in assigning the Molteno Formation a Late Triassic age. Based on the constraining tetrapod fossil assembages of the underlying Burgersdorp Formation and overlying Elliot Formation (Lucas and Hancox, 2001), coupled to palaeobotanical and palynological studies and correlation with better dated sequences elsewhere in

Gondwana, the Molteno Formation is probably of Carnian (Late Triassic) age (Anderson et al., 1998).

The nature of the Molteno–Elliot contact was previously poorly understood, however Bordy et al. (2005) redefined it based on lithological changes (including the gross and internal geometries of the sandstone units and contained lithofacies associations); the presence/absence of coal seams and paleosols; and on palaeocurrent patterns, sandstone composition and grain-size variations.

2.2.4.2. Elliot Formation. Although previous studies of the Elliot Formation in the MKB of South Africa had shown the Formation to consist of continental red beds of fluvial, lacustrine and aeolian origin (e.g. Botha, 1968; Eriksson, 1983, 1985; Johnson, 1976; Johnson et al., 1996, 1997; Kitching and Raath, 1984; Le Roux, 1974; Smith and Kitching, 1997; Smith et al., 1993; Visser and Botha, 1980) few field-based geological investigations dealing with the stratigraphy, sedimentology, depositional environments and basin development had been undertaken prior to the various works of Bordy et al. (2004a,b,c,d,e).

Architectural element analysis of the sandstones of the Elliot Formation has revealed two contrasting geometries resulting from different fluvial depositional styles (Bordy et al., 2004c). The lower parts of the Formation are interpreted as deposits of perennial, moderately meandering fluvial systems, whereas the upper reaches represent ephemeral fluvial processes. No coal deposits occur within the Elliot Formation.

Palaeontologically the Elliot Formation is important for its Late Triassic to Early Jurassic dinosaur and associated fauna (Kitching and Raath, 1984; McPhee et al., 2014; Olsen and Galton, 1984; Reisz et al., 2013; Sidor and Hancox, 2006; Smith and Kitching, 1997; Warren and Damiani, 1999; Yates and Kitching, 2003; Yates et al., 2004). This list is by no means definitive but would give the interested reader a good overview and covers most of the main fauna known.

2.2.4.3. Clarens Formation. This unit was first described as a separate lithologic entity by Dunn (1878), who introduced the name "Cave Sandstone". The present name was proposed by N.J. Beukes (personal communication to the SACS Karoo working group) and derived from the village of Clarens in the north-eastern Free State. According to Beukes (1969) the maximum thickness of the unit is some 305 m to the north-east of Barkly-East in the Eastern Cape Province. Most authors agree that the sandstone dominated deposits of the Clarens Formation represent aeolian depositional systems, with minor fluvial input (Eriksson, 1981, 1983, 1986; Eriksson et al., 1994; Holzförster, 2007). As for the Elliot Formation, no coal deposits occur in the Clarens Formation. Palaeontologically, the basal Clarens preserves a similar dinosaurian fauna to the uppermost Elliot Formation (Kitching and Raath, 1984).

2.2.5. Drakensberg Group and associated intrusives

As mentioned above the top of the Karoo Supergroup succession is formed by up to 1.4 km of basaltic lavas of the Drakensberg Group (Johnson et al., 1996; Veevers et al., 1994). Associated with the outpourings of such vast volumes of basaltic magma are numerous feeder dykes and sills. Due to their effect on the coals of South Africa, significant work has been undertaken on the nature of the dolerite intrusions (Busio, 2012; De Oliveira and Cawthorn, 1999; G. P. Du Plesiss, 2008; J. J. Du Plesiss, 2008; Hagelskamp, 1987; Van der Walt, 2012) and their immense impact is discussed in detail for the individual coalfields.

These intrusions tend to negatively affect the coal qualities in places, and mapping of their occurrences is critical for mine planning purposes. Both magnetic and non-magnetic dolerites are documented. Near vertical dykes display little displacement associated with their transgression through the seams. On the other hand sill transgressions always result in some displacement, the magnitude being dependant on a number of factors including sill thickness and the presence and orientation of pre-existing zones of weakness. These intrusions introduce local structural complexity by displacing seams relative to one another and isolating blocks of coal. Associated with all sill transgressions are sympathetic and antithetic slips within a variable zone either side of the intrusion. Another effect that the dolerite has is to locally burn or devolatilise the coal. Factors affecting the degree of burning include the temperature of the intrusion, the duration of molten flow and the attitude of the intrusion.

The age of the Drakensberg lavas and associated dolerites is bracketed at between 185 and 180 Ma based on ^{40}Ar–^{39}Ar geochronology (Duncan et al., 1997; Jourdan et al., 2005), which places them as being of Early Jurassic age.

3. Previous research on the coals of South Africa

3.1. Trace element chemistry

Willis (1983) conducted the first trace element studies on South African coals and fly ash. Dale (1995, 2003) compared the levels of trace elements in internationally traded South African coals with Australian export thermal coals.

One of the main features of South African coals is that they have higher in situ ash, and hence mineral contents, on average than their counterparts in the northern hemisphere. Despite this, South African and other Permian coals of the southern hemisphere contain lower concentrations of sulphides, halogens, and trace elements relative to those of their northern hemisphere (Carboniferous) counterparts (Wagner and Hlatshwayo, 2005).

Previous work undertaken by Cairncross (1989) on a variety of South African coals, and by Wagner and Hlatshwayo (2005) specifically on the Highveld Coalfield (Fig. 1) coals, provide a good indication of the likely concentrations of the trace elements in South African coals.

Pinetown et al. (2007) investigated the quantitative evaluation of mineral matter in coal deposits in the Witbank and Highveld coalfields, and linked this data to the potential for acid mine drainage generation. Malaza (2013) discusses the trace element geochemistry of coals of the Soutpansberg and Limpopo coalfields (Fig. 1).

3.1.1. Sulphur in South African coals

Environmental pollutants such as sulphur dioxide, sulphuric acid and hydrogen sulphide have been linked to the presence of sulphur in coal and as such an understanding of the nature of the sulphur in the coal is important. Sulphur occurs in South African coals in three forms, these being sulphide, sulphate and organic sulphur. Sulphide minerals are mainly pyrite, marcasite and siderite. Primary (or organic) forms of sulphur are trapped in the organic matrix at the time of peat formation. Secondary (or inorganic) sulphur occurs along cleats and fractures. The type and nature of the sulphur is important in terms of the degree of liberation during beneficiation. Currently, there are limited published studies on the investigation of sulphur compounds, especially organic sulphur compounds, in South African coal (Laban and Atkin, 2000; Wagner and Hlatshwayo, 2005). To partially rectify this situation Kalenga (2011) undertook work into the characterisation and distribution of the sulphur components in South African coals.

Roberts (1988a) discussed the relationship between macerals and sulphur content of some South African Permian coals and showed that since pyritic and organic sulphur are associated with vitrinite in coals from the MKB, sulphur content mirrors the trend of this maceral group i.e. increasing from west to east.

The average sulphur content of South African coals is generally quite low, and where elevated often amenable to reduction via beneficiation. Mehliss (1987) notes that at that time washed export grade bituminous coal from the Witbank Coalfield (Fig. 1) had averaged 0.62% and the Ermelo Coalfield 1.00%. Anthracite values for the coalfields of KZN for the years 1981–1985 were documented as being 1.26% (1.75% raw). Gonenc et al. (1990) note that it is generally less than or equal to 1%, Wagner and Hlatshwayo (2005) 0.40–1.29%, and Roberts (2008)

1.47%. Hsieh and Wert (1985) have reported that the total sulphur in South African coal ranges from 0.59 to 9.45%, whereas Olivella et al. (2002) report the range to be up to 15.1%. The senior author has also seen isolated values of greater than 15% due to the nugget nature of pyrite.

Pyrite in the coal is also one of the main components responsible for the wear and abrasion and high level of coal abrasiveness index (AI) in South African coals (Fosso-Kankeu et al., 2013). Weeber et al. (2000) postulated a possible relationship between low ash fusion temperatures (AFT) and an increase in the iron content present in the form of pyrite, as well as to the form in which pyrite is present.

3.1.2. Nitrogen in South African coals

Nitrogen is a major coal component subordinate only to sulphur in the hazard it poses to the environment. Roberts (1991) undertook a study into the influence of coal type and rank on the nitrogen content of the coals of the MKB. He showed that vitrinite and nitrogen in individual coal bands are positively correlated, whereas inertinite and nitrogen are negatively correlated. Both nitrogen and sulphur content are therefore positively correlated with the vitrinite maceral group in the MKB, increasing from west to east.

3.1.3. Phosphorus in South African coals

Phosphorus, essential to plant life, is an intrinsic mineral in coal, which cannot be easily removed by beneficiation. South African coals contain varying concentrations of phosphorus, which can have a number of detrimental effects on downstream usage, and the phosphorus content is one of the important specifications in terms of coal quality used in the metallurgical industry (Xaba, 2004). Low phosphorous (less than 0.010%) coals suitable for the metallurgical industry occur in the Witbank, Ermelo, Klip River, Utrecht, Nongoma, Sonkhele, Waterberg, Soutpansburg and Limpopo coalfields and probably in the Kangwane Coalfield (Fig. 1) as well.

3.2. Petrological studies

For most of the 20th century optical petrography has been the primary petrological and mineralogical tool used to characterise coal. Detailed petrographic works on the coals of South Africa were presented by Snyman (1961), Steyn and Smith (1977), Falcon (1978), Falcon et al. (1984), Falcon (1986a,b) and Holland et al. (1989).

Falcon (1986a,b) recognised a considerable variation in the petrography, grade and rank of coals within the Karoo Supergroup succession. This was attributed to changing climatic, tectonic and sedimentary settings with time. Falcon and Ham (1988) also cover various aspects of coal petrography in their paper on the characteristics of southern African coals.

Holland et al. (1989) undertook maceral group and mineral matter analyses of the basal four seams of an area to the south of Middelburg in the Witbank Coalfield. This work showed that in general the coal seams are inertinite-rich, with the inertinite content commonly greater than 55%, but ranging from 20% to 80%. The vitrinite content generally varies between 0% and 10% and exinite (liptinite) contents are low, being generally less than 10%, and reaching a maximum of about 15%. The general role of coal petrography in understanding the properties of South African coal is covered by Snyman (1989).

Glasspool (2003) used petrology as one of a suite of techniques to examine the No. 2 Seam from a single locality near the town of Ogies in the Witbank Coalfield (Fig. 1). He then compared the petrographic composition of this single locality to an average Witbank Coalfield coal as determined from the compilation of data from 34 mines from within the coalfield (Boshoff et al., 1991).

Fabianska and Kruszewska (2003) discuss the relationship between petrographic and geochemical characterisation of selected South African coals and note that the Beaufort Group coal seams are enriched in vitrinite.

Whilst these studies have shown the high petrological variability of South African Permian-aged coals, in general these coals have a higher inertinite content in comparison to most Carboniferous-aged northern hemisphere coals. Major portions of the inertinite (up to 60%) consist of low-reflecting semifusinite, commonly known in South African petrography as 'reactive semifusinite' (Hagelskamp and Snyman, 1988).

3.3. Palynological studies

The palynology of coal-bearing strata in South Africa has been intensely investigated due to their economic importance. Rillett (1954) reported on the palynology of coal seams near Dannhauser in KwaZulu-Natal. Hart (1963, 1964a,b, 1965, 1966a,b, 1969a,b,c, 1970) is responsible for a major contribution to Gondwanan Permian palynology. In South Africa, he studied the Dwyka, Ecca and Beaufort groups in the Cape Province as well as many boreholes from Gauteng and the Free State and thus this work formed the basis for review by subsequent workers. It should be noted however that the bulk of this research was associated with the sedimentary rocks enclosing the coal, not on the coal seams themselves.

Two main palynostratigraphic schemes have been established in the 1970s and 1980s for the coal-bearing Karoo succession and work in this respect is ongoing. J.M. Anderson (1977) subdivided the Dwyka, Ecca and Beaufort groups of the northern Karoo into seven zones. Falcon et al. (1984) and Falcon (1986c) investigated the palynoflora of the Witbank and Highveld coalfields and erected four zones and five subzones. Falcon (1989) also documented the role of palynology for analysis of the quality and distribution of the No. 2 Seam in the Witbank Coalfield.

Falcon et al. (1984) also showed that palynomorphs could be extracted from the coal seams themselves, and that all the coals investigated by these authors contained miospores in quantities ranging from 2 to 12%. MacRae (1988) identified six recognisable biozones in the coal-bearing strata of the Waterberg and Soutpansberg–Pafuri basins in the Limpopo Province. Aitken (1993, 1994, 1998) worked on the Vryheid Formation in the Witbank and Highveld coalfields, as well as at Lindley in the Free State Coalfield. He proposed a new microfloral biozonation scheme for the northern Karoo, with ten zones for the Permian and Lower Triassic. Millsteed (1994, 1999) reported on the Early Permian palynomorph assemblages of the Sasolburg Vereeniging Coalfield. Recently, Barbolini (2010) addressed the palynology of coal deposits of Botswana for correlation with the South African coals. In her PhD thesis, submitted in 2014, she proposes a first comprehensive biozonation for the Main Karoo Basin based on palynomorphs. Published palynological studies on the Molteno Formation lag behind.

3.4. Age of the coals

Coals in South Africa range in age from Early Permian to Late Triassic, with the majority being of Permian age, comparable to other Gondwanan coals in Sub-Saharan Africa, Madagascar, India, Australia, Antarctica and South America. As previously noted by Cairncross (2001) the absolute age of the coal-bearing units in South Africa are not well constrained, as to date zircon bearing tuff horizons have not been discovered. Most, if not all Permian age determinations and correlations therefore rely on palynology (Aitken, 1994, 1998; MacRae, 1988; Millsteed, 1994, 1999; Ruckwied et al., 2014; Visser, 1992).

Based on these palynological studies the Vryheid Formation is dated as Artinskian, with possible extension into the Kungurian (Aitken, 1994, 1998; Look and Visser, 1985; McLachlan and Anderson, 1973; Millsteed, 1994, 1999; Visser, 1990). Based on the presence of age-diagnostic index taxa Millsteed (1994) suggested an Artinskian (Aktastinian to lower Baigendzhinian) age for the Vryheid Formation in the Free State. Recent studies led to the conclusion that coal deposits of the

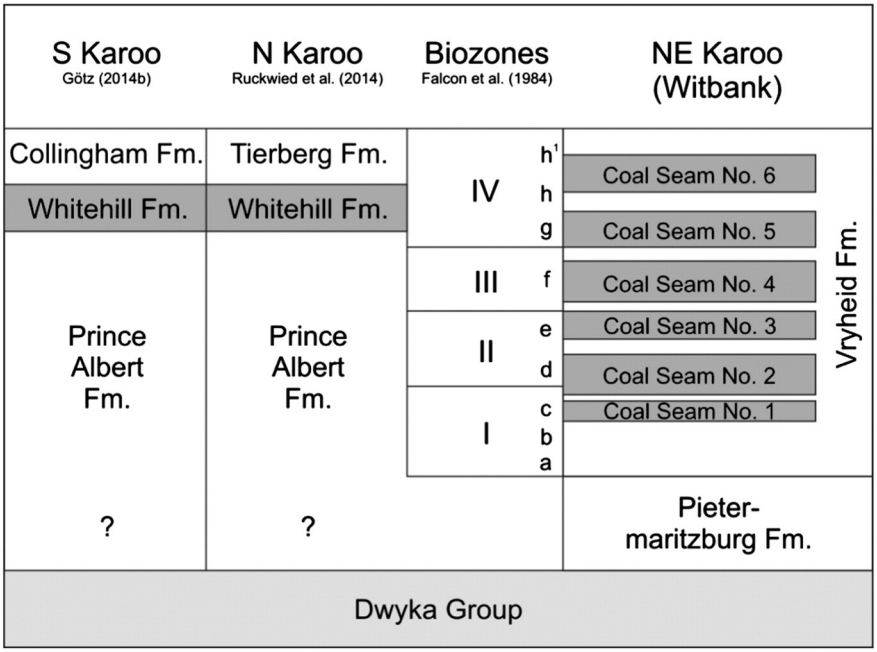

Fig. 7. Cross-basin correlation of Permian deposits using palynology. Fm. = Formation.

Vryheid Formation correlate to the organic-rich black mudstones of the uppermost Prince Albert and Whitehill formations (Ruckwied et al., 2014). New palynological data from the Witbank Coalfield and the north-eastern part of the MKB have enabled the establishment of a new basin-wide correlation scheme (Ruckwied et al., 2014) (Fig. 7).

Based on this new basin-wide correlation three main ages are documented for coal formation in South Africa; these being the Early Permian (Artinskian–Kungurian); Middle to Late Permian (Ufimian–Kazanian); and Late Triassic (Carnian). Not a lot of work has yet been undertaken on the palynological representation and age of the coals of the Nongoma, Somkhele, Kangwane, Limpopo, Soutpansberg (Mopane, Tshipise and Pafuri basins) and Springbok Flats coalfields (Fig. 1).

4. The coalfields of South Africa

Although differences exist in the literature as to the total number of coalfields in South Africa, 19 are generally accepted (Fig. 1), covering an area of some 9.7 million hectares (ha). The distinction between coalfields is based on geographic considerations and variations in the mode of sedimentation, origin, formation, distribution and quality of the coals. These variations are in turn related to specific conditions of deposition and the local tectonic history of each area.

The majority of coal mined to date in South Africa has however come from only six or seven of these coalfields, and for these coalfields, where hundreds of mines exist, individual mines are not mentioned in the text unless specifically required. For the newer coalfields, and those that have yet to be exploited, individual mines and projects are discussed, as most of the available data pertains to them and they form the entire knowledge base. Coal seam thicknesses are provided for the individual coalfields but it should be noted that these are highly variable within any one coalfield and should be taken only as an overall guide. Unless otherwise stated all coal qualities provided are on an air dried basis. For most coalfields coal qualities provided include general Calorific Value (CV), Ash % (Ash), Volatile Matter % (VM), Inherent Moisture % (IM), Fixed Carbon % (FC) and Total Sulphur (TS). For thermal coals CV is presented first in the tables, whereas for anthracite the FC is. Dry Ash-free Volatile (DAFVOL) percentages are also presented where required to show areas of devolatilised coal.

The Witbank and Highveld coalfields (Fig. 1) are the best documented and described and are here presented first, as they set the standard for the descriptions of many of the coalfields that follow.

4.1. Witbank Coalfield

4.1.1. Introduction

Whilst there is no clear record of when coal mining began in the Witbank Coalfield, it is known that by 1889 four small collieries (Brugspruit, Steenkoolspruit, Maggies Mine and Douglas Colliery) were operating (Falconer, 1990; Smith and Whittaker, 1986a,b). Over a century and a quarter later this coalfield is still one of the most important in South Africa, supplying more than 50% of South Africa's saleable coal. It produces both metallurgical coal and thermal coal for the export and local markets, and hosts many of the major coal-fired power stations in South Africa including Kendal, Duvha, Komati and Arnot. The coalfield is fairly mature in terms of its exploration and exploitation and it is unlikely that it will see any new large coal mines.

The coalfield is named after the city of Witbank, which was renamed to Emalahleni in 2006. Whilst some argument for renaming the coalfield might therefore exist, the name Witbank Coalfield is however retained here due to its historical significance.

4.1.2. Location

The Witbank Coalfield is situated in the northern part of the MKB, extending from roughly 25°30′S to 26°30′S by 28°30′E to 30°00′E, and covering an area of over 568,000 ha. It extends some 90 km in a west–east direction, from the towns of Springs in the west to Belfast in the east, and 50 km in a north–south direction, from the town of Middelburg in the north to Rietspruit in the south. The northern boundary of the coalfield is formed by pre-Karoo basement rocks, whilst the southern boundary in the central portion of the basin is widely considered to be the sub-outcrop against a basement palaeohigh known as the Smithfield Ridge (Fig. 8), a broadly east–west trending, crescent shaped ridge of pre-Karoo felsites, granites and diabase of the Bushveld Igneous Complex (BIC). This ridge extends for some 60 km between the farms Smithfield 44IS in the west and Fentonia 54IS in the east, as both a

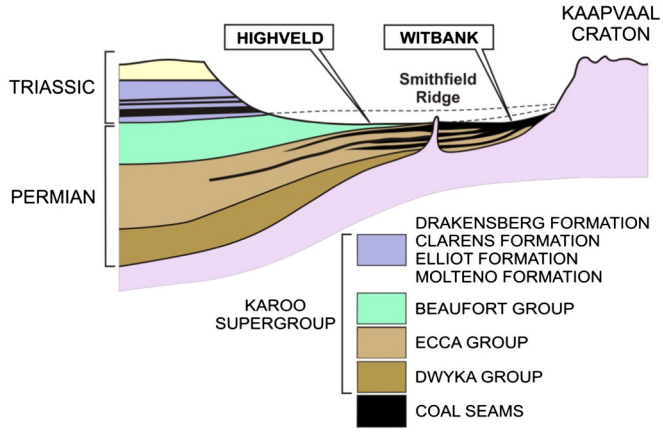

Fig. 8. Schematic north–south transect of the Witbank and Highveld coalfields separated by the Smithfield Ridge.
After Falcon (1986a).

surface topographic high as well as in the subsurface (Le Blanc Smith, 1980a). To the east and west of the central portion, the southern boundary is rather arbitrarily defined. The extreme eastern and western boundaries are also defined by the sub-crop of the coal-bearing sedimentary succession against the pre-Karoo basement.

We here informally sub-divide the coalfield into three fairly distinct geographical areas, these being the western, central and eastern sectors. The central sector is probably the best known and is host to many of the large mines and tied mine mouth power stations.

4.1.3. Exploration and exploitation history

It is beyond the scope of this work to fully detail over 120 years of exploration and exploitation history in the Witbank Coalfield, so instead some highlights are documented below. In 1872, both Thomas Baines and Woolf Harris document coal in the Witbank Coalfield. Following on the identification of coal in the Vandyksdrift area, it is believed that Harris started the Maggies Mine around 1873 (Falconer, 1990). As mentioned above, four small collieries were in production by 1889 and a Government Mining Engineer's report refers to the production of coke in 1890, which would suggest that coal mining operations were well established in the coalfield by that time. The first certain commercial company record however dates only from 1895, when the Home Coal Estates Company was formed to take over the Maggies Mine. Mining in the vicinity of the town of Witbank also began in 1895 when the Cassel Coal Company opened Landau Colliery (Schalenkamp, 2006). The coalfield has been in continuous exploitation since this time, providing a near 120 year record of mining and exploration history.

The main end users of the coal were the gold mining industry and its associated businesses and infrastructure, including the railways. The gold mining companies bought heavily into the coal resources and for the first half of the twentieth century, nearly all coal mines in the Witbank Coalfield were owned by the large gold-mining houses.

This exceptional history has also meant that this coalfield is South Africa's best documented and understood. The Witbank Coalfield has been the home to a number of firsts in South Africa, including the introduction of the first continuous miner (CM), in 1947 at the Klipfontein Colliery, and the first large dragline, which was introduced at Optimum Colliery in 1971. The Witbank Coalfield is also home to the first black owned and managed coal mine in South Africa (Scott, 1998). This occurred in March of 1997 when Kuyasa Mining (www.kuyasamining.co.za) began production from its Ikhwezi Colliery, situated approximately 25 km from the town of Delmas in the western part of the Witbank Coalfield. Following on the change in mineral legislation in South Africa in 2004, the coalfield became the focus of renewed exploration and exploitation by a number of new junior and mid-tier miners including Continental Coal (http://www.conticoal.com/), Keaton Energy Holdings (http://www.keatonenergy.co.za/), Mbuyelo Resources (http://mbuyelo.com/), Sable Mining (http://www.sablemining.com/) and Universal Coal (http://www.universalcoal.com/). Much of this new exploration work has focused on the western sector of the coalfield.

From these new entrants four new surface coal mines have been established in the past few years. These include from west to east Universal Coal's Kangala Colliery, Mbuyelo's Eloff/Manungu Colliery, Keaton Energy Holdings (Keaton) Vanggatfontein Colliery and Continental Coal's Vlakvarkfontein Colliery. These four opencast operations will together generate around 8 Mtpa of coal.

4.1.4. Research history

The earliest meaningful research into the coals of the Witbank Coalfield was that of Wybergh (1922) who interpreted the origin and palaeoenvironmental setting of the seams. Due to the sensitive nature of the data, published accounts of the coalfield between this early work and the 1980s is scarce, fragmentary and generalised, with the most comprehensive work being that of De Jager (1976). Since this time exploration and mining in the Witbank Coalfield over the years has allowed for the description of various clastic depositional systems that are associated with the five coal seams (Fig. 9).

The general geology of the Witbank Coalfield has been extensively studied, and was the focus of much research during the 1980s and 1990s during the time of the National Geoscience Programme's Witwatersrand Coal Research Group. Specific studies that have focussed on aspects of the sedimentology of the Witbank Coalfield (and its included coal seams) include those of Le Blanc Smith and Eriksson (1979), Le Blanc Smith (1980a,b,c), Cairncross (1980), Winter (1985), Cairncross (1986), Cairncross and Cadle (1988a,b), Holland et al. (1989), Cadle and Cairncross (1993), Grodner (2002), Grodner and Cairncross (2006) and Uys (2007).

Floor rolls on the No. 2 Seam at Greenside Colliery were noted by Atkinson and Leach (1979) as being responsible for the introduction of the first load–haul–dump unit, to supplement the conventional equipment in use by separately loading and dumping stone derived from the blasting of the footwall humps or rolls. They are described as being protuberances into the seam floor, varying in height between 0.5 and 3.5 m, and covering areas of 100 m^2 or more.

The same year saw the publication of one of the earliest works to geostatistically analyse the coals of the Witbank Coalfield, specifically the No. 2 Seam reserves of the Greenside Colliery (Wood, 1979). This work showed the No. 2 Seam to be composed of four different zones (plies) and discusses the presence in the colliery of muck-belts which were then believed to be erosion channels filled by the poorer quality zone 4. This work further shows the value of utilising geostatistical methodologies to understand the mining blocks and the relationship between borehole spacing and block size.

Le Blanc Smith and Eriksson (1979) document various facies for the Dwyka Group and basal part of the Vryheid Formation in he north-central part of the Witbank Coalfield. These authors showed that outwash sediments associated with the waning Dwyka ice age, accumulated as fluvioglacial and glaciolacustrine deltaic deposits.

Based on subsurface data from over 1200 boreholes, Le Blanc Smith (1980a,b,c) determined various aspects of the Witbank Coalfield stratigraphy and the palaeoenvironmental controls on coal formation. He further attempted to remove the inadequacies of the existing lithostratigraphy by defining a genetic stratigraphy for the Witbank Coalfield based on the recognition of ten aerially extensive marker horizons, allowing for the subdivision of the succession into eleven Genetic Increments of Strata (GIS) and four Genetic Sequences of Strata (GSS).

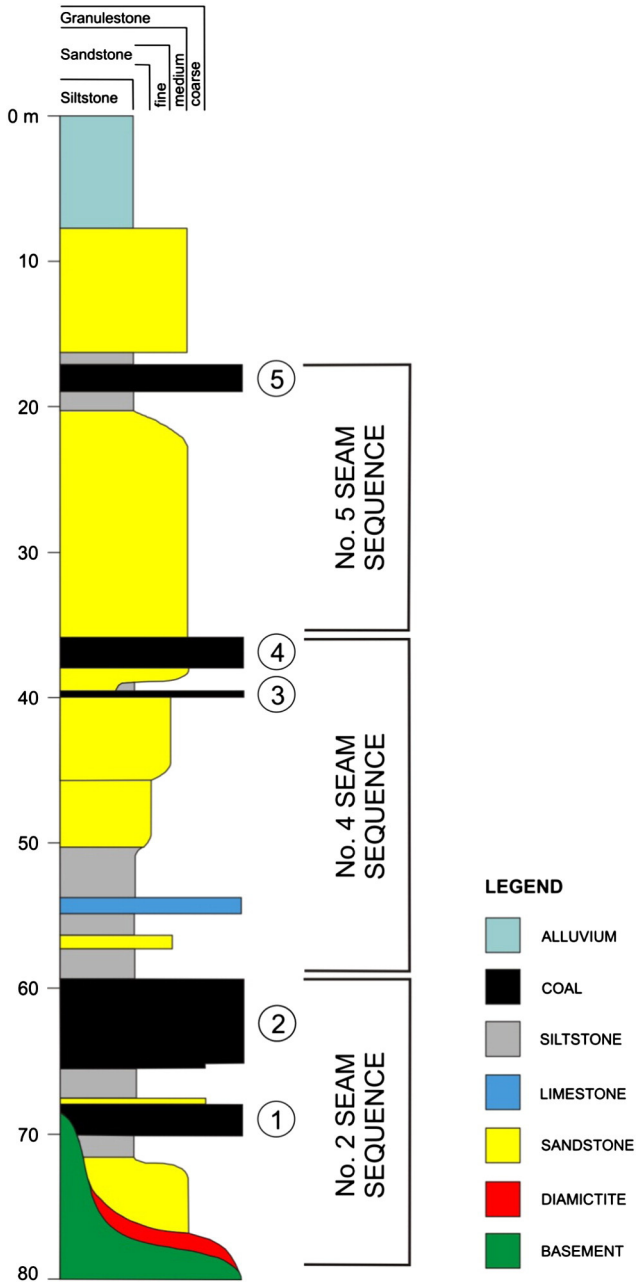

Fig. 9. Generalised stratigraphic column for the Vryheid Formation in the Witbank Coalfield. Individual coal seams are numbered from No. 1 at the base to No. 5 at the top. Redrawn from Cairncross and Cadle (1988).

To overcome a lack of uniformity in borehole core descriptions, Le Blanc Smith (1980c) also erected a useful logical letter facies coding system for the Witbank Coalfield, the basis of which is still used today in coal exploration programmes.

Cairncross (1980) described the role of anastomosing fluvial channels in the No. 2 Seam at Van Dyks Drift Colliery, and the deleterious effect these had on coal seam distribution and quality. Winter (1985) and Cairncross (1986) related coal quality to interpreted processes of fluvial sedimentation and to differential compaction of the peat swamp. Cairncross (1986) also documented the importance of clastic partings in the No. 2 Seam at Arnot Colliery leading to splitting of coal, through deposition of sediments by braided or anastomosed fluvial systems. Cairncross and Cadle (1988a) described the No. 1 and No. 2 seams in the east Witbank Coalfield with respect to their distribution, thickness and quality.

In a special publication of the Geological Society Hart and Leahy (1983) documented the geochemical characterisation of the coal seams in the Witbank Coalfield. Macfarlane (1985) described stone-floor rolls from the underground Tavistock Colliery in the southeast Witbank Coalfield and interpreted them as being the preserved tops of scroll bars in a meandering river system. Cairncross et al. (1988) also describe floor rolls from the Witbank Coalfield and felt that Macfarlane's (1985) model was incorrect and that the floor rolls observed in the Witbank Coalfield were the abandoned floors of anastomosing rivers, similar in character to modern analogues in the Okavango Delta of Botswana. Floor rolls are positive topographic features that protrude upwards into a coal seam and cause rapid seam thinning, dangerous floor conditions, production and grade control problems, and drainage problems.

Holland et al. (1989) undertook sedimentological and petrographic research on subsurface data from an area 20 km south of the town of Middelburg. Seventy logged boreholes drilled on a 100 m × 50 m grid pattern provided the data base for this investigation. This work showed that coal seams formed in fluvial environments are thick and laterally continuous, and have higher inertinite and mineral matter contents than coals formed in lower delta plain environments, which are generally thin and laterally discontinuous. This work also showed that in the area, two distinct sedimentary successions underlie the No. 1 Seam, one in a palaeovalley setting and the other in palaeovalley flank settings. In the same year Falcon (1989) published a study on the macro- and micro-factors affecting coal-seam quality and distribution in southern Africa, with a focus on the No. 2 Seam in the Witbank Coalfield.

Cairncross et al. (1990) looked at the geochemistry and sedimentology of coal seams from the Witbank Coalfield as a means of seam fingerprinting and identification. Based on drill core and outcrop studies, Cadle and Cairncross (1993) delineated a 2–5 km wide channel system in the southern part of the central Witbank Coalfield and showed the channel–fill sequence to represent the deposition of a bed-load dominated braided fluvial system.

Grodner (2002) and Grodner and Cairncross (2003) established a regional, three-dimensional sedimentological model of the clastic strata of the Vryheid Formation and pre-existing basin floor topography of the western part of the Witbank Coalfield. As part of a MSc study, Schalenkamp (2006) reported on the financial viability, and the effective and responsible utilisation of reserves within the previously mined areas of the Witbank Coalfield.

Based on data from 924 boreholes Uys (2007) documented the lithostratigraphy of the most northern proximal setting of the Witbank Coalfield, and offered an interpretation of the various depositional environments. She notes that in contrast to the greater Witbank Coalfield, but concurrent with other studies in the more northern proximal regions, fluvial systems dominate over deltaic systems in her study area.

As part of the Coaltech 2020 research programme two projects have also been undertaken on the dolerites of the central Witbank area by twin brothers. Gideon du Plesiss (G. P. Du Plesiss, 2008) looked at the relationship between geological structures and dolerite intrusions on four collieries (Bank, Goedehoop, Koornfontein and Optimum) south of the Ogies dyke. Johannes du Plesiss (J. J. Du Plesiss, 2008) undertook a detailed study on the petrochemical characterisation of the dolerites at the Koornfontein, Bank and Goedehoop collieries. This work focussed on the mineralogy and geochemistry of the dolerites and the behaviour and metamorphic influence of a 20 m thick bifurcating dolerite sill (the Witbank sill) and provides a number of proximate analyses that show that the dolerite sill caused a localised increase in rank, with areas of high moisture content corresponding to devolatilised areas.

Mahanyele (2010) presents an interpretation of high resolution airborne magnetic data flown over selected areas (Delmas, Vandyksdrif, Arnot and Belfast) in the Witbank Coalfield. This work focussed on the identification and delineation of faults, dykes and sills and concluded that structural disturbance was more severe in the eastern

sector. This work also provides geological descriptions of the four areas and provides a number of useful stratigraphic sections and borehole logs.

The descriptions of the general geology and coal seams which follow draw on these previous works as well as the senior author's personal experience in the Witbank Coalfield.

4.1.5. Geology

Given that the Witbank Coalfield is elongated over 180 km in a west to east direction, it is not surprising that the basement to the Karoo Supergroup succession is varied. From west to east the basement rocks include metasedimentary, metavolcanic and dolomitic rocks of the Neoarchaean Transvaal Supergroup, metasedimentary and metavolcanic rocks of the Palaeoproterozoic Waterberg Group and BIC age intrusives (felsites and granites) (Fig. 10).

The changing nature of the basement plays a major role in the nature of the palaeotopography created. For example, in the far east of the Witbank Coalfield (Fig. 10), where dolomites of the Transvaal Supergroup form the basement, abnormally thick coals filling karst topography are known. A similar but more extreme case is documented at the Syferfontein Colliery in the West Rand outlier (Stuart-Williams, 1986).

In some areas close to the north-western basin margin, the stratigraphic column is reduced to only 80 m. It was also the focus of much of the academic research, including the works of Cairncross (1979) in the Van Dykes Drift area, Le Blanc Smith and Eriksson (1979) to the west of Witbank, and Holland et al. (1989) to the east of Witbank. Cadle and Cairncross (1993) described a sandy bedload dominated system with lateral accretion surfaces from the southern part of the central sector. More recently it has been covered in the regional geological model of Grodner (2002) and Grodner and Cairncross (2006) and various Competent Persons' Reports available on various companies' websites (Goldschmidt et al., 2010a). Two areas to the south and southeast of Van Dyks Drift were also included in a high resolution aeromagnetic study by Mahanyele (2010).

The eastern sector is also well known from the works of Cairncross (1986), Cairncross and Cadle (1988a,b), and Uys (2007). Here the basement is mainly Rooiberg felsites and BIC gabbronorites and late stage granites. The top part of the succession has been lost to erosion, so that the No. 2 Seam is the main seam of economic interest.

The western sector has not been the subject of as much academic work, mainly due to the fact that the coal is generally of poorer quality than in the central and eastern sectors. For this reason it was also not previously extensively mined or explored. This changed dramatically post 2004, and the sedimentology of the region has now been described in a number of Technical and Competent Persons' Reports filed electronically on SEDAR and on various companies' websites (Dekker and van Wyk, 2008; Gemmell, 2009; Goldschmidt et al., 2010b; Hancox, 2011). These technical reports also present the raw coal qualities for the various projects, both as tables and grids.

Dwyka aged glacial scouring and the induced basement palaeotopography is by far the greatest factor impacting on the distribution of the coal seams in the Witbank Coalfield. The northern margin of the MKB in the Witbank Coalfield displays vast valleys and ridges left after the scouring ice-sheets migrated across this part of Gondwana. Five regional palaeovalleys, trending roughly NNE–SSW, have been identified (Fig. 11). These include the Grootvlei Valley extending from North of Nigel and trending in a southerly direction towards the South Rand Coalfield; Vischkuil Valley, north-east of Springs trending towards Devon; Coronation Valley running from north of Coronation Kromdraai Colliery, north-west of Witbank, southwards towards Springbok Colliery and then extending to the south-east towards Hendrina; Bank Valley extending southward from north-west of Middelburg to Bank Colliery and subsequently linking to the Coronation Valley; Arnot Valley trending from north of Arnot southwards to the east of Arnot Colliery.

These valleys created variable accommodation space, which was subsequently filled by the sedimentary rocks of the Dwyka and Ecca (Vryheid Formation) groups. The valleys merge to the southwest and their impact on the nature of the sedimentary succession becomes less. Palaeotopographic highs between these valleys include those composed of Elsburg metaquartzite and Ventersdorp lavas on either side of the Grootvlei Valley; a prominent Pretoria Group metaquartzite and diabase ridge extending from Dryden towards Leslie; and a felsite ridge extending south-eastward from Kendal to link with the granite and felsite Smithfield Ridge which forms part of the southern boundary of the Witbank Coalfield.

The basal Pietermaritzburg Formation of the Ecca Group is not present in the Witbank Coalfield and rocks of the Dwyka Group are directly overlain by the coal bearing Vryheid Formation of the Ecca Group. Ambiguity exists as to when the true stratigraphic position of the coal-bearing rocks in the Witbank Coalfield was first recognised. Smith and Whittaker (1986b) described the geological work of Mellor (1906) who defined the current nomenclature of the five seams in the area. Du Toit (1954, p. 283) however states that it was not until 1918 that the "Transvaal Coal Measures were found to be part of the middle portion of the Ecca series".

Most authors however now agree that five (Cairncross, 1986) or sometimes six (Le Blanc Smith, 1980b; Cadle et al., 1990) coal seams occur within an approximately 70 m thick succession of the Vryheid Formation. They are generally numbered from No. 1 Seam at the base of the sequence to No. 5 at the top. Descriptions of each of these seams are provided below within the sequence stratigraphic architecture. The nature of the floors and roofs to the various seams are of particular importance, especially for underground development and extraction, and they are described in detail below.

As the lithostratigraphic nomenclature for the Karoo Supergroup outlined by SACS (1980) does not include sub-formational level divisions, various inadequacies are evident when detailed sedimentological investigations are undertaken (Holland et al., 1989). As such, academic studies moved from strict lithostratigraphic classification to palaeoenvironmental interpretation. To account for the genetic nature of the stratigraphy, a number of informal models were erected.

This approach was adapted for the Witbank Coalfield by Le Blanc Smith (1980a), Winter (1985), Cairncross (1986) and Winter et al. (1987). The details of these genetic models are reviewed in Grodner and Cairncross (2003) and are not repeated here. Cairncross (1986) adapted a straightforward approach to the stratigraphic analysis of the Vryheid Formation strata in the Witbank Coalfield, subdividing the entire column into three sequences which contain the five coal seams. These units (the terminology of which is followed in this paper) are from the base up the No. 2 Seam, No. 4 Seam and No. 5 Seam sequences (Fig. 9).

Cairncross's (1986) No. 2 Seam Sequence equates to Le Blanc Smith's (1980a) Witbank Genetic Sequence of Strata (GSS) and incorporates the No. 2 Seam. The overlying No. 4 Seam Sequence equates to the Coalville GSS of Le Blanc Smith (1980a) and extends from the roof of the No. 2 Seam to the No. 4 Seam, incorporating the No. 3 Seam where present. The uppermost No. 5 Seam Sequence is the equivalent of the Middelburg GSS of Le Blanc Smith (1980a) and extends from the roof of the No. 4 Seam to the No. 5 Seam. As Cairncross's (1986) study was a more detailed local scale analysis, he did not find it necessary to define an equivalent to Le Blanc Smith's (1980a) Van Dyks Drift GSS.

4.1.6. Seam sequences

The No. 2 Seam Sequence (Fig. 9) includes the succession from the top of the basement to the top of the No. 2 Seam, which may be up to a maximum development of 60 m in places (Le Blanc Smith, 1980a). This sequence is probably the least well documented or understood succession in the entire MKB stratigraphy and should be the focus of studies

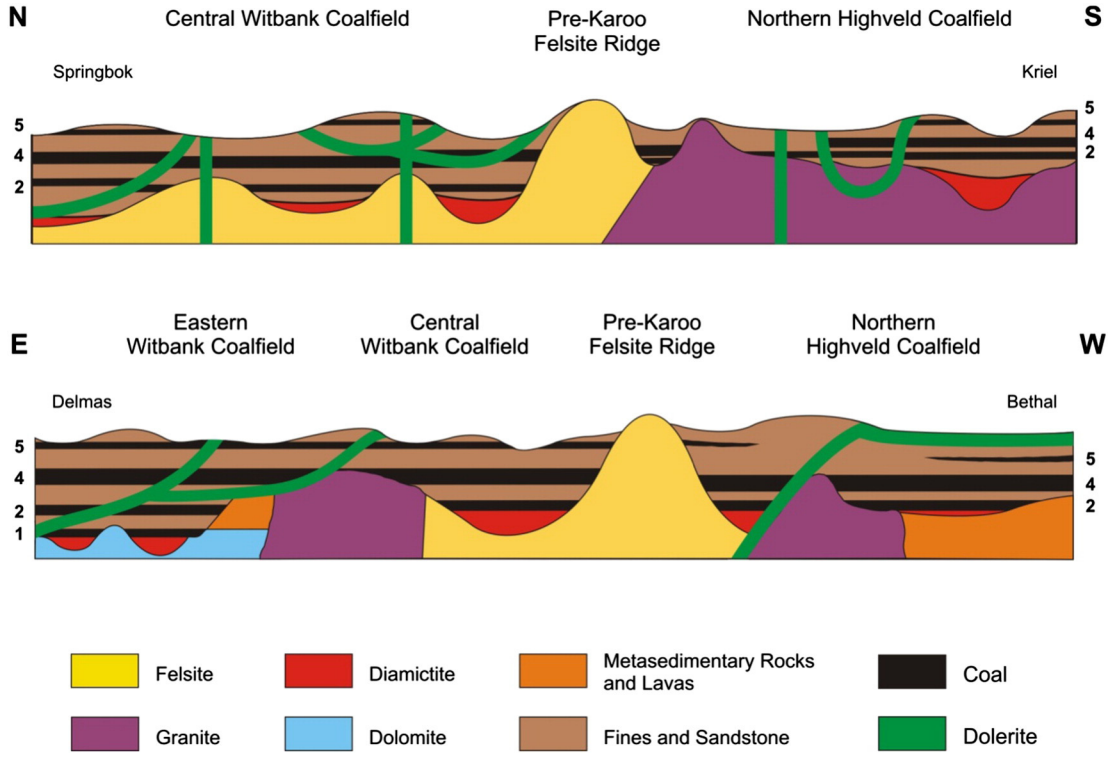

Fig. 10. North–south and East–west cross sections of the Witbank and Highveld coalfields showing the relation between the pre-Karoo basement and the Permian coal-bearing series. After Smith (1970).

in the future. It incorporates the rocks of the Dwyka Group, as well as the overlying No. 1 and No. 2 coal seams. It should be noted that we accept that the Dwyka has separate Group status, but that it is described below as the basal part of the No. 2 Seam Sequence.

Unfortunately, many exploration boreholes drilled within the Witbank Coalfield have not fully penetrated the Dwyka Group (which is often incorrectly referred to as basement) and as such the thickness variations are not as well-known as for parts of the Vryheid Formation.

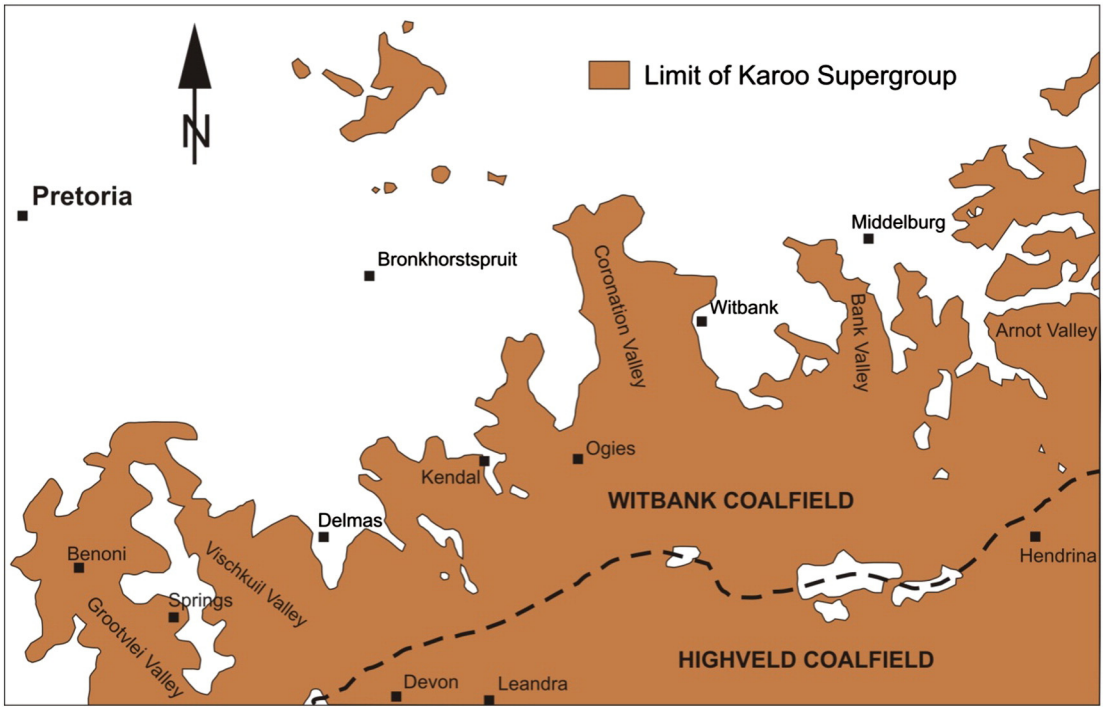

Fig. 11. Limit of the Karoo Supergroup Rocks in the Witbank Coalfield showing the five recognised palaeovalleys. The black dashed line represents the approximate position of the Smithfield Ridge.
After Smith and Whittaker (1986a).

The thickness of the Dwyka Group in the Witbank Coalfield also varies considerably dependant on the nature of the underlying topography. It ranges from being thin or absent over the most prominent pre-Karoo topographic highs, to over 25 m thick in the central part of the Witbank Coalfield (Le Blanc Smith and Eriksson, 1979) to 30 m thick (Glasspool, 2003) in the deeper palaeovalleys. Le Blanc Smith and Eriksson (1979) note that the fill consists of poorly sorted matrix-rich diamictites, laminated sandstones and siltstones, stratified pebbly mudstones and cross-stratified conglomerates.

In the western Witbank Coalfield the No. 2 Seam Sequence tends to be much more variable in nature than it is in the central part. This is mainly due to the irregular nature of the Transvaal Supergroup (Malmani Group) dolomite floor. The Dwyka Group outcrops in the area around Delmas and is also well known from borehole core, which show the succession to be between 0 and 10 m in thickness. The base of the No. 2 Seam Sequence is usually formed by poorly sorted matrix-rich diamictites, with angular to rounded basement clasts, set in a matrix of fine- to medium-grained sandstone, which may be highly carbonaceous in places. Maximum clasts sizes documented by the authors are in the region of 30 cm. According to Le Blanc Smith (1980a) the Dwyka Group diamictites may in turn be overlain by a succession up to 36 m thick of mudstone and siltstone, which grades upwards to sandstone and conglomerate that form the floor of the No. 1 Seam or its carbonaceous mudstone equivalent.

In the Vischkuil Valley of the far western region of the Witbank Coalfield and in the Delmas region, the clastic interval (above the diamictites where present) beneath the No. 1 Seam is much thinner and less complex than that described by Le Blanc Smith (1980a) for the Witbank Coalfield in general, and is more similar to the succession described by Cairncross and Cadle (1987) for the north-east of the Coalfield. Variability is the norm, with the succession, where present, formed by variable thicknesses of matrix supported conglomerate, medium- to coarse-grained sandstone, finely laminated siltstones and mudstones, and insignificant stringer coals in places. Thick units of apparently massive to thinly laminated, very fine-grained sandstone to mudstone may also occur. These are interpreted as glacial flour deposits and are restricted to the stratigraphic interval below the No. 1 Seam.

In the New Largo area (west central Witbank Coalfield), whilst not always present, the Dwyka Group is formed by a succession of polymictic diamictites and poorly sorted, coarse to very coarse-grained sandstones, with rare occurrences of varved and massive mudrocks. Thicknesses of up to 12 m have been intersected, but the entire Dwyka Group has been penetrated in only a few boreholes. In the eastern sector, Uys (2007) describes the Dwyka Group as being composed of up to 2 m of massive, sand or clay matrix supported conglomerate (diamictite) containing angular pebbles, cobbles and boulders. The diamictite grades upwards into very coarse-grained sandstones and minor lenses of siltstone and mudstone, including varved units.

Whilst the thicknesses are highly variable, the nature of the Dwyka succession is remarkably similar in all areas of the coalfield. Generally the base of the Dwyka Group consists of rudaceous material of glacial origin (diamictite unit) accumulated as ground moraine and glaciomarine, including diamictite, varved and interlaminated siltstones and mudstones with dropstone pebbles, as well as fluvioglacial gravel and conglomerates.

The paraglacial model of Le Blanc Smith and Eriksson (1979) is generally sound for the basal part of the No. 2 Seam Sequence in the Witbank Coalfield. Generally the succession is formed by basal diamictites formed during glacial retreat, overlain by various glacial outwash deposits including reworked diamictites (which form better sorted conglomerates), glaciodeltaic sandstones and glaciolacustrine deposits (including varves and dropstones). Upon abandonment of this outwash plain, shallow rooted vegetation developed giving rise to the peats which formed the No. 1 Seam. The immediate floor to the No. 1 Seam is also highly variable and may be formed by basement, Dwyka Group diamictite, reworked diamictite, very coarse to coarse and medium- to fine-grained sandstone, or carbonaceous siltstone and mudstone.

Development of the seam occurs mostly in palaeovalleys and tends to pinch out against the palaeohighs and seam development and thickness is highly variable. Holland et al. (1989) document a maximum recorded thickness of 6 m for the No. 1 Seam in a palaeovalley in the central sector of the Witbank Coalfield. Smith and Whittaker (1986b) note that it is best developed in the northern part of the Coalfield, where it is between 1.5 m and 2 m thick. In the western sector the No. 1 Seam is not usually well-developed and where present forms a coal and carbonaceous mudstone rich interval. It is of poor quality and is not usually included as part of the resource base except where it joins with, and forms the basal part of the No. 2 Seam. Even in this instance, it is sometimes left in surface operations as a non-select basal ply.

At the Kendal Colliery in the west-central Witbank Coalfield, the No. 1 Seam is only developed as a thin marker unit, with a rooted basal contact (Hancox, 2011; Fig. 12).

In the far eastern part of the Witbank Coalfield the No. 1 Seam, where present occurs between 0.25 m and a little over 2 m thick. It may be sub-divided into bright coal, dull coal and lustrous coal. The bright coal is occasionally laminated and may contain disseminated pyrite. Dull coal is often described as gritty or granular (Uys, 2007) and may contain pyrite or siderite nodules. The basal 20–30 cm of the No. 1 Seam in this area tends to be a carbonaceous siltstone or mudstone in places. Uys (2007) divides the seam into a No. 1 Lower-Lower Seam, No. 1 Lower Seam and No. 1 Seam. The No. 1 Lower-Lower Seam is a thin ply that occurs only in isolated areas and pinches out against basement at places. It averages only 0.29 m and consists of dull coal with occasional thin laminae of bright coal. The parting between this lowermost seam and the No. 1 Lower Seam is composed of between 1.96 and 2.36 m of granulestone and reworked diamictite. The No. 1 Lower Seam is also thin (averaging 0.36 m) and discontinuously formed around basement highs and consists of mainly dull coal (Uys, 2007). The parting between this ply and the overlying No. 1 Seam is formed by a thin (average 0.43 m) reworked diamictite that may in fact represent a debris flow deposit. Uys (2007) further notes that the No. 1 Seam is laterally persistent across the area of her study and that it appears relatively unaffected by the pre-Karoo basement.

Where economically extracted the No. 1 Seam typically consists of high quality lustrous to dull coal, with local sandstone and siltstone partings, and may be a source of export quality thermal coal (Falcon, 1989; Smith and Whittaker, 1986b; Snyman, 1998) and low phosphorus metallurgical coal (Barker, 1999; Cairncross, 2001). In other places it may be formed by a high Ash unit containing reworked Dwyka Group lithologies. It is however often misidentified and miscorrelated.

The immediate roof to the No. 1 Seam is variously formed by reworked diamictite (Fig. 12) or dolomitic breccia, and fine- to coarse-grained sandstones. The succession between the No. 1 and No. 2 seams is also highly variable, but is often formed by a generally coarsening, then fining-upward succession until the base of the No. 2 Seam. In the far eastern sector the parting between the No. 1 and No. 2 seams is variously formed by either a coarse-grained sandstone or siltstone and mudstone unit. Where developed normally this unit is fairly consistent and ranges from 0.40 to 0.60 m in thickness.

Cairncross and Cadle (1988a,b) interpret the succession that forms the clastic parting between the No. 1 and No. 2 seams as being deposited by coarse-grained bedload dominated fluvial deposits. In the western sector this is not however the case and the succession seems to be the product of a prograding deltaic unit, with various reworked diamictites forming as debris flow deposits.

Due to the fact that the Dwyka Group and basal part of the No. 2 Seam Sequence may not be developed in areas of the coalfield, the floor to the No. 2 Seam is highly variable, and this heterogeneity is

Fig. 12. Borehole core from Kendal Colliery showing diamictites of the Dwyka Group and the thin (8 cm) nature of the No. 1 Seam. TNW core diameter (60.5 mm). From Hancox (2011; Fig. 7.4).

important from a mining and environmental perspective, especially in the western sector of the coalfield where the No. 2 Seam may sit directly on dolomitic basement. The floor to the No. 2 Seam may therefore be formed by fresh or palaeoweathered dolomites or metasedimentary rocks of the Transvaal Supergroup, on Dwyka Group lithologies, on any lithology of the No. 1–No. 2 parting, or directly on coal of the No. 1 Seam, thus forming a thick composite seam. This last option is particularly prevalent in the western sector of the Witbank Coalfield, which at Exxaro's Leeupan Mine is up to 14 m thick (Goldschmidt et al., 2010b). To the west of this on Mbuyelo's Eloff project area the lowermost coal may form a composite seam up to 20 m in thickness (Hancox, 2011).

In places the No. 2 Seam is split into a No. 2 Lower (2L) and No. 2 Upper (2U) by an intra-seam parting (lens) of clastic sediment deposited from a braided river system during peat accumulation (Fig. 13). The clastic lens deleteriously affects coal thickness and quality (Cairncross and Cadle, 1988a,b). This No. 2 Seam split is also documented for the central part of the Witbank Coalfield by Holland et al. (1989) and is known to be up to 15 m in thickness in the Kendal–Ogies area (Hancox, 2011). In the central sector there is sometimes an additional intra-seam parting, creating an upper No. 2A Seam as well (Fig. 14).

The majority of the coal resources in the Witbank Coalfield are attributed to the No. 2 Seam, which also contains some of the best quality coal. The seam averages 6.5 m in thickness in the main-central part of the Coalfield, and thins to approximately 3 m towards the east. In the Delmas region it may be up to 7 m thick. The seam generally displays well-defined zoning, with up to seven zones of coal of differing quality (Jeffrey, 2005a). Historically the basal three zones have been mined for low Ash metallurgical and thermal export coal and in places the basal five zones are still mined for production of thermal coal for the export market. The top zone, which may be up to 3 m thick, is generally of inferior quality (high Ash), and is only suitable for the local Eskom market. This zone has historically not been mined when the No. 2 Seam was extracted by underground mining.

Given the high degree of variability exhibited by the No. 2 Seam, it is difficult to present an average set of qualities for the seam. This variability is enhanced in the western sector where dolerites often devolatilize the seam. Technical reports for the new projects in the western sector show the raw CV's of the No. 2 Seam to vary from 3.0 MJ/kg to 24.7 MJ/kg, Ash from over 40% to around 22%, raw VM from 12 to 25% (with dry ash-free volatiles (DAFVOL) varying from 13.5% to 43%), and TS between lows of 0.5% and highs of over 10%. The reader interested in specific quality data for the western sector is referred to Goldschmidt et al. (2010a,b), Hancox (2011) and to the Universal Coal, Sable and Keaton Energy websites.

The No. 4 Seam Sequence (Fig. 9) comprises the succession incorporating the immediate roof of the No. 2 Seam to the top of the No. 4 Seam, and equates to the Coalville GSS of Le Blanc Smith (1980a) and the succession referred to as the Roof of No. 2 Seam to Floor of No. 4 Seam Sequence by Grodner (2002) and Grodner and Cairncross (2003). The most characteristic feature of this sequence is its coarsening-upward nature, as noted by previous workers such as Cairncross and Cadle (1987).

The immediate roof of the No. 2 Seam is less variable than its floor, being composed of either a coarse-grained sandstone to granulestone where a channel is developed above it (such as at the Kendal Colliery), or a unit of laminated to rippled siltstone or mudstone.

In the Delmas area of the western sector the succession between the No. 2 and the base of the No. 3 Seam (where present) comprises a basal, highly carbonaceous siltstone, interbedded siltstone and fine-grained sandstone, which is frequently bioturbated grading upwards into a medium- to coarse-grained arkosic sandstone. According to Cairncross and Cadle (1987) the succession to the base of the No. 3 Seam is usually formed by delta progradation, with delta abandonment allowing for the formation of the No. 3 Seam peat development.

The No. 3 Seam is only poorly developed and when present is usually less than 0.5 m thick. It is often of a good quality coal, but is not generally economically extracted due to its thin development. Where it attains a thickness greater than 0.5 m, it may represent a potential shallow resource for opencast mining. In the far western sector it is sometimes greater than 0.5 m, but often has highly elevated sulphur values (4%), which are not dramatically lowered by beneficiation.

The roof to the No. 3 Seam is variously formed by medium- to coarse-grained sandstones or carbonaceous siltstones. The interburden succession between the top of the No. 3 Seam and the base of the No. 4 Seam comprises a second coarsening-upward sequence from carbonaceous siltstones, or fine-grained sandstones through medium- to coarse-grained arkosic sandstones. Over much of the central Witbank area this interburden is fairly thin, being between only 0.6 and 2 m at the Kendal Colliery. At places the No. 3 and No. 4 seams are also known to coalesce. The fact that the top of the succession is formed by sandstone usually makes for a good mining floor to the No. 4 Seam in the coalfield; however this may also be formed by a fining-upward succession of carbonaceous siltstones and mudstones at places.

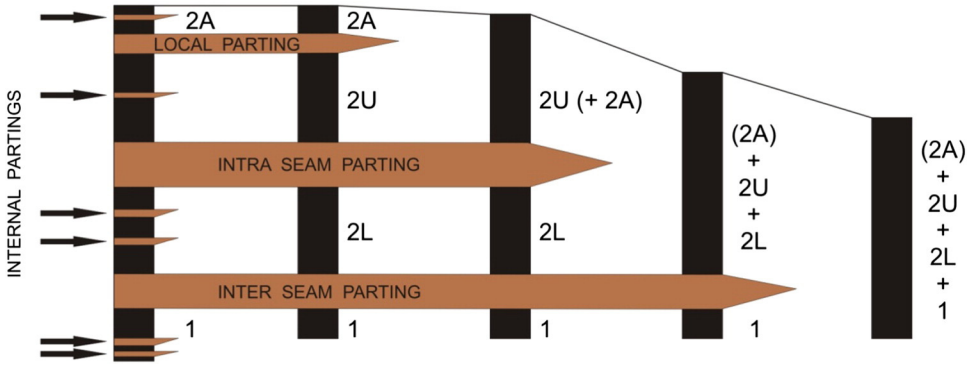

Fig. 13. Different partings and coal layers within No. 2 Seam common to the Witbank Coalfield. From Cairncross and Cadle (1988a).

The No. 4 Seam is the second most important source of coal in the Witbank Coalfield and varies in thickness from approximately 2.5 m in the central Witbank Coalfield to around 6.5 m elsewhere. In places, the Seam is divided into a No. 4 Lower (No. 4L), No. 4 Upper (No. 4U) and No. 4A seams, separated by sandstone and or siltstone partings. At the Kendal Colliery the interburden sequence between the No. 4L and No. 4U seams is formed by a coarse to very coarse, well-cemented sandstone, which changes in thickness from 7.5 m to over 20 m within the confines of the mine. In the Delmas area the No. 4 Seam can obtain thicknesses exceeding 6 m and may be formed by a composite seam comprising up to four different coal zones (plies) that have different aerial distributions.

Holland et al. (1989) concluded that the No. 4 Seam accumulated as peat in an upper delta plain environment. Deposition of fine-grained sediment within an embayment, and later, deposition of mudstone, siltstone and sandstone during the accumulation of the coal bed, split the No. 4 Seam into the No. 4 Lower, No. 4 Upper, and No. 4A sub-seams.

The No. 4 Seam usually contains dull to dull lustrous coal, and because of the poor quality of the No. 4U Seam the mining horizon is generally restricted to the No. 4L Seam. The coal is used predominantly as a local power station feedstock. As for the No. 2 Seam the qualities of the No. 4 Seam across the Witbank Coalfield are highly variable (and as such a single quality table is not provided here). Generally however the No. 4 Seam is poorer in quality than the No. 2 Seam. In the western sector the raw CV for the No. 4 Seam varies from 4.0 MJ/kg to 25.81 MJ/kg, with the DAFVOL percentages varying from 14.3 to 40.2% dependent on the proximity of dolerites.

The base of the No. 5 Seam Sequence (Fig. 9) is formed by the roof of the No. 4 Seam as described below. This sequence corresponds to the Middelburg GSS of Le Blanc Smith (1980a) and the Roof of No. 4 Seam to Floor of No. 5 Seam Sequence of Grodner (2002) and Grodner and Cairncross (2003). The immediate roof to the No. 4 Seam may be composed of a succession of fines (carbonaceous siltstones), or more commonly by a thick unit of medium- to coarse-grained sandstone, with a sharp, erosive contact into the underlying coal or carbonaceous mudstone.

The No. 5 Seam generally lies some 25 m above the No. 4 Seam and the sequence between the No. 4 and the base of the No. 5 Seam is formed by a thick succession of interbedded sandstones and siltstones, culminating in the rocks that form the immediate floor to the No. 5 Seam. Over most of the Witbank Coalfield the immediate floor to the No. 5 Seam is composed of carbonaceous fines. This poor quality floor has caused significant issues with the mining of the No. 5 Seam, particularly in underground situations.

According to Cairncross (1990) the No. 5 Seam is generally only present above basement palaeotopographic highs. It is best developed in the central Witbank Coalfield and has been extensively eroded over large areas of the coalfield, including the entire eastern sector. Even on a project scale it may be present in some areas and eroded away in others, making its correct resource definition problematic.

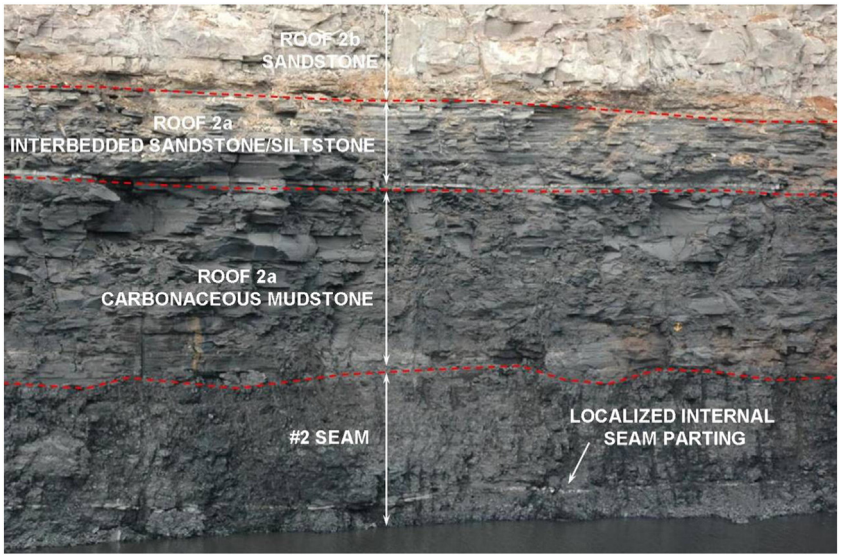

Fig. 14. No. 2 Seam (#2 Seam) overlain by carbonaceous mudstone and siltstone (Roof 2a) grading upwards into fine-grained sandstone (Roof 2b). Eastern Witbank Coalfield.

Where present the No. 5 Seam has an average thickness of around 1.8 m, being developed between 0.5 and 2 m. The seam consists of mixed, mainly bright, banded coal with thin clastic partings in a few localities. The quality of the coal in the No. 5 Seam is generally fairly high (except in the extreme western parts of the coalfield where it is not of economic quality) generally being a high-vitrinite bituminous coal. As for the No. 2 and No. 4 seams, there is significant variability, with company data for the western sector suggesting raw calorific values for the No. 5 Seam that vary from 5.1 MJ/kg to 26.26 MJ/kg. The volatiles are usually quite high, except where devolatilised by dolerite, or through weathering. In places the No. 5 Seam is of high quality (Smith and Whittaker, 1986b) and may be a source of metallurgical coal for both the domestic and export markets, including the ferro-manganese industry.

The immediate roof of the No. 5 Seam is formed by a coarse-grained glauconitic sandstone informally referred to as the Glauconite Sandstone Marker (Fig. 15). This marker is important in exploration and mining as it forms an easily recognisable unit immediately above the No. 5 Seam, although the laminated nature of the sandstone may lead to weak mine-roof conditions that requires extensive support if mined underground.

Where fully preserved in the western sector of the coalfield the sequence above the Glaucontic Sandstone Marker is formed by a coarsening-upward sequence (Fig. 16) beginning with approximately 2 m of carbonaceous siltstone and fine-grained sandstone, and that coarsens upwards into an 8 m thick package of fairly well-worked, medium- to coarse-grained, cross-stratified sandstone.

Above the capping sandstone of the first coarsening-upward cycle, the succession is built by a series of stacked coarsening-upward cycles of carbonaceous siltstones that grade upwards into bioturbated fine-grained sandstones and medium- to coarse-grained sandstone (Fig. 17), culminating in the development of a carbonaceous mudstone interval (the stratigraphic equivalent of the No. 6 Seam coal zone).

4.1.7. Structure and intrusions

Apart from where locally tilted by dolerite intrusions the coal seams, and their bounding strata, are generally flat lying although gently undulating with a regional dip to the south and south-east of less than a degree. The internal structure of the strata and coal seams becomes complex in areas of dolerite intrusion, where dips of up to 1 in 8 (7°) have been observed. The strata (including coal) are also often faulted, although the displacements are rarely more than a few metres. Small scale faulting may be a function of differential compaction during burial and lithification, as well as to the effects of the dolerite intrusions. Both magnetic and non-magnetic dolerites are documented (Campbell, 1994).

Dolerite dykes in the Witbank Coalfield vary in thickness from less than a metre to over 14 m. According to Jeffrey (2005a) the dykes trend east, northeast and north. Dykes and sills may be present at all stratigraphic levels, often being prevalent near the Dwyka Group Basement contact, as well as transgressively through the stratigraphy to positions above the No. 5 Seam. The most prominent dyke in the Witbank Coalfield is the Ogies Dyke, which has a strike length of over 100 km, running from the town of Ogies in the west to beyond the Optimum Mine in the east. This dyke effectively splits the coalfield into a northern portion and a larger central southern portion. The dyke attains a maximum thickness of 14 m and sedimentary strata up to 20 m in either side of the dyke have been subjected to deformation and devolatilisation.

There appears to be a higher density of dykes in the central-southern portion of the Witbank Coalfield, as indicated by intersections during mining operations. Sills also appear to be more prominent in the central-southern portion. The effects of burning and devolatilisation are more severe with sills as they can persist over extensive areas in close proximity to the coal seams whilst dykes only affect coal along the zone of intersection. Dolerite sills at surface also have the effect of increasing the depth to the top of the targeted coal seam and will also affect the blasting requirements for stripping where present. Where encountered in an underground mining situation, dolerite sills and dykes may have a significant effect on water retention and roof goafing.

4.2. Highveld Coalfield

4.2.1. Introduction

Whilst similar to the Witbank Coalfield in many ways, including the overall general stratigraphy, the Highveld Coalfield is considered as a distinct entity, and is separated from the Witbank Coalfield by the Smithfield Ridge (Figs. 8, 11). Economically the coal resources within the Highveld Coalfield are important to the long-term life of Sasol's Synthetic Fuels (SSF) and Sasol Chemical Industries (SCI), which requires some 50 million tonnes a year. The geographic area encompassed by the coalfield is also the home to Eskom's Kriel, Matla and Tutuka power stations.

4.2.2. Location

The Highveld Coalfield is situated in south-eastern Gauteng and Mpumalanga and covers an area of approximately 700,000 ha, extending over a distance of approximately 95 km from Nigel and Greylingstad in the west, to Davel in the east, and about 90 km in a north–south direction.

As mentioned above, the northern margin of the Highveld Coalfield is defined by the Smithfield Ridge (Figs. 8, 11). The western part of the northern boundary is poorly defined and the demarcation around Leslie and Devon is rather arbitrary. In the west and south-west the Coalfield is bordered by outcrops of granite and rocks of the Witwatersrand Supergroup. The eastern boundary is approximately demarcated by a line extending from Hendrina in the north-east, through Davel and Morgenzon, to the Klip River Coalfield in the south (Fig. 1). The southern boundary is located south of Standerton along the Klip River to its confluence with the Vaal River, and from there along the Vaal River to a point south of Greylingstad.

4.2.3. Exploration and exploitation history

The date of the earliest coal exploration and exploitation in the Highveld Coalfield is not known, but Venter (1934) mentions that prior to 1899 a vertical shaft had been sunk 55 m to the No. 4 Seam on the farm Driefontein 69 IS in the Bethal District. Venter (1934) further identified three coal seams of which the upper and middle coal seams were correlated with the No. 5 and 4 coal seams of the Witbank Coalfield. He briefly described the coal seams and indicated their presence at various localities. The logs of several boreholes are presented and the dolerite sills present in the north of the coalfield are described.

Major coal exploration programmes were initiated in the Highveld Coalfield in the early 1960s by Anglo American Corporation (AAC) of South Africa Limited and General Mining and Finance Corporation Limited. In 1969 the Coal Division of the Anglo American Corporation was awarded the tender to supply coal to the new 3000 MW power station to be erected at Kriel (Buchan et al., 1980), which is situated midway between the towns of Ogies and Bethal. It was the start of production of AAC's Kriel Colliery in 1975 that marked the commencement of large scale mining operations in the Highveld Coalfield. This was followed by Matla Coal Limited and Sasol's Secunda Collieries, which were brought into production in 1978 and 1979, respectively.

The Twistdraai Colliery was opened in 1980 to produce coal for Sasol's Secunda synthesis plant. It reached its original design capacity of 8.5 Mtpa during 1986 and 1987. Exploration carried out between 1990 and 1995 indicated that the coal had export potential and since 1995 it has been producing low-Ash thermal coal for the export market, as well as a higher Ash middling product for the SSF plant. In 2006, ownership of Twistdraai was transferred to a new Black Economic Empowerment (BEE) company, Igoda Resources, formed as a joint venture between Sasol Mining (65%) and Exxaro (35%).

Fig. 15. Thick (0.90 m) development of the Glauconitic Sandstone Marker (between the dotted lines) above the No. 5 Seam in the Delmas region of the Witbank Coalfield. Keaton Energy's Vanggatfontein Colliery.

Following the opening of the big three, the next major colliery to come on line was AATC's New Denmark Colliery (NDC). The mine was established in 1982 with the first coal won in 1983. At a depth of some 200 m it is the deepest underground colliery mining the No. 4 Seam in South Africa. The colliery operates one of the few long walls in South Africa and has variously held the long wall record during the 1990s and into the new century. It is contracted to supply Eskom's Tutuka Power Station with coal.

Total Coal South Africa (Pty) Limited (TCSA) opened the Dorstfontein Coal Mine in February of 1999 (Meyer, 2003). It also purchased the Forzando mine from JCI in 1998 and opened the Forzando South operation in 2006.

Anglo American's Inyosi Coal's (AAIC) Elders block has also been the subject of much exploration, with over 420 boreholes drilled on the property (Sibiya, 2001). A pre-feasibility study was undertaken in 2005 and in January 2011 a conceptual study commenced to re-examine the potential of a multi-product mine at Elders. The proposed Elders Colliery plans to produce approximately 4.5 Mtpa Run of Mine (RoM) coal from six CM sections from the No. 2 and No. 4 Seam operations, to supply coal for both export and domestic markets. Mining is planned for approximately 20 years, commencing on the No. 2 Seam in the first quarter of 2017 (SRK, 2013).

Most recently Keaton has drilled out their Sterkfontein project, one of the last remaining large resource blocks in the Highveld Coalfield. This project is situated 10 km southwest of the town of Bethal, and east of the underground workings at Twistdraai. This project focusses solely on the No. 4 Seam and various tables and grids of qualities and wash yields may be found in Dekker and van Wyk (2008).

4.2.4. Research history

Early workers such as Wybergh (1928) and Venter (1934) describe various aspects of the Highveld Coalfield. Sehlke and van der Merwe (1959) report on the results of 13 boreholes drilled in the "Standerton" Coalfield. Modern work began with the work of Smith (1970) who documented the distribution of coal quality and correlated the coal seams of the Witbank and Highveld coalfields.

Cadle and Hobday (1977) recognised three phases of sedimentation in the Vryheid Formation of the Highveld Coalfield, these being a lower delta-dominated phase; a fluvially dominated coal zone and an upper deltaic succession. Van Vuuren and Cole (1979) took the subdivision

Fig. 16. Coarsening-upward succession above the glauconitic marker. Vanggatfontein Exploration Project (Borehole VG07-47 m; 40–56 m depth). NQ core diameter (47.6 mm).

further, recognising eight cycles of sedimentation, with each cycle defined as the regressive sequence of strata between successive transgressions.

Winter (1985) investigated parts of the northern Highveld Coalfield during his PhD studies and provides a full description of the various genetic sequences encountered. He related the qualities of the No. 4 Seam to the proximity of fluvial palaeochannels, showing that the coals situated close to the palaeochannels are generally of low-quality. Jordaan (1986) provides an overview of the Highveld Coalfield including various aspects of the sedimentology and stratigraphy, coal qualities, and the structure and nature of the dolerite intrusions.

Working in an area to the south-southeast of the town of Secunda, Hagelskamp et al. (1988) recognised eight successive lithofacies associations, from which they derived a three-dimensional palaeoenvironmental model. This work was based on the logs of some 400 boreholes, most of which penetrated through the entire Karoo Supergroup succession. Coal distribution and coal quality characteristics for the No. 4 Lower Seam were also linked to the depositional features of the model. According to Hagelskamp et al. (1988) the identified depositional phases commenced with sub-glacial, glaciofluvial and glaciolacustrine settings, with associated Gilbert-type deltas. These are followed by meandering and minor braided fluvial settings, characterised by laterally and vertically highly variable lithofacies, in which the main coal-bearing strata were formed.

Tony Cadle's doctoral thesis (Cadle, 1995) is probably one of the most encompassing documents detailing the sedimentological and depositional systems of the Vryheid Formation in the Highveld Coalfield. The general characteristics of the Highveld Coalfield are also provided in Snyman (1998).

Sibiya (2001) presents work on Anglo American Inyosi Coal's (AAIC) Elders Block, near the town of Kriel. This work was based on the study of over 250 boreholes and included descriptions of the coal seams and their bounding facies (including petrography), cross-sections and various contour and isopach maps for the No. 2 and No. 4 seams on the project area.

Based on data from 900 (out of 1951) borehole logs, the roof conditions of the No. 4 Seam at NDC was the subject of a study by Stanimirovic (2002). A genetic stratigraphic approach was followed with detailed descriptions of the No. 4 Seam Genetic Sequence being provided. This work was then used to describe the various roof conditions that exist for the No. 4 Seam.

Meyer (2003) describes the feasibility of thin seam coal mining at TCSA's Dorstfontein Colliery, describing the regional and local geology of the area, as well as the nature and quality of the seams. In particular he records the presence of floor rolls on the No. 2 Seam at the Dorstfontein Coal Mine (Highveld Coalfield) and noted that in the north-western part of the mine excessive floor rolling prevented production. Whilst not positively explaining these rolls, Meyer (2003) felt that they were related to basement palaeotopography. Wakerman (2003) describes aspects of Eyesizwe Coal's Schurvekop exploration area in the Highveld Coalfield, with resources on the No. 4 Lower Seam only.

Busio (2012) looked at the effects of three dolerite sills on coal qualities in what he termed the "Secunda" coalfield. Coal quality data was provided by Sasol Mining Secunda. This work showed that the relationship between the intrusive sill and the coal qualities is a complex one and that factors other than simple intrusion width, such as the role of hydrothermal fluids, must be considered in relation to their contact metamorphic effects. Van der Walt (2012) reports on the petrology, petrography and geochemistry of anomalous intrusions and shows them to be related to diatreme activity.

As for the Witbank Coalfield the description of the general geology that follows draw on these previous works as well as the senior author's personal experience in the Highveld Coalfield. Given the close similarities with the Witbank Coalfield stratigraphy, the sequences are not documented in as much detail to avoid unnecessary repetition.

4.2.5. Geology

Whilst being very similar to the stratigraphic succession in the Witbank Coalfield a generalised stratigraphic section for the northernmost Highveld Coalfield is provided as Fig. 18.

The basement changes over the area of the Highveld Coalfield from basement granites, gabbros and norites of the BIC, to Witwatersrand Supergroup metaquartzites, and Transvaal Supergroup metaquartzites and metavolcanics (Fig. 10). At TCSA's Dorstfontein Mine the basement is documented as being Nebo granite (Meyer, 2003).

The thickness of the Karoo Supergroup strata in the Highveld Coalfield varies from extremely thin in the north, to in excess of 300 m in the Standerton area. This is due to the uneven nature of the pre-Karoo topography in the Coalfield. Van Vuuren and Cole (1979) identified two major pre-Karoo valleys. The first extends southwards from Leslie, to past Greylingstad, and is postulated to be a possible extension of the Vischkuil valley of the Witbank Coalfield. The other extends southeastwards from between the towns of Bethal and Standerton towards Volksrust. Boreholes drilled to basement in the NDC lease area also showed a deeply incised pre-Karoo topography. As in the Witbank Coalfield the Pietermaritzburg Formation is absent in the Highveld Coalfield, with the Dwyka Group being overlain directly by rocks assignable to the Vryheid Formation.

Fig. 17. Stacked coarsening-upward cycles of carbonaceous siltstones into bioturbated fine-grained sandstones and medium- to coarse-grained sandstones. Vanggatfontein Exploration Project (Borehole VG07-46 m; 38–56 m depth). NQ core diameter (47.6 mm).

The irregular nature of the topography played a major role in controlling the thickness of the basal Dwyka Group sequence. Dwyka Group lithologies in these palaeovalleys may attain thickness in excess of 100 m, whereas over palaeohigh areas, the Dwyka Group may be thin or absent (Hagelskamp et al. 1988; Sibiya, 2001; Van Vuuren and Cole, 1979). The thickness of the Dwyka Group at the NDC is recorded as being between 4.6 and 24 m (Stanimirovic, 2002).

Although Dwyka Group lithologies do not outcrop in the Highveld Coalfield they are well known from borehole data. Lithologically the succession consists of massive diamictite, with lesser matrix-supported conglomerates and coarse-grained sandstones, with occasional siltstone and sandstone interbeds, pebbly mudstones and varved siltstone. The diamictites are composed of sub-angular to sub-rounded clasts, set in a fine-grained pale brown dirty matrix. In the NDC area the clasts are mostly granites, quartzite, mudstones, and calcareous sandstones. As for the Witbank Coalfield these rocks are believed to be the products of glacial and post-glacial depositional environments.

Outcrop sections of the Vryheid Formation are equally rare, but the vast amount of borehole data provides a clear picture of the sedimentary succession. For the area to the south-southeast of Secunda, Hagelskamp et al. (1988) documented a thickness of between 80 and 130 m for the succession between the top of the Dwyka Group and the base of the "main coal zone", noting that sedimentologically it was dominated by sandstones, siltstones and mudstones with sporadic seamlets and coalified plant debris. Each of the sequences is described in detail. These authors also note that the "main coal zone" contained the No. 3, No. 4L and No. 4U seams and that this unit was overlain by another coarsening-upward deltaic sequence some 40 m thick. This unit is known to vary in thickness from 60 m to 100 m, and is composed of micaceous mudstone and siltstone grading upwards into grey to white medium-grained sandstone, which is sometimes glauconitic. It is capped by the No. 5 Seam, that as for the Witbank Coalfield has a glauconitic sandstone in the roof which forms a useful stratigraphic marker. The Volksrust Formation is locally present on high ground in the Standerton area.

4.2.6. Coal seams

All the seams of the Witbank Coalfield are present in the northern part of the Highveld Coalfield (Jordaan, 1986) however as one moves south into the basin the No. 2 Seam is often not well-developed, and does not play an important role as an economic seam. The parting thicknesses between various seams vary from east to west and from north to south in the Coalfield. Various typical seam profiles for the No. 2 and No. 4 seams are provided in Jordaan (1986).

The No. 1 Seam is discontinuous and is mainly developed in the eastern part of the Coalfield, particularly in the Kriel area. Elsewhere in the Coalfield it is patchily developed and thin. As in the Witbank Coalfield it is topographically controlled and restricted to glacial valleys.

The No. 2 Seam is developed at a depth of approximately 30 m in the northern margin of the Coalfield and up to a depth of 240 m in the southwest. It ranges in thickness from 4 m along the northern margin and up to 10 m in valleys in the west. The seam thins to less than a metre in the east and southeast, and may change down dip into carbonaceous mudstone, such as is seen on KEH Sterkfontein Project area. Siltstone and mudstone partings are present and distributed throughout the seam splitting it into a 2U and 2L seam. In most cases it is mined selectively because of the partings.

The No. 3 Seam is intermittently developed and thin, being generally less than 0.5 m thick. It may locally be up to 1 m thick in the western part of the Secunda reserve area. Hagelskamp et al. (1988) document the No. 3 Seam as averaging between 0.5 and 0.6 m in their study area. Where the parting between the No. 3 and No. 4 Lower Seam becomes thin (less than 0.5 m) the two seams are mined as one unit.

The No. 4 Seam is the major economic coal seam developed in the Highveld Coalfield and forms the bulk of the coal resources. The seam lies at a depth of 15 m in the Kriel area, deepening to around 300 m to the east of Standerton. Stanimirovic (2002) documents an approximate depth of 200 m below surface at NDC.

The minable section usually contains dull lustrous coal with minor amounts of mixed coal and dull coal. Coal is mined as a synthetic fuel feedstock for Sasol. The seam is divided into two units, the No. 4 Lower (4L) and No. 4 Upper (4U) Seam. The sandstone parting between the No. 4L and No. 4U Seam varies from about 2 m in the north (Kriel area) to approximately 3 m in the central part of the Coalfield, thickening to 15 m in the southern Balfour area. Hagelskamp et al. (1988) document it as being between 5 and 14 m to the south-southeast of Secunda and note that it is formed by an irregular succession of coarse-grained to gritty sandstones and granulestone, with medium- to fine-grained sandstones, siltstones and mudstones.

The No. 4L Seam averages 4 m in thickness, varying from less than 1 m to 12 m in the Matla area. In areas where the seam is thinner, the full seam is mineable, whereas in the thicker coal areas the mining horizon is restricted to the lower 3.5 m to 4 m of the seam. At New Denmark the No. 4 Seam is comparatively narrow at an average height of 1.8 m, being as low as 1.6 m in places. On Keaton's Sterkfontein project area in the east of the coalfield, the No. 4 Seam is on average 1.87 m thick, being thicker in the south, where it has an average thickness of 3.04 m (Dekker and van Wyk, 2008). In certain instances the No. 4L Seam may contain a torbanitic unit.

Over part of the reserve area at Sasol's Twistdraai Mine the No. 3 and No. 4L seams converge into a single unit that averages 3.6 m in thickness (ranging from 2.7 to 4.5 m). The average thickness of the No. 4 Seam alone here is 3.3 m, ranging from 2.4 to 3.6 m.

Roof lithologies prevailing are variable and consist of very coarse to fine-grained sandstone, inter-laminated sandstone and siltstone, carbonaceous mudstone and coal. Erosion of part of the seam is attributed to channel scouring during high discharge periods. The seam floor consists generally of siltstone, fine-grained sandstone or laminated siltstone and mudstone. Roof conditions to the No. 4 Seam at NDC are covered in detail in Stanimirovic (2002).

The No. 4U Seam is only of mineable thickness in the western part of the Coalfield, where it occurs between 1 m and 5 m above the No. 4L Seam. The average thickness of the seam is 2 m, varying between 1.5 m and 3.4 m (Jordaan, 1986).

The No. 5 Seam is widely developed at a depth of between 15 and 150 m. It ranges in thickness between 0.30 and 3 m. A 0.4–0.6 m hard siltstone parting may be present in places along the northern margin of the Coalfield, which often renders the seam uneconomic. Where this parting is not present, a high-grade product may be produced through beneficiation. On Keaton's Sterkfontein Project in the southern part of the Coalfield the No. 5 Seam is present in most of the holes at an average depth of 132 m and forms a thin (usually less than 30 cm) dull coal seam, which is a prominent marker horizon, between 15 and 60 m above the No. 4 Seam (Dekker and van Wyk, 2008). It is not considered as being economic. At Twistdraai to the southwest, this seam is on average 1.4 m thick but is not currently mined. At Matla the No. 5 Seam is of good quality (25–27 MJ/kg raw CV) but was only extracted to a limited scale due to the high levels of contamination from the poor floor and roof.

4.2.6.1. Coal qualities. General coal qualities for various areas of the Highveld Coalfield are provided in Jordaan (1986) and these are also reproduced in Snyman (1998). Jordaan (1986) covers the Leslie, Kriel and Val areas for the No. 2 Seam and the same areas plus the New Denmark area for the No. 4 Seam. He provides typical qualities for the mineable section in the Leslie area of 14.3% Ash and 26.31 MJ/kg CV but notes that the No. 2 Seam qualities are not however normally this good, usually varying between 22 and 35% and with CV's varying between 20 and 23 MJ/kg. Where mined the No. 3 Seam is generally an export quality (28.1 MJ/kg CV) thermal coal.

The No. 4L Seam is generally a low grade bituminous coal with a raw Ash content of between 20 and 40% and a CV of between 18 and

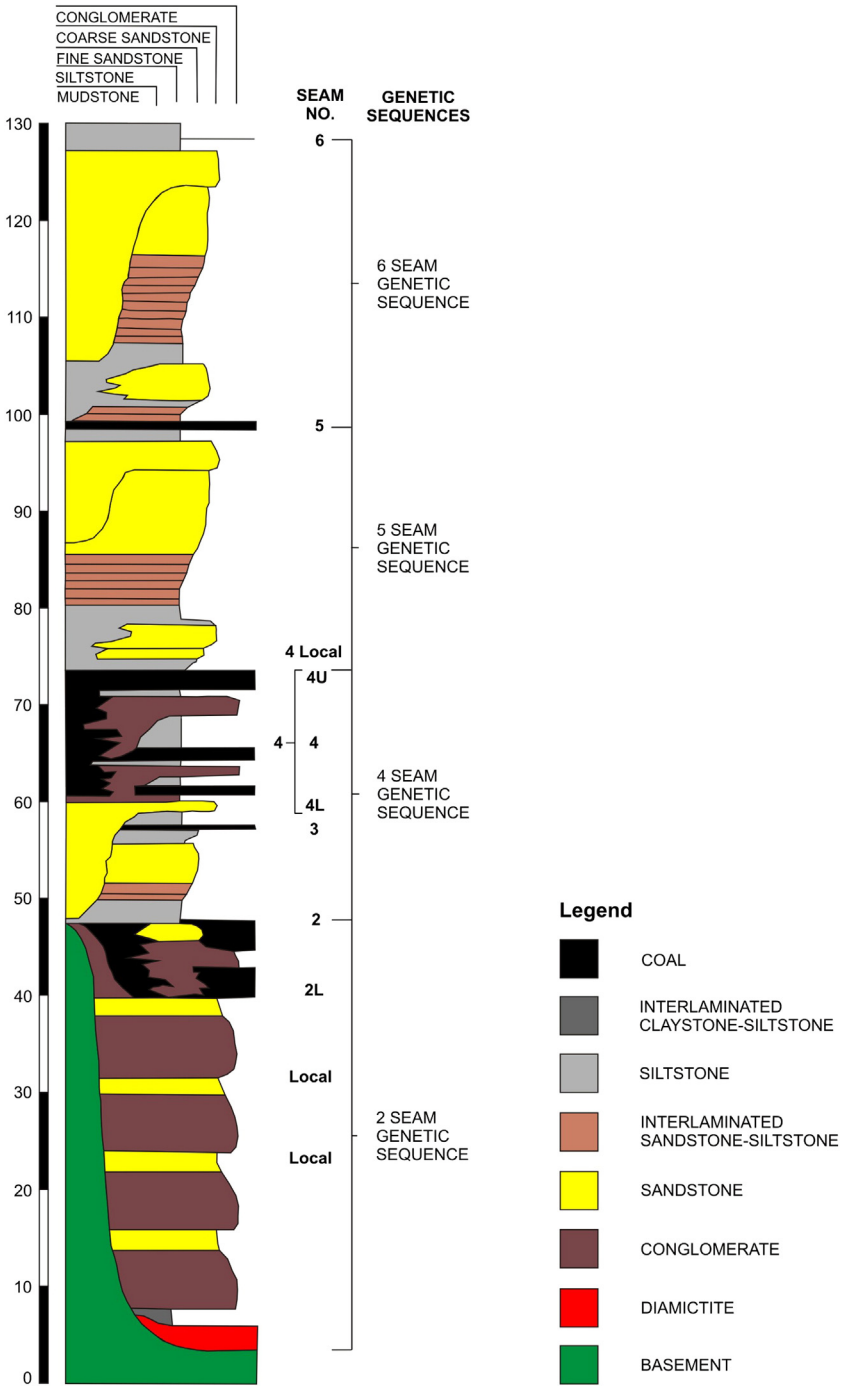

Fig. 18. The generalised stratigraphy and depositional sequence of the Highveld Coalfield. From Winter (1985).

25 MJ/kg. Coal qualities for the No. 4 Seam on the Sterkfontein project are presented in Dekker and van Wyk (2008) and show that the raw coal is suitable as a feed stock for local power generation, and that once beneficiated could produce an export quality prime product at an average theoretical yield of 50% with a middlings product at a theoretical yield of 33%. At Twistdraai the raw Ash content of the No. 4L Seam varies between 18 and 36%.

Hagelskamp et al. (1988) provide contour maps of the CV of the No. 4L Seam in the area to the south-southwest of Secunda, and show that the CV ranged between less than 18 MJ/kg and more than 26 MJ/kg, with the upper and lower limits corresponding to highs and lows in the Ash concentrations. The quality of the No. 4U Seam is extremely variable, but is generally a low grade bituminous coal with an Ash content of 25% and a calorific value of 25 MJ/kg (Jordaan, 1986).

4.2.7. Structure and intrusions

The coal seams in the Highveld Coalfield are mainly flat lying to gently undulating, with a very gentle regional dip to the south. Dolerite dykes and sills are common in the Coalfield and are often positioned above the coal zone. The dolerite sills have been the subject of classification mainly by the Sasol geologists who name them in terms of their stratigraphic position the B4, B6 and B8 sills.

All three (B4, B6, and B8) of these dolerite sills are present in the NDC lease area. The two top sills (B4 and B8), which are generally in

excess of 100 m above the No. 4 Seam, have no direct influence on the coal seam geometry. The upper fragmented portion of the sills is one of the water aquifers in the area and goafing of these sills may lead to large amounts of water flowing into underground workings. Experience to date indicates that the sills do not act as a separate beam when goafing takes place and settle together with the sandstone and siltstone.

The porphyritic B6 sill at NDC is on average 2 m thick, ranging from 0.2 to 4 m and transgresses various stratigraphic horizons, including the No. 4 Seam. Borehole data indicates that this sill lies well below the No. 4 Seam in most areas, but intrudes into the No. 4 seam in the 400 block at Central Shaft, in the area underlying the Thuthukani Township and in the Southwest block. A variable displacement is associated with the B6 sill intrusion where it transgresses the No. 4 Seam. Where this B6 sill is in close proximity to the No. 4 Seam it has caused extensive burning.

Dolerite dykes are also common in the area. The dykes are considered to be of the same age as the sills. Two types of dykes have been recognised at NDC, namely types A and B. Both types are porphyritic in texture and are considered not to have intruded the B4 sill, which overlies most of the lease area, and are possibly feeder dykes to the B4 sill. Dyke type A is generally 0.5–4.5 m thick and occurs at 700–1500 m spacing, with a common northerly to northeast strike direction. The width of devolatilisation associated with these intrusives is approximately twice the width of the dyke. Dyke type B varies in thickness between 9 and 70 m and has a common strike of N70°E. The extent of burning and devolatilisation associated with the coal seam caused by this dyke has averaged up to three times the width of the dyke. Van der Walt (2012) recently described explosive diatreme activity within the NDC mining lease area, which he linked to dolerite intrusives.

4.3. Ermelo Coalfield

4.3.1. Introduction

Compared to the adjacent Witbank and Highveld coalfields, the Ermelo Coalfield hosts thinner seams, is more sedimentologically and structurally complex, and is not as well studied nor understood. During the 1980s it was a fairly prolific producer, but in the next two decades production declined (Jeffrey, 2005a; Snyman, 1998). Since 2004 this coalfield has however seen resurgence in exploration and mining due to the higher quality of the coals in relation to the Witbank and Highveld coalfields, as well as its proximity to the Richards Bay Coal Terminal (RBCT) export coal line. The Ermelo Coalfield was previously called the Eastern Transvaal Coalfield.

The Ermelo Coalfield is home to Eskom's 1600 MW capacity Camden Power Station and its commissioning in 1967, mothballing in 1990, and subsequent recommisioning between 2006 and 2008, have played an important role in the history of the coalfield. The 2000 MW Hendrina Power Station occurs in the northern part and the southernmost part of the coalfield hosts the 3600 MW Majuba Power Station.

4.3.2. Location

The Ermelo Coalfield is located in the districts of Carolina, Dirkiesdorp, Hendrina, Breyten, Davel, Ermelo and Morgenzon in the southeast Mpumalanga Province. It extends approximately 75 km east–west, and 150 km north–south, covering an area of about 11,250,000 ha (Fig. 19). The northern and eastern boundaries of the Ermelo Coalfield are defined by the sub-outcrop of the coal-bearing strata against pre-Karoo basement. In the west, the Ermelo Coalfield shares a boundary with the Witbank and Highveld coalfields, and to the south with the Klip River and Utrecht coalfields of KZN (Greenshields, 1986). Between the Ermelo and westernmost part of the Highveld Coalfield there is an area of poor (thin) coal development where no coal mining takes place.

4.3.3. Exploration and exploitation history

Small scale production of coal in the Ermelo Coalfield began as early as the 1850s. Coal has also been mined on the “Spitzkop” farm since the early 1900s, with the coal being transported to Durban by ox wagons. According to Barker (1999, p. 20) the earliest recorded coal mining activities in the Ermelo Coalfield were at Kwaggafontein 81 IT, where a total of 360 tonnes were extracted between 1903 and 1904. By the 1920s the Townlands Colliery, just to the west of Ermelo was mining a 1.2–1.5 m thick seam.

The only area that was subjected to systematic prospecting prior to the 1950s was that bordering the route of the railway line from Breyten to Ermelo. Various collieries were established in this area, including Union, Witrand and Consolidated (Cape) Collieries to the north of Breyten, the Albion, Spitzkop, Grenfell, Breyten, Black Diamond, Carlchew (Consolidated) and Klipstapel mines in the environs of Breyten, and Mooifontein and Bellevue mines north of Ermelo. A mine was also opened up at Estanis on the Breyten-railway line.

Historical exploration was undertaken by the likes of Federale Mynbou Beperk and Trans-Natal Coal Corporation Limited (Trans-Natal) and Goldfields Mining and Development Limited (Goldfields). Trans-Natal later absorbed Federale Mynbou and in 1994 itself became part of the Ingwe Coal Corporation (Ingwe), through the merging of its coal assets with Randcoal Limited. Ingwe later became a wholly owned subsidiary of BHP Billiton.

Federale Mynbou Beperk exploration work in the early 1960s in the general area to the east of the town of Ermelo, led to the delineation of the ‘Usutu Coalfield’ and the commissioning of the Usutu Colliery, which was the initial and sole supplier to the Camden Power Station. In 1975 the Usutu Colliery was the largest single producer of coal in South Africa supplying Camden with 435,000 tpm.

In 1964 as part of a regional reconnaissance to determine possible coal potential a few widely spaced boreholes were drilled by General Mining & Finance Corporation. In 1966 the area that was to become the Ermelo Mines mining lease was subjected to the first phase of a more detailed geological examination, with between 40 and 50 boreholes drilled. The next phase of exploration was from 1971 to 1976 and encompassed roughly 300 cored boreholes, including some large-diameter hole for bulk sample testing. In 1976 shaft sinking on the Ermelo mines commenced, with coal production beginning in 1977. The mines ongoing exploration programme increased the number of boreholes that were drilled to the basement rocks to enable the proper evaluation of a dolerite sill structure and its effects on the mineability of the coal and from 1981 it became the norm to drill all boreholes to basement for structural interpretation purposes. Ermelo Mines closed in 1997 after 20 years of production (Paulson and Stone, 2002).

By 1975, three collieries were active in the coalfield, producing approximately 3.0 Mtpa. By 1985 the production had increased to 8.0 Mtpa, most of which was contributed by the Ermelo and Usutu collieries (Snyman, 1998).

Based on the drilling of some 400 boreholes and resources of over 1.0 Gt (Chapman and Cairncross, 1991), Majuba Colliery was initiated in the early 1980s as a joint development between Eskom and Rand Coal. The project was supposed to be a dedicated mine mouth colliery able to supply the Majuba Power Station 12 Mtpa of coal for an estimated period of 40 years. The mine was planned to mine bituminous coal from the Gus (C Seam) Seam by the long wall mining method. The average mining depth was 280 m below surface. Underground mining operations began in 1988 and complications were encountered with the underground mining conditions subsequent to the establishment of the mining infrastructure required to support long wall mining operations. As a result it was decided to consider CM operations and bord and pillar mining. Due to the intrusion of dolerites, the coal seam elevation varied by as much as 70 m. Due to the severe nature of the structural complexity caused by the dolerite intrusions underground mining activity ceased in 1990, with a total production reported to the Department of Mineral Resources (DMR) of only 611,000 tonnes.

Production decreased in the coalfield following the mothballing of the Camden Power Station in 1990. According to Jeffrey (2005a) there

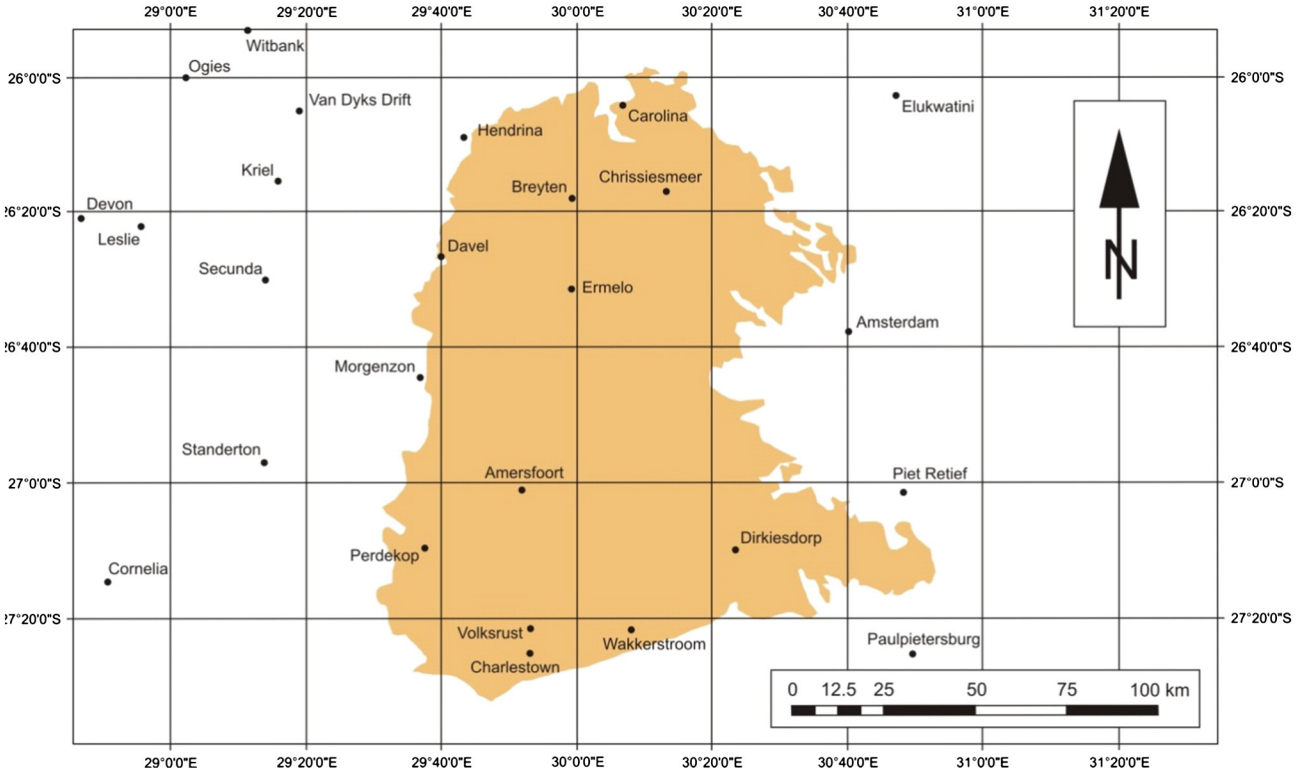

Fig. 19. Geographic extent of the Ermelo Coalfield.

were ten operating collieries in the Ermelo Coalfield in 2002, however most of these were small to medium size. According to the DME (2010) in 2009 there were seven operating collieries in the Ermelo Coalfield, these being the Golfview, Droogvallei, Savmore, Umlabu, Kopermyne, Spitzkop, and Tselentis collieries. Until recently mining in this coalfield was decreasing, with most mines closed with reserves. Following on the re-commissioning of the Camden Power Station in 2006, the coalfield once again became the focus of renewed exploration activity, with a number of opencast and two new underground operations having begun since this time.

Between 2006 and 2013 (when it was subsumed by CCL) Mashala Resources drilled a significant number of boreholes in various exploration projects in the Ermelo Coalfield. Two of these projects have subsequently been brought to account by CCL, these being the Ferreira opencast mine, and the Penumbra underground operation. Ferreira closed at the end of 2012 but was a conventional opencast contract mining operation with an average RoM production of 55,000 tpm. Development of Penumbra commenced in September 2011, with first coal delivered in December 2012. Penumbra has an estimated gross saleable reserve of 5.4 Mt from a gross coal reserve of about 68.3 Mt. The mine aims to produce 64,000 tpm RoM of thermal coal for the export market (http://www.conticoal.com/). Mining is by bord and pillar mining methods utilising two continuous mining sections and one conventional (drill and blast) mining section (Telfer et al., 2013).

Coal of Africa (http://www.coalofafrica.com) acquired an interest in the Mooiplaats Colliery in 2007. The company subsequently drilled an additional 581 boreholes, which led to the development of their Mooiplaats underground coal mine. The mine is located directly to the south of the Camden Power Station and was commissioned in June of 2007, with production commencing in November of 2008. In 2014 the mine was on care and maintenance with various strategic restructuring alternatives being considered by the company.

Majuba Colliery is the focus of a project by Eskom to validate the economic viability of employing Underground Coal Gasification (UCG) Technology on the large resource base and has a 6 MW thermal UCG pilot plant near Majuba.

4.3.4. Research history

Compared to the Witbank and Highveld coalfields the Ermelo Coalfield has been the focus of relatively little academic work. Wybergh's (1928) publication remains one of the most comprehensive accounts of the region. This work, coupled to the various explanations of the geological sheets (Visser et al., 1947, 1958), the account of the coalfield in De Jager (1976) and the various notes in Cadle and Hobday (1977) and Steyn and Beukes (1979) sum up the status of academic research prior to the 1980s.

In an excursion guidebook for the Sedimentology Division of the Geological Society of South Africa, Stavrakis (1982) describes various aspects of the geology and sedimentology of the Ermelo Coalfield, including a detailed description of the sedimentology and depositional systems of the Sheepmoor area, where he recognised eight coal seams and seven clastic marker horizons.

An undated report (from an undisclosed area) by van Alphen identifies 13 lithofacies and seven sedimentary units for the Vryheid Formation in the Ermelo Coalfield, noting their uniform thickness and the presence of a major west–east orientated palaeochannel. This work was based on 149 cored boreholes, six of which were drilled to basement.

Greenshields (1986) provides the most comprehensive overview of the coalfield to date, including aspects of the stratigraphy, sedimentology and depositional environment, descriptions of the coal seams, coal qualities and the nature of the structure and dolerite intrusions. As part of a regional overview of the coal in the eastern sector of the MKB, Stavrakis (1989) also discusses aspects of the stratigraphy, sedimentology and depositional environments.

De Oliveira (1997) provides details of the stratigraphic sequence encountered at the Majuba Colliery including a number of typical borehole logs. This study included work on the dolerites and led to a later publication by De Oliveira and Cawthorn (1999) that documented the

dolerite intrusion morphology at Majuba Colliery. These authors used data from 88 boreholes to construct cross-sections through the colliery, and showed that based on the texture, geochemistry, and mode of emplacement, four different dolerite types (T1 to T4) exist.

In his PhD thesis, Wakerman (2003) covers various aspects of the then Eyesizwe Coal's Ermelo, Sheepmoor and Carolina exploration areas in the Ermelo Coalfield. For each of these areas he supplies a description of the general geology, as well as thickness ranges for the various seams included in the various resource statements. Raw and washed quality data is also supplied for each seam and area.

4.3.5. Geology

Rocks of the Permian Vryheid Formation and Jurassic aged dolerites dominate the surface exposures of the coalfield. A generalised stratigraphic section for the Ermelo Coalfield is provided as Fig. 20.

As in the Witbank and Highveld coalfields the Vryheid Formation is the coal bearing horizon in the Ermelo Coalfield and five coal seams are also recognised within an 80–90 m thick sedimentary succession. Unlike in the Witbank and Highveld coalfields, the seams are given letters as codes (Fig. 20) and are named from the top to bottom the A to E seams (Wybergh, 1928).

The basement to the Ermelo Coalfield is less well known than for the Witbank and Highveld coalfields, as few boreholes have been drilled through to it. Where documented it is formed mainly by Archaean basement granites, BIC intrusives, or metasedimentary strata of the Transvaal Supergroup (Greenshields, 1986). De Oliveira and Cawthorn (1999) document granitic gneiss basement at Majuba Colliery in the far southwest of the coalfield. Wakerman (2003) notes that in the Sheepmoor project area two boreholes intersected basement, one of which penetrated greenstone belt metavolacanics and the other, Archaean granite.

The basement is overlain by rocks attributable to the Dwyka Group, which throughout the Ermelo Coalfield are only poorly developed, except in the far south where the unit exhibits variable thickness (Greenshields, 1986). Where developed the Dwyka is usually confined to palaeovalleys and consists of diamictites, sandstones and siltstones, attributed to glacial deposits, such are formed as moraines and in glacial outwash fans and lakes, and on sandur plains. Wakerman (2003) notes that on the Sheepmoor project area the Dwyka Group is between 3 and 30 m thick, and consists of massive polymictic diamictite capped by interbedded siltstones and mudstones. He further notes that some units contain well-rounded dropstones of exotic provenance.

The Pietermaritzburg Formation is not exposed in the Ermelo Coalfield and is rarely intersected in its entirety in any of the boreholes drilled during exploration programmes. According to Greenshields (1986) it is thinly developed or absent in the centre of the Ermelo Coalfield, but may reach a thickness of up to 75 m in the south of the coalfield. Van Alphen (1990) documents a thickness of 12 m for the Pietermaritzburg Formation in his field area. Wakerman (2003) documents thicknesses of between 3 and 48 m for the Sheepmoor project area.

Where present the strata of the Pietermaritzburg Formation effectively blanket and fill the glacial palaeotopography and as such topography does not have the strong control that it does in the Witbank and Highveld coalfields. As for the rest of the northern part of the MKB, the Pietermaritzburg Formation is formed by characteristically blue-grey, micaceous mudstone and siltstone. Wakerman (2003) documents the succession at Sheepmoor as being formed by massive to horizontally bedded carbonaceous mudstone that is often highly bioturbated.

In the northern parts of the coalfield, where neither the Pietermaritzburg Formation nor the Dwyka Group are developed, the Vryheid Formation unconformably rests on basement. Elsewhere it disconformably overlies the Dwyka Group or the Pietermaritzburg Formation (Ecca Group).

In the Ermelo Coalfield the thickness of the Vryheid Formation varies between 170 and 350 m (Greenshields, 1986) and as mentioned above contains five coal seams. Two stratigraphic marker horizons occur within the sequence that may be useful in exploration drilling (Stavrakis, 1991). These are a glauconitic sandstone unit, which overlies the B Seam package, and the bioturbated *Siphonicnus*-zone that occurs below the C Seam and which may be used as a marker to terminate exploration drilling. Wakerman (2003) documents a 3 m thick E "shale" marker (a sandy bioturbated mudstone) in the floor of the E Seam, which he felt made a prominent end of hole (EOH) marker when the D and E seams are being targeted. The overlying Volksrust Formation is only present along the western and southern escarpment areas, where it can achieve a thickness of up to 106 m (Greenshields, 1986).

4.3.6. Coal seams

The coal seams in the Ermelo Coalfield are generally flat-lying to slightly undulating and as for the Witbank and Highveld coalfields, are separated by fine- to coarse-grained sandstones, siltstones and mudstones. The A, D and E seams are usually too thin to be of economic interest and historically the C Seam group was the most important in the Carolina–Breyton area, and the B Seam group in the Ermelo area. Rapid seam thickness variations characterise the coalfield.

The E Seam may reach a thickness of up to 3 m, but is of economic importance only in isolated patches in the north of the Ermelo Coalfield (Greenshields, 1986). The coal is mostly bright and banded, has a competent sandstone roof and floor and is sometimes split by a thin sandstone or carbonaceous fines parting (Greenshields, 1986). In the central and southern part of the coalfield, it is developed as a torbanite or as a carbonaceous siltstone or mudstone unit, and locally becomes too thin for mining (Greenshields, 1986).

The coal of the D Seam is of good quality, but in general is too thin (0.1–0.4 m) to be of economic importance (Greenshields, 1986). The coal is not split by partings and consists of large amounts of vitrain and occasional durain bands (Greenshields, 1986; Jeffrey, 2005a).

The C Seam group has been one of the main seam packages of economic importance throughout the Ermelo Coalfield. It is usually split by several partings which can lead to miscorrelation of the seams (Greenshields, 1986). In general the C Seam is subdivided into the C Upper (CU) and C Lower (CL) seams. The CU Seam is well-developed over the entire coalfield and is often split by partings of different lithologies, such as sandstone, siltstone or mudstone, reaching a composite thickness of 0.7–4 m. It has historically been mined in several collieries of the Ermelo Coalfield, including the Golfview, Usutu, Goedehoop, Union, and Kobar collieries (Greenshields, 1986), as well as more recently at the Ferreira opencast mine.

The CL Seam is not developed throughout the entire coalfield, but where developed is between 0.5 and 2 m thick. It locally grades into carbonaceous siltstone and mudstone, which often form the roof of the seam, whereas the floor mostly consists of sandstone. It has historically been mined at the Savmore, Anthra, Ermelo, Golfview, and Wesselton mines (Greenshields, 1986; Paulson and Stone, 2002). Several other mines in and around the towns of Ermelo and Breyten have at times extracted coal from this seam including the Spitzkop, Bellevue, Grenfell, Usutu, Consolidated Marsfield, and Union collieries. The CL was also the main target seam at CCL's Ferreira opencast mine and it is also currently being mined underground at their Penumbra mine, where it occurs at an average depth of around 100 m. It is the thickest of all the coal seams intersected here, reaching a thickness of more than 1.5 m over large parts of the project area. Locally seam floor rolls may negatively influence the thickness of the CL Seam in the Ermelo Coalfield.

The B Seam group varies in thickness from 1 to 2.7 m and may be split into three units. Greenshields (1986) terms these the B1, B and BX seams, but they are more commonly referred to as the B Lower

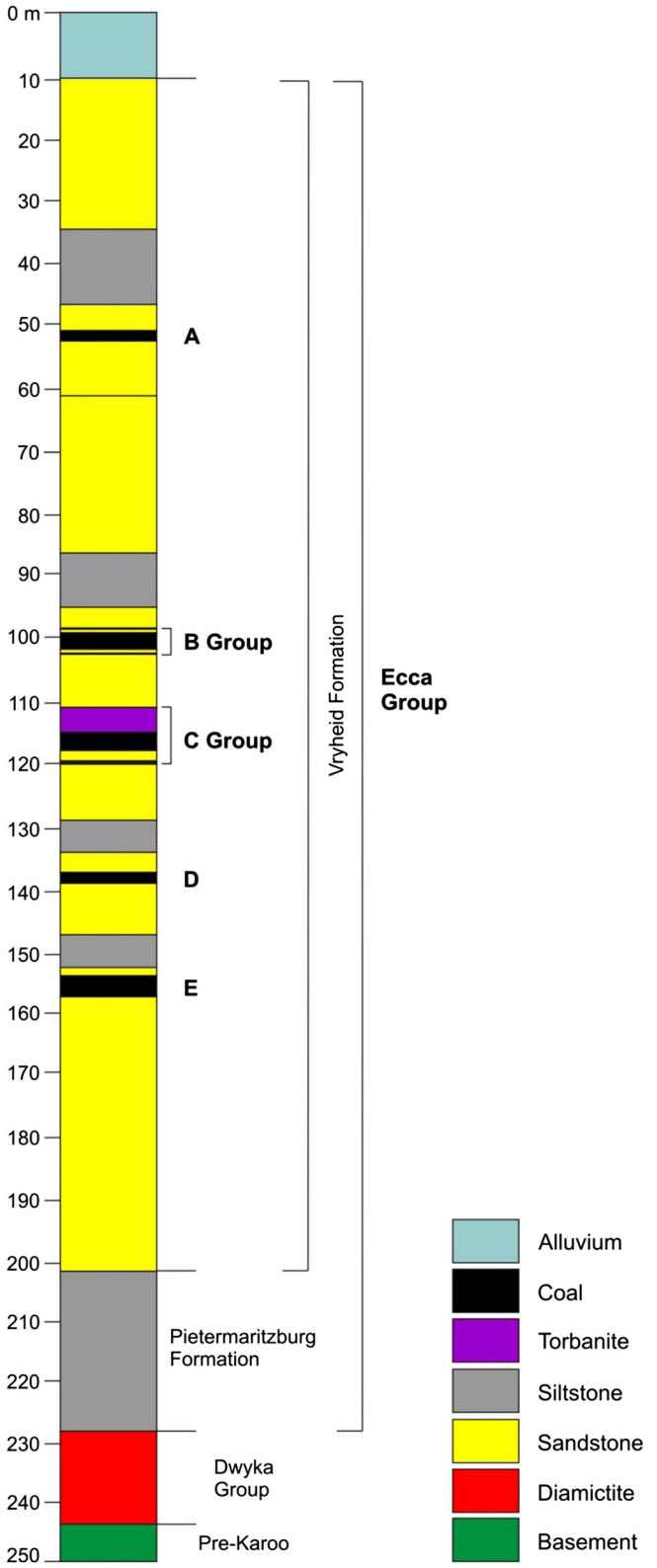

Fig. 20. Stratigraphic column of the Karoo Supergroup in the Ermelo Coalfield including the underlying pre-Karoo basement rocks.
After Greenshields (1986).

(BL), B Upper (BU) and BX seams. Greenshields (1986) notes, that the quality of the B Seam is in general inferior to that of the C Seam. This seam tends to be somewhat better developed in the north-eastern and eastern parts of the Ermelo Coalfield and has historically been mined at the Droogvallei, Spitzkop, Savmore, and Consolidated Marsfield collieries, and was the seam mined at CoAL's Mooiplaats Colliery, where it is between 0.6 and 2.87 m thick. The BU was mined at the end of the mine life at the old Usutu Colliery, and the BL at the Ferreira mine. At Mooiplaats the BU Seam occurs at depths of between 90 and 140 m and ranges in thickness between 0.15 m in the southeast to over 3 m in the north.

The A Seam occurs only in the northern and central parts of the coalfield, where it varies in thickness from 0 to 1.5 m (Greenshields, 1986). Wakerman (2003) provides a weighted average thickness of 0.94 m for the seam in the Sheepmoor exploration area. Over most of the Ermelo Coalfield however this seam has been removed by erosion. Like in the Witbank and Highveld coalfields for the No. 5 Seam, the A Seam is overlain by a green glauconitic sandstone that forms a useful marker horizon and denotes the transition from a fluvio-deltaic to a marine depositional environment.

4.3.6.1. Coal qualities. The coal of the Ermelo Coalfield, whilst variable in quality, is generally of better quality than that of the Witbank and Highveld coalfields. Greenshields (1986) provides average air-dried raw quality parameters for all the economic seams as shown in Table 1.

Wakerman (2003) provides raw coal qualities for the A Seam in the Sheepmoor area as being 11.93% Ash, 27.27 MJ/kg CV, 30.45% VM, 3.85% IM and 0.39% TS. He notes that the most important feature of this coal was the low sulphur, which meant it could be used as a blend to reduce the higher sulphur values in the CL Seam.

For the BU Seam at Mooiplaats a theoretical yield of 61% can be achieved for a bituminous product with CV of 27.5 MJ/kg. The average theoretical yield for a lean coal product with an equivalent CV is somewhat lower at 47%. Average TS contents for both coal types are moderate to relatively high, ranging from about 1.4–1.8% for the washed product.

The CL Seam is generally of a good bituminous quality and beneficiates well. Historically the Golfview Colliery prime export product on the CL and CU seams was a 11.3% Ash, 32.4% VM, 0.9% TS coal, at 27.38 MJ/kg gross as received (GAR), and 28.11 MJ/kg gross air dried CV.

Telfer et al. (2013) provide grids for the raw CV, Ash and VM on the CL at Penumbra and note that the raw CV is variable, increasing from 16 MJ/kg in the east of the project to 28 MJ/kg in the west. The raw CV to the south of the project area is generally lower than 16 MJ/kg, with small isolated areas of over 26 MJ/kg. The raw Ash of the CL Seam for the majority of the project area is between 15 and 35%, with an isolated high reaching up to 60%. In general, the raw Ash increases towards the south of the project area. The raw VM increases from the south-western portion of the project area to the northeast. In the central portion of the area the VM content reaches up to 28%.

4.3.7. Structure and intrusions

As for the Witbank and Highveld coalfields, large areas of the Ermelo Coalfield are affected by Jurassic aged dolerite intrusions, and these intrusives are probably the single most disruptive aspect of the coalfield (Barker, 1999). The dolerites form thin sub-vertical dykes and thick (30–50 m) bedding parallel sills. Several have been identified and mapped based on cross-cutting relationships and petrological characteristics (Visser et al., 1958). In places thin stringers may occur within the coal seam succession creating difficult mining conditions. Both the B4 and the B6 sills are present in this area, with the B6 sill normally underlying the CL Seam. The B4 sill often breaks through the coal seams to surface and causes dislocations of the coal seams into blocks. Associated with these intrusions is faulting that causes displacement of the coal seams (Greenshields, 1986). Faulting occurs with increasing frequency towards the south of the coalfield; with displacements of up to 250 m. Faults are almost without exception intruded by dolerite.

The dolerite intrusions have also caused large volumes of coal to have been converted to low volatile lean bituminous or anthracitic coals. In places the coal may also have been totally destroyed by burning due to the dolerite intrusions. Dolerite intrusions may also be the cause

of methane and water build-ups, with the coalfield known to be gassy (Paulson and Stone, 2002).

At the Usutu Colliery the West Mine was separated from the East and South Mines by a dolerite sill, which caused a vertical displacement of the coal seams between these mining areas by some 50–60 m. Many dykes occurred in the workings, some of which were grey and non-magnetic, others green and magnetic. Bad roof conditions were common in the vicinity of dikes, particularly in the case of the B Seam workings. Close to the major dolerite sill the coal was devolatilised and/or burnt. Dolerite intrusions are also very common in the Mooiplaats Colliery area and have been intersected in a number of boreholes and underground mining panels.

To the east at the Sheepmoor projects area Wakerman (2003) notes that the entire area was overlain by a 115 m thick sill, which following the KZN nomenclature he named the Ingogo sill. He further notes that in places this sill bifurcates and in places transgressed the coal zone creating displacements of up to 100 m.

4.4. Coalfields in the Free State

Three main coalfields (Free State, Vereeniging–Sasolburg and South Rand) occur within the Free State Province and these are often grouped together leading to some confusion. Additionally, a misconception is presented in the literature that the coal occurs as continuous seams from the Kroonstad–Welkom area of the Free State Coalfield in the west, to the South Rand Coalfield in the east. Distinct pre-Karoo palaeohighs with no coal development separate the individual coalfields (Esterhuizen and Van Heerden, 2011) and even within the three coalfields smaller coal-bearing basins are generally present, such as the Cornelia, Sigma and Coalbrook sub-basins within the Vereeniging–Sasolburg Coalfield. We therefore describe each of these coalfields below as separate entities.

4.4.1. Free State Coalfield

4.4.1.1. Introduction. To avoid confusion and to distinctly separate it from the other coalfields that occur in the Free State Province, various workers have suggested that the Free State Coalfield should rather be termed the Orange Free State (OFS)–Vierfontein Coalfield (Gilligan, 1986), the Vierfontein–Welkom–Reitz Coalfield (Barker, 1999) or the Kroonstad–Welkom Coalfield (Esterhuizen and Van Heerden, 2011; Mayes and Prévost, 2013). Whilst we here retain the term Free State Coalfield, we agree that this coalfield should be renamed.

Although it is the single largest coalfield in South Africa and is the last remaining largely untapped coal resource in the MKB, the Free State Coalfield is less well-known than the other coalfields of the MKB. It was mined by small operators in the past, but no mining is currently taking place. Exploration activity has recently focussed on this coalfield and the potential for unlocking the deep (350–450 m) stranded coal deposits of this coalfield seems to lie with UCG technology.

4.4.1.2. Location. The Free State Coalfield is located in the north-western Free State Province (Fig. 21) and covers an area of about 15,000,000 ha (Gilligan, 1986). It stretches from the Vaal River in the north to Theunissen in the south, overlying nearly all of the Free State goldfields. The northern and western limits are subcrops against basement. The southern boundary is taken as the limit of coal deposition and is believed to be south of the town of Theunissen. The eastern boundary is a common boundary with the adjoining Vereeniging–Sasolburg Coalfield.

4.4.1.3. Exploration and exploitation history. Mining of the shallow northern coal outcrop took place before any recorded investigations. This activity comprised a number of small mines of limited extent, including the Kroonstad Estate Mine, which supplied coal to De Beers in Kimberley. Gilligan (1986) provides coal production and quality figures for the Witkop (1911–1917) and Kroonstad Coal Estates (1911–1921) mines.

Commercial deposits of deeper coal were discovered in the Free State Coalfield (Kroonstad–Welkom–Virginia area) in the 1930s during gold exploration. Drilling for coal took place between 1936 and 1937 in the vicinity of the present Vierfontein Colliery (Nel and Verster, 1962). Further exploration drilling in the same locality took place in the second half of the 1940s, prior to the sinking of the shaft for the Vierfontein Colliery. Production at Vierfontein Colliery began in 1951, with mined coal supplied directly to Eskom's 360 MW Vierfontein Power Station. The discovery and establishment of the Vierfontein Colliery drove additional coal exploration work during the 1950s and 1960s. Exploration drilling was undertaken in the Welkom region, in an area immediately west of Odendaalsrus in the 1950s (Gilligan, 1986), with further prospecting work undertaken in the Mirage Siding area between 1964 and 1965, and then in the area north of Kroonstad during the 1970s.

Gilligan (1986) documents that some 46 Mt of coal had been supplied from the Vierfontein Colliery since production began. He further provides production figures for 1978 (which amounted to 1.47 Mt of saleable coal) and notes that at the time the mine had reserves of about 15 Mt of coal. The Vierfontein Power Station was one of the casualties of Eskom's closure programme, with the plant being decommissioned in November 1990.

Trans-Natal began prospecting for coal in the Theunissen Coal deposit area in 1980, completing some 240 boreholes by 1981. By February 1982 a drilling programme at a borehole spacing of 1 borehole per 100 ha was completed, which took the total to some 534 boreholes drilled. As previously mentioned Trans-Natal eventually became part of the BHP Billiton stable and during 2008 BHP drilled an additional 76 boreholes on these tenements.

According to their web page (http://www.mega-africa.co.za) Groenfontein Collieries (Proprietary) Limited is the current holder of the new order mining rights over the area surrounding the old Vierfontein Colliery, and aims to revive this mine as a captive mine, for a 600 MW mouth-of-mine Independent Power Producer (IPP).

4.4.1.4. Research history. The Free State Coalfield has not been the focus of anywhere near as much academic study as for the Witbank, Highveld and Ermelo coalfields and to date only a very limited publication list exists. Previous reference to coal in the Free State Coalfield has been made in Wybergh (1922), Cousins (1950), Nel and Jansen (1975), Coetzee (1966), Nel and Verster (1962), Petrick et al. (1975), and De Jager (1976).

Aspects of the sedimentology and stratigraphy of the Karoo Supergroup in the Free State Coalfield are described in Behr (1965), McKinney (1968), Vos and Hobday (1977), Van Vuuren and Cole (1979), Cadle (1982), Gilligan (1986), Stavrakis (1986) and Stavrakis and Smyth (1991).

Behr (1965) describes heavy mineral concentrations in beach deposits in the Bothaville area. Hart (1966a) included the area as part of his biostratigraphic study on the lower Karoo Supergroup deposits

Table 1
Raw coal qualities for the Ermelo Coalfield.
From Greenshields (1986).

Calorific value (MJ/kg)	Ash (%)	Volatiles (%)	Inherent moisture (%)	Fixed carbon (%)	Total sulphur
24	23	26	3	48	1.2

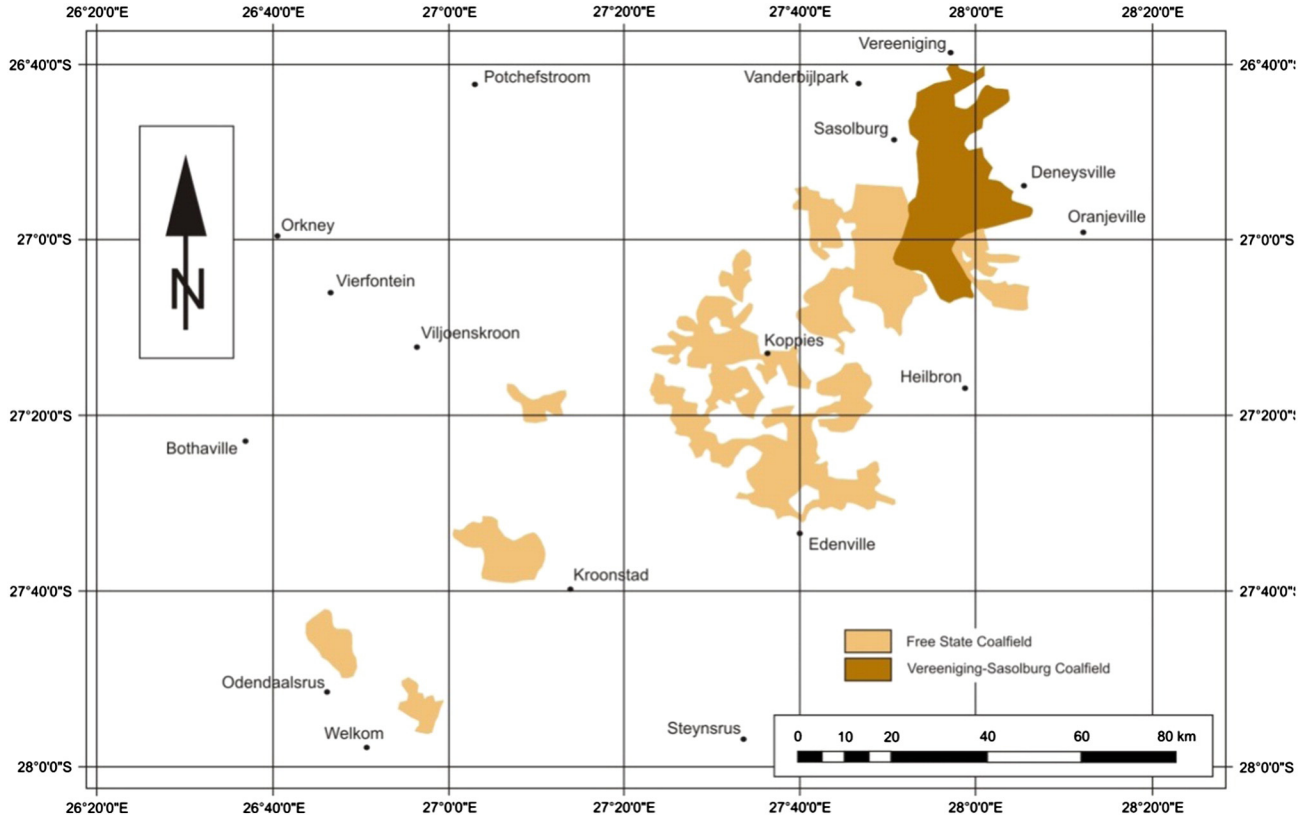

Fig. 21. Aerial distribution map of the Free State and Vereeniging–Sasolburg coalfields showing the patchy nature of the coal occurrences.

of southern Africa. McKinney (1968) provides a palaeoenvironmental analysis of the Ecca Group in the Vierfontein–Bothaville area. As part of a large study on the coalfield of the northern MKB, Van Vuuren and Cole (1979) covered the general stratigraphy and depositional environments of the Free State Coalfield and this work formed the basis of the geology provided in the review paper by Gilligan (1986).

Gilligan (1986) provides a detailed interpretation of the depositional environments of the Vryheid Formation in the Free State Coalfield based on two boreholes (DWN5 and DC2) drilled to the south and southwest of the town of Welkom. DWN5 was drilled to a depth of some 570 m, with the EOH in diamictites of the Dwyka Group. Stavrakis (1986) describes the sedimentary succession of the Dwyka and Ecca groups in detail, linking coal seam distribution and qualities to various depositional environments. Stavrakis and Smyth (1991) build on this work, also linking coal petrology to the depositional environment and providing maceral compositions for the various seams.

4.4.1.5. Geology. Few outcrop exposures exist and most of what is known about the Free State Coalfield comes from borehole data. The Free State Coalfield is underlain by a fairly rugged glacially-incised pre-Karoo basement, consisting generally of Transvaal (dolomites and metasedimentary rocks), Ventersdorp (lavas), and Witwatersrand supergroup (metasedimentary rocks) lithologies, separated from the low-lying granites and schists to the south by a massive palaeoscrap (Van Vuuren, 1981; Van Vuuren and Cole, 1979). These valleys and scarps effectively subdivide the Free State Coalfield into a number of distinct sub-basins (Van der Merwe, 2011; Fig. 22).

These basins and valleys were carved out during the Dwyka aged glaciation, and glacial conditioning prior to and during deposition in this coalfield, probably more than in any other, is the overriding control on sedimentation, the stratigraphy produced, and coal seam distribution (Stavrakis and Smyth, 1991). The valleys and channels can be 5–12 km in width and require high-tech exploration to delineate the topography in order to improve efficiency and accuracy in locating economic coal deposits. This makes for more costly exploration and provides various challenges for eventual extraction. This is one of the main reasons for the limited exploitation that has occurred in the coalfield compared to its neighbours.

The lithology of the pre-Karoo floor also plays an important role in the floor dips (Van der Merwe, 2011). In the lavas and metaquartzites the floor is relatively consistent, with only a gentle dip, which in turn provides for fairly stable mining conditions. Where the floor is formed by dolomites and cherts of the Transvaal Supergroup however, karst topography may be present, providing for a strongly undulating floor, with major and minor depressions.

Stavrakis (1986) felt that the tectonic framework of the Free State Coalfield could be considered in terms of two structural blocks (which he termed the northern and southern facies), and which exhibited different sets of structural elements. The northern facies (or terrane) was made up of several large pre-Karoo synclines and anticlines, curvilinear with respect to the Vredefort Dome. The southern facies (terrane) is structurally different, being composed of horst and graben type topography, with a north–south elongation. These different terranes played an important role in the nature of the topography created by the Dwyka glaciation. The folding amplitude within the pre-Karoo rocks in the northern terrane increases with increasing distance from the Vredefort Dome, and this trend is mirrored in the glacial valley pattern of the Karoo floor. For example, the width of the Koppies Valley is only 4 km, whilst the farthest concentric valley attains a width of 27 km in the synclinorium to the west of Kroonstad. This concentric system of ridges and valley appears to die out along the sub-outcrop position of the Malmani Subgroup between Bothaville and Kroonstad (Stavrakis, 1986). Exploration drilling in the Steynsrus, Edenville, and Villiers area, north-east of Heilbron, appears to confirm the existence of a structural hinge line within the basement rocks that form the floor to the Karoo Supergroup fill.

In the south the Dwyka valleys occupied the sites of Proterozoic grabens and half-grabens. Horst blocks and dome-like structures

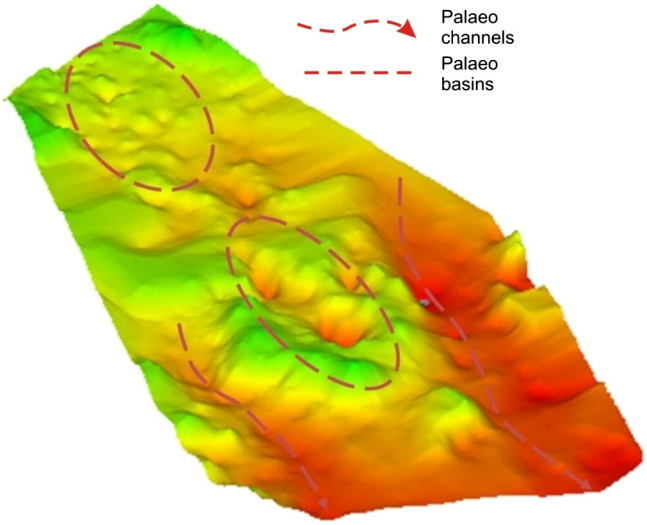

Fig. 22. General basement structure of the Free State Coalfield.
From Van der Merwe (2011), used with permission from Sasol.

formed elevated palaeotopography prior to Karoo fill. In the area of the Free State Goldfields graben the Karoo floor topography varies in elevation by 770 m over a distance of 8 km. Linear depressions oriented at high angles to the main valley axes and occurring at higher elevations are evident on the Karoo floor. These are interpreted as palaeo-hanging valleys of the Dwyka glaciation (Cousins, 1950; Stavrakis, 1986).

As mentioned above, coal does not occur as continuous seams across the entire Free State Coalfield, with smaller coal-bearing basins being generally present within the coalfield, separated by distinct areas where there is no coal development. Differential compaction and radial fracturing and jointing also make for difficult structural conditions and variable coal qualities. All of the above features impact on the geometry of any potential resource blocks, as well as on their potential economic extraction.

The general stratigraphy of the Free State Coalfield has been described in detail by Stavrakis (1986) and is provided as Fig. 23.

Within the Free State Coalfield the thickness of the Karoo Supergroup increases from Vierfontein in the north to Welkom in the south, mainly due to an increasing amount of the Volksrust Formation (Ecca Group) and Beaufort Group being preserved towards the south. This fact also leads to the coal seams of the Vryheid Formation being deeper in the south.

Much of the pre-Karoo basement is not covered by Dwyka Group lithologies and must have been topographic highs during the deposition of the Dwyka. Where the Dwyka does occur it may be as much as 317 m thick where it fills in the north–south incised valleys (e.g. the Virginia Valley). This fill is described in detail in Visser and Kingsley (1982).

As for the Witbank, Highveld and Ermelo coalfields, the Dwyka Group in the Free State Coalfield is dominated by diamictites, conglomerates, sandstones, interbedded mudstones, and in this coalfield, at least one coal seam (Stavrakis, 1986). The diamictites at the base of the Dwyka Group are postulated to have originated as subaqueous debris flows (Stavrakis and Smyth, 1991), with the interbedded mudstones representing the distal equivalents of the diamictites. The sandstone and conglomeratic facies are thought to represent fluvio-glacial, valley-fill, sandur type deposits (Stavrakis and Smyth, 1991).

The Pietermaritzburg Formation is not present over the entire coalfield, but in the deeper parts of the basin in the south, it overlies the Dwyka Group and records a period of basinal transgression. Stavrakis and Smyth (1991) believe this transgression to be in the order of a 100–150 m rise in basinal water levels. The Pietermaritzburg Formation forms the base of a generally coarsening-upward cycle that culminates in the basal sandstones of the Vryheid Formation, on which the first peat swamps were developed.

In the Free State Coalfield the Vryheid Formation consists of medium-grained, thickly bedded, arkosic sandstones, with subordinate bioturbated siltstone layers and occasional laminated siltstones and carbonaceous mudstones and coals. Conglomerates are rare. Three major (upward-coarsening) sedimentary successions (cycles 2 to 4 in Fig. 23) have been identified (Stavrakis, 1986), each capped by a coal seam (described individually below). In each unit basin-ward progradation is separated from the next cycle by a major coal seam. The total sequence is nowhere greater than 100 m thick and thins towards the south. Each of the coarsening-upward cycles grade upward from pro-delta carbonaceous siltstones into medium- to coarse-grained sandstones.

Stavrakis (1986) documents four coal seams for the Free State Coalfield that he termed the Dwyka, Bottom, Middle and Top seams. Gilligan (1986) however only documents two coal seams within the coalfield, referring to them either as the Top and Bottom seams, or Upper and Lower seams. He notes that over the greater part of the coalfield only one seam is usually well-developed. In addition Gilligan (1986) notes that the Lower Seam develops a number of splits, particularly in the Welkom area. He further notes, that the Bottom Seam has a wider distribution than the Top Seam, forms the major part of the coal resources at Welkom and was the seam exploited at the Vierfontein Colliery.

Within the limits of the Free State Coalfield, the Vryheid Formation is overlain by up to 300 m of generally upward-coarsening light to dark grey mudstones, siltstones and sandstones of the Volksrust Formation, in cyclic units between 30 and 50 m in thickness. Stavrakis (1986) recognises three subdivisions which he designated as F1–F3. It is of interest to note that over the Theunissen–Heilbron palaeohigh, the Volksrust Formation rests directly on basement.

4.4.1.6. Coal seams. Various coal seam nomenclatures exist in the literature for the Free State Coalfield and different terminologies are used by the various exploration companies. Cadle (1982) used a No. 1 to No. 4 seam terminology for the Free State Coalfield and broadly correlated these seams with the No. 1, 2, 4 and 5 seams in the Witbank Coalfield. Gilligan (1986) refers to the two seams of economic interest as the Top and Bottom seams, whereas Stavrakis (1986) and Stavrakis and Smyth (1991) refer to the seams as the Dwyka, Bottom, Middle and Top seams (Fig. 23). Like Cadle (1982), Prevost (2011) also refers to the No. 1 to No. 4 seams. We here follow the nomenclature of Cadle (1982) with other seam names provided in parenthesis where applicable as parts of the seam descriptions come from Stavrakis (1986). We accept that this nomenclature may need to be changed in the future to standardise usage or if formal naming codes are designed for the South African coalfields.

The No. 1 Seam (Dwyka Seam of Stavrakis, 1986) may be up to 13 m thick in places, and according to Stavrakis (1986) and Stavrakis and Smyth (1991) is found interbedded with, or overlying, lithologies of the Dwyka Group. If this is in fact the case, and the Pietermaritzburg Formation does in fact overly this seam stratigraphically (as depicted in Fig. 23), then this would be the only positively documented occurrence of a well-developed coal seam in the Dwyka Group in South Africa. Dwyka aged coals are known from other sub-Saharan Karoo aged depositories and this aspect of the stratigraphy should be a focus of future research work.

In many localities the No. 1 Seam rests directly on basement along the flanks of palaeovalleys (Stavrakis and Smyth, 1991). Intra-seam sandstone partings are common in the proximal reaches of the coalfield. In the middle of the coalfield the No. 1 Seam comprises a zone composed of bands of coal interbedded with laminated mudstone and siltstone, whereas in the most distal reaches it consists of only a very thin coal, or a carbonaceous or sapropelic mudstone (Stavrakis, 1986). Petrographic studies on the No. 1 Seam undertaken by Smyth (CSIRO, Australia) showed the seam to be composed of highly laminated coal comprising thin (0.25 mm) vitrinite bands alternating with 0.5 mm bands of clay containing scattered sporinite and inertodetrinite.

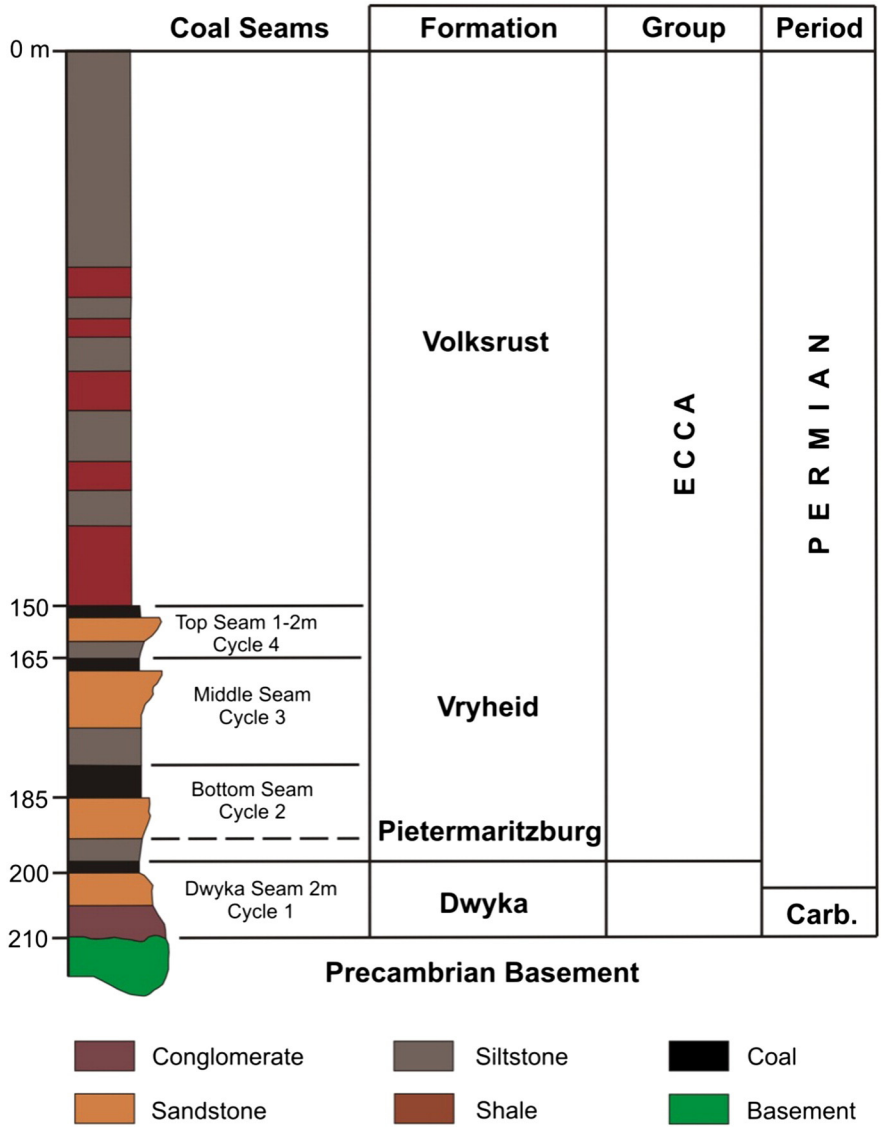

Fig. 23. Idealised stratigraphic section for the Free State Coalfield. Carb. = Late Carboniferous Period. After Stavrakis (1986).

The No. 2 Seam (Bottom Seam) occurs some 10–20 m above the No. 1 Seam at the top of Cycle 2 (Supercylce A) of Stavrakis (1986). It is developed over most of the Free State Coalfield and ranges in thickness from 7 to 12 m. It is the most important seam from an economic perspective and together with the No. 1 Seam compromises over 85% of the coal resources of the Free State Coalfield (Stavrakis, 1986). Where mined at the Vierfontein Colliery the No. 2 (Bottom) Seam was up to 2.5 m thick and was a dull banded coal with some bright coal stringers, and rare bands of cannel coal. Here both the roof and floor conditions were good, being composed of a hard sandstone floor and a competent sandstone roof. At Welkom, where the No. 2 (Bottom) Seam can be up to 8 m thick, it is dull to shaley coal, with a thick (2.75 m) siltstone parting towards the bottom of the seam. Floor conditions are considered good, but the nature of the roof is more variable, ranging from carbonaceous mudstone and siltstone through to a fine-grained sandstone.

Petrographic studies have shown the No. 2 Seam to be composed of laminated inertodetrinite/semifusinite with subordinate micrite and clay minerals. The sulphur content is variable, but often very low, with euhedral pyrite present. Based on his palynological assessment Hart (1966a) equated the No. 2 (Bottom or Lower) Seam with the No. 2 Seam in the Witbank area of the Witbank Coalfield.

In places the No. 1 and No. 2 coal seams have coalesced, forming a coal zone of up to 22 m in thickness. Such thick seams are present in the Wolwehoek Valley and in depressions in the basement between Koppies and Viljoenskroon (Stavrakis, 1986).

The No. 3 (Middle) Seam occurs stratigraphically some 20 m above the No. 2 Seam at the top of Cycle 3 of Stavrakis (1986). In the Free State Coalfield the No. 3 Seam ranges in depth below the surface from about 200–500 m, is generally less than 3 m thick, and is of fairly poor quality. Petrographically the coal contains equal amounts of inertodetrinite, micrinite and clay minerals (Stavrakis, 1986). From an area south of the Koppies valley to Hennenman the seam has a high mudstone and sulphur content (up to 6%). The pyrite is framboidal and does not decrease substantially with beneficiation. The immediate roof to the No. 3 Seam is often composed of glauconitic sandstone.

The No. 4 (Top) Seam occurs between 2 and 20 m above the No. 3 Seam in the Free State Coalfield and is not present over large areas. In small isolated sub-basins to the west of the town of Kroonstad it may attain a thickness of between 3 and 4 m. Where preserved the coal quality is generally better than that for the No. 1, 2 and 3 seams. The quality of the No. 4 Seam is strongly controlled by depositional environment, with poor development of the seam in the Theunissen, Virginia, Hennenman, Steynsrus, Edenville and Heilbron valleys. Petrographic studies of the

No. 4 Seam show layering and the preservation of woody structure in the coal (Stavrakis, 1986). Vitrinite makes up 30% of the macerals, inertodetrinite 20% and semi-fusinite 5%, with the balance being formed by micrinite (20%), clay and pyrite.

In the southern Theunissen area only a single potentially economic seam (termed the No. 3 Seam) has been reported (Prevost, 2011) as well as a reference to an uneconomic No. 4 Seam. Here the parting thickness between the No. 3 and No. 4 seams is between 20 and 40 m. Elsewhere in the coalfield a composite of the No. 2 and No. 3 seams has been referred to.

4.4.1.6.1. Coal qualities. Stavrakis (1986) provides quality data for the No. 1 Seam (Dwyka Seam) for three of his seven sub-areas of the Free State Coalfield and these are reproduced as Table 2. Stavrakis (1986) further notes that the quality of the No. 1 Seam is downgraded by the numerous intraseam partings and is in general of very poor quality.

The raw coal qualities for the No. 2 Seam (Bottom Seam) in the various sub-areas of the Free State Coalfield are provided as Table 3.

According to Stavrakis (1986) the No. 2 (Bottom) Seam has a flat wash curve and cannot be beneficiated to a 27.5 MJ/kg CV with a yield in excess of 30%. Gilligan (1986) also states that the washing characteristics are poor and that the No. 2 (Bottom) Seam coal is dull and is not amenable to beneficiation, nowhere being better than low grade thermal coal.

The No. 2 Seam coal received at the Vierfontein Power Station was initially a 22.10 MJ/kg CV, however by the 1950s this had dropped to 20.93 MJ/kg. Over time the coal averaged a CV of 21 MJ/kg, Ash content of about 22%, and a VM content of around 20%. The TS content is not mentioned. Qualities for Vierfontein crushed coal are also provided in Bulletin 68 (1964) and Bulletin 102 (1987) of the Fuel Research Institute. For 1964 qualities are given as: 22.33 MJ/kg CV; 24.0% Ash; 20.5% VM; 6.5% IM; and 1.30% TS. In the 1987 Bulletin 102 these are given as: 20.4 MJ/kg CV; 22.8% Ash; 22.3% VM; 8.9% IM and 1.43% TS.

Gilligan (1986) provides typical raw quality data for the No. 2 (Bottom) Seam at Vierfontein as being: 20.53 MJ/kg CV; 27.7% Ash; 21.4% VM; 5.6% IM; and TS of 1.4%. He further supplies the Ash Fusion Temperature (Initial deformation — reducing atmosphere) as being +1400 °C. Gilligan (1986) also provides typical quality data for the various plies (zones) of the No. 2 (Bottom) Seam at Welkom and these are presented as Table 4.

As mentioned above, the No. 3 (Middle Seam) is of fairly poor quality and only one analysis is included in Stavrakis (1986), this being for the 2.3 m thick No. 3 (Middle) Seam at Hennenman. Raw qualities are given as: 15.95 MJ/kg CV; 31.4% Ash; 26.4% VM; 3.5% IM; and 0.74% TS. The No. 4 (Top) Seam is of far superior quality than the No. 3 Seam. Stavrakis (1986) provides data for the Welkom, Hennenman and Kroonstad areas as presented in Table 5.

Gilligan (1986) describes the 5 m thick No. 4 (Top) Seam in the Welkom area as being lustrous and banded, with some bright stringers, and provides typical raw qualities of: 24.0 MJ/kg CV; 37.9% Ash; 19.0% VM; and 3.9% IM. It should however be noted that the Ash–CV relationship seems to be outside of the norm.

Mayes and Prévost (2013) report average raw qualities for the southern deep sector of the coalfield, between Welkom and Theunissen, as being between 19 and 20 MJ/kg CV, 30–35% Ash, 20% VM and 0.5% TS. They further noted that there was very poor upgrading potential and indicated theoretical yields of only 45% for a 24.5 MJ/kg CV coal. Van der Merwe (2011) described the coal as dull, and notes that the qualities are generally that of high inherent Ash, yet with vitrinite contents of up to 30%, but that the coals are not amenable to beneficiation.

According to the Mega Africa website (http://www.mega-africa.co.za) the coal in their Groenfontein Collieries project area has a typical CV in the range of 16–23 MJ/kg on an adb, with an Ash content of between 16 and 30%, a VM content of between 16 and 30% and a TS content in the range of 1.0–1.4%. It is not mentioned which seam this refers to.

From the above it is evident that in general the coals of the Free State Coalfield are of low to moderate quality, with high Ash and TS contents.

4.4.1.7. Structure and intrusions. Structurally the Free State Coalfield is fairly complex, due mainly to the inherited structural controls from the basement, as well as from the Jurassic dolerite intrusives. Pre-Karoo basement strata were subjected to extensive faulting and folding, mainly around the Vredefort Dome, and some of these faults were re-activated during Karoo deposition, providing a strong control on the nature of the glacial valleys created. Some of these faults were also re-activated during the Jurassic (Van der Merwe, 2011) resulting in small- to large-scale displacements.

As for all of the other northern MKB coalfields, Jurassic aged dolerite dykes and sills are common throughout the Free State Coalfield. Stavrakis (1986) estimated that some 40% of the resources in the coalfield had been adversely affected by the dolerite intrusions. At least three major dolerite sills (No. 4, No. 5 and No. 6 sills) are present and vary in thickness between 20 and 150 m. According to Van der Merwe (2011) the No. 4 Sill (B4) is up to 120 m thick and is a coarsely crystalline dolerite, which has only a mild metamorphic effect, and which causes mainly horizontal joints. The No. 5 Sill (B5) on the other hand, whilst only being a medium crystalline dolerite some 60 m thick, causes vertical joints and has a severe metamorphic effect. The No. 6 Sill (B6), which is only 20 m thick, is more finely crystalline, causes vertical jointing and has an extreme metamorphic effect. Van der Merwe (2011) also notes that both true and pseudo dolerite dykes occur. True dykes have a consistent thickness, predictable strike and minor metamorphic effect, whereas pseudo-dykes (which are actually offshoots from sills) are irregular and unpredictable and have a severe metamorphic effect. Typical dolerite sill thicknesses and associated displacements in the Vierfontein Colliery area are noted as being about 30 m (Gilligan, 1986).

4.4.2. Vereeniging–Sasolburg Coalfield

4.4.2.1. Introduction. The Vereeniging–Sasolburg Coalfield is historically important to South Africa as it was originally mined to supply the first feed for the Sasol One plant, for the conversion of coal to liquid (CTL) fuels and petro-chemicals via the Lurgi gasification process. It is also home to Eskom's 3600 MW Lethabo Power Station.

The Vereeniging–Sasolburg Coalfield has previously been described in some detail by Steyn and Van der Linde (1986) and as little has changed since this time, this paper is the basis for this review. As for the Free State Coalfield, coal occurs mainly in isolated to partially isolated depositories. Steyn and Van der Linde (1986) therefore sub-divided the Vereeniging–Sasolburg Coalfield into three basins, namely the Cornelia, Coalbrook, and Sigma basins (here referred to as sub-basins) and these are covered separately below.

4.4.2.2. Location. Like the Free State Coalfield, the Vereeniging–Sasolburg Coalfield (Fig. 21) also occurs in the Free State Province, extending from just south of the town of Vereeniging in the north, to approximately 20 km north of Heilbron in the south, and from Sasolburg in the west to Deneysville in the east. The coalfield is around a maximum of 30 km wide and roughly 50 km long in a north–south direction and covers an area of 208,494 ha (Barker, 1999).

4.4.2.3. Exploration and exploitation history. There is some disagreement in the literature as to whether coal was discovered in the Vereeniging–Sasolburg Coalfield in 1871 by Karl Gottlieb Mauch, or in 1878 by George William Stow. No matter the discoverer, coal was being commercially exploited during the 1880s and 1890s and supplied to the diamond and gold mining industries in Kimberley and the Witwatersrand.

In 1880 Stow met the diamond magnate Sammy Marks, who realised the importance of Stow's discovery and authorised him to

Table 2
Typical seam thickness and raw qualities for the No. 1 Seam in the Free State Coalfield. Areas are stated from west to east.
From Stavrakis (1986).

Seam	Area	Thickness (m)	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	TS (%)
No. 1 (Dwyka)	Welkom	3.4	17.59	38.6	22.3	3.9	1.19
No. 1 (Dwyka)	Hennenman	10.7	18.34	33.4	21.0	3.9	0.55
No. 1 (Dwyka)	Kroonstad	3.2	15.77	43.5	18.6	3.8	1.12

Table 3
Typical seam thickness and raw qualities for the No. 2 Seam in the Free State Coalfield. Areas are stated from west to east.
From Stavrakis (1986).

Seam	Area	Thickness (m)	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	TS (%)
No. 2 (Bottom)	Vierfontein	2.4	20.7	25.8	21.1	6.7	–
No. 2 (Bottom)	Wesselbron	2.4	17.6	35.7	23.2	6.6	1.1
No. 2 (Bottom)	Welkom	6.3	16.73	36.7	20.5	4.5	0.29
No. 2 (Bottom)	Kroonstad	3.2	15.77	43.5	18.6	3.8	1.12

purchase all the farms on which he considered coal to exist. Stow purchased the 5675 morgen (=4860 ha) farm Leeuwkuil (meaning Lion's pit) which lay on the northern bank of the Vaal River. This was the first mine to produce in the coalfield and was also the only colliery to mine coal commercially on the north side of the Vaal River. It was later to become known as the Bedworth Colliery and during 1884 produced 360 t of coal. By 1885 this figure had doubled to over 700 t, all of which was dispatched to Kimberley. The discovery of gold on the Witwatersrand in 1886 dramatically increased the demand for coal and by 1889 the Bedworth Colliery was producing 200 t of coal per week (http://www.vaaltriangleinfo.co.za/history/resources/coal_1.htm).

Donald McKay, who had seen an outcropping of coal on the farms Kookfontein and Waldrift before Marks had registered his company, persuaded Cecil John Rhodes to purchase these farms (totalling 5600 morgen or around 4800 ha) and in 1881 they became equal partners in the mine which was later to be known as Springfield Colliery.

In July of 1892 better seams were found on the Free State side of the Vaal River approximately 60 m below the surface. Initial mining was difficult due to seeping water and shifting ground. In March 1894 President Reitz opened the sinking of a new shaft on the Free State side, named Cornelia in honour of his mother. A reasonable seam of coal was intersected at a depth of almost 140 m, but the seam was so intruded by dolerite dykes that a flood of water broke through, and eventually the mine was abandoned. The following year another shaft was sunk near the Vaal River, with the seam intersected at a depth of a little over 40 m. This was to become known as the Cornelia Colliery No. 2 Shaft and was to produce coal for the next 33 years.

Between 1960 and 1985, the Anglo American Corporation of SA Limited (AAC), Iscor Limited (Iscor), Goldfields, and Sasol all explored in the coalfield, with numerous boreholes being drilled. After 2004 most of the old order mineral rights to the northern part of the Sasolburg–Vereeniging Coalfield were converted to new order rights and are currently held by Sasol and Anglo. Only the deeper areas to the south of the Sigma and Coalbrook sub-basins became available for new exploration post 2004. Currently Absolute Holdings are focussed on exploration of a 14,500 ha area to the south of the Coalbrook sub-basin, providing gross tonnes in situ (GTIS) figures of some 1.4 Gt of Inferred Resource for their Heilbron Project.

Only two mines are presently operational in the Vereeniging–Sasolburg Coalfield. The Sigma Colliery supplies coal to Sasol and the New Vaal Colliery, which is a modern surface (opencast) operation that supplies coal to the Lethabo Power Station.

4.4.2.4. Sigma sub-basin. Whilst the Sigma sub-basin currently has only one producer, Sasol Mining Division's Sigma Colliery, situated directly south of the town of Sasolburg, it is of importance to the South African economy in that since 1952 this mine has been the major supplier of low-grade coal as product feed to the original Sasol plant (later named Sasol One and now called Sasol Chemical Industries). It is owned by the Sasol Mining division and is made up of the Sigma/Mohlolo underground workings and the Wonderwater surface mining operations. It is from these workings that most of the knowledge of the geology and coal resources of the Sigma sub-basin has been documented.

4.4.2.4.1. Location. The Sigma sub-basin is situated along a north–south line at the western edge of the Vereeniging–Sasolburg Coalfield. Geologically the western margin of the sub-basin is formed by a pre-Karoo outcrop of the Vredefort Dome and the eastern extremity by

Table 4
Typical seam qualities, Saaiplaas, Welkom area.
From Gilligan (1986).

Seam	Zone	Thickness (m)	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	TS (%)
No. 2 (Bottom)	3	1.5	17.7	39.4	18.1	4.1	–
No. 2 (Bottom)	2	4.2	16.0	44.8	18.5	2.9	–
No. 2 (Bottom)	1	1.5	14.9	49.7	18.1	2.6	–

Table 5
Typical seam thickness and raw qualities for the No. 4 (Top) Seam in the Free State Coalfield. Areas are stated from west to east.
From Stavrakis (1986).

Seam	Area	Thickness (m)	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	TS (%)
No. 4 (Top)	Welkom	4.7	20.71	34.1	21.8	3.9	1.17
No. 4 (Top)	Hennenman	1.2	21.3	28.8	24.3	3.8	2.41
No. 4 (Top)	Kroonstad	3.7	22.36	24.6	26.0	3.4	1.49

a ridge of Ongeluk Formation (Transvaal Supergroup) lava, which separates it from the Cornelia sub-basin to the east.

4.4.2.4.2. Exploration and exploitation history. Mining in the Sigma sub-basin began in the early 1950s at the Sigma Colliery. Early bord-and-pillar extraction mining methods however left much of the resource unmined, and during the 1960s total extraction methods, such as long walling and pillar extraction, were introduced to improve extraction (Cillié and Savage, 1961). These mining methods were however found to have limited application at the Sigma Colliery and the rib-pillar method was introduced in 1980 (Laybourne and Watts, 1990). Current exploration interest is focussed on the south-eastern portion of the Sigma sub-basin.

4.4.2.4.3. Geology. The Sigma sub-basin is underlain by rocks of the Ventersdorp and Transvaal supergroups (Nel and Jansen, 1975; Fig. 24). Lavas of the Ventersdorp Supergroup are predominantly found in an area in the central part of the sub-basin and prominent outcrops of Transvaal Supergroup dolomites extend from near the Klip River southwards to Vereeniging and beyond. Along the north-eastern part of the Sigma sub-basin volcanic rocks of the Hekpoort Andesite Formation have been intersected in boreholes. The basement at Sasol's Wonderwater surface mine is formed by lavas of the Ventersdorp Supergroup and the topography is relatively smooth, giving rise to flat lying coal seams.

The general palaeoslope is from north to south with an average dip of less than a degree. Dwyka Group diamictites occur at the base of the succession and are thickest in areas overlying dolomites (Fig. 24).

4.4.2.4.4. Coal seams. The coal zone in the Sigma sub-basin is between 30 and 40 m thick and contains three coal units, comprising four coal seams termed C1, C2A, C2B and C3 (De Beer et al., 1991; Fig. 24). The coal seams extend over an area of approximately 300 km^2 and occur at depths below surface of between 20 and 250 m. The wide variation in depth results from a general southward dip in the strata, coupled with a northward-sloping land surface.

The basal coal unit occurs directly on or near the Dwyka Group diamictites and is referred to as the C1 (De Beer et al., 1991) or No. 1 Coal Unit (Steyn and Van der Linde, 1986). This unit is only present in the deeper valleys and is thus not present over the entire sub-basin. The seam varies in thickness from being absent to 5 m, with an average thickness of 3 m. The No. 1 Coal Unit is frequently split into two coal seams by a sandstone parting. The parting between the No. 1A Seam (the basal seam) and the No. 1B Seam varies in thickness between 0 and 3.5 m and the parting between the Number 1B and 1C varies in thickness from 0 to 1.7 m. The No. 1A and 1B seams and the No. 1B and 1C seams in many cases form a single unit with no internal partings.

The No. 1 and 2 coal units are separated by an upward fining clastic unit consisting of a basal conglomerate and very coarse sandstone, which grades upwards into finer sandstone. The conglomerate is present over the entire area of the sub-basin and is interpreted as a fluvio-glacial outwash deposit (Steyn and Van der Linde, 1986). The No. 2A, 2B, and 3 seams occur throughout the sub-basin.

The No. 2 Coal Unit is generally divided into two coal seams by a brown mudstone layer rarely greater than a metre in thickness. The two coal seams are known as the No. 2A (C2A) and No. 2B (C2B) seams. In places the parting between the two seams does not exist and the two seams may form a composite seam in excess of 6–8 m in thickness (Steyn and Van der Linde, 1986).

The parting between the No. 2B Seam and the No. 3 Coal Unit is of variable thickness and consists of a succession of mudstone, siltstone, and sandstone, with an average thickness of 13 m, increasing to the south. The No. 3 Coal Unit (C3) consists of one coal seam and varies between 0 and 5 m in thickness. This coal unit is present over most of the sub-basin and occurs at a depth of 60 m in the north and 200 m in the south. The No. 3 Seam is overlain by a laminated mudstone or siltstone layer which separates the No. 3 Seam from the No. 3 Coal Seam Marker. The No. 3 Coal Seam Marker is normally less than 1 m thick and is overlain by alternating sandstone and siltstone package. A thin glauconitic sandstone layer directly overlies the No. 3 Coal Seam Marker and serves as an additional guide for exploration and correlation. The sandstones above the coal seams are mainly white, fine- to medium-grained and horizontally stratified to massive (Steyn and Van der Linde, 1986).

At Sasol's Wonderwater mine the No. 2A and No. 3 seams are extracted together, along with the siltstone parting between them where developed. In the northern area of the mine the parting does not occur and the two seams coalesce and are mined as one unit.

4.4.2.4.4.1. Coal qualities. The raw qualities of the coal (adb) as provided in Steyn and Van der Linde (1986) are presented in Table 6.

4.4.2.4.5. Structure and intrusions. At Sasol's Wonderwater opencast mine the structures observed are predominantly the result of regional horizontal stresses (Van Heerden, 2004a). At Wonderwater the predominant strike direction of the dolerite dykes is northwest–southeast and their thicknesses are generally less than 2 m. Faults are typically normal with throws of less than 2 m. A major fault strikes west–east across the mining area and downthrows the northern area by some 20 m. On either side of this fault is a zone of highly jointed rock (Van Heerden, 2004a). Jointing is common in all lithological units and three major joint sets have been identified, these being: bedding joints, shear induced joints, and vertical joints (Van Heerden, 2004a).

Dolerite sills, up to 35 m thick, cover extensive areas in the Sigma sub-basin, and their presence has a profound influence on the volatile content of the coal in places. The dolerites also affect the rock mechanics conditions of the mining operations (De Beer et al., 1991). Two major dolerite sills are present in the Sigma sub-basin. Both of these intrusions are present in the southern sector, but only the younger one is present in the northern sector. There are two known occurrences where dolerite sills transgress the coal seams. The first is in the southern part where a dolerite sill intersected the No. 3 Seam causing a displacement of 85 m. The second is in the northern part where the displacement of the coal seams is approximately 65 m.

Numerous dolerite dykes have also been encountered at the Sigma Colliery during underground mining operations, with the majority being located in the southern sector. Associated post-Karoo faults, with displacements of up to 4 m have been encountered during underground operations (Steyn and Van der Linde, 1986).

4.4.2.5. Cornelia sub-basin

4.4.2.5.1. Introduction. The Cornelia sub-basin hosts the New Vaal Colliery (NVC), an example of how a mined-out colliery was resuscitated by surface (opencast) mining methods. Lethabo was fully operational by December 1990 and holds the distinction of being the power station in South Africa which burns the lowest CV (15–16 MJ/kg) and highest Ash (42%) coal. As for the Sigma sub-basin, most of what is known about the geology of the Cornelia sub-basin comes mainly from work at NVC.

4.4.2.5.2. Location. The Cornelia sub-basin forms the north-eastern sector of the Vereeniging–Sasolburg Coalfield and extends in a north–south direction from the town of Vereeniging in the north, to the northern margin of the Coalbrook sub-basin in the south. The western boundary with the Sigma sub-basin is formed by a palaeohigh of Ongeluk Formation lava and the eastern margin by the subcrop against a basement composed of the Chuniespoort Group.

4.4.2.5.3. Exploration and exploitation history. Mining commenced in the general area during the late 1800s using underground bord-and-pillar methods, and ceased in 1965 in the Maccauvlei east area of the now defunct Cornelia Colliery. Mining began in the NVC lease area in 1931 and continued until 1969, by which time some 61% of the area had been undermined. Early bord-and-pillar methods however left some 93% of the original resource underground and in the late 1970s feasibility studies were carried out on mining the remaining coal reserves by open-cast methods. Technical investigations continued through to the 1980s, leading to the establishment of the NVC in 1983, with the first saleable coal being produced in December of 1985. NVC

is a captive colliery and its main function is to supply coal to Eskom's 3600 MW Lethabo Power Station until 2030.

The NVC is located in the Free State Province, immediately south of the town of Vereeniging. The site covers a land area of roughly 8 km by 6 km and operates as an open cast mine to a depth of 80 m. The colliery consists of two distinct mine lease areas covering approximately 2800 ha. These two resources are known as the Maccauvlei East (Mac east) Reserve Block and the Maccauvlei West (Mac west) Reserve Block. With the mine at full production some 17.8 Mtpa are produced from the two reserves.

The Mac east reserve was the first to be mined in 1985 and the coal is mined by open-cast methods only. The mineable reserves are in three coal seams totalling 18.1 m on average in thickness, and the floor of the mine is at an average depth of 50 m below the surface topography. There are old underground workings present in this coal seam, averaging a height of 2.7 m. The mining method used for the historic underground workings was bord and pillar mining.

The Mac west block is a reserve that was later secured by AATC, with mining beginning in 2008. An estimated 35% of the bottom seam and a portion of the middle seam were historically mined by Cornelia Colliery. The remaining Mac west reserves are currently also being extracted using open-cast mining methods and are also entirely dedicated to Lethabo Power Station. NVC is currently the highest producer of RoM coal in the AATC group (Mothemela and Chabedi, 2013). The remaining reserves at Mac west, which amounted to approximately 95 Mt in 2004, are being mined over a period of approximately 24 years to tie in with the expected life of mine (LoM) of the Mac east coal mining operations, currently planned to cease in 2030. Eskom would however like to keep the Lethabo Power Station running until 2050, and needs to secure coal supply to this date. AATC can fulfil this requirement if the life of NVC is extended by 20 years. AATC proposes to extend its existing open-cast mining operations by mining new coal reserves located to the south of the existing colliery. These operations will include both open-cast and underground mining within the New Cornelia Block 1 and New Cornelia Vaalbank reserves (Golder and Associates, 2011).

4.4.2.5.4. Geology. For this review the historical use of the term coal unit (Steyn and Van der Linde, 1986) has not been retained and the terminology of Laybourne and Watts (1990) has rather been used. These authors also provide a typical stratigraphic column through the NVC mining area and this is provided as Fig. 25.

The northern part of the Cornelia Basin is underlain by a basement of dolomites of the Chuniespoort Group and lavas of the Hekpoort Formation (both units of the Transvaal Supergroup). The thickness of the basal Dwyka Group generally varies between 3 and 4 m, but can reach thicknesses of up to 15 m in topographic lows. The basal portion of the Dwyka Group is formed by diamictite, with angular to well-rounded pebble sized clasts of dolomite, chert and metaquartzite, set in a brown argillaceous matrix. The diamictite facies is overlain by variable layers of reworked diamictite and sandstone, which varies in thickness between 4 and 5 m and forms the floor to the Bottom Seam. In the northern part of the sub-basin this succession contains a thin coal seam, which is referred to as the Lower Bottom Seam, and which may reach a thickness of up to 1.5 m.

4.4.2.5.5. Coal seams. The main coal zone is in the order of 30 m in thickness and contains three coal seams, which are referred to as the Bottom, Middle and Top seams. The Bottom Seam, which in places is deposited directly on reworked diamictite, varies in thickness, but has an average of 4 m, of which the lower 2.5 m was historically mined underground. The Bottom Seam may be correlated with the No. 1 Seam of the Sigma Colliery area, as well as the No. 1 Seam encountered at the Coalbrook Colliery in the Coalbrook sub-basin, as discussed below.

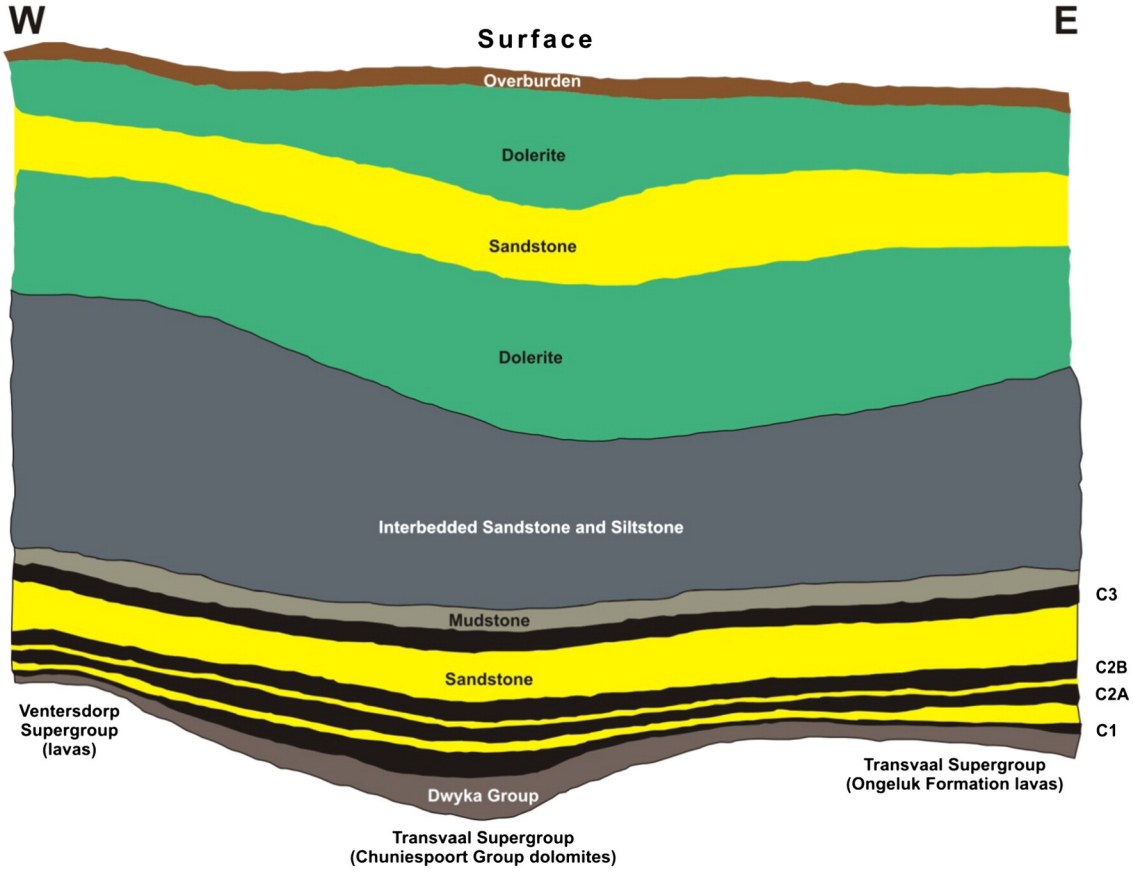

Fig. 24. West–east simplified stratigraphic profile at the Sigma Colliery showing the nature of the basement and the control on the thickness of the Dwyka Group and basal C1 Seam. From De Beer et al. (1991).

The Middle Seam is separated from the Bottom Seam by an interbedded succession of conglomerate and siltstone up to 2 m in thickness. To the south, thin interlayered coal seams are also present. The Middle Seam may consist of two sub-seams, which are locally known as the Lower Middle Seam, and the Upper Middle Seam. A brown carbonaceous mudstone forms the parting between these two seams and varies in thickness between 0.6 and 0.9 m. The Lower Middle Seam is commonly thicker than the Upper Middle Seam and achieves its maximum thickness of 7.5 m in the southern section of the Cornelia mining area (Steyn and Van der Linde, 1986). Most of the historic workings took place in selected horizons of the Middle Seam.

The Middle Seam is separated from the Top Seam by a black micaceous siltstone, which grades upwards into mudstone. The Top Seam may also consist of two sub-seams, locally known as the Top Seam and the Coal Marker (Steyn and Van der Linde, 1986) or Leader Seam. The Top Seam reaches a maximum thickness of 10 m, however where historically mined underground the average selected seam mining height was only 3.2 m. The Coal Marker Seam may reach a maximum thickness of 1 m. The quality of the Top Seam is generally the lowest of the three main seams.

4.4.2.5.5.1. Coal qualities. Steyn and Van der Linde (1986) provide the raw coal qualities of the three main seams and these are presented in Table 7.

At the NVC all three seams are mined simultaneously and blended to provide an average CV of about 16 MJ/kg and a 37.5% Ash content.

4.4.2.5.6. Structure and intrusions. The nature of the palaeotopography is an important contributor to the structure of the Cornelia sub-basin. Basement highs (Chuniespoort Group dolomite pinnacles and ridges) and lows (palaeokarst doline features) of varying scales result in changing dips, strikes and gradients over short distances (Van Heerden, 2004a). At NVC the highly undulating nature of the palaeofloor is also believed to be the controlling factor in terms of the observed joint patterns and structural discontinuities (Stewart and Letlotla, 2003; Van Heerden, 2004a).

Two major faults with a regular east–west strike have produced a graben-type structure in the Cornelia sub-basin. The displacement of the coal units varies from 70 m in the west to only 5 m in the east. A high frequency of minor faulting is present in the Bottom Seam and a few of these faults can be traced up to the Middle Seam (Steyn and Van der Linde, 1986).

A dolerite sill up to 60 m thick occurs in the upper part of the succession, but becomes thinner to the north due to erosion. It generally occurs some 40 m above the Top Seam. In the south it transgresses the coal seams in three areas, creating small areas of uplifted and devolatilised coal. The presence of the faults, floor dips, numerous sinkholes and the previously undermined areas makes for challenging mining conditions at NVC.

4.4.2.6. Coalbrook sub-basin

4.4.2.6.1. Introduction. The Coalbrook sub-basin can be viewed as a southerly extension of the Sigma and Cornelia sub-basins. Whilst currently without an active colliery, the Coalbrook sub-basin was previously the host to the Coalbrook and Clydesdale collieries, both of which are now defunct. One of these, the Coalbrook Colliery, is infamous in South African coal mining history as being the site of the nation's worst coal mining disaster, when on the 21st of January, 1960, 435 (some reports refer to 437) men died in an underground collapse (Van der Merwe, 2006). To this day this rates as the seventh worst coal disaster globally in terms of lives lost.

Table 6
Coal qualities for the Sigma sub-basin.
From Steyn and Van der Linde (1986).

Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	FC (%)
No. 3	19.3	29.8	21.0	5.2	44.0
No. 2B	18.0	32.2	20.0	6.6	41.2
No. 2A	18.2	30.9	21.9	6.6	40.6

4.4.2.6.2. Location. The Coalbrook sub-basin extends from the southern edges of the Sigma and Cornelia sub-basins southwards towards Heilbron and eastwards to the Vaal Dam.

4.4.2.6.3. Exploration and exploitation history. Initial exploration in the Coalbrook sub-basin was focussed on the north and central areas. Van der Merwe (2006) notes that the earliest borehole logs for Coalbrook date to the early 1900s, and that the first Coalbrook shaft was sunk in 1905. From 1932 onwards, attention turned to mining south and east of the original shaft. In 1950 the planning of a thermal power station in the district started. Coalbrook was awarded the contract for coal supply and in 1954 the first generators came on line. This had a dramatic impact on the mine, requiring a five-fold increase in the daily production rates, and in part leading to the disastrous roof collapse (van der Merwe, 2006). Coalbrook North was the sole supplier of coal to Eskom's Taaibos Power Station; with the South Colliery providing coal to the Highveld Power Station. The Taaibos and Highveld power stations each had a capacity of 480 MW and were the largest and most up-to-date power stations in the Eskom system at that time. The process of closing down Taaibos and Highveld power stations began in 1986 and in 1994 a decision was made to decommission and dispose them.

AAC, Iscor, Goldfields and Sasol all explored for coal in this area between 1960 and 1985, with 49 boreholes drilled between 1960 and 1985 according to the records of the Council for Geosciences (CGS). The greenfield Heilbron Project is currently being assessed in the south of the Coalbrook sub-basin. These properties are located in the northern part of the Free State Province, approximately 26 km south-southeast of the town of Sasolburg and 28 km north of Heilbron. Here the depth of the coal zone varies between 125 and 270 m.

4.4.2.6.4. Geology. The Coalbrook sub-basin was deposited on rocks of the Transvaal Supergroup, and in the east and west on rocks of the Ventersdorp and Witwatersrand supergroups, respectively (Nel and Jansen, 1975). The Dwyka Group ranges in thickness between 0 and 45 m, being thickest in the palaeovalleys over dolomitic floors. The succession is generally formed by a basal diamictite unit, which grades up into coarse-grained sandstones. The overlying Vryheid Formation consists predominantly of sandstone, siltstone and mudstone, with coal seams in the lower parts. The succession becomes finer grained towards the east where it attains a maximum thickness of 263 m (Steyn and Van der Linde, 1986). According to the 1:250,000 geological map, surface outcrops within the Coalbrook sub-basin consist mostly of argillaceous rocks (predominantly grey to black siltstones and mudstones) of the Volksrust Formation, which is approximately 100 m thick.

4.4.2.6.5. Coal seams. Three coal units (4 seams) are present in the succession and are numbered in ascending order the No. 1, No. 2 and No. 3 coal units. Of these coal units only the No. 3 has more than one seam and the term unit and coal seam may be used interchangeably for the No. 1 and No. 2 coal units. The No. 1 and 2 seams are very intimately associated, being separated by only a sandstone or siltstone parting that ranges in thickness from 0 to 8.5 m in thickness. The average parting thickness between the No. 2 Seam and the No. 3 Coal Unit is 20 m and the stratigraphic succession consists of interlayered sandstone, siltstone and laminated mudstone.

The No. 3 Coal Unit consists of two separate seams, namely the No. 3 Upper (3U) and No. 3 Lower (3L) seams (Steyn and Van der Linde, 1986). They are separated by a thin, black or brown mudstone parting ranging in thickness between 0.5 and 7 m. The No. 3U Seam is overlain by a mudstone parting of between 1.0 and 3.2 m, which separates it from the overlying No. 3 Marker Seam, which ranges in thickness between 0.2 and 0.8 m. The immediate roofs of the No. 3L and 3U seams are composed of very weak friable brown mudstones.

For the southern Heilbron area of the Coalbrook sub-basin the depth of the coal zone varies between 125 and 270 m, with the average for the area being between 180 and 220 m for the coal zone. Borehole

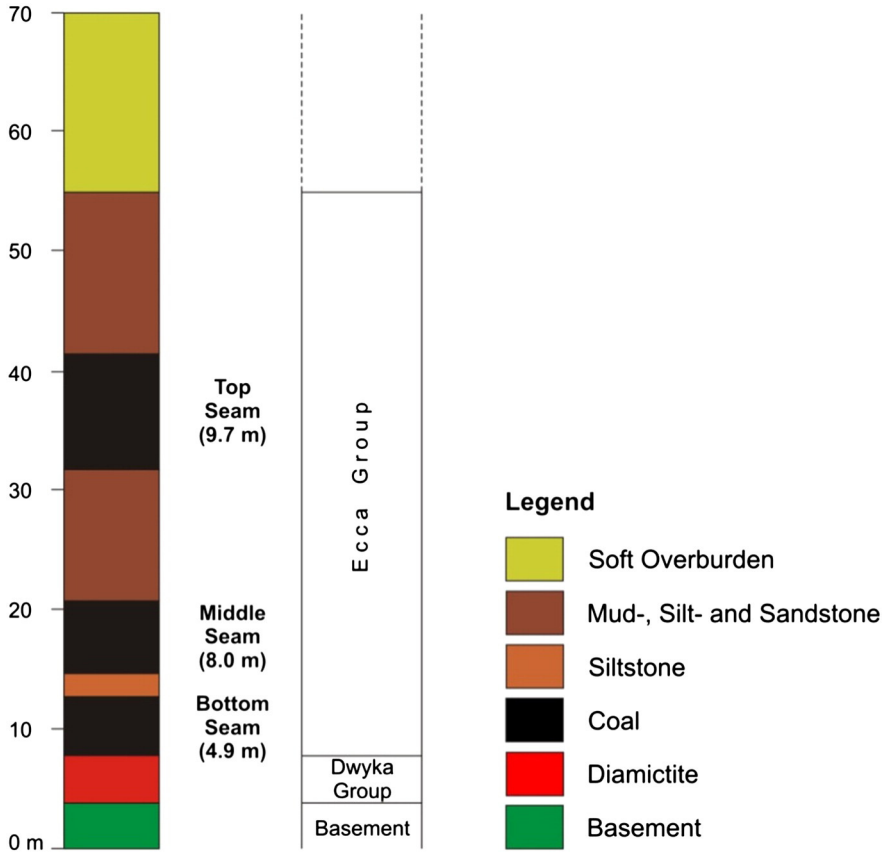

Fig. 25. General stratigraphy of the New Vaal Colliery (NVC).
From Laybourne and Watts (1990).

information from drilling done on the Heilbron farms supports the general geological description provided above. It was found that here the lower (No. 1) and middle (No. 2) coal units are separated by a clastic parting with a thickness of roughly 5 m, whereas the upper coal unit (No. 3) is situated approximately 20 m above the middle unit.

4.4.2.6.5.1. Coal qualities. Steyn and Van der Linde (1986) provide raw qualities for the three seams and these are presented in Table 8. Similar raw coal qualities are provided by Absolute Holdings for their Heilbron coal assets.

Little data is available concerning the wash characteristics of the coal from the Coalbrook sub-basin, but what does exist suggests that the yields are variable for the different seams, and that they are very low for an export quality product, with beneficiation required to even provide a constant 30% Ash product for Eskom.

4.4.2.6.6. Structure and intrusions. Over most of the Coalbrook sub-basin the sedimentary strata of the Karoo Supergroup are relatively flat, except for minor undulations (Steyn and Van der Linde, 1986). Due to the basin morphology, the general dip in the area is to the south-southeast. An increase in gradients occurs towards the edges of the sub-basin and is accompanied by the thinning and eventual pinching-out of the seams against the pre-Karoo basement palaeohighs.

As for the other sub-basins of the Vereeniging–Sasolburg Coalfield, Jurassic aged dolerite intrusions are common. A dolerite sill, varying from a few metres to more than 125 m in thickness, is present throughout the Coalbrook sub-basin, and forms an undulating, intrusive mass above the coal seams (van der Merwe, 2006). Displacement of strata (by up to 85 m) by dolerite sills is a common occurrence in this part of the Vereeniging–Sasolburg Coalfield. In the central area of the coalfield the dolerite plunges beneath the coal seams, elevating an oval-shaped area of coal-bearing strata 2500 m by 1000 m in extent, by some 50 m above its original position.

When the base of the sill is within 30 m or less of No. 3 Seam the effect of the dolerite intrusion (and the associated deformation stresses) becomes very noticeable. This includes a marked deterioration of the roof, numerous faults and fractures in the coal, and the volatile content of the coal decreasing. At the southern end of the Coalbrook sub-basin the coal of the upper unit has lower volatile content, which is a direct result of the position of a prominent dolerite sill, some 80–100 m thick, which is situated above the coal zone.

Minor faults (maximum displacement of 5 m) are also encountered in the region related to dolerite dyke intrusions. Two major dolerite dykes, which strike northeast to southwest, traverse the Coalbrook Colliery area (van der Merwe, 2006).

4.4.3. South Rand Coalfield

4.4.3.1. Introduction. Coal was previously mined in the South Rand Coalfield on a small scale by various companies that are now defunct, and on a larger scale by AAC at their Springfield Colliery. At present there are no active mines in the coalfield and it remains a large, low grade coal resource. The surface area encompassed by the coalfield is also home to Eskom's Grootvlei Power Station, which was commissioned in 1969 and has an installed capacity of 1200 MW.

Table 7
Raw coal qualities (adb) from the Cornelia Basin. Note: the CV in the table in Steyn and Van der Linde (1986) reads 2.6. It should be noted that the Ash–CV relationship for the Lower Seam is unusual and further data should be sourced.
From Steyn and Van der Linde (1986).

Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	FC (%)
Upper	18.2	30.0	23.1	6.2	40.7
Middle	20.6	26.4	20.0	1.8	51.8
Lower	19.43	21.9	23.8	6.9	47.4

4.4.3.2. Location. The South Rand Coalfield covers an area of some 60,000 ha (Henderson, 1986), lying within a southerly trending basin situated between the town of Heidelberg in the north and Villiers (Vaal Dam) in the south, in the Gauteng Province.

4.4.3.3. Exploration and exploitation history. Initial detailed exploration work in the South Rand Coalfield was undertaken by Sawyer (1898) and Moseley (1909), as summarised in Wybergh (1922). Initial investigations and mining were concentrated along the northern sub-outcrops of coal and comprised a series of adits and small-working that were short lived due to ventilation difficulties and roof collapse. More intensive mining commenced at the turn of the century at the now closed Spes Bona, Transvaal Coal and Perseverance collieries. Mining progressed to the deeper portions of the coalfield, where the now defunct South Rand Colliery exploited an unusually thick (25 m) composite coal seam.

The greatest concentration of exploration boreholes in the South Rand Coalfield have been drilled around the area of the now defunct South Rand and Springfield collieries, and most of what is known about the geology of this coalfield comes from this area. Springfield Colliery was started in 1948 to supply the requirements of Eskom's early Klip Power Station, at the rate of 200,000 tpm. In its later life it also supplied the Grootvlei Power Station. According to Henderson (1986) coal from the mine was particularly prone to spontaneous combustion problems. Underground sections at Springfield Colliery were eventually closed due to steep gradients and poor and unstable mining conditions caused by dolerite intrusions and faulting. The mineral rights to this resource currently reside with AATC and recent studies have sought to bring this large resource back into production.

4.4.3.4. Geology. As in the Free State and Vereeniging–Sasolburg coalfields, the South Rand Coalfield occurs within a large, deep, southerly trending palaeovalley on the northern margin of the MKB. It is effectively isolated from adjacent coal-bearing areas by basement palaeohighs of Ventersdorp and Witwatersrand Supergroup strata, and less commonly Archaean amphibolites and granites. A significant feature of the centre of the coalfield is the presence of large granite bosses, which form prominent topographic highs.

Although not well documented for the coalfield, Dwyka Group lithologies form the base of the Karoo Supergroup succession. The three borehole logs provided in Henderson (1986) show the Dwyka Group lithologies in the centre of the basin to be between 20 and 30 m thick, and formed by a basal diamictite of up to 10 m, overlain by an upper unit of medium- to coarse-grained sandstone. Henderson (1986) further notes that conglomeratic strata along the southern margin of the basin may represent the distal equivalent of the Dwyka Group in the north of the coalfield.

The remainder of the sedimentary succession in the South Rand Coalfield is essentially composed of Vryheid Formation sandstones, siltstones, mudstones and coal (Fig. 26), with occasional conglomeratic lenses, which may even occur within the coal seams themselves.

The total thickness of strata above the coal zone may reach a maximum of 220 m, much of which may be attributed to the presence of an up to 150 m thick dolerite sill.

4.4.3.5. Coal seams. Three main seams occur in the coalfield, as well as a poorly developed uppermost Ryder Seam (Fig. 26). The No. 1 Seam has an average thickness of 2.8 m (Henderson, 1986) and is composed of dull-lustrous coal with scattered bright streaks and bands. The seam is usually of better quality than that of the overlying No. 2 Seam and generally has a competent sandstone roof and floor. The No. 1 Seam was mined mainly in the central and north-eastern areas of the Springfield Colliery. The interburden between the No. 1 and No. 2 (or Main Seam) seams is formed by a sandstone dominated succession up to 20 m thick.

The No. 2 Seam (Main Seam) varies in thickness from over 20 m in the northern and central areas of the Springfield Colliery lease area to less than 2 m in the south-western parts, averaging 10 m (Henderson, 1986). The No. 2 Seam is the only regionally continuous mining horizon throughout the coalfield. Although the quality is fairly constant throughout the No. 2 Seam, mining regulations and restrictions at the time of exploitation only allowed for a maximum mining height of 5.5 m. Innovative mining methods will therefore need to be considered to make the extraction of this seam economic. Based on the presence of a glauconitic sandstone marker above the seam, the No. 2 Seam in the South Rand Coalfield has previously been tentatively correlated with the No. 4 Seam in the Witbank Coalfield (Henderson, 1986). In the central part of the South Rand Coalfield, siltstones and mudstones form the roof of the No. 2 Seam, whilst at the basin edge, erosively based fluvial channel sandstone units comprise the roof. Lateral to the thick composite seam of the central area, partings of conglomerate, sandstone, and mudstone are present, effectively splitting the No. 2 Seam into two or more thinner seams.

The No. 3 Seam is on average 5 m thick and is a widespread coal seam that was mined extensively in various areas of the Springfield Colliery. In many places the No. 2 and No. 3 seams coalesce, or are separated by too thin a parting to allow the seams to be mined independently. In the South Rand Coalfield the uppermost Ryder Seam averages 2.3 m in thickness (Henderson, 1986) and is of inferior quality to the other seams, with a CV averaging 18 MJ/kg or less. Coupled to poor mining conditions, caused by an incompetent siltstone roof, this meant that this seam was of low priority, and it was not mined historically. The name “Ryder” was derived from a sub-economic seam of irregular distribution that occurs in the coalfields of South Wales.

4.4.3.5.1. Coal qualities. Henderson (1986) provides raw (and float F1.70) qualities for various plies of the typical seam sections in the Springfield Colliery area. These included a single ply for the No. 1 Seam, four plies for the No. 2 Seam and two plies for the No. 3 Seam. These raw coal quality values are provided as Table 9.

According to Henderson (1986) the washability characteristics are poor and no low-Ash, higher grade fraction is recognisable in the seams. This seems to be borne out by the F1.70 data presented in Henderson (1986), which shows that whilst relatively high yields could be achieved (especially for the No. 1 Seam and the better plies of the No. 2 and lower No. 3 Seam), nowhere was a CV of greater than 24.60 MJ/kg obtained, and as such at the time it was not considered as export quality coal.

The composite seam (No. 1, 2 and 3 seams) encountered at the Springfield Colliery may be divided into 11 zones, the qualities of which are provided in Henderson (1986; Figure 6, p. 1959). Henderson (1986) also provides coal quality values for the underground areas of the South Rand Coalfield as follows: 21.4 MJ/kg CV; 25% Ash; 21.1% VM; 5.4% IM; and 0.7% TS. For the open cast operations the figures are: 19.5 MJ/kg CV; 28.0% Ash; 23.3% VM; and 0.8% TS. Ash fusion temperatures are quoted as being +1400 °C for all temperatures of deformation, for both underground and open cast areas.

4.4.3.6. Structure and intrusions. The area relative to other coalfields is structurally complex due to the numerous dolerite intrusions and relatively severe faulting throughout. A thick, coarsely-crystalline dolerite sill overlies most of the central part of the coalfield. Locally, this sill is in excess of 100 m thick, but thins out and is absent towards the eastern and western extremities. Sub-vertical to vertical fracturing of the sill is

Table 8
Raw qualities (adb) for the coal seams of the Coalbrook Basin.
From Steyn and Van der Linde (1986).

Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	FC (%)
No. 3	19.9	29.3	19.8	4.3	46.6
No. 2	19.6	28.9	21.3	5.8	44.0
No. 1	21.7	24.3	23.4	5.6	46.7

common throughout. Where the sill is within 30 m or less of the coal zone it has often caused devolatilisation of the coal, and for large areas of the coalfield the raw volatiles drop below 18%. Associated dolerite dykes are usually porphyritic.

4.5. Coalfields of KwaZulu-Natal

Whilst never being the largest producers by tonnage, the coalfields of KZN have historically played an important role in the coal industry of South Africa for the high quality of the coals produced. Historically the Klip River, Utrecht and Vryheid coalfields (Fig. 1) have been the most important and they were the subject of two pioneering surveys in the first half of the 20th century (Blignaut and Furter, 1940; Wybergh, 1925), as well as follow up work by Blignaut (1951). They were also collectively the focus of much research by the Durban Coal Group of the University of Natal in the late 1970s (Tavener-Smith, 1979) and the 1980s, as summarised in Tavener-Smith et al. (1988). Since 2007 the Somkhele Coalfield has also become a significant contributor, which coupled with the Nongoma Coalfield (Fig. 1) represent the future for new mining in KZN. The locations of each coalfield are presented below under the individual coalfields, as are their individual exploration histories.

Most of the major mining houses divested of their KZN coal assets in the early 2000s and activity in the KZN coalfields is now dominated by junior to mid-tier mining and exploration companies. Presently only six medium scale collieries are operational, three in the Klip River Coalfield, one in the Vryheid Coalfield, one in the Nongoma Coalfield, and one in the Somkhele Coalfield. A number of new and advanced exploration projects may however see this number increase in the near future.

Here we group the MKB foreland basin Klip River, Utrecht and Vryheid coalfields, and split them from the Somkhele and Nongoma coalfields (Fig. 1), which are rift related. Of these, the largest and historically the most important is the Klip River Coalfield (Mintek, 2007; Snyman, 1998). It is also the best documented and is covered here first to act as the basis for comparison with the Utrecht and Vryheid coalfields.

4.5.1. Klip River Coalfield

4.5.1.1. Introduction. The Klip River Coalfield was historically the most important anthracite and coking coal producing area of South Africa and according to the most recent overview of the coal resources of KZN (Mintek, 2007) the Klip River Coalfield still has the greatest percentage of high potential projects in the Province.

4.5.1.2. Location. The Klip River Coalfield has its apex in the north beyond the town of Newcastle and continues to Ladysmith in the south and to Dundee in the south-east. It covers an area extending from 25°30′S to 26°30′S by 28°30′E to 30°E, and covers a total area of approximately 600,000 ha, of which roughly 50% can be considered to be potentially coal bearing (Bell and Spurr, 1986a).

4.5.1.3. Exploration and exploitation history. Although there is some evidence for coal extraction in KZN by the indigenous population, the earliest recorded discovery of coal by Europeans within the Klip River Coalfield was in 1838, with the Steenkoolstroom acquiring its name from outcrops of coal utilised by Commandant Andries Pretorius and his men in that year. The Talana Colliery opened near Dundee in 1860 and was South Africa's first underground coal mine. Small quantities were also mined from outcrops in the Dundee area between 1860 and 1870.

The earliest records of boreholes being drilled in the coalfield is by the Natal Administration between 1882 and 1885 (Bell and Spurr, 1986a). In 1889 Peter Smith founded the Dundee Coal Company and established it on the London Stock Exchange. By 1898 sinking of the first shaft at the Durnacol and Natal Steam collieries had begun and by 1903 more than 500,000 tpa were being produced from 19 mines, mainly in the Dundee area (then referred to colloquially as Coalopolis). For the next half a century the Klip River Coalfield continued to expand, with various new collieries, such as Kilbarchan and Ballengeich (Natal Cambrian) opening, and some that had begun in the late 1800s, such as Natal Navigation, closing.

During the mid-1960s, extensive exploration programmes were undertaken by many mining houses, and it was during this period that mines such as Indumeni and Ingagane were brought on stream. In 1986, nine collieries were operative in the Klip River Coalfield (Bell and Spurr, 1986a) with a combined annual sales tonnage of approximately 5 Mt. All of these have subsequently closed. They are listed as Table 10.

Of these, probably one of the best known, and longest producing, is the Durban Navigation Collieries (Durnacol) mine. The history of Durnacol is well chronicled in Anthony Hocking's, 1995 book titled "Durnacol — The Story of the Durban Navigation Collieries", as well as in a number of papers and research articles (Smith, 1985). This operation, situated in the Dannhauser Magisterial District, supplied coking coal to Iscor. Smith (1985) notes, that at that time the Colliery was producing some 225,000 tpm of RoM coal by conventional methods and long-walling. Both manual and mechanised methods were used to extract pillars in developed bord-and-pillar sections. The colliery stopped production in 2000, having operated for 75 years.

Bell and Spurr (1986a; Table 1, p. 2037) also list over 40 defunct collieries in the Klip River Coalfield, the most significant of which (over 10,000 tonnes per month RoM) are included as Table 11.

Coal was also mined in the southern Elandslaagte area of the Klip River Coalfield, being historically mined by the likes of Platberg, Elandslaagte and Natal Steam collieries. Of these, only the Newcastle Platberg Colliery was still operational at the time of the Bell and Spurr (1986a) paper. This colliery commenced operations in 1950 and produced both thermal and coking coal, mainly from the Top Seam, which was developed to a thickness of up to 1.6 m.

Since 1986, the number of active collieries has dropped to three, two of which only opened post 1986. Current operations include Shanduka Coal's Springlake Colliery (www.shanduka.co.za) and Forbes Coal's Magdalena and Aviemore collieries (http://www.forbescoal.com/). Advanced stage exploration projects include Ikwezi Coal's Newcastle Project (http://ikwezimining.com), Miranda Mineral Holdings Limited (http://www.mirandaminerals.com) Coal Division's Seshikhona, Yarl and Burnside/Boschoek projects, and Keaton's Braakfontein Project.

Shanduka's Springlake Colliery is situated to the immediate north of the town of Dannhauser. This colliery has been in operation for over 30 years and is one of South Africa's largest producers of anthracite. Coal is mined from both the Top and Bottom seams, with the main production coming from the Bottom Seam, with a seam width of 1.8 m. The underground operation consists of one incline shaft and one vertical shaft, with the deepest mining taking place 120 m below surface. The surface operation comprises two opencast pits, which are mined to an average depth of 30 m. According to previous owner Petmin's web site (http://www.petmin.com) the colliery has a resource base of some 24.44 Mt mineable in situ tonnes (MIST), and produces 1.04 Mt of RoM coal a year, with 413,000 t coming from underground and 628,000 t from the opencast operations. Dependent on the yield this provided for sales tonnages of around 570–600,000 tpa. By April 2014 the opencast resources were nearly mined out and production was focussed on the Umnotho shaft underground sections (Van der Merwe, 2014).

Forbes Coal provides all of their technical documents on their website, which may be freely downloaded. Their Magdalena Colliery's opencast operation and decline are situated 22 km to the north-east of the town of Dundee. The Magdalena property, which consists of the Magdalena underground mine, the Hilltop exploration area, and the

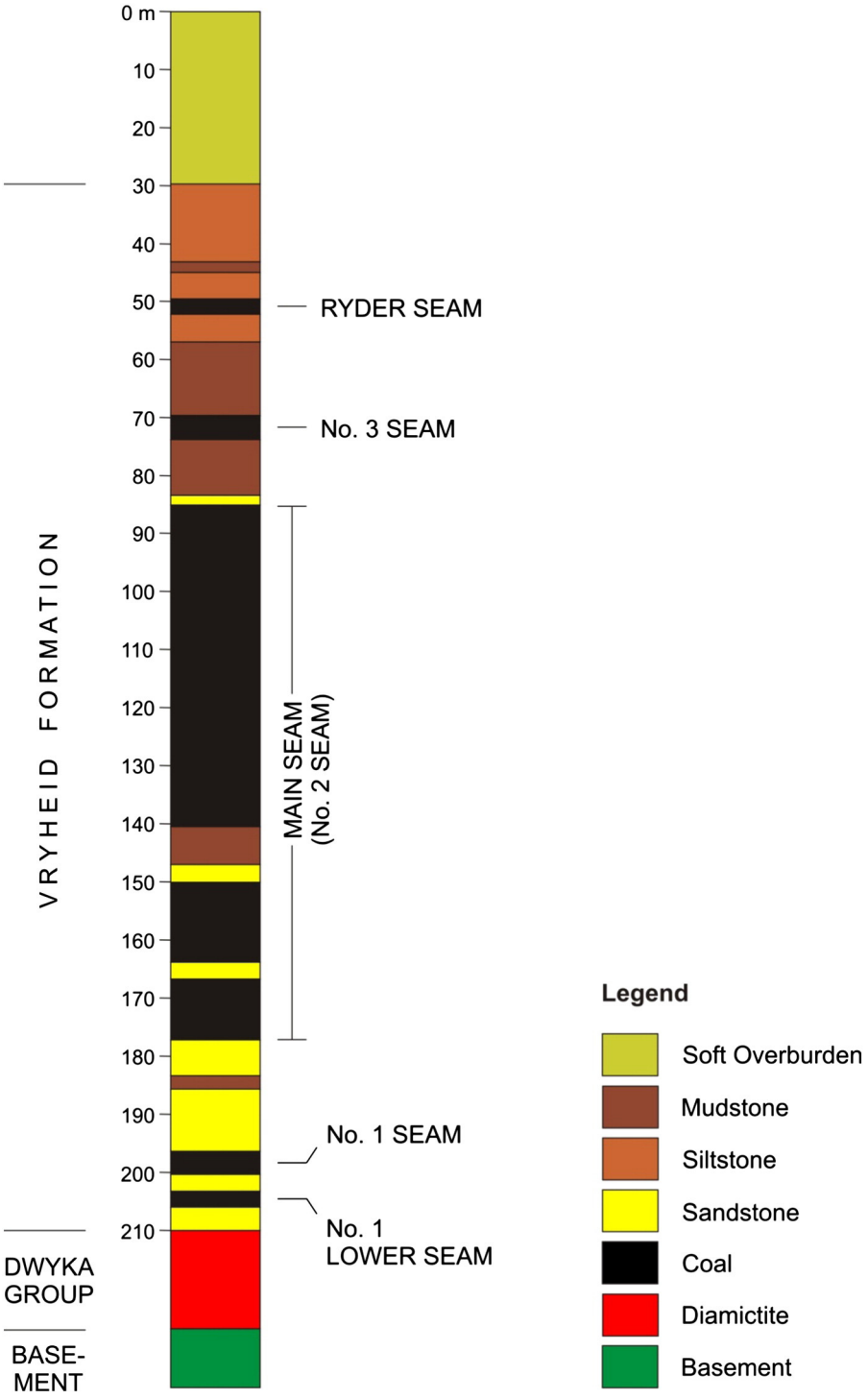

Fig. 26. Generalised stratigraphy of the South Rand Coalfield. After Dempers (2011).

Table 9
Raw coal qualities (adb) for the various seams and plies at the Springfield Colliery. From Henderson (1986).

Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	FC (%)
No. 3 (Ply 2)	15.59	42.6	17.2	3.9	36.3
No. 3 (Ply 1)	22.21	20.3	23.0	5.2	51.5
No. 2 (Ply 4)	22.70	21.9	25.1	4.5	48.5
No. 2 (Ply 3)	24.17	16.8	26.0	4.8	52.4
No. 2 (Ply 2)	22.52	21.4	20.9	4.8	52.8
No. 2 (Ply 1)	17.87	35.4	18.5	3.8	42.3
No. 1	22.34	23.4	21.9	4.4	50.3

Magdalena opencast, has a compliant Measured and Indicated coal resource of 59.13 Mt, with an additional 13.43 Mt in the Inferred category for Hilltop (Muller et al., 2012). The average theoretical yield for both seams at a RD of 1.50 is 80.31% (Muller et al., 2012). Press releases by Forbes Coal document average monthly RoM production at Magdalena of around 86,800 t during 2013–2014. The 2013 financial year sales figures are documented on the web site as being 958,000 t.

Forbes Coal's Aviemore Colliery is situated some 10 km to the north of the town Dundee. The mine footprint area has recently been significantly expanded and now has total Measured and

Indicated GTIS resources of 41.59 Mt, with an additional 17.78 Mt in the Inferred category (Muller et al., 2012). The original Aviemore mine area has only a small resource remaining. Coal is mined by underground bord-and-pillar methods on the 1.8–2 m thick Bottom Seam.

Miranda Mineral Holdings Limited Coal Division (Miranda) is an exploration company which has focused its attention on the Klip River Coalfield around the Dundee, Glencoe and Dannhauser areas. Their Yarl Project lies some 10 km to the north of Dannhauser and is the subject of a Competent Person's Report (CPR) by Peet Meyer (Meyer, 2008), who subdivided the resource into a southern Normal Block and northern Uplifted Block. Meyer (2008) provides an average width for the Top Seam of 1.18 m, and for the Bottom Seam 0.93 m, for the deeper Normal Block. The average depth for the Top Seam given is 141 m and for the Bottom Seam is 159 m. The limited analytical data suggests that both the Top and Bottom seams are low Ash bituminous coals.

Miranda's Sesikhona Project is located approximately 11 km west of the town of Dannhauser. This project covers four contiguous farms namely Verdriet, Weltevreden, Kliprots and Kliprand, and covers an area of 864 ha. It is the first of the group's exploration projects that will be converted to a mining operation. The deposit consists of high grade anthracite of which approximately 40% is mineable using surface mining techniques. The DMR granted Miranda a mining right for Sesikhona on the 8th of January 2009. Miranda also holds rights to the Burnside and Boshoek projects to the west of the town of Glencoe. Here both the Top (1.05–1.25 m) and Bottom (1.4–2 m) seams both occur at potentially mineable underground thicknesses.

Ikwezi Mining holds a number of advanced exploration projects, the most advanced of these being their 70% held Ntendeka Colliery (Newcastle Phase 1 Project), which has a JORC compliant resource of 294 Mt of coal, predominantly on the Top Seam.

Keaton's Braakfontein Project area is located some 10 km east-southeast of the centre of the town of Newcastle. The complete succession of coal seams as previously documented for the northern Klip River Coalfield are present, but the project is focussed on the resources of the Top Seam.

The southernmost areas of the Klip River Coalfield are also currently the focus of exploration activity, with renewed interest being taken in the area surrounding the defunct Platberg Colliery, as well as a new integrated coal and power project in the Colenso area (James, 2014).

In conclusions, exploration boreholes drilled in the Klip River Coalfield must now number between three and four thousand and many properties have also been investigated from surface outcrop by means of prospect adits. Currently a number of new exploration programmes are also being undertaken, many of which are fairly far advanced and may lead to new mines being opened.

4.5.1.4. Research history. Some forty years after the initial discovery North was commissioned to investigate and report on coal occurrences in the area. Since North's (1881) report, a number of papers and memoirs have been written concerning Coal in the Dundee area, most notably those of Du Toit (1918), Wybergh (1925), Blignaut et al. (1940) and Blignaut et al. (1952), who prepared a comprehensive report on the area for the Department of Mines and Economic Affairs.

In the mid-1970s a resurgence of exploration interest occurred and it was in this period that Visser et al. (1976) published the then most comprehensive account of the area. Subsequent to this report four major references occur that have a bearing on the Klip River Coalfield. These are the seminal paper on the Klip River Coalfield in the Mineral Deposits of Southern Africa (Bell and Spurr, 1986a), Angus Christie's PhD Thesis (Christie, 1988), a Geological Survey Bulletin on sedimentary models for coal formation in the Vryheid Formation of northern Natal (Tavener-Smith et al., 1988) and the overview of the Klip River Coalfield in Snyman (1998).

Wakerman (2003) documents the Milnedale Project on the farm Yarl 2962, presenting an overview of the general geology of the area, as well as raw and wash qualities for the target seam. This area was subsequently the focus of exploration work by Miranda and others (Meyer, 2008). Various other CPRs pertaining to Miranda's properties in the Klip River Coalfield are available on the company's website.

Table 10
Major collieries in the Klip River Coalfield that were operational in 1985 but are now defunct.
From Bell and Spurr (1986a).

Colliery	Average RoM (per month)	Coal type produced
Indumeni	30,000	Coking coal
Northfield	55,000	Coking coal
Kilbarchan	160,000	Thermal and coking coal
Ballengeich	36,000	Thermal coal
Durban Navigation	120,000	Coking coal
Newcastle Platberg	26,000	Thermal coal
St George's (opencast)	5–10,000	Coking coal
Dewars Anthracite	20,000	Anthracite
Natal Coal Exploration	14,000	Anthracite

4.5.1.5. Geology. Unlike in the northern coalfields of the MKB, where palaeotopography played a major role, in the Klip River Coalfield (and in the Utrecht and Vryheid coalfields) the basement palaeotopography does not impact on coal seam development. This is due to the fact that the basement palaeotopography is either levelled out or covered by the filling of the Dwyka Group, Pietermaritzburg and lower Vryheid formations, prior to peat formation in middle Vryheid Formation times.

No exposures of basement rocks occur in the Klip River Coalfield and few boreholes have penetrated through the Dwyka Group into basement. From the published geological map (1:250,000 2830 Dundee map) it is evident that the basement to the Klip River Coalfield should be composed of metasedimentary and metavolcanic rocks of the Swazian System, pre-Pongola undifferentiated granites, and metasedimentary and volcanic rocks of the Namibian Natal Structural and Metamorphic Province.

Outcrops of the Dwyka Group are rare in the Klip River Coalfield, with only two documented occurrences on the 1967 1:50,000 geological sheets 2829B (Elandslaagte) and 2830A (Dundee). In the Mazabeku River Valley some 91 m of massive bluish diamictite are exposed, and along the Sibindi River some 61 m (Visser et al., 1976). The diamictite is unstratified and has a fine-grained siltstone to mudstone matrix. Included clasts range from mm sized grains to boulders of over 1 m in diameter and the most common clast types are of pinkish granite and grey gneiss. In the few deep boreholes drilled through to the basement it is apparent that the thickness of the Dwyka Group varies considerably and that the floor topography is uneven.

The Dwyka Group is conformably overlain by dark, blue-grey to black, micaceous siltstones and mudstones of the Pietermaritzburg Formation (Ecca Group), which in places rests unconformably on the basement. As for the Dwyka Group, very few exploration boreholes penetrate the entire thickness of the Pietermaritzburg Formation. The limited borehole information available shows a maximum thickness

Table 11
Major defunct collieries in the Klip River Coalfield.
From Bell and Spurr (1986a).

Colliery	Average RoM (per month)	Coal type produced
Elandslaagte	10,000	Thermal coal
Natal Steam	11,000	Thermal coal
Natal Navigation	40,000	Thermal and coking coal
St George's	13,000	Coking coal
Burnside	40,000	Coking coal
Dundee	10,000	Thermal coal
Wallsend	11,000	Anthracite
Natal Cambrian	20,000	Steam coal
Natal Coal Exploration	60,000	Thermal coal
Ingagane	30,000	Thermal coal

for the unit of around 90 m (Visser et al., 1976). The Pietermaritzburg Formation shows a general coarsening-upward trend, grading upwards into rhythmically alternating siltstones and bioturbated sandstones of the lower part of the Vryheid Formation.

The total thickness of the Vryheid Formation in the Klip River Coalfield is approximately 310 m. Based on the original work of Blignaut and Furter (1940, 1952), Tavener-Smith (1983) and Christie (1988) proposed three informal lithostratigraphic subdivisions for the Klip River Coalfield (Fig. 27), these being: a Lower Sandstone unit dominated by medium- to coarse-grained sandstones deposited by prograding high-constructive lobate or braid deltas; a middle Coal Zone, which varies in thickness between 30 and 80 m (Tavener-Smith et al., 1988) and has coal seams associated with fluvial deposits; and an Upper Zone once again dominated by prograding high-constructive lobate or braid deltas. The Lower and Upper zones may also be distinguished in the field by their trace fossil assemblages (Christie, 1988; Stanistreet et al., 1980).

The upper sandstone unit is only 15 m thick in the north of the coalfield, but thickens and becomes progressively more sandstone rich to the south. The overlying Volksrust Formation in the Klip River Coalfield outcrops along the Biggarsberg range, on high ground around Dannhauser, Glencoe, and Newcastle, and in small outliers on Mpate Mountain. The Volksrust Formation has a maximum measured thickness of 183 m (Steart, 1920).

4.5.1.6. Coal seams. Five seams are known (Fig. 27) and various nomenclatures exist for these seams. We here follow Bell and Spurr (1986a), with the nomenclature of Christie (1988) in parenthesis. Only two seams, known as the Top (or No. 3 Seam) and Bottom (or No. 2 Seam) seams, are usually commercially exploited, with some resources also attributable to the Extra-Bottom (or No. 1 Seam). These seams occur stratigraphically approximately 200 m above the top of the Pietermaritzburg Formation and 120 m below the base of the Volksrust Formation.

The Top and Bottom seams are separated by between 0.3 and 15 m of predominantly coarse-grained to pebbly, cross-stratified sandstone, which fines upwards into carbonaceous siltstone and mudstone. A number of minor seams are also impersistently developed.

The Extra-Bottom Seam forms the stratigraphically lowest coal horizon in the coalfield. This seam is not usually targeted for economic extraction and as such is rarely intersected in boreholes. Due to this fact, its distribution is not as well-understood as that of the overlying, commercially exploitable seams. The Extra-Bottom Seam attains its maximum development to the north and northeast of Durnacol village. Immediately north of the town of Dannhauser it forms a single seam approximately 0.60 m thick, whereas elsewhere it may be spilt by a sandstone parting of between 0.50 and 1.8 m. The seam is only sporadically developed in the area between Dannhauser and Dundee (being complex and discontinuous). In the vicinity of Dundee and Wasbank (and immediately to the southeast of these towns) the Extra-Bottom Seam is developed as a zone of thin, discontinuous, dull and shaley coal, each up to 0.35 m thick, but more normally being less than 0.15 m. This zone is highly bioturbated by *Siphonichnus* traces (Christie, 1988).

The Bottom Seam is one of the two major economic seams of the Klip River Coalfield. The thickest development of this seam occurs in the east central parts of the coalfield, and it thins towards the west and southwest, thickening again to the far south in the vicinity of the town of Colenso. This seam is also important in that it displays a characteristic and persistent internal macroscopic composition which has been used by previous workers as an aid to correlation (Christie, 1988). Between Dundee and Elandslaagte, and as far north as Dannhauser, the lower part of the seam comprises between 0.18 and 0.25 m of mixed, mainly bright or bright coal. This is overlain by a clastic parting which varies in thickness from 0.10 to 0.60 m (averaging 0.20 m). This parting is mainly comprised of a carbonaceous mudstone capped by a thin sandstone. The upper part of the seam is more complex than the lower interval, and in the area between Dundee and Dannhauser it is made up of bands of mixed- to mixed, mainly bright coal, separated by a clastic parting.

Whilst variable, the immediate roof to the Bottom Seam is usually formed by a well-cemented medium- to coarse-grained sandstone (previously sometimes referred to as the Gus Sandstone in old AAC reports). The remainder of the parting to the floor of the Top Seam is variable in thickness, being up to 15 m in places. It is usually formed by a fining-upward sequence dominated by massive to cross-stratified, coarse-grained sandstone, which in places where rapid abandonment of the fluvial system took place, also forms the immediate floor to the Top Seam. Where the abandonment phase was more gradual the immediate floor to the Top Seam may also be composed of carbonaceous sandstone.

The Top Seam is the uppermost economic coal within the Klip River Coalfield. It attains its maximum thickness of 3.6 m to the northeast of Alcockspruit and Dannhauser (Christie, 1988) and is also thicker in the northern reaches of the coalfield. Elsewhere it is usually developed to a thickness of between 0.80 and 3.6 m. Southeast of the Dundee–Vryheid line the seam thickness decreases to between 1.2 and 1.8 m. The Top Seam comprises mainly dull coal. Clastic partings within the seam are rare and are only present to any real extent immediately north of the town of Dundee. It should be noted that at places the Bottom Seam merges with the Top Seam to form the main economic horizon, which is informally referred to as the "Main" Seam.

The immediate roof to the Top Seam is variable, but is often formed by a fine- to medium-grained sandstone with carbonaceous laminae or else a coarse-grained competent sandstone. Above the Top Seam, the succession comprises approximately 12–16 m of sandstone and very coarse sandstone to the floor of the Marker Seam (the No. 4 Seam of Christie, 1988). This regionally extensive thin seam (rarely thicker than 0.15 m) is referred to as the "Marker" Seam (Fig. 28) due to it being invaluable as delineating the uppermost level of the Coal Zone during exploration drilling. This seam is often capped by a thin glauconite rich sandstone.

Thinning of the economic seams, both to the north and south of the Klip River Coalfield is evident. In the south, beyond Ladysmith and Pomeroy, no commercially exploitable coal seams have been intersected. In the northern part of the coalfield the Top Seam is thickest and has been most extensively worked, whilst in the central area, the Bottom Seam is thicker and contains better quality coal. Between Newcastle and Pomeroy area the Top Seam is again of greater importance, the Bottom Seam not being developed to an exploitable thickness.

As noted above roof and floor conditions of the coal seams are highly variable, with mudstone, siltstone and micaceous sandstone being present. In general, the Top Seam roof is weaker than that of the Bottom Seam, as it more usually comprises micaceous sandstones. The coarse-grained, cross-stratified sandstone that forms the parting between the seams creates a competent roof for the Bottom Seam. The floors to both the seams are commonly incompetent fine-grained sandstone or micaceous siltstone, or mudstone. No significant floor rolls have been recorded, but irregular roof contacts occur, particularly to the Bottom Seam, where they are related to channel scour.

Gas is a common hazard in all mines in the coalfield and many disasters have resulted from methane explosions, most notably at the Old Campbell and St George's collieries. Gas is most commonly found in fissures associated with dyke intrusions.

4.5.1.6.1. Coal qualities. Historically the quality of the coal being produced from the Klip River Coalfield varied considerably according to the seam being mined and the proximity of the seam to dolerite intrusions. Bell and Spurr (1986a) provide a table of the typical qualities of some coals found in the coalfield. It should however be noted that these are not the qualities being mined today, nor those found in the majority of new exploration boreholes.

The Bottom Seam, where it is developed to a mineable thickness, is generally higher in quality than the Top Seam. In the central part of

the coalfield, where the Bottom Seam has been the most extensively mined, the best quality coals are still produced. To the north and south of this area, the quality deteriorates and the greater part of the production comes from the Top Seam. The quality of the coal in both Top and Bottom seams is quite variable, with changes in rank from bituminous to anthracite taking place over tens of metres. A notable feature of the Klip River Coalfield is the generally high sulphur and phosphorus content of the coal.

Generally the coals of the Klip River Coalfield have fairly good washing characteristics in terms of reduction of Ash content, whilst still providing economically acceptable yield values. In certain parts of the coalfield (e.g. at Kilbarchan Colliery) it was possible, by a two-stage washing process, to produce both a blend coking coal fraction and a middling thermal coal (Bell and Spurr, 1986a). In the central part of the coalfield at the Indumeni, Northfield, and Durban Navigation collieries, the Bottom Seam yielded a good coking coal, with an average swelling index (SI) in excess of 6.5 and a Roga index exceeding 60. At present no operational collieries in the Klip River Coalfield are producing coking coal, but some exploration potentials still exist for small coking coal resources.

For Springlake Colliery coal product qualities provided in the 2007 Mintek report show a CV of 29.71 MJ/kg, Ash of 11.90%, VM of 4.9%, with a FC of 80.2% and TS of 1.99%. The current typical product is a 15% Ash, 8–10% VM, less than 1.8% TS coal (Van der Merwe, 2014).

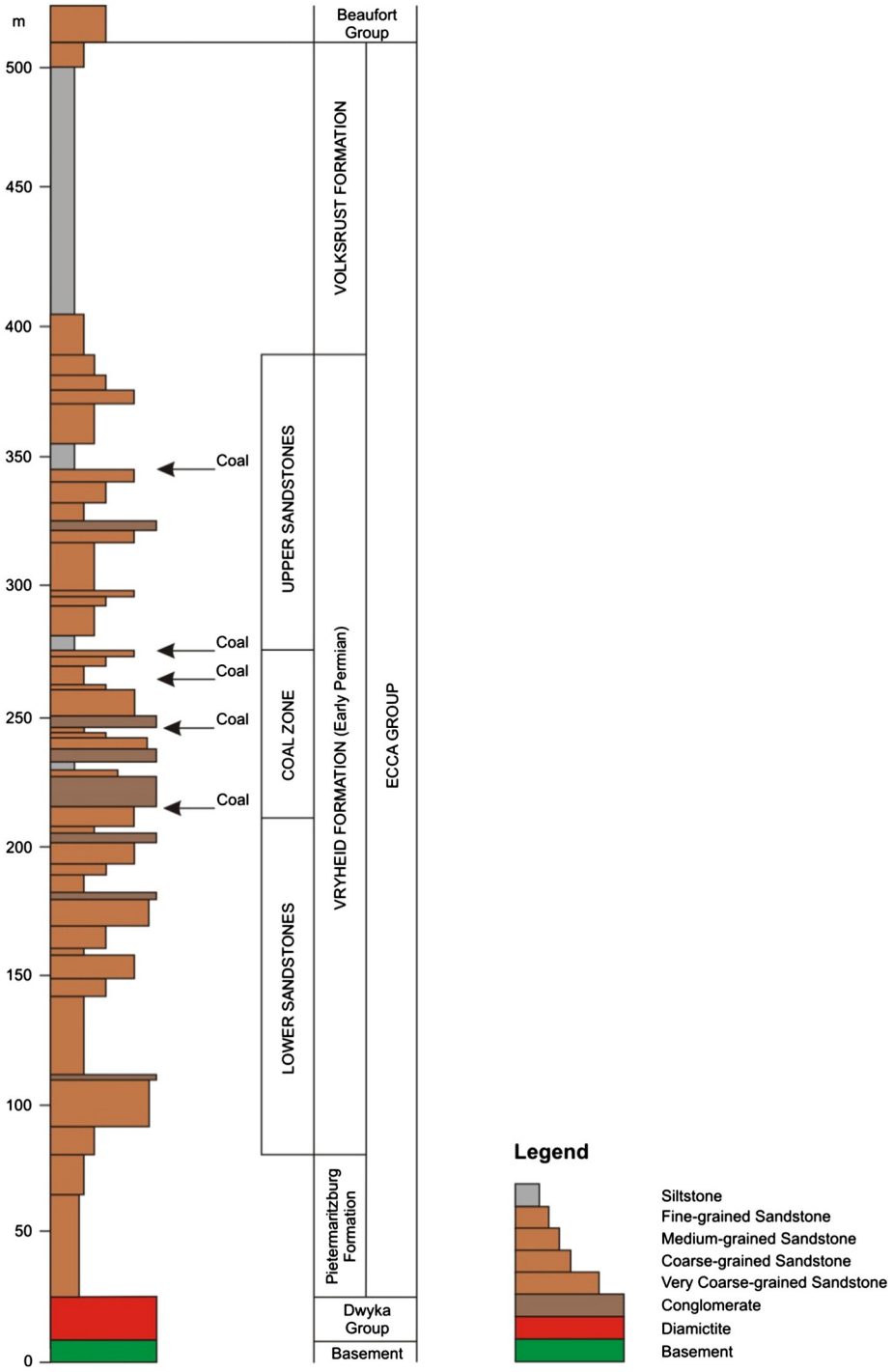

Fig. 27. Stratigraphic subdivision of the Klip River Coalfield.
After Roberts (1988b).

At the Magdalena Colliery coal qualities vary per area and per seam, but generally for the underground operations the washed coal (at a 1.5 RD) is a medium volatile (16.3% VM) bituminous coal with a high CV (29.60 MJ/kg) and a TS of 1.55%. The average theoretical yield for both seams is 80.31% (Muller et al., 2012). Product qualities (at a 1.5 RD float) for the old Aviemore mine underground sections are a FC of 77.76%, Ash of 13.34%, VM of 7.19% and TS of 2.01, at a 74.31% theoretical yield. The theoretical yields for a similar product (although with a higher TS of around 2.41%) are around 60% for the new resource areas at Aviemore (Muller et al., 2012).

4.5.1.7. Structure and intrusions. The coal zone has only a gentle dip to the south, usually being less than 3°. Steeper dips are however locally encountered in the vicinity of dolerite intrusions. Large scale displacements are fairly common, with faulting related to the intrusion of dolerite dikes and sills and extensional tectonics associated with the break-up of Gondwana. The maximum reported displacement in the Klip River Coalfield is 137 m, with an uplift of 229 m measured in an area to the north of the coalfield (Blignaut et al., 1940).

Based on petrological and chronological grounds nine types of dolerite sill have been distinguished (Blignaut, 1952), the four major ones being, from oldest to youngest, the Zuinguin, Utrecht, Ingogo, and Talana dolerites. Feldspar phenocrysts are characteristic of certain sills (e.g. the Talana sill). Linear or slightly sinuous dykes are common and appear to be concentrated in certain areas. Two weakly developed alignment trends, northwest–southeast and northeast–southwest, are apparent. Dykes range in thickness from a few centimetres to tens of metres and may or may not be associated with small displacements. Metamorphic effects are confined to local bleaching and induration at contacts together with burning or devolatilisation of the coal seam.

4.5.2. Utrecht Coalfield

4.5.2.1. Introduction. Although coal was first produced from the Utrecht Coalfield in the late 1800s, this coalfield has played only a minor role in South Africa's coal production, and at no time did it ever rival the importance of its neighbours, the Klip River and Vryheid coalfields (Fig. 1). Unlike the Klip River and Vryheid coalfields, coal from the Utrecht Coalfield (with the exception of coal from the Balgray Colliery), and some small coking coal deposits, has no special attributes that make it more marketable than other KZN coals. Development of the Utrecht Coalfield has furthermore been hampered by numerous problems including the lack of adequate infrastructure, the large amount of dolerite intrusions and certain quality problems intrinsic to the coal, most notably the moderately high sulphur and phosphorous contents, as well as the low AFT (Spurr et al., 1986).

4.5.2.2. Location. The Utrecht Coalfield covers an area of 500,000 ha within the magisterial districts of Utrecht and Paulpietersburg (Spurr et al., 1986). The coalfield extends from the town of Paulpietersburg in the north-east, in a south-westerly direction through the Elandsberg and Schurweberg mountain ranges. The western limit is defined by a barren, dolerite intruded area, which separates the Utrecht Coalfield from the northern portion of the Klip River Coalfield. In the north, where the Utrecht Coalfield lies adjacent to the Ermelo Coalfield, the boundary is drawn along the Pongola River and the Loskop fault.

4.5.2.3. Exploration and exploitation history. According to Spurr et al. (1986) coal was first produced in 1889 and by 1896 the Welgedacht Colliery had begun production (Barker, 1999). After the incorporation of Utrecht into Natal (now KZN) in 1902, coal exploration in the area increased and resulted in 1910 of the opening of the Utrecht Colliery. This was an adit mine driven into the hillside to the north of the town of the same name. Many other topographic adit mines sprang up but unfortunately the records of many of these small hillside adit operations were either never kept or have been lost.

Exploration work for coking coal was carried out by Iscor between 1939 and 1945, and by the Irrigation Department (for the then Geological Survey) between 1952 and 1959 (Sehlke and Van der Merwe, 1959). Intense prospecting of the Utrecht Coalfield in the early and middle 1960s led to the opening up of collieries such as Balgray, and the Zimbutu and Umgala sections of the Welgedacht Exploration Company. Active exploration in the coalfield was continued during the 1970s by companies such as Iscor, Trans-Natal, Anglo American, Aloe Minerals, and the Rand London Corporation. During this period several new collieries were opened, all of which have since closed through depletion of resources or because of geological difficulties. At the end of 1981, there were eight collieries operating in this coalfield, four producing anthracite, three thermal (steam) coal, and one coking coal. None of these collieries are still active and are therefore included in Table 12 documenting the defunct collieries in the Utrecht Coalfield.

From the time when mining started until the early 1960s no more than four or five collieries were operative at any one time and the bulk of production came from only three collieries, these being the Utrecht Colliery and the two Northern Natal Navigation operations (Dumbe and Makateeskop).

Two mines, owned by D and G Mining (D and G Anthracite) and the Rand London Corporation (Zoetmelk Colliery), were operational in the area in the past, and were contiguous to each other. D and G Anthracite were active from 1979 to 1981 and produced approximately 240,000 product tpa of anthracite (Spurr et al., 1986). Exploration on the adjacent Zoetmelksrivier properties was undertaken in the 1940s by the Geological Survey of South Africa, with subsequent drilling undertaken by Clydesdale (TVL) Collieries Limited in 1964–1965. During the 1980s the Alfred Seam was subsequently exploited by open-pit and underground mining on the farms Zoetmelksrivier 86, producing approximately 200,000 product tpa of anthracite (Spurr et al., 1986). Due to various setbacks and financial constraints the operation was placed under liquidation in 1991. Auger Mining (Pty) Limited used the opencast pit high walls left exposed on Vryheid 159 to extract a bulk sample from the coal seam using a 0.9 m diameter auger (Fig. 29). This coal was mined to provide information on the suitability of the machinery and the marketability of the coal. Zoetmelksrivier 86 was one of the 18 farms identified in the 2007 Mintek report to have high potential, and to be worthy of additional exploration.

The 1981 sales tonnage derived from the Utrecht Coalfield was just over 3.5 Mt, which possibly represents the highest level of production at any time since mining commenced in the 1890s (Spurr et al., 1986). The 2010 DMR coal report does not list any active collieries in the Utrecht Coalfield; although a number of old discard dumps are currently being re-processed and the senior author is aware of one small opencast pit operation supplying a coking coal fraction to Arcellor–Mittal in Newcastle (Hill, pers. comm.). Current exploration is targeting fairly small (less than 10 Mt), fairly deep (150 m) anthracite resources, and collieries that previously closed with reserves. In mid-2014 a private exploration company was targeting the area to the northwest of the coalfield for anthracite and export thermal coal, and a number of other small exploration targets had been drilled out in the area to the east-northeast of the town of Wakkerstroom.

4.5.2.4. Research history. The first geological reference to the Utrecht Coalfield is that of Molengraaff (1898) with the coalfield being first mapped geologically by W.A. Humphrey in 1912. The first authoritative account detailing with the coal occurrences is that of Wybergh (1925). Further mapping was undertaken between 1937 and 1939, which eventually led to the publication by Blignaut et al. (1952). In a Bulletin of the Geological Survey of South Africa Sehlke and Van der Merwe (1959) provide a record of boreholes 1 to 31 drilled for the Department of Mines in the Utrecht Area. Following a review of the coalfield by Visser et al. (1976), the most recent geological publication on the coalfield is the compilation of Spurr et al. (1986) and the various works of Roberts (1986, 1988b) who undertook the first detailed

Fig. 28. The "Marker" Seam in the Klip River Coalfield.

study of the parameters affecting coal distribution. Since this time little academic research has been taken on the Utrecht Coalfield.

4.5.2.5. Geology. As in the Klip River Coalfield the basement does not play a role on the development, distribution or quality of the coal seams. Dwyka Group rocks are absent or thinly developed over most of the coalfield, with mudstones and siltstones of the Pietermaritzburg Formation directly overlying the basement in most places. As for the Klip River Coalfield, the mudstones and siltstones of the Pietermaritzburg Formation coarsen towards the top, grading into delta front and delta plain bioturbated sandstones and siltstones of the lower part of the Vryheid Formation (Cadle and Hobday, 1977).

The total thickness of the Vryheid Formation in the area ranges from approximately 300 m in the west, to 380 m in the east. The coal zone, including the sedimentary succession from the Coking to the Fritz seams (Fig. 30), comprises fluvially dominated, fining-upward, conglomeratic sandstone cycles, usually capped by carbonaceous fines or coal. One or more sandstone dominated, regressive deltaic depositional sequences overlie the coal zone.

The overlying Volksrust Formation occurs at surface towards the northern part of the coalfield. Spurr et al. (1986) note it as being around 70 m thick in a borehole drilled on Schurvekopje 128, which was collared in Beaufort Group rocks. Like elsewhere in KZN this unit is dominated by dark grey siltstones and mudstones.

4.5.2.6. Coal seams. From the base up the four economic seams present in the coal zone of the Utrecht Coalfield are the Coking, Dundas, Gus and Alfred seams (Fig. 30). Other seams such as the Targas, Rider, Fritz and Eland (Fig. 30) are too thin to be mined based on current mining equipment capabilities.

The Coking Seam (Fig. 30) is generally thin, reaching a maximum thickness of 1.5 m at Makateeskop (Spurr et al., 1986), but with an average thickness of only 0.9 m. The seam generally comprises good quality, mainly bright, thinly banded coal and includes intra-seam partings of sandstone or siltstone where it thickens. Roof and floor rocks are normally competent, both being either medium- to coarse-grained or medium- to fine-grained sandstones.

The Dundas Seam (Fig. 30) occurs approximately 15 m above the Coking Seam and has a maximum documented thickness of 2.6 m (Spurr et al., 1986). In the west of the Utrecht Coalfield the thickness of the Dundas Seam is highly variable and where exploited, the seam attained a thickness of approximately 2 m. It generally comprised an upper mixed dull and bright ply, a central bright portion, and a bottom, mixed coal and fines zone. It yielded bituminous coal and was also worked by Kangra Holdings at Longridge as a source of export quality anthracite. According to the Mintek (2007) report the Dundas Seam accounts for only 8% of the remaining resource tonnage in the Utrecht Coalfield. Where mined historically the roof of the Dundas Seam was generally competent, being composed of medium-grained sandstone. The floor was incompetent carbonaceous siltstone and mudstone, which caused various mining problems. In the east of the coalfield the seam is thin, yet the absence of the bottom and poorer top portions improves its quality. Here both the roof and floor are of variable competence (Spurr et al., 1986).

The Gus Seam (Fig. 30) occurs approximately 17 m above the Dundas Seam and was the most extensively worked seam of the Utrecht Coalfield. It has a maximum thickness of 3.3 m and attains an average thickness of over 1 m in the southern part of the coalfield. To the north the seam splits into an Upper and Lower sub-seam, separated by a 3–12 m thick sandstone parting. In the vicinity of the town of Utrecht the Gus Seam may be divided into three distinct quality zones or plies. The upper part of the seam is mainly dull coal, the central part predominantly bright coal, and the bottom part is generally poor quality dull coal, with a consistent siltstone or mudstone parting. The seam roof and floor competence is variable, being moderately high in the vicinity of the town of Utrecht, to extremely poor at the Kempslust Colliery, where thinly laminated fine-grained sandstone formed an extremely incompetent roof (Spurr et al., 1986). According to the Mintek (2007) report the Gus Seam accounts for 30% of the remaining resource tonnage in the Utrecht Coalfield, ranking it second behind the Alfred Seam.

The Alfred Seam (Fig. 30) occurs approximately 14 m above the Gus Seam. The seam has a maximum thickness of 3.8 m and averages 1.9 m. At the now defunct Umgala and Zimbutu collieries the mineable section was some 3 m thick (Spurr et al., 1986). The coal is generally dull to dull-lustrous, with interbanded bright coal. In places e.g. at Zoetmelksrivier, the Alfred Seam is a composite seam (composed of three separate plies) which ranges in thickness from 1.5 m to 3 m. The upper part of the seam consists of carbonaceous mudstone and poor quality high Ash coal (>40%). The roof to the Alfred Seam was generally reported to be moderately competent, except near areas of dolerite dyke intrusion. The floor was normally formed by a medium- to coarse-grained sandstone, strong enough to support mechanical equipment. Historically the Alfred Seam was not as extensively worked as the Gus Seam for reasons of quality. In 1981 however, the bulk of the Utrecht Coalfield production was being won from the Alfred Seam (Spurr et al., 1986) as it was worked by both the Zimbutu and Umgala collieries, as well as by the Zoetmelksrivier 86 Colliery. The Mintek (2007) report ranks the Alfred Seam as the most important in the Utrecht Coalfield with some 54% of the remaining resource tonnage attributed to it.

4.5.2.6.1. Coal qualities. The quality of the coal varies from high rank, low volatile anthracite to coking coal. Spurr et al. (1986) provide a table

Table 12
Major defunct collieries in the Utrecht Coalfield. NNNC = Northern Natal Navigation Collieries.
From Spurr et al. (1986).

Colliery	Average product tonnes (per annum)	Coal type produced
Utrecht	235,000	Anthracite
Dumbe (NNNC)	175,000	Thermal and coking coal
Makateeskop (NNNC)	365,000	Thermal coal
Umgala (underground)	822,000	Thermal coal
Umgala (surface)	522,000	Thermal coal
Zimbutu	310,000	Thermal coal
Balgray	370,000	Anthracite
Longridge	400,000	Anthracite
Kempslust	235,000	Coking coal
Zoetmelksrivier 86	20,000	Anthracite
Elandsberg Anthracite	84,000	Anthracite
Boemendaal Consolidated	240,000	Anthracite

of typical colliery products, as well as raw borehole sample values, which illustrate the range of qualities. They further note that the Ash content is seam specific, with the Alfred Seam generally containing over 25% raw Ash, whilst the Gus and Dundas in places contained the lowest recorded Ash levels in South African coals, with raw values as low as 5%. As for the Klip River Coalfield the distribution of VM is controlled by dolerite distribution, sill thickness and temperature of intrusion. TS in the borehole samples provided in Spurr et al. (1986) range from a low of 0.6 for the Gus and Coking seams, to a high of 7.5% for the Alfred Seam on Klipfontein 31.

4.5.2.7. Structure and intrusions. Five major dolerite intrusions are recognised within the Utrecht Coalfield (Spurr et al., 1986) and dolerite intrusions significantly affect the rank and quality of the coals in the coalfield. They are also the main cause of any structural discontinuities and faults, with throws of up to 150 m documented where dolerite sills (particularly the Zinguin Sill) intrude through the coal zone (Spurr et al., 1986). Sills that occur below the coal zone have a greater metamorphic effect on the coals than sills that occur above the coal zone. Of the dolerites of the Utrecht Coalfield the Zuinguin Sill appears to have had the lowest temperature of intrusion, as, even with its great thickness, it can approach within 50–60 m of a seam and have relatively little effect on the coal (Spurr et al., 1986).

4.5.3. Vryheid Coalfield

4.5.3.1. Introduction. Historically the Vryheid Coalfield was an important producer of high quality coking coal and anthracite, producing the highest quality anthracite in South Africa. It has however been extensively mined and in mid-2014 only one significant mine was producing, as well as some ongoing small scale topographic mining and dump reclamation.

4.5.3.2. Location. The Vryheid Coalfield is separated from the Utrecht Coalfield by an area that does not preserve coal due to Cenozoic to Recent erosion. The coalfield is oval in shape with an east–west long axis. The potential coal-bearing area extends from the town of Kingsley in the west to Louwsburg in the east and from Nkambule in the north to Gluckstadt in the south. The total area of the coalfield is some 2,500,000 ha, of which approximately 15% is considered to be coal bearing (Bell and Spurr, 1986b).

4.5.3.3. Exploration and exploitation history. According to Bell and Spurr (1986b) the earliest recorded commercial exploitation in the Vryheid Coalfield was in 1898, with coal being mined from the Hlobane and Zuinguin mountains. Unlike in the Dundee area the rail line only reached Vryheid in 1906 and it took the creation of a branch line in 1908 to open up the development of the Hlobane sector. The expansion of the Vryheid Coalfield received a welcome boost in 1913 with the establishment of South Africa's first coke oven to the east of the town of Vryheid. In 1916 Natal Ammonium opened its anthracite mine in the Ngwibi Mountain area and by 1923 the coalfield was producing around 2 Mtpa (Bell and Spurr, 1986b). Although Bell and Spurr (1986b) list 14 active collieries for the Vryheid Coalfield, none of these are still being mined and the most important of these are included below as now defunct collieries (Table 13).

Of these the largest was the Hlobane Colliery, which began life in 1909, and mined coking coal for its own coke batteries. This mine was unfortunately also the site of a gas explosion in 1944 that killed 57 people, as well as a second some 39 years later to the day, which killed 68, ranking it as the second worst coal mining disaster in South Africa after Coalbrook. Heritage Colliery began production in 1978 (Bell and

Fig. 29. Local stratigraphic succession in the historic contour surface mine (Pit A; old D and G workings) on the farm Vryheid 159, showing the holes in the lower part of the Alfred Seam left by the auguring operations.

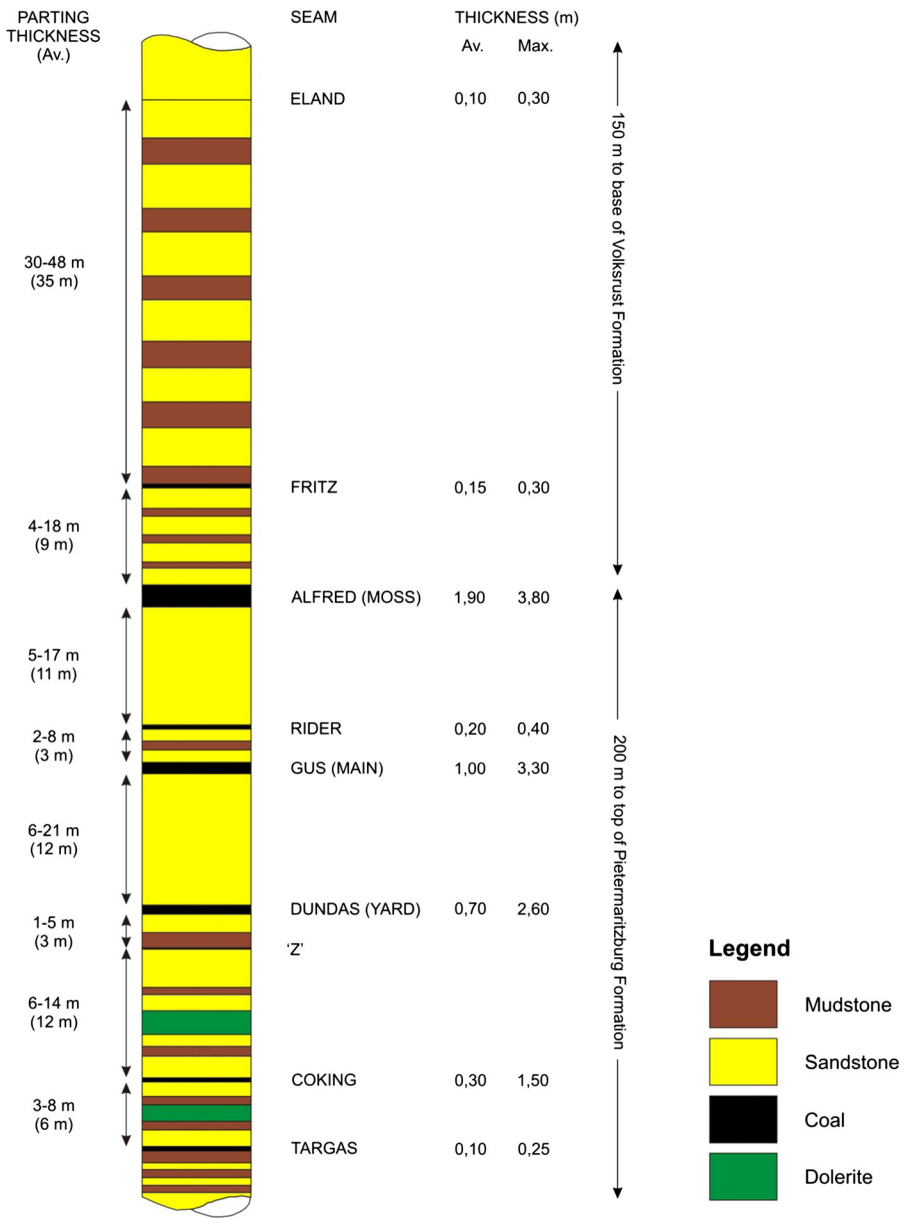

Fig. 30. General stratigraphy of the coal zone in the Utrecht Coalfield. Older seam terminology is in parenthesis. From Spurr et al. (1986).

Spurr, 1986b) and produced bituminous coal for the local and export markets on the Lower Dundas Seam. This defunct mine has recently become the focus of renewed exploration and exploitation interest.

Presently only Keaton's Vaalkrantz Colliery is operating in the coalfield. This underground mine is situated some 14 km east of the town of Vryheid near the southern end of the coalfield. It was historically mined, and has been in current production since 2003. At this time a small tonnage of anthracite from the Alfred and Gus seams is produced, with the primary product sold into the domestic metallurgical market and a secondary product sold into the Brazilian iron ore pelletising market. A coal briquetting plant has recently been brought into production on the Property. Keaton also owns the Koudelager Project, an advanced drilled out development property to the west of the mine.

Through its acquisition of Riversdale Mining, Rio Tinto has a 74% stake in the Riversdale Anthracite Colliery (RAC), an undeveloped anthracite resource in the southern reaches of the Vryheid Coalfield. As for the Utrecht Coalfield current exploration is ongoing within the rest of the coalfield, but mostly targeting only relatively small tonnages of high quality anthracite.

4.5.3.4. Research history. The first geological report was written in the late 1800s (Molengraaff, 1898) and part of the area was later mapped by W.A. Humphrey in 1912 and 1913. Several other early contributors to the literature on this coalfield include Heslop (1917), Du Toit (1918), Steart (1920), Wybergh (1925), and Humphrey and Krige (1932). The most comprehensive historical report on the area is that of Blignaut et al. (1940). Bell and Spurr (1986a) give a general overview of the stratigraphy and sedimentology of the lower part of the Karoo Supergroup, including the coal-bearing Vryheid Formation.

4.5.3.5. Geology. The general stratigraphy of the Vryheid Coalfield is very similar to that of the Utrecht Coalfield. The basement to the Vryheid Coalfield is varied, being composed of metasedimentary rocks of the Archean Swaziland Supergroup, metaquartzites and lavas of the Mesoarchaean Pongola Supergroup, and post-Pongola aged granitic and diabase intrusions.

The Dwyka Group is well developed, with an average thickness of some 150 m. It is however appreciably thicker in pre-Karoo glacial valleys and thinner or absent over pre-Karoo basement highs. It is not

well known from borehole data but exposures occur to the north of the now defunct Vryheid Colliery and in the valley between the Enyati and Thabankulu mountains (Bell and Spurr, 1986b). Good outcrop sections of the Dwyka Group also occur along the R34 road to Melmoth, and are well exposed in the valley en route to the old Denny Dalton gold mine. Like elsewhere in the MKB the Dwyka Group is composed of a basal sequence of diamictites, with various basement clasts up to 3 m in diameter. This is overlain by a cross-stratified sandstone unit, which grades upwards into dark grey siltstones and mudstones (Bell and Spurr, 1986b).

The overlying Pietermaritzburg Formation also averages 150 m in thickness (Johnson et al., 1975). It is well exposed in the Zuinguin (Zungwini) tunnel (Barker, 2014) and as for the Klip River and Utrecht coalfields, is dominated by blue-grey siltstones and mudstones attributed to deposition in deep water. The upper contact of this formation is transitional into delta front and delta plain siltstones and sandstones of the basal Vryheid Formation, which commonly have abundant trace fossils present. The overlying coal-bearing succession of the Vryheid Formation ranges in thickness from 150 to 220 m and comprises a stacked succession of upward-fining, coal-capped cycles. These cycles begin with cross-stratified coarse-grained sandstones, which fine upwards into siltstone, carbonaceous mudstone and coal.

4.5.3.6. Coal seams. At least nine discrete seams have been identified in the main coal zone. These are identical in name and character to those found in the Utrecht Coalfield (Fig. 30), with the addition of the Bonas Seam. Several have been exploited historically, with varying degrees of economic success. The greatest number of superimposed coal seams worked simultaneously was at the now defunct Enyati Colliery, where four seams were extracted (Bell and Spurr, 1986b). The change in thickness and character of the seams and of the associated roof and floor strata is one of the most striking features of the Vryheid Coalfield. Intra-seam partings are discontinuous over short distances and complicate seam correlation and coal seams "shale out" into carbonaceous siltstones and mudstones over short distances.

As for the Utrecht Coalfield, from the base up the most important seams are the Coking, Dundas, Gus and Alfred seams. Most minor seams, such as the Targas Seam, which is situated beneath the Coking Seam, are only sporadically developed with little lateral extent. The Fritz Seam could possibly be economic because of its good quality, bright coal, but it is generally too thin for economic extraction.

The Coking Seam is generally thin (rarely thicker than 1 m) and although it is of a high grade (as it is in Utrecht Coalfield) it has not been exploited over the entire coalfield. The roof to the Seam is fairly competent, being mainly formed by cross-stratified, medium-grained sandstones. The floor is usually composed of fine-grained micaceous sandstones, which grade laterally to grey carbonaceous siltstones and mudstones, forming a moderate to poor mining floor (Bell and Spurr, 1986b).

The overlying Dundas Seam in the Vryheid Coalfield often contains two splits in the northern and central parts, namely the Lower and Upper Dundas seams (Bell and Spurr, 1986b). The Lower Dundas Seam reaches a maximum thickness of 2.5 m and is composed of interbedded bright and dull coal that often has a thin siltstone and sandstone parting in the top portion. Historically both coking and thermal coal were produced from this seam. Roof and floor conditions were variable, with the floor often comprising a weak micaceous mudstone. Where the Lower Seam split thickens to 1.5 m the quality drops. The Upper Dundas Seam is around 1 m thick and historically produced a good coking coal. Micaceous siltstone and mudstone generally composed the roof and floor, giving rise to incompetent conditions. In the south, the Upper Dundas Seam is often replaced by carbonaceous mudstone (Bell and Spurr, 1986b).

The Gus Seam ranges in thickness from 0.5 to 2 m. The coal is finely interbedded and bright and lustrous, often with a thin sandstone or siltstone lens near the top (Bell and Spurr, 1986b) that historically gave rise to extraction problems. No exploitable coal resources exist in the east of the coalfield as the coal grades into carbonaceous siltstone and mudstone. Whilst variable in places, in general the immediate roof of the Gus Seam is formed by coarse-grained, well-stratified sandstone, which forms a competent beam and good roof. The floor however is fairly poor, consisting of fine- to medium-grained sandstone often interbedded with thin, siltstone rich bands.

The Alfred Seam is of a poorer quality than the other seams. Moderate quality thermal coal and low-grade coking coal were historically produced and anthracite is currently produced from this seam at the Vaalkrantz Colliery. The immediate floor is composed of medium-grained and well-stratified sandstone. The roof however is poor, being formed by fine-grained sandstones and carbonaceous siltstones.

4.5.3.6.1. Coal qualities. Bell and Spurr (1986b) provide a table of typical product qualities for various coal types in the Vryheid Coalfield, including raw screened values for bituminous and anthracitic Gus and Alfred. These are provided as Table 14.

The Coking Seam is not presently being exploited, but where worked historically, such as at Zuinguin Mountain, it was unaffected by dolerite intrusion and was of high grade, yielding a good coking coal, commonly with a raw ash content of 7–8%. As for the Utrecht Coalfield the Gus Seam is generally of better quality than the Alfred Seam.

4.5.3.7. Structure and intrusions. As for the Klip River and Utrecht coalfields, numerous dolerite dykes and sills intrude the Vryheid Coalfield and the surface geology is a mix of dolerite exposures and sedimentary rocks of the Vryheid Formation. Displacements of up to 150 m are associated with these intrusions. Dolerite dykes may negatively affect the coal qualities and preferentially intrude into coal seams at places.

4.5.4. Nongoma Coalfield

4.5.4.1. Introduction. Barker (1999) includes both the Nongoma and Somkele (Somkhele) coalfields as the southern extension of the Kangwane–Swaziland (Beaufort Group) coalfields, and whilst they are genetically related, they are here treated as separate entities, with the Nongoma covered first as it has both Ecca and Beaufort group coals, whilst the Somkhele Coalfield is hosted only in the Beaufort Group.

Apart from at Rio Tinto's Zululand Anthracite Colliery (ZAC), the main part of Nongoma Coalfield is yet to be exploited on a commercial basis, being mined to date only on an artisanal level. Because of its comparatively limited mining and exploration history, the Nongoma Coalfield is one of the most poorly understood in South Africa. A number of internal reports are known to exist, but the authors do not have access to these. The coalfield is therefore best known from what little that is freely available about ZAC, and from various reports and company announcements from when ZYL (http://www.zyllimited.com/) explored the Mbila Project.

Table 13
Major defunct collieries in the Vryheid Coalfield.
From Bell and Spurr (1986b).

Colliery	Average RoM tonnes (per month)	Coal type produced
Buffalo	12,000	Thermal and coking coal
Enyati	40,000	Thermal and coking coal
New Tendega	16,000	Thermal and coking coal
Hlobane	125,000	Coking coal
Vrede (Vryheid Coronation)	50,000	Coking coal
Vryheid Coronation	50,000	Coking coal
Aloe Anthracite	12,000	Anthracite
Alpha Anthracite	30,000	Anthracite
Natal Ammonium	40,000	Anthracite
Natal Anthracite	55,000	Anthracite
Leeuwnek	10,000	Coking coal
S7L Rietvlei	±20,000	Anthracite
Tselentis Rietvlei	±45,000	Anthracite
H.C. Contractors	10,000	Coking coal
Heritage	±25,000	Thermal coal

4.5.4.2. Location. The Nongoma Coalfield is situated in central KZN and stretches from east of Gluckstadt in the west, where it shares a common boundary with the Vryheid Coalfield, to a north–south running boundary in the east, where it abuts against the Somkhele Coalfield (Fig. 1). Its southern boundary is formed by the Pongola River and it extends northwards to a common boundary with the northern extent of the Somkhele Coalfield, which then continues into Swaziland (Fig. 1).

4.5.4.3. Exploration and exploitation history. In 1940 F.A. Stuart first expressed the view that substantial tonnages of anthracite existed at Nongoma. Reconnaissance exploration specifically for coking coal was later undertaken in 1949 by Fred Furter in the area for Natal Navigation Collieries. Furter concluded that only anthracite would be found in the area.

Exploration interest in Mbila first began in 1958, but unfortunately the records of this work no longer exist. Substantial exploration activity occurred on the Mbila Project in the 1970s. In 1974 Trans-Natal and South Cape Exploration commenced large scale work, which included field mapping, 98 cored boreholes and six bulk sampling pits. This work was described in an unpublished internal report of May 1975 on the prospecting undertaken in Bantu Reserve No. 12, and confirmed the presence in the Nongoma/Mbila area of four distinct blocks of coal in the lower Ecca Group, and two blocks within the overlying Beaufort Group.

Between 1970 and 1980, when Ubombo Mines (Trans-Natal) and subsequently BHP Billiton (who took over a major stake in Trans-Natal) took over, some 439 boreholes were drilled on the property. In February of 1982 a geological report on the Msebe anthracite prospect was undertaken for the Mining Corporation Limited. In 1988 a joint venture agreement between Trans-Natal and Southern Sphere gave Trans-Natal three leases totalling approximately 24,000 ha, and Southern Sphere a further three leases amounting to 63,000 ha. Randcoal Limited and Trans-Natal merged in 1994 to form Ingwe (which is now wholly owned by BECSA) and exploration continued under this company.

Mbila Resources (Pty) Limited (Mbila) became involved in the project in 2004 and in 2006 the first independent CPR on the Mbila project was authored by Dawie van Wyk (ZYL Investor update presentation). Since this time much exploration has been undertaken on the project area with a series of 81 boreholes drilled within the potential opencast portions of the S Block between 2006 and 2008, and 44 boreholes drilled during 2010 and 2011. In April of 2013 an updated CPR was authored on the resources and reserves of the Mbila Mining area (Meyer, 2013; ZYL Investor update May 2013). Hatherly and Sexton (2013) provide a combined Measured and Indicated Resource for the Mbila Project area (Mbila Ecca Group and Mbila and Msebe Beaufort Group) of 87.42 Mt, with an additional 37.52 Mt in the Inferred category.

Rio Tinto's Zululand Anthracite Colliery (ZAC) is the only operating mine in the Nongoma Coalfield. The colliery complex is located approximately 48 km northeast of Ulundi within the magisterial districts of Nongoma and Mahlabatini. Exploration activity in the vicinity of ZAC occurred in 1976 and the early 1980s and showed the deposit to be structurally complex and extensively intruded by dolerite. ZAC was opened in 1985 to supply low Ash, high carbon anthracite to the domestic and export markets. In February 2005 Riversdale Mining announced that it had entered into a conditional agreement to acquire 74% in ZAC together with its Black Economic Empowerment (BEE) partner. Following the conversion of the mineral rights from old-order to new-order rights in December 2005, settlement of the ZAC acquisition was completed. Between this time and 2010 the mine was operated by Riversdale and produced high grade anthracite from low seam heights in a number of separate structural blocks (Engelbrecht, 2008). This was achieved by underground bord-and-pillar extraction methods at six separate shafts, as well as some historic surface mining. Mining depths vary between 25 and 270 m. In 2010, when it was taken over by Rio Tinto, ZAC has an output of 700,000 tpa and is currently the largest producer of high quality anthracite in South Africa.

4.5.4.4. Research history. In his seminal works on the geology of Natal and Zululand, W. Anderson (1901, 1904, 1907) lists Nongoma amongst his eight coalfields of coastal Zululand and provides general descriptions of the Dwyka and Ecca Group rocks and their included coals. Following on this work, for many years little to no academic interest was taken in this coalfield, and it was only in the early 1980s that research refocussed on this coalfield, with Whateley (1980a,b) and Turner et al. (1981) discussing various sedimentological aspects of the Nongoma graben.

Thirion (1982) published the first comprehensive report on the coals of the Nongoma Coalfield. This report covered the results of exploration undertaken in the Msebe area of the coalfield, including 19 cored boreholes. At the time a small (25 Mt) high Ash, medium rank anthracite deposit was outlined. A 1:10,000 scale map of the area is provided and the geology of the area is discussed in some detail.

Turner and Whateley (1983) published on the structural and sedimentological controls of coal deposition in the Nongoma graben, noting that sedimentation was contemporaneous with graben formation. Since this time little to no work has been published on the coalfield, other than internal reports and conference proceedings relating to ZAC and the Mbila Project area.

4.5.4.5. Geology. The Nongoma graben, which hosts the Nongoma Coalfield, developed in response to crustal thinning and the first phase of extensional tectonics (rifting) prior to continental break-up and the separation of east and west Gondwana (Turner et al., 1981; Whateley, 1980a,b). It is unique in KZN for hosting potentially mineable coals in both the Vryheid and Emakwezini formations. Contemporaneous sedimentation led to the deposition of a thick sequence of coal-bearing fluvio-deltaic rocks (Fig. 31). According to Whateley (1980b) and Turner et al. (1981) the Ecca Group in the Nongoma Graben comprises a lower progradational deltaic sequence, a middle fluviatile sequence and an upper transgressive deltaic sequence. Detailed descriptions of these sequences and their lithofacies components are presented in Whateley (1980b).

The coalfield may be divided into the Nongoma West and Nongoma East sections (Mintek, 2007) each containing distinctly different lithologies. Individual coal-bearing areas are separated from each other and coal is not continuously developed across the coalfield. Nongoma West is unique and displays no characteristics similar to any other coalfield in KZN. Within this area coal is restricted to three seams within the Vryheid Formation of the Ecca Group. A generalised stratigraphic profile of the Karoo Supergroup fill of the Nongoma Graben in the Masebe area of the Nongoma Coalfield is provided as Fig. 31.

Dwyka Group lithologies occur at the base of the succession and are documented as being 10 m thick in the Mbila area (Hatherly and Sexton, 2013). The Pietermaritzburg Formation does not seem to occur. The Vryheid Formation is around 100 m thick and is sandstone dominated, becoming interbedded with carbonaceous siltstones and mudstones towards the top, near its transition into the overlying Volksrust Formation, which like in the rest of KZN is formed by grey to dark grey siltstones and mudstones.

4.5.4.6. Coal seams. Three coals, the M − 1, M and M + 1 are recognised in the Ecca Group in the Mbila area (Fig. 31), and these have been termed the Lower, Middle and Upper seams in the southern reaches of the Nongoma coalfield near ZAC (Barker, 1999). At Mbila the M − 1 Seam overlies a weak siltstone floor and averages only 0.2 m in thickness. It is only viably extracted using surface mining methods. Overlying this seam is a 1 m parting, which in turn is overlain by the M Seam. This seam is the only economical seam present in the western area, where it is 1–1.2 m thick. The interburden between this seam and the overlying M + 1 Seam is formed by siltstone. As with the M − 1 Seam, this seam only averages 0.2 m. A weak siltstone roof overlies this, followed by a more coherent sandstone roof.

In the southern reaches of the Nongoma coalfield the Lower Seam is up to 3.28 m thick, the Middle Seam up to 5.71 m thick and the Upper

Table 14
Typical coal qualities for the Gus and Alfred seams in the Vryheid Coalfield.
From Spurr et al. (1986).

Coal Type	Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	FC (%)	TS (%)	P (%)
Bituminous	Gus	28.9	16.5	20.8	2.0	60.7	0.85	–
Anthracite	Gus	31.5	10.7	10.0	1.7	77.6	0.80	0.003
Lean bituminous	Alfred	28.3	18.0	15.0	1.8	65.2	1.0	0.018
Anthracite	Alfred	27.4	18.6	7.5	3.2	70.7	1.2	0.018

Seam 2.44 m (Barker, 1999). At ZAC the seam mined is referred to as the Main Seam and is confined to a sandstone dominated unit, with the immediate roof to the Main Seam formed by an 11 m thick sandstone. Engelbrecht (2008) notes, that the Main Seam is between 2 and 2.4 m thick where it is extracted at ZAC, with extraction heights as low as 1.2 m having been recorded. Here the coal seams dip at ±2° to the east.

In parts of the Nongoma Coalfield an additional two coal seams (referred to as the A1a and A1b) are documented as occurring either in the uppermost Volksrust Formation (Fig. 31) or in the lower Emakwezeni Formation. They occur approximately 80–100 m above the M + 1 and unless closely associated with the A2 Seam are not targeted for economic extraction.

In the eastern sector of the Nongoma Coalfield, coal seams are hosted within the Emakwezini Formation (Adelaide Subgroup) of the Beaufort Group. The seams have been grouped into three zones (the A, B and C) based on thickness and geological character (Fig. 31). The coals do not form discrete seams but are rather interbedded coals and mudstones, more similar in nature to the Waterberg Coalfield (Fig. 1) thick interbedded coals than any other KZN seams.

The lowermost A Zone contains the prominent and thick (up to 4 m) A Seam. In some places this seam is split into an A1 and A2 seam, with the latter being the thicker of the two. Separating this zone from the overlying B Zone is a sandstone succession and a weak carbonaceous siltstone floor. The B Zone is often referred to as the Mining Zone and is characterised by thick seams, however with a weak floor and roof. Four seams exist within this zone, namely the B1, B2, B3 and B4 seams, with the interburden between the seams being mainly black carbonaceous siltstone and mudstone. The B1 Seam averages the greatest thickness of 4 m, with the remaining seams averaging around 2.5 m. The overlying C Zone coal seams are minor, irregularly spaced and tend to be laterally discontinuous. These seams may be locally mineable by opencast mines. Stringers above this zone are sometimes classified into a fourth, D Zone.

4.5.4.6.1. Coal qualities. Thirion (1982) provides raw quality data for the Emakwezini Formation coals in the Msebe area as being 24.98% Ash and 7.5% VM. In the Ecca Group the M Seam is generally metallurgical anthracite with low phosphorus content. Raw RDs are around 1.5 and yields of between 71 and 77% may be obtained for a 10% Ash, sub 6% VM, 82–83% FC product. Beaufort Group qualities are not as high. Table 15 provides yields and quality data for the washed coal product specifications at the Mbila project area.

4.5.4.7. Structure and intrusions. The Nongoma Coalfield is fault bounded and there is intense faulting within the coalfield. At Mbila major faults strike southwest, sub-parallel to the stratigraphy and repeat the eastwards dipping succession. Subsidiary faults follow a variety of directions. Each of the resource blocks is fault bounded. In general the strata dip towards the east at angles varying from 10 to 15°, except where dolerite sills may cause a localised steepening of the dip up to 25°.

In the south of the coalfield at ZAC the entire area is structurally complex, with faults with throws of up to 170 m documented between resource blocks, creating both horst and graben structures (Engelbrecht, 2008). Numerous Jurassic aged dolerite intrusions intersect the succession and in places also the coal seams. These occur as both massive (90 m thick) sills and smaller transgressive off-shoot dykes. At ZAC they occur mainly above the Main Seam and have not negatively affected the coal. These dolerite intrusions have burnt the coal beyond economic potential in some other parts of the coalfield and a thorough understanding of their occurrence and morphology is critical to any exploration project.

4.5.5. Somkhele Coalfield

4.5.5.1. Introduction. The Somkhele (sometimes referred to as Somkele after the spelling of the village from which it gets its name) was formerly referred to as the Hlabisa and Lake St. Lucia Bay Coalfield (W. Anderson, 1901). Along with Nongoma, the Somkhele Coalfield is more complex than the other coalfields of KZN, and because of its comparatively limited mining history, is not as well-understood (Jeffrey, 2005a). As in the Nongoma Coalfield, the coals in the Somkhele Coalfield differ from those in the rest of KZN in that they are hosted in the Upper Permian Emakwezini Formation (Adelaide Subgroup) of the Beaufort Group (Bordy and Prevec, 2008; Jourbert, 1994).

4.5.5.2. Location. Geographically the Somkhele Coalfield covers a 5–8 km wide zone that extends from the Swaziland border in the north, to Dukaneni in the south. The southern sector, which hosts the Somkhele Mine, is bounded on the eastern side by a line extending north–south through the towns of Somkele, Emakwezeni and Heatonville. The western boundary is formed by the eastern boundary of the Nongoma Coalfield (Fig. 1) and is faulted.

4.5.5.3. Exploration and exploitation history. Coal was first discovered in the Somkhele area in 1892 by a gold prospector, David Brown. This led a decade later to the opening of a small mine within the confines of the current Petmin (http://www.petmin.co.za/) lease area, with the first coal being exported in 1903. By 1907 some 20,000 tonnes had been mined via two underground workings on the 400 ft and 600 ft levels (W. Anderson, 1907). Historic records suggest eventual production of some 40,000 tonnes, with the mine closing in 1909 due to harsh working conditions and severe outbreaks of malaria.

Exploration for coal in the area resumed in the 1960s (Marshall, 1966) and since this time Johannesburg Consolidated Investments (JCI), Purity Investments (Pty) Limited, Mining Corporation, and Afriore South Africa Limited have actively explored the area. JCI went as far as developing a small test shaft in the 1970s in part of Somkhele collieries Area 1, which is now Petmin's North Pit 1.

Only one colliery, Petmin's Somkhele mine (http://www.petmin.co.za/) is currently operative in the coalfield. The mine is situated 85 km northwest of Richards Bay and produces a standard grade, low sulphur, and low phosphorus anthracite for both the domestic ferroalloy and the export market. According to their website the mine is currently South Africa's largest producer of metallurgical anthracite. Somkhele has a current 20-year LoM at annual production of more than 1.2 Mtpa of saleable coal. As of the 30th of June 2012 management estimates were 56.5 Mt of opencast reserve, which equated to approximately 30 Mt of saleable product.

Exploration is currently also being undertaken in the Somkhele Coalfield by various junior companies, some of which are at an advanced stage and may lead to further mining operations in the not too distant

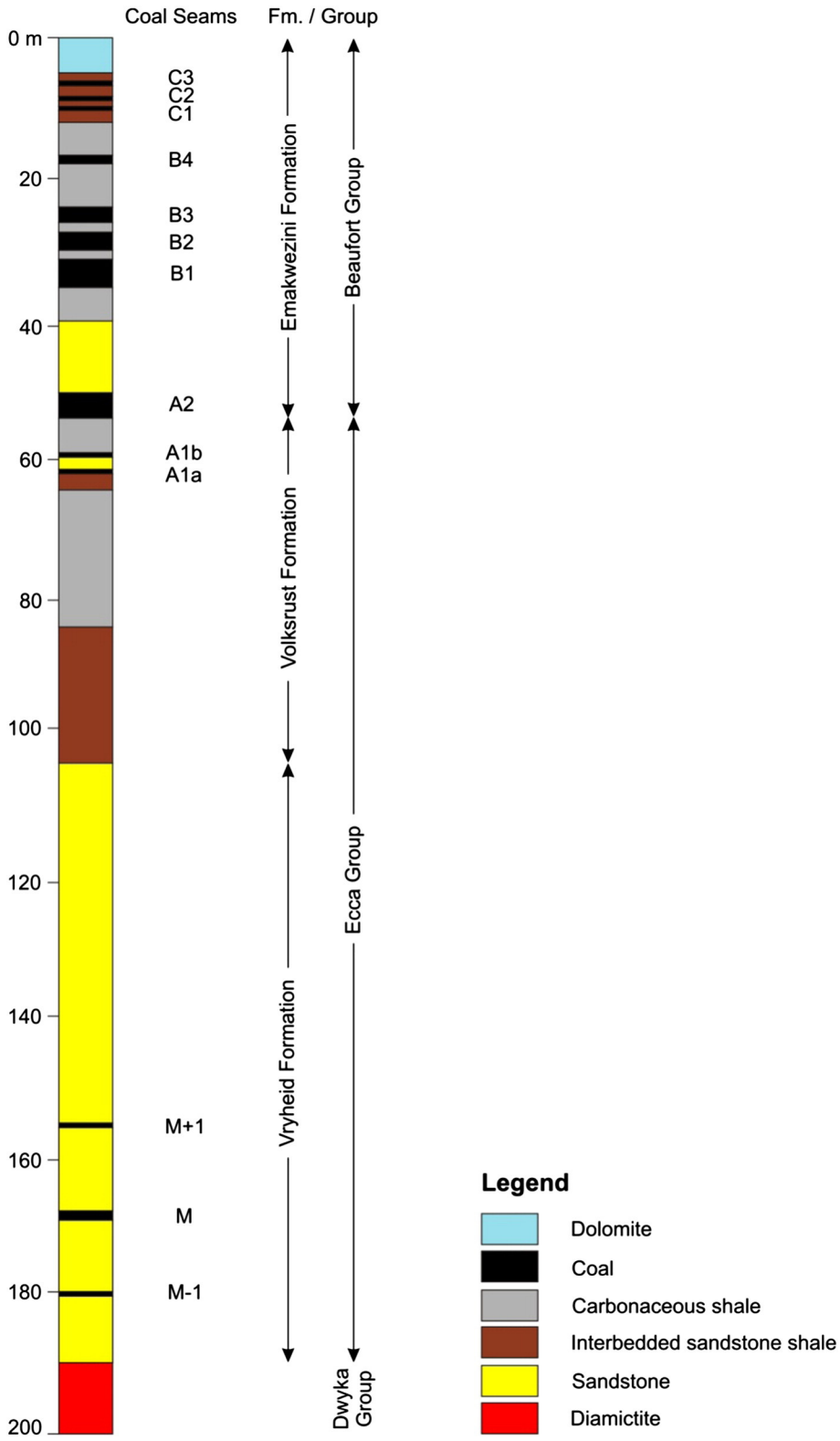

Fig. 31. Generalised stratigraphic profile of the Karoo Supergroup fill of the Nongoma Graben in the Masebe area, Nongoma Coalfield. From Hatherly and Sexton (2013).

future. The most advanced of these is the Fuleni Reserve One Project (Fuleni), which is situated approximately 45 km north east of Richards Bay and immediately 5 km south west of the Somkhele mine (Tovela, 2011).

4.5.5.4. Research history. The earliest documentation on the sedimentology and palaeontology of the Somkhele Coalfield is contained in the seminal works of W. Anderson (1901, 1904, 1907), who describes various aspects of the "St. Lucia Bay" coalfield, and who provided

Table 15
Mbila anthracite properties.
From ZYL ASX Release 29 August, 2012.

	Ecca Seam	Beaufort Seam — primary product	Beaufort Seam — secondary product
Yield %	64.3	51.2	17.3
Ash %	9.7	14.9	22.0
IM %	2.1	1.1	1.0
VM %	5.1	5.8	5.5
FC %	83.1	78.2	71.4
Gross CV MJ/kg	31.58	29.45	25.4
TS %	1.04	0.65	0.84
Phosphorous %	0.008	0.012	–

various plant fossils to Etheridge at the Sydney Museum of New South Wales (Etheridge, 1903). Most early works dealt with the plant fossils found near Somkele (Etheridge, 1903; Plumstead, 1970; Seward, 1907) and few other academic works exist, other than the recent work of Bordy and Prevec (2008) and Tovela (2011).

Bordy and Prevec (2008) provide a brief review of the earlier accounts of the lithology and flora of the Emakwezini Formation, as well as descriptions of new plant fossils from the area. The sedimentology and environments of deposition of the Emakwezini Formation are covered in detail and this work is followed below for the overview of the general geology.

From a study of 17 boreholes and several outcrop sections on the Fuleni project area, Tovela (2011) established a sequence stratigraphic framework for the Emakwezini Formation and discusses the controls on cyclicity and provenance of the sedimentary sequence. A useful reference borehole log (UR 1348) is presented in this work, as well as a number of east–west and north–south profiles. A full description of the various sedimentary facies and units is also provided.

4.5.5.5. Geology. The general stratigraphy of KZN as pertains to the Somkhele Coalfield is provided in Fig. 32.

The general geology of the coal-bearing succession is best known from various descriptions available for the Somkhele mine area (Bordy and Prevec, 2008) as well as for the Fuleni project to the south (Tovela, 2011). The general stratigraphy, sedimentology and palaeontology presented below are amalgamated from these publications.

The Lebombo Basin (which is home to the Somkhele, Swaziland and Kangwane coalfields) is an elongated Phanerozoic depression that stretches in a north–south direction from the Limpopo River in the north, to Empangeni in the south, for a total of some 700 km. Within the Somkhele Coalfield some 600–900 m of Ecca Group and Dwyka Group lithologies underlie the coal-bearing Emakwezini Formation (Fig. 32). These are not however described here as they are not known in much detail and are not relevant to the description of the producing coal seams in the coalfield.

The Emakwezini Formation, which is the sole representative of the Beaufort Group in the southern half of the Lebombo Basin, is restricted to a narrow, faulted, meridional outcrop and subcrop belt in Swaziland and north-eastern KZN. The unit is also present in the subsurface along the western side of the Lebombo Basin from Empangeni to at least as far north as Komatipoort (Bordy and Prevec, 2008). It is estimated that the Emakwezini Formation attains a thickness of ±490 m near the village of Somkele (Marshall, 1966), although Bordy and Prevec (2008) provide a figure of 570 m, which is more similar to the figures of ±550 m to the west of Somkele and at Emakwezini (Watson and McGeorge, 1977). Genis (1961) notes that it thins southwards to ±370 m west of Empangeni; however, according to Du Preez (1982), the Emakwezini Formation is ±500 m thick in this area. North of the Somkhele Coalfield the Emakwezini Formation thins dramatically, attaining a thickness of only 130–150 m in Swaziland (Davies, 1961) and near Komatipoort (Du Toit, 1918).

Lithologically the Emakwezini Formation is dominated by fossiliferous, grey, greenish-grey and brown mudstones, with intercalated coal seams, and subordinate white or yellow-white, and medium- to coarse-grained feldspathic sandstones. The coal seams are associated mainly with the mudstones and whilst usually less than 1 m thick, they may locally attain thicknesses of up to 15 m.

4.5.5.6. Coal seams. Unlike in the Vryheid Formation hosted coalfields, where up to eight coal seams (or coal zones) are recognised within sandstone dominated package, in the Somkhele Coalfield only four coal seams (or coal zones) exist (Fig. 33). The seams are named in ascending order: A (or Lower Seam), B (or Main Seam), C (or Upper Seam 1), and D (or Upper Seam 2). At the Somkhele mine all of the seams dip at approximately 22° to the southeast (Fig. 34). The B Seam coal zone is the main seam package of economic importance in the Somkhele Coalfield, and is the only seam targeted at the Somkhele mine.

The lowermost A Seam occurs at the boundary between the Lower and Middle Emakwezeni formations. The B Seam occurs some 50 m above the A Seam within the Middle Emakwezini Formation, and some 60 m below the base of the Upper Emakwezini Formation, which hosts the D Seam. The C Seam occurs at the contact between the Middle and Upper Emakwezeni formations, and following sequence stratigraphic concepts, should rather be included in the Middle Emakwezeni Formation at the top of the sedimentary cycle (Tovela, 2011).

4.5.5.6.1. Coal qualities. Somkhele metallurgical anthracite typically has a low sulphur content (<1%), low calcium, and low phosphorus contaminants (<0.01% in seams B1 and B3, and 0.018–0.022% in Seam B2, producing a weighted average of 0.015%). The sized product is therefore a viable reductant for the titanium and ferrochrome industries in South Africa, and competes with bituminous coals, chars and cokes as a carbon feedstock in the metallurgical industry. The unsized product is used for the pelletizing and sintering of iron ore.

Grobler (2006) provide coal qualities at a 1.6 RD float density for the coal only components of the Somkhele Colliery, as he believed that this would best approximate the product. Whilst these have now changed significantly due to practical mining constraints they are provided as Table 16.

4.5.5.7. Structure and intrusions. The Somkhele Coalfield is developed on the south-eastern margin of the MKB and forms part of the Natal Monocline, a structure associated with the rifting of Gondwana in the Jurassic and Lower Cretaceous periods. The strata are inclined fairly consistently eastwards to south-eastwards at angles up to 30° (average 15–20°).

Large areas of the Somkhele Coalfield are affected by dolerite intrusions of Jurassic age and these intrusives are probably the single most disruptive aspect of the coalfield (Barker, 1999). The area is characterised by a relatively high frequency of dyke intrusions, with cross-cutting dykes in nearly all directions present. The dolerites form sub-vertical dykes and bedding parallel sills. In places a major sill some 90 m thick occurs, between 110 and 130 m above the B Seam. Dolerite intrusions can negatively influence the coal qualities and disrupt mining. Faults with throws of up to 1300 m are documented in the coalfield.

4.6. Kangwane Coalfield

4.6.1. Introduction

Although previously referred to as a sector of the Lebombo Coalfield (a narrow, elongate, north–south trending tract of coal-bearing rocks which extends several hundred kilometres from Zululand in the south, through Swaziland, to Pafuri in the north), the Kangwane (Kangwane, Nkomati or Komatipoort) Coalfield is here discussed as a separate entity, although one with certain similarities to the Nongoma Coalfield and the coalfields of Swaziland. It has historically been mined to only a

limited extent and is currently the focus of some acquisition and exploration activities.

4.6.2. Location

The Kangwane Coalfield forms a 72 km long (south–north oriented), 33 km wide area situated in the eastern part of the Mpumalanga Province. Geographically it extends from near Komatipoort in the north, to the Mananga Border Post at the Swaziland border in the south, and covers an area of some 210,000 ha.

4.6.3. Exploration and exploitation history

Exploration history in the Kangwane Coalfield may be traced back into the early 1900s when four boreholes and a trial shaft were sunk to the north of the town of Kangwane. Unfortunately the results from this early exploration were not encouraging and no further work was undertaken until the 1950s when the Geological Survey (now the Council for Geoscience) mapped the entire area and drilled fifteen boreholes, also to the north of the town of Kangwane.

In the late 1970s the Mining Corporation Limited identified the coal potential of the Nkomazi Region (Kamhlushwa) and between 1979 and 1981 explored the area and delineated a substantial anthracite resource (Schutte and Ehlers, 1981) from a total of 243 diamond drill holes. During 1975, the Geological Survey drilled an additional two boreholes, which were situated only 3.5 km north of the Swaziland border. One of these boreholes, which was collared to test the Volksrust Formation coals, intersected dolerite and minor sedimentary strata, but no coal. The second borehole intersected good quality coals of the Vryheid Formation at a depth exceeding 200 m.

In 1982, the mineral rights over some 40,000 ha was registered in the name of Kangwane Mineral Exploration (Pty) Limited. This area was sub-divided into three sub-areas, each of which had a strike extent of approximately 11 km. These blocks were termed from north to south, the Kangwane Anthracite, Nkomati Anthracite and Southern Anthracite blocks. Randel (1989) notes that Iscor drilled 43 core boreholes in the Southern Anthracite block.

In 1984, Messina Limited entered into an agreement with Kangwane Mineral Exploration to exploit the Nkomati Anthracite block on a 60/40 share arrangement and a box-cut was undertaken. The planned mining operation was however never realised. Messina Limited's shareholding in Kangwane Mineral Exploration was purchased by the Dania Corporation Limited in June of 1991 and a small operation was established, with 50,000 tonnes produced by the end of that year. Various problems were however encountered and mining operations halted by 1992. In 1993 Benicon Coal Proprietary Limited (Benicon) purchased Nkomati from Dania Corporation and fairly small amounts of anthracite (less than 200,000 tpa) were sporadically mined from sequential opencast pits between 2003 and 2006 by Benicon. In 2007 Sentula Mining (http://www.sentula.co.za/), who were formerly known as Scharrighuisen Mining, bought Benicon. Mining continued at surface and an underground operation was established via two adits driven from a box-cut. Operations at the mine were placed on care and maintenance at the end of May 2011 pending the resolution of regulatory and environmental issues. At the time of the publication of this article Sentula were disposing of this asset to a consortium led by Miranda Minerals.

The central and southern blocks were acquired by ZYL and have recently been the focus of exploration work on what they term the Kangwane Central and Kangwane South areas. The company has previously documented Joint Ore Reserves Committee (JORC) compliant resources of 177.7 Mt for the Kangwane Central project, and 99.7 Mt for the Kangwane South project.

4.6.4. Research history

Academic work on the Kangwane Coalfield is very limited and the senior author is not aware of any masters or doctoral studies that have been undertaken on the sedimentology or coal geology of this coalfield. Coal outcrops in this coalfield were first recorded to the north of Kangwane in 1897 by Molengraaff (in Snyman, 1998), which were subsequently described by Kynaston in 1906 (noted in Wybergh, 1928) as a memoir on the Komatipoort Coalfield. Half a century later Schutte and Ehlers (1981) documented the Nkomati Anthracite deposit in an interim report for the CGS, and in an open file CGS report Randel (1989) documents the geology and coal potential of the Southern Anthracite (Pty) Limited Block.

4.6.5. Geology

Representative outcrop sections of the Karoo Supergroup rocks are rare in the area due to the extensive weathering and recent alluvial and fluvial covers. The Karoo Supergroup succession in the Kangwane Coalfield consists of, from bottom to top, the Dwyka Group (which may be absent in places), and the Vryheid and Volksrust formations of the Ecca Group. Locally Beaufort and Stormberg Group equivalents may occur, and the succession is capped by the Lebombo Group volcanics, which are the temporal equivalent of the Drakensberg Group in the MKB.

The exploitable coal seams are hosted in the fine- to coarse-grained sandstones and subordinate mudstones and siltstones of the Vryheid Formation. These strata strike essentially north-northeast south-southwest and dip to the east at between 5 and 15°, with a more gentle (2°) southerly dip. They occur unconformably on either Archaean basement granites or on diamictites of the Dwyka Group. This easterly dip is accentuated in places by minor faulting with down-throws to the east.

4.6.6. Coal seams

Seam nomenclature is not standardised. Up to 14 coal seams were delineated during the various drilling programmes and these are hosted in the Vryheid and Volksrust Formation equivalents. In the far northern part of the coalfield the coal seams are found concentrated over a narrow zone with subordinate partings, however, these partings tend to thicken south- and eastwards.

Generally there are only four to five discrete coal seams present within the Kangwane Coalfield and they are usually relatively thin, but may reach mineable widths in places. Where they reach mineable heights up to four thicker, potentially exploitable seams occur, generally towards the bottom of the package, which following the ZYL terminology are numbered from the bottom to top, the No. 1 to No. 4 seams (Fig. 35).

The No. 1 Seam, which is best known from the northern Nkomati Anthracite block, occurs at the bottom of the sedimentary succession, where it lies unconformably on either basement granites or Dwyka Group lithologies where present. At the Nkomati mine it is restricted to the Nkomati anthracite Matadeni resource area, where it averages approximately 1.1 m in thickness. According to Snyman (1998) it may be up to 10 m thick in places.

At the Nkomati mine area the No. 2 Seam may be split into a No. 2 Lower (No. 2 L) and No. 2 Upper (No. 2 U) seam. The No. 2 L (also known as the Main) Seam is the most prominent coal seam and ranges from 2.0 to 8.7 m in thickness. The No. 2 U Seam lies approximately 10 m higher in the succession than the No. 2 L Seam, with the parting formed by a dark grey mudstone to siltstone. It averages 2.4 m in thickness in the Madadeni area, but is more erratic in the Mangweni area where it reaches over 6 m, but averages only 0.9 m. It is also more frequently disrupted and devolatilised by the overlying dolerite sill.

The No. 3 Seam occurs approximately 10 m above the No. 2 U Seam, with the parting between the two formed by medium- to coarse-grained sandstone, or interbedded sandstone and mudstone unit. The immediate floor to the No. 3 Seam may therefore be either medium-grained sandstone or dark grey carbonaceous siltstone. The seam itself is only present in restricted areas, and where developed consists of a 1 m thick seam of bright coal. The immediate roof to the No. 3 Seam is normally formed by medium- to coarse-grained sandstone, which fines upwards into dark grey mixed sandstone and siltstone, and dark grey carbonaceous mudstone. Where present the No. 4 Seam is

	GROUP	FORMATION (SACS, 1983)	FORMATION (Cilliers, 1951)		Representative Rock Type	Average thickness (m)
Karoo Supergroup	Stormberg (Upper Triassic)	Drakensberg Basalt	Drakensberg	Lebombo Group	Lava, amygdaloidal	2500+
		Clarens Sandstone	Cave Sandstone	Clarens Formation	Sandstone, fine-grained	45
		Elliot	Redbeds	Nyoka Formation	Mudstone, clayey	250
		Molteno	Molteno	Ntabeni Formation	Sandstone, medium- to coarse-grained	100
	Beaufort (U. Permian-L. Triassic)	Beaufort	Beaufort	Emakwezini (Normandian) Formation	Sandstone, siltstone, mudstone, coal	570
	Ecca (Permian)	Volksrust Shale	Upper Ecca	Volksrust Formation	Intercalated shale and bright coal	140
		Vryheid	Middle Ecca	Vryheid Formation	Sandstone and grit, intercalated carb. siltstone, thick coals	550
		Pietermaritzburg Shale	Lower Ecca		Shale, sandstone and grit	200
	Dwyka (Carbon.)	Dwyka	Dwyka	Dwyka	Tillite	not exposed

Fig. 32. Stratigraphic nomenclature of the Karoo Supergroup in the Somkhele Coalfield. It should be noted that certain of the unit names are informal and have not yet been accepted by the South African Committee for Stratigraphy (SACS).

usually less than 1 m in thickness and is normally too thin to be considered economic. In the ZYL Kangwane southern block area their No. 4 Seam is divided into a No. 4 Lower (No. 4 L) that averages 1.43 m in thickness, and a No. 4 Upper (No. 4 U) Seam that averages 1.2 m thickness.

Ashton (2011) provides a different nomenclature for the Vryheid Formation hosted coal seams in Sentula's Nkomati mine area, referring to them as the 3 Seam (Lower or No. 1 Seam), 5/6 Seam (Middle or No. 2 Seam), 7 Seam (Upper or No. 3 Seam) and 9 Seam (Top or No. 4 Seam). He further notes that they occur over a total thickness of ±70 m of sandstone and that regionally the up to 8 m thick Lower Seam, and the Middle Seam are the most prominent, whilst the Upper and Top seams are sporadic and excluded from resource calculations.

In the northern sector, approximately 300–400 m above the No. 1 Seam, an additional set of thin (rarely greater than 2 m in thickness) set of coal seams occur, which are hosted in a mudstone dominated succession that is considered to be the Volksrust Formation equivalent. Ashton (2011) refers to these as the 2/4, 6 and 8 seams.

4.6.6.1. Coal quality. Coal qualities are similar to those in the Somkhele Coalfield, but with a higher Ash content (Barker, 1999). Snyman (1998) notes that the raw coal normally has an Ash content of between 20 and 25%, with a mean theoretical yield of 67% at a 1.7 RD. The No. 1 Seam is generally of low grade (Ashton, 2011) and is not included in reports or resource estimations. Based on the June 2012 CPR (Meyer, 2012) ZYL provide the following raw qualities for the combined No. 2, 3, 4L and 4U seams (Table 17).

Washed for a 16% Ash product only the No. 1, No. 2 and No. 4L seams provide for theoretical yields of above 60% (Table 18).

4.6.7. Structure and intrusions

As for the Nongoma and Somkhele coalfields, the Kangwane Coalfield is structurally complex due to the tectonic control on its formation, as well as late stage extensional tectonics related to the break-up of Gondwana. Most of the faults which have affected the coal zones appear to run parallel to the general strike of the Vryheid Formation sedimentary rocks and the fold axis of the Lebombo monocline. It is suggested that the east–west tensional forces, which prevailed during the formation of the Lebombo monocline, played a major role in the faulting pattern and also gave rise to the graben structures (block faulting). Prominent faults, which have affected the coal horizons, appear to be strike faults with vertical throws of up to 100 m. These faults dissect the coal measures into various isolated blocks.

A dominant feature of the geology in the Kangwane Coalfield is the presence of major Jurassic aged dolerite dykes and sills, which transgress the sedimentary package in a complex and irregular fashion, displacing or eliminating the coal seams. The sills in particular seem to transgress from a position below the No. 1 Seam to a level above the No. 4 Seam and may be up to 40 m thick. Delineating the areas of sill breakthrough is important as they tend to cause seam displacement and burning. A major transgressive dolerite sill outcrops in two geographic areas in the northern part of the Sentula Nkomati Mine lease area, known as the Mangweni Block, and numerous sub-vertical north–south trending dolerite dykes of variable thickness have been delineated by an aeromagnetic survey (Ashton, 2011). For Sentula's Nkomati mine area the structural interpretation from the aeromagnetic data show a vast amount of north-northeast trending dykes of the Rooi Rand Dyke Swarm, and the structural complexity in the northern block has discouraged exploitation in that region (Ashton, 2011). These dolerite dykes also occasionally intersected the coal seams in the underground operations, consequently limiting such operations due to loss of coal and bad ground conditions.

4.7. Springbok Flats Coalfield

4.7.1. Introduction

The Springbok Flats Coalfield occurs outside of the boundaries of the MKB and may be considered as the first of the northern coalfields to be described here. A number of large exploration projects have been undertaken that have shown significant coal resources to occur within

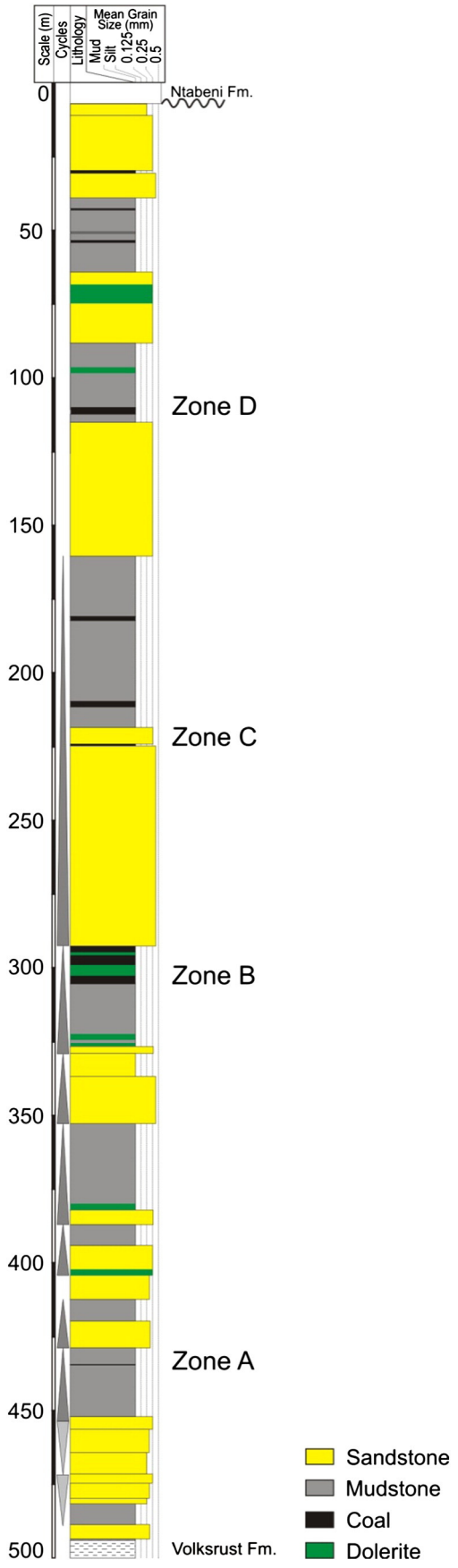

Fig. 33. Stratigraphy of the Emakwezini Formation at Somkhele mine. From Bordy and Prevec (2008).

the Springbok Flats Coalfield, mainly hosted within the Warmbad Formation of the Ecca Group (Fig. 36).

Whilst being amenable to surface and underground mining, none of these have however been put into production, mainly due to the co-occurrence of uranium, and concerns about whether coal containing uranium can be burned, or if the uranium can be extracted from the coal. Due to the depths of the coal in parts of the coalfield, CBM exploration activity has increased in the past few years.

4.7.2. Location

The Springbok Flats Coalfield covers an area of some 800,000 ha within an elongate basin extending some 200 km in a northeast–southwest direction and is approximately 50 km wide, in the Limpopo Province (Fig. 1). Various authors have split the coalfield into several distinct sub-basins for descriptive purposes (De Jager, 1986; Linning et al., 1983). These may be divided into three separate coal resource areas, called the Tuinplaats, Warmbaths (or Bela Bela) and Roedtan areas as indicated in Fig. 37.

4.7.3. Exploration and exploitation history

Borehole data in the CGS database show that over two thousand boreholes have previously been drilled by the Geological Survey, Trans-Natal and Anglo American Exploration. Many of these have however been drilled for uranium exploration as well as coal.

Wagner (1927) compiled one of the earliest reports on the Karoo Supergroup in the Springbok Flats Coalfield. Unfortunately the drilling on which this report was based was done with a jumper drill and therefore no analyses for the coal were reported. During the thirty year period following World War II, the coalfield was drilled extensively by the then Government Geological Survey and between 1951 and 1957 the Geological Survey of South Africa drilled an additional 27 boreholes in the north-eastern part of the Springbok Flats Coalfield. A further investigation was conducted by the Geological Survey between 1970 and 1973, which delineated a large (nearly 2.5 Gt) coal resource in the south-western sector of the coalfield. During this investigation an attempt was made to correlate the various coalfields in the then Northern Transvaal (now Limpopo Province), however subsequent investigations have shown some of these early correlations to be inaccurate.

Trans-Natal embarked on a large-scale coal and uranium exploration programme during 1973, which covered the entire Springbok Flats Coalfield. The programme included the drilling of more than 1400 boreholes and 300 deflections, but was put on hold in 1982 due to surplus energy capacity in South Africa at the time, as well as a collapse in the uranium price. Canyon Springs Investments 82 (Pty) Ltd (CSI), that has HolGoun (http://holgoun.co.za/holgoun-thermal-coal-project) as the controlling shareholder, has been granted a mining right for coal in respect to an area of some 20,590 ha that was previously covered by the exploration undertaken by Trans-Natal. During 2009, an additional drilling programme was completed by HolGoun in order to increase the confidence in the resource. According to their website, Canyon Springs will initially be developed as a surface mine to produce 1.5 Mtpa of coal to local power stations and the domestic market, with CVs ranging from 20 to 26 MJ/kg.

Most recently, the CGS has drilled an additional five boreholes, which are to form the basis of a PhD study on the uranium mineralisation and provenance of the sedimentary rocks of the Springbok Flats Basin.

4.7.4. Research history

Due to the presence of both coal and uranium various aspects of the Springbok Flats Coalfield have been covered academically. As part of explanation sheet No. 17 (Springbok Flats) Wagner (1927) described various aspects of the Karoo stratigraphy in the north-eastern part of the Springbok Flats geographic area, including the first map of the "coal measures shale". Since this time various workers have addressed

Fig. 34. Somkhele opencast mine showing the steep dip of the coal seams and intervening sandstone units.

academic topics and a few of the more important for understanding the coal-bearing sequence are provided below.

Visser and Van der Merwe (1959) report on the boreholes drilled by the Geological Survey between 1951 and 1957 in the north-eastern Springbok Flats Coalfield (Roedtan area). De Jager (1986) provides a number of borehole logs for boreholes drilled by the Geological Survey between 1970 and 1985 and Christie (1989) compiled an internal report for the Geological Survey on the demonstrated coal resources of the Springbok Flats Coalfield. This report is however still classified by the CGS and was therefore not available for scrutiny.

4.7.5. Geology

The basement to the Springbok Flats Coalfield is known from a number of boreholes drilled by Trans-Natal in the 1970s and is composed of granites and felsites of the BIC as well as older metasedimentary rocks of the Pretoria Group (Transvaal Supergroup). Like in some of the coalfields of the northern part of the MKB, the nature and palaeotopography of the basement relief plays an important role in the quality and distribution of the coal seams, with the coal zone known to pinch-out in the vicinity of palaeohighs. Both the Molteno Formation (north of Roedtan) and the Clarens Formation are known to occur resting directly on basement rocks, thereby effectively limiting the extent of the Permian aged coal repository.

SACS (1980) and Johnson et al. (2006) both recognise the full development of the Karoo Supergroup in the Springbok Flats Coalfield (Fig. 38) although in a markedly reduced form. Presently however no formal nomenclature or general stratigraphy has been accepted by SACS.

In several areas of the Springbok Flats, the Dwyka Group forms the basal part of the Karoo Supergroup. The thickness of this unit varies from a few cm to a maximum of 34 m and consists mainly of poorly sorted diamictites. The diamictites are matrix supported with both argillaceous and arenaceous occurring. In certain areas these deposits are stratified and accompanied by rhythmites. Extrabasinal clasts range in size from a few mm to as much as 1.5 m in diameter. The pebbles comprise fragments of angular to sub-rounded felsite, granite and metaquartzite that originated from the pre-Karoo basement in the vicinity.

The Ecca Group was deposited unconformably on an uneven pre-Karoo basement surface or directly onto the Dwyka Group lithologies. The Ecca Group was originally sub-divided into three main lithological units, which from the base upwards have variously been called the Lower Coal Bearing Unit or Lower Ecca Shale Stage (Du Toit, 1954), the Middle Ecca "Coal Measures", and the Upper Coal Bearing Unit or Upper Ecca Shale Stage. Various authors have split these into various formations (the Warmbad, Turfpan and Merinovlakte formations) however Johnson et al. (2006) lump them into the Hammanskraal Formation, in which he recognises a Lower and Upper Coal Zone (Fig. 38). Recent work by Myburg (2012) allows for the Lower and Middle stages to be grouped together under the Vryheid Formation, with the old Upper Ecca stage equating to the Volksrust Formation. Where present and documented the average thickness of the Beaufort Group in the Springbok Flats Coalfield area varies between 25 m on the farm Roodekoppies 167JR and 35 m on Troya 151JR.

4.7.6. Coal seams

From the bottom upwards the coal seams in the Springbok Flats Coalfield have previously been referred to as the: Lower Seam, Middle Seam (comprising the Lower Middle Seam, Upper Middle Seam and Top Marker Seam), and Upper Seam (Fig. 39).

Two coal horizons, as much as 12 m thick in the deeper parts of the basin, have been reported at depths between 10 and 1200 m below surface. This coal zone thins where it approaches the flanks of palaeohighs or where it was eroded away by the overlying Molteno Formation sandstones. Uranium is known to occur in coal and carbonaceous mudstones in the upper part of the coal zone.

The Lower Seam is sporadically and poorly developed in the Tuinplaats area and is of no economic interest. The overlying Middle Seam constitutes the main coal resource target and may in places be split by a carbonaceous mudstone parting (with intercalated thin coal bands) into a Lower Middle Seam and Upper Middle Seam. In the northern and western parts of the Tuinplaats area this parting thins and the full

Table 16
Average coal qualities for Somkhele Area 1 at a 1.6 RD float density.
After Grobler (2006).

Coal Seam	FC (%)	Ash (%)	CV (MJ/kg)	IM (%)	VM (%)	TS (%)	P (%)	Yield (%)
B (Main) Seam	72.53	16.54	29.2	1.83	9.1	0.66	0.0199	72.33

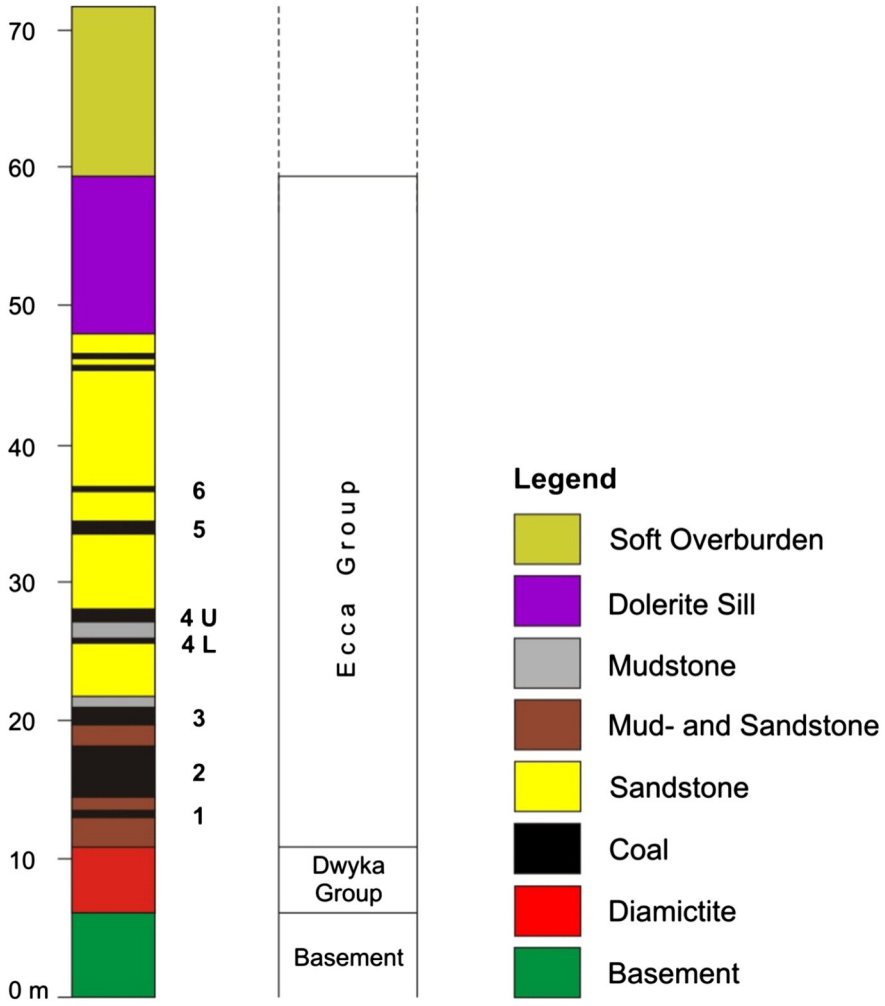

Fig. 35. General stratigraphy of the coal-bearing succession in the Kangwane Coalfield.

Middle Seam package is potentially mineable. To the south, where the parting thickens, the Lower Middle Seam is the selected potentially economic horizon.

4.7.6.1. Coal quality. Very little publically available information exists regarding the coal qualities in the Springbok Flats Coalfield and the general qualities presented in Table 19 are taken from Linning et al. (1983).

De Jager (1986) notes that the analysis carried out on coarse crushed material (−51 mm) of the coal seams in the boreholes drilled by the Geological Survey in the early 1970s, gave raw values of between 30 and 55% Ash, CVs of sub 22 MJ/kg, IM of up to 6%, and VM of 28% and higher. He further notes that the coal responded well to beneficiation at a RD of 1.65. Sulphur may be highly variable and nuggety, with values as high as 4.82% documented for coals on the farm Berlin 643 KR. The sulphur does however respond to beneficiation and is below 0.84% for a 1.7 RD float (Linning et al., 1983).

4.7.7. Structure and intrusions

Except for those in the proximity of basement highs, where dips of up to 7° are known, the coal seams within the Springbok Flats Coalfield have a regional dip of between 1 and 2° to the north. The coalfield is structurally complex due to it being a fault bounded basin and various faults transect and compartmentalise the coalfield.

Few dolerites are documented within the coalfield and according to Linning et al. (1983) no dolerites were encountered in any of the Trans-Natal boreholes. A 30 m thick dolerite sill is however known around the periphery of the coalfield.

4.8. Waterberg Coalfield

4.8.1. Introduction

The Waterberg Coalfield contains between 40 and 50% of South Africa's remaining coal resources and is considered to be the last major coal resource in the country. It should therefore be the basis of the republic's power generation industries' long-term future as the current mining areas in the MKB become depleted over the next 15 years. Only Exxaro are currently extracting any meaningful coal from this coalfield, from their Grootegeluk Mine, which is situated some 17 km west of the town of Lephalale. It is the largest opencast coal mine in the world and operates the world's largest coal beneficiation complex, producing some 18.8 Mtpa of coal products from 38 Mtpa RoM, using a conventional truck and shovel operation.

The coalfield is also the home to Eskom's Matimba Power Station, the largest direct dry cooling power station in the world. Construction is also currently underway on Medupi, a second dry-cooled, base load station in the coalfield. The planned operational life of this new station is 50 years (http://www.eskom.co.za/).

Table 17
Raw coal qualities for the Kangwane southern sector. Phos. (%) = percentage phosphorous in coal.
From ZYL Investor presentation, June 2012.

FC (%)	Ash (%)	CV (MJ/kg)	VM (%)	IM (%)	TS (%)	Phos. (%)
57.57	23.61	21.03	6.27	1.60	0.22	0.032

Table 18
Washed coal specifications based on exploration to date.
From ZYL Investor presentation, June 2011.

	Kangwane Anthracite Project	Neighbouring Nkomati Anthracite Mine
Ash (%)	16–22	20.3
VM (%)	4.8–7.8	7.6
FC (%)	74.75–78.10	75.1
TS average (%)	0.52	0.7
Phos. content (%)	0.02–0.002	–
CV (MJ/kg)	27.78–28.10	28.4

4.8.2. Location

The Waterberg Coalfield is situated 400 km northwest of Johannesburg in the Limpopo Province (Fig. 1), immediately north of the Waterberg mountain range. The coalfield strikes approximately 90 km east–west and 40 km north–south, and covers an area of some 360,000 ha. It extends from the Palala shear zone and basement outcrop in the east, to the Botswanan border in the west. The northern boundary is defined by the Melinda Fault Zone, with basement outcrops of the Limpopo Belt outcropping to the north of this zone. The southern boundary is formed by the Eenzaamheid Fault Zone, to the south of which Waterberg Group rocks occur (Fourie et al., 2009). The Daarby Fault essentially separates the deposits within the coalfield into shallow and deep resource areas (Fig. 40).

4.8.3. Exploration and exploitation history

In March 1920 the intersection of thick coal seams was reported from a water-boring operation on the farm Grootegeluk 459LQ, 25 km west of the town of Lephalale (formerly Ellisras) in the Limpopo Province. This was the discovery hole for the Waterberg Coalfield, following which a reconnaissance study of the area was undertaken by A.L. Du Toit and H.F. Frommurze. A few other boreholes were drilled in the vicinity and the coals samples were sent for analysis. The results of this drilling were published in 1922 in the South African Journal of Industries (Trevor and Du Toit, 1922). As coal of coking quality was of no significance and there was more than sufficient supply for electricity generation, the coalfield was largely ignored and no additional boreholes were drilled for the next twenty years.

During the period 1941 to 1952, the Geological Survey Division of the Department of Mines determined the extent of the Waterberg Coalfield and the qualities of the coal by means of geological mapping, 143 boreholes, and two prospecting shafts (Cillié, 1951, 1957; Cillié and Visser, 1945). The first extensive drilling subsequent to the Geological Survey work was exploration drilling undertaken in 1955 in a joint programme by Iscor and Sasol. Samples of coal for coking tests were obtained from 22 large diameter boreholes (254 mm core), drilled along a line between the prospecting shafts on Grootegeluk 459LQ and Hieromtrent 460LQ during 1959/1960. Sasol undertook an additional 120 borehole programme during 1965/66 and since this time Sasol, Anglo Coal, Goldfields, and Iscor/Kumba (Exxaro) have over various periods conducted coal exploration programmes in the Waterberg Coalfield, which resulted in over 450 boreholes having been collared and drilled.

In May of 1973 Iscor began an intensive exploration programme on six farms originally purchased in 1957 for a final assessment of the resource and quality of metallurgical coal on these properties. Following on a positive feasibility study the Iscor board approved the opening of the Grootegeluk mine in February 1974, with the commissioning date set for the 1st of July, 1978 (Alberts, 1982). Difficult economic conditions in South Africa in the early 1970s, coupled to Iscor's commitment to other capital projects saw the postponement of the commissioning to the middle of 1980. The coal mine and beneficiation plant at Grootegeluk were commissioned on the revised schedule, with the first train of metallurgical coal loaded and dispatched to the Vanderbijlpark works on the 23rd of July, 1980 (Alberts, 1982).

Iscor was privatised in 1989, and in 2001 unbundled as Kumba Resources and Iscor (which was bought by Mittal in 2005). Kumba Resources separated into Kumba Iron Ore and Exxaro Resources in 2006, with the coal assets owned by Exxaro. According to the Exxaro website (http://www.exxaro.com/) of the 18.8 Mtpa production, some

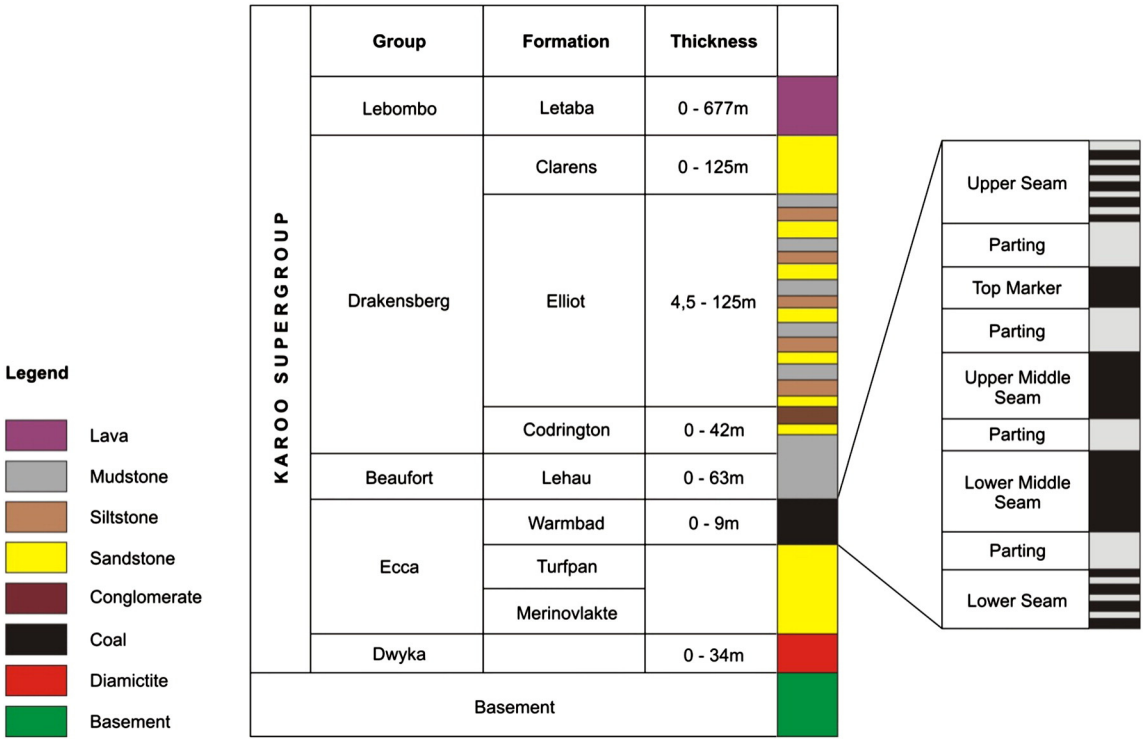

Fig. 36. Generalised stratigraphy of the Karoo Supergroup in the Springbok Flats Coalfield showing the position of the main coal-bearing succession within the Warmbad Formation. After Myburg (2012).

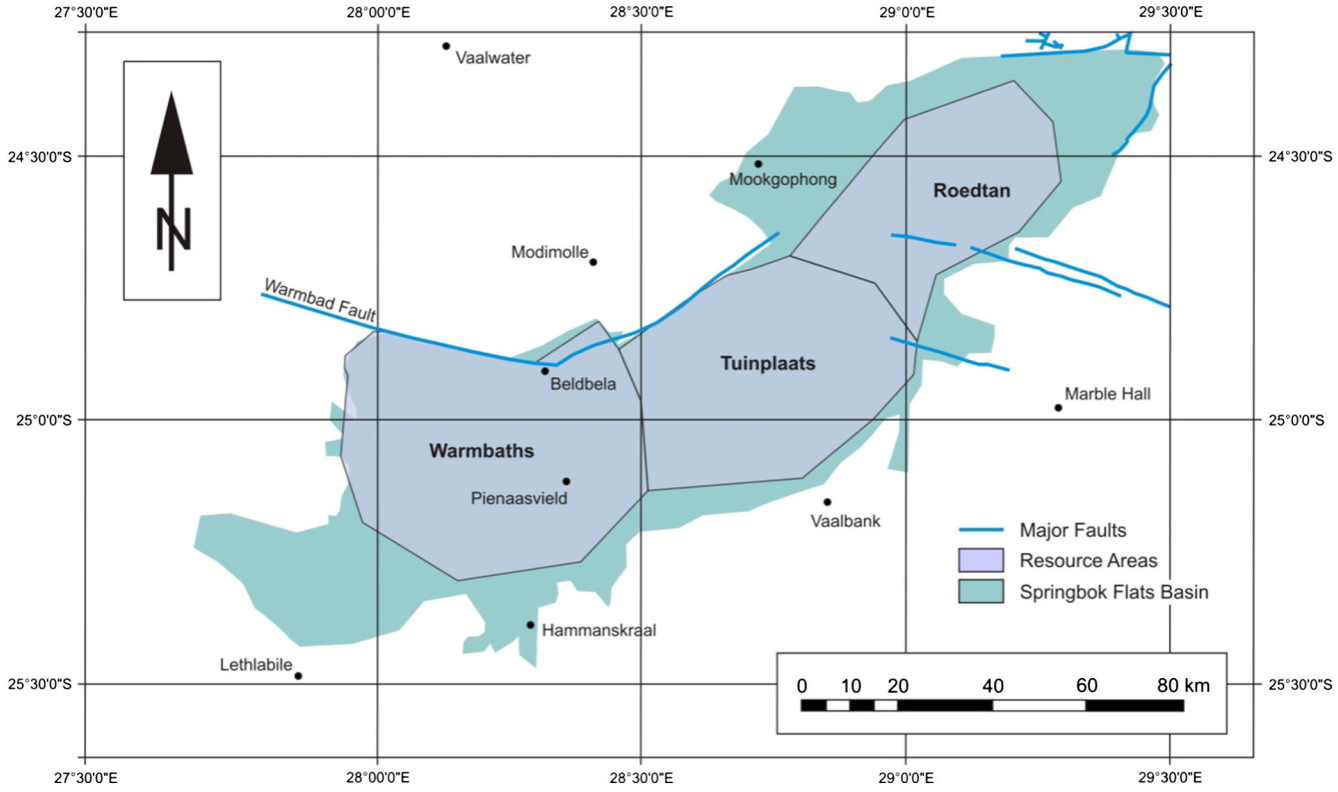

Fig. 37. Resource areas in the Springbok Flats Basin.

14.8 Mt is thermal coal, which is transported directly to Eskom's Matimba power station via a 7 km conveyor belt. An additional 1.5 Mtpa of metallurgical coal is sold domestically to the metals and other industries. Grootegeluk produces 2.5 Mtpa of semi-soft coking coal, the bulk of which is railed directly to Mittal SA under a long-term supply agreement. Approximately 1 Mtpa of semi-soft coking coal and thermal coal is exported through the Richards Bay Coal Terminal (RBCT) or sold domestically. Exxaro plan on escalating Grootegeluk's production to 36 tpa by 2017. According to Dreyer (2011) at the end of 2010 Grootegeluk had reserves of 2986 Mt from a total resource base of 4887 Mt. Sasol has the exploration right to nine properties in the Steenbokpan area, about 10 km west of the Grootegeluk Mine.

Apart from four prospecting shafts, no underground mining has ever been undertaken in the Waterberg Coalfield and given the huge open-pit resources it is unlikely that the coalfield will see an underground operation in the near future. The potential for CBM production in the deeper eastern portion of the Waterberg Coalfield was identified by Anglo Coal in the early 1990s where the seams contain higher volumes of CBM gas, which have the potential to be economically exploited. Anglo Coal, initially in partnership with Shell, was involved in exploration for CBM and AATC currently holds exploration rights for gas (CBM) covering an area of approximately 110,000 ha in the Waterberg Coalfield. This is the leading CBM play in South Africa with five test wells that are currently flaring methane. Exxaro have also conducted limited CBM investigations with Batepro as a partner.

A number of juniors have recently entered the coalfield and exploration activity is at an all-time high. The most advanced of all of these projects is Resource Generation's Boikarabelo Project, which according to a release on their website (http://resgen.com.au/) should see first production in 2015.

4.8.4. Research history

Whilst not the subject of as much academic interest as the Witbank, Highveld and northern KZN coalfields, the Waterberg Coalfield has been the focus of considerable academic research. The lack of exposure has however meant that most of this work has been mostly based on either borehole cores or opencast pit faces at the Grootegeluk Mine.

The earliest available report documenting the lithological succession of the Waterberg Coalfield seems to be a Department of Mines publication by François Alwyn Venter dated 1944/45. The work provides records of the first twenty boreholes sunk in the coalfield for the Department of Mines and documents the earlier work undertaken in 1920 as well. The work undertaken by the Department of Mines during the 1940s and 1950s is well documented in the works of Cillié and Visser (1945), and Cillié (1951, 1957).

Alberts (1982) documents the conception, planning and establishment of the Grootegeluk Mine. In it he documents the history of the development of the Waterberg Coalfield and provides the first stratigraphic zonation of the coal-bearing succession, as well as qualities for a primary and secondary product for each of zones 5–11 and raw coal qualities for zones 1–4. The Waterberg Coalfield was not addressed as a separate entity in the 1986 Mineral Deposits work, being covered as part of the overview of the coal occurrences of the then Transvaal Province (De Jager, 1986), which in turn was largely based on his earlier work (De Jager, 1983). Siepker (1986) provides a complete overview of the stratigraphy, sedimentology and depositional environments of the Karoo fill of the Ellisras (Waterberg) sub-basin, including aspects of the various controls on the accumulation and this work provides the most comprehensive academic coverage of the sub-basin to date.

For the western part of the coalfield Spears et al. (1988) document what they believed to be the first recorded occurrence of a tonstein in the coalfields of South Africa and which they placed stratigraphically in the Volksrust Formation.

During a wave of genetic stratigraphy studies of the Karoo Supergroup, Beukes et al. (1991) established a genetic stratigraphy for the Waterberg Coalfield built on seven genetic increments of sedimentation (GIS1–7). Faure et al. (1996a) provide additional work on the sedimentology and palaeoenvironments of the Karoo Supergroup in the

Du Toit (1954) Haughton (1969)		S.A.C.S. (1980)	De Jager (1983) McRae (1988)	Johnson et al. (2006)	CGS Database	
Stormberg Series	Bushveld Amygdaloid	Letaba Formation	Letaba Formation	Letaba Formation	Letaba Formation	Drakensberg Group
	Bushveld Sandstone	Clarens Sandstone Formation	Clarens Sandstone Formation	Clarens Formation	Clarens Formation	Beaufort Group
	Bushveld Mudstone	Irrigasie Formation	Elliot Formation	Irrigasie Formation	Elliot Formation	
			Molteno Formation		Molteno Formation	
Ecca Series	Upper Ecca Shale Stage	Ecca Group (formations not named)	Beaufort Group	Upper Coal Zone	Volksrust Formation	Ecca Group
	Middle Ecca Coal Measures Stage		Vryheid Formation	Hammanskraal Formation	Vryheid Formation	
	Lower Ecca Shale Stage		Pietermaritzburg Shale Formation	Lower Coal Zone		
Dwyka Series		not named	Dwyka Group	Dwyka Group	Dwyka Group	

Fig. 38. Variously proposed stratigraphic nomenclature for the Karoo Supergroup in the Springbok Flats Coalfield. From Myburg (2012).

Waterberg Coalfield and coupled with organic chemistry data, link the facies and sedimentology to aspects of the thermal history. Faure et al. (1996b) provide various geochemical data on the mudstones of the Karoo Supergroup in the 'Ellisras Basin' and use this data to discuss the provenance.

In early 2008 a high-resolution airborne geophysical survey was completed across the Waterberg Coalfield covering the Ellisras sub-basin completely, as well as small parts of the adjacent area. The work was described as part of a Coaltech research project (Fourie, 2008). The survey was flown at 200 m line spacing at an altitude of 80 m and recorded magnetic, total count radiometric, uranium, thorium and potassium count data, and points for a digital terrain model (Fourie, 2009) and the data was used to re-interpret the structure of the Ellisras sub-basin (Fourie et al., 2009), and showed the Karoo Supergroup fill to be twice the thickness originally believed.

Based on the logs of some 830 boreholes supplied by the CGS, Mtimkulu (2009) undertook a provisional basin analysis study of the Waterberg sub-basin. The main aim of this work was to relate the formation and fill of the Karoo Supergroup strata to their syn-sedimentary controls. Roux (2011) relates the coal wash table data and analysis obtained from exploration drill core with the RoM material being processed in Grootegulk's beneficiation plants. Wagner and Tlotleng (2012) studied four RoM coals and density fractioned samples to determine their trace element content and showed that the concentrations of most trace elements in the RoM coals exceed the global averages and certain global ranges, and generally exceed values reported for other South African coalfields.

Chabedi (2013) looked at the issue of the deep coal resources within the Waterberg Coalfield and notes that the deep eastern part of the coalfield will need to be exploited by multi-seam underground mining on a scale never before attempted in South Africa, concluding that the best mining method would be total extraction using long wall mining.

In the most recent work on the coalfield Sullivan et al. (2013) investigated the practical application of vectar processed densities from geophysical logs in proving coal seam lateral continuity. This work showed that the correlation between measured densities and those derived from vectar processed densities is better than 95%, and that further manipulation of such data allows for the various coal seams and zones to be correlated to a high degree of certainty.

4.8.5. Geology

Geologically the Waterberg Coalfield occurs in the fault-bounded Ellisras sub-basin, considered to be an embayment of the much larger Kalahari Basin, which underlies a vast area of Botswana (Catuneanu et al., 2005). This sub-basin is variously considered as a half-graben (Fourie et al., 2009) or graben structure (Sullivan et al., 2013). The basement consists of Archaean Beit Bridge Complex in the north and Proterozoic Waterberg Group in the south (Brandl, 1996). To the northeast and east, the Constantia Suite and BIC (Villa Nora and Nebo granites) are developed. A comprehensive description of the various floor rocks to the coalfield may be found in Johnson et al. (2006).

The stratigraphic sequence in this sub-basin therefore consists of a basement of Late Palaeoproterozoic metaconglomerates and meta-quartzites of the Waterberg Group (Transvaal Supergroup), and/or basic rocks of the BIC. These are unconformably overlain by sedimentary rocks equivalent of the Dwyka, Ecca, Beaufort and Stormberg groups (Fig. 41) in the MKB. Some authors prefer to use different terminologies, with the Waterkloof, Wellington, Swartrant, Goedgedacht, Grootegeluk, Eendragtpan, Greenwich, Lisbon, Clarens and Letaba formations recognised from bottom to top (Brandl, 1996; Johnson et al., 2006). We here follow Beukes et al. (1991) and Faure et al. (1996a) in using equivalency with the lithostratigraphic nomenclature of the MKB, with the substitution of the Grootegeluk Formation as the correlative of the Volksrust Formation.

The Dwyka Group (Waterkloof and Wellington formations of Brandl, 1996; and GIS1 of Beukes et al., 1991) represents the base of the Karoo Supergroup and comprises diamictite, conglomerates and mudstone. It rests unconformably on Waterberg Group and pre-Waterberg Group basement and according to borehole data (Wakerman, 2003) is only well-developed in the southern half of the Ellisras sub-basin. It is generally 20–30 m thick, but reaches a maximum thickness of 160 m in the southwest and 180 m in the southeast. Where the unit is fully developed, the base comprises a unit of diamictites, with dark-grey, horizontally laminated mudstone and siltstone containing sandstone lenses and scattered millimetre-sized grains. This unit becomes more siltstone rich and lighter coloured towards the top.

Beukes et al. (1991) describe their GIS 1 (Dwyka Group equivalent) as comprising diamictite, poorly sorted conglomerate, granulestone to medium-grained sandstones, laminated mudstones and intercalated mudstones and granulestones. These authors attribute these lithologies to ground moraine; braided outwash systems; splay deposits; lacustrine varves and turbidites and subaqueous debris flows.

Wakerman (2003) notes that in Eyesizwe's Waterberg South Project area the best reference section of the Dwyka Group lithologies can be observed in the detailed borehole log of GK2 on the farm Kleinpan, and from boreholes GK59 and GK28 on the farm Kalkpan. He documents these lithologies as being presented by diamictite, carbonaceous siltstone and finely laminated graded mudstone. He notes that the diamictite is usually very thinly developed (being less than 60 cm thick), unstratified, ungraded and matrix supported. The matrix consists

of off-white to greyish white and silt-sized grains with partially sub-rounded small pebbles scattered throughout the unit. Wakerman (2003) further notes that the laminated mudstones comprise repetitions of individual units approximately 4 cm in thickness. Each unit consists of a basal light-coloured siltstone, which forms approximately 60–80% of the unit. Towards the top, the layers become finer-grained, dark mudstone. The contacts between the individual units are sharp. Collectively, units form a sequence up to 6 m thick. The carbonaceous off-white laminated siltstones are often associated and inter-laminated with the laminated mudstone and diamictite. The siltstone attains a maximum thickness of 10 m. Soft-sediment deformation is present in the lower part of the carbonaceous siltstone. Wakerman (2003) attributes these lithologies to lacustrine (varved) deposition.

In the Waterberg North Project area the Dwyka Group is composed predominantly of diamictite with large pebbles, cobbles and even boulders scattered in off-white to grey coarse arkosic sandstone-rich matrix (Wakerman, 2003). The pebbles consist mainly of quartz and are angular to sub-rounded. The pebble size decreases towards the top of the unit (Siepker, 1986).

Pietermaritzburg Formation equivalent strata overlie the Dwyka Group (Beukes et al., 1991; De Jager, 1986). Beukes et al. (1991) document this as their GIS 2, which they felt represented a coarsening-upward sequence of prodelta siltstone with interbedded glaciogenic debris flow and debris rain deposits, delta front coarse sandstones; and delta plain coarse- to very coarse-grained sandstone channel deposits, and sandstone/siltstone splay deposits.

The Vryheid Formation equivalents in the Waterberg Coalfield are dominated by sandstones and predominantly dull seams of coal (Fig. 42). The Ecca Group coals of the Waterberg Coalfield were originally divided into zones 1, 2, 3, 4A, 4, 5A, 5B, 5C, 6A, 6B, 6C and 7, numbered from the bottom up (De Jager, 1976). Most subsequent authors have accepted the numbering for the seams in the Vryheid Formation (the predominantly dull coal seams 1, 2, 3, 4A and 4); however the coals in the overlying Grootegeluk Formation have generally been named as zones 5–11 (Fig. 42).

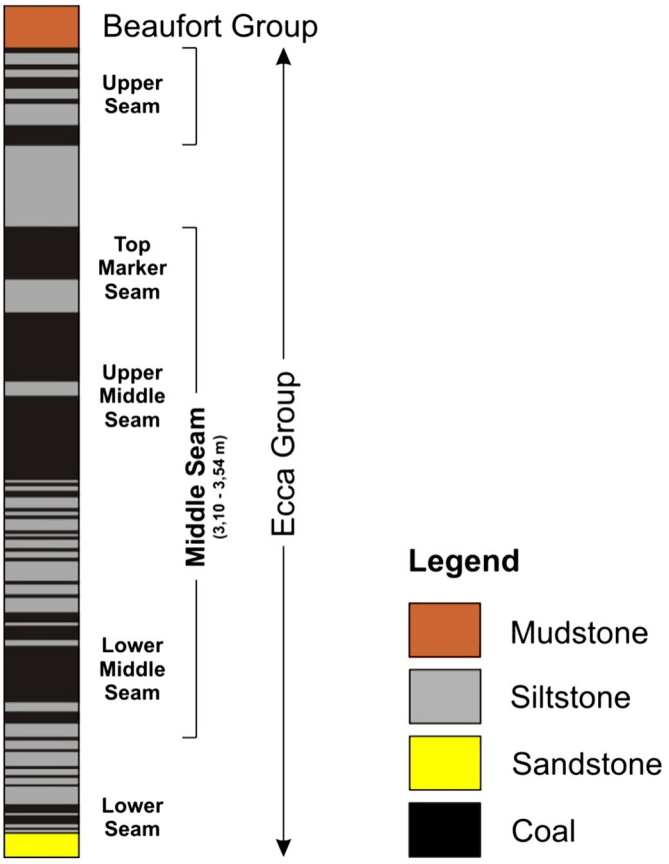

Fig. 39. Generalised stratigraphic column of the coal-bearing succession in the Tuinplaats area of the Springbok Flats Coalfield.
After Myburg (2012).

Table 19
Raw coal analyses for the Upper Middle Seam and Lower Middle Seam, Northern Block, Settlers-Tuinplaats area.
From Linning et al. (1983).

Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	TS (%)
Upper Middle Seam	23.5	27.8	30.2	2.1	2.86
Lower Middle Seam	20.6	34.6	26.8	2.5	2.41

The Vryheid Formation in the Waterberg Coalfield is approximately 55 m thick, and like its counterpart in the Witbank and Highveld coalfields, is dominated by coarse sandstones, carbonaceous mudstones and coal seams that range in thickness from 1 to 6 m thick. This lower part of the succession is typical of the multiple seam deposits as defined by SANS 10320 (2004).

Beukes et al. (1991) note that the succession from the sandy upper part of GIS 2 to the top of GIS 5 is the lithological equivalent to the Vryheid Formation of the MKB. The coal-bearing strata of the Vryheid Formation were formed in a shallow east–west trough with the inflow of sediments from an east-northeast direction.

The overlying Grootegeluk Formation of the Waterberg Coalfield is between 70 and 90 m thick and consists of relatively thin bright coal seams interbedded with numerous mudstone and carbonaceous mudstone layers. This is the equivalent of GIS 6 of Beukes et al. (1991), which these authors equate to the Volksrust Formation in the MKB. It should be noted that Dreyer (2011) reverts to using the Volksrust Formation for the sedimentary succession containing the upper coal zones. The coal and mudstone occur in seven identifiable cyclical repetitions of mudstone and coal sequences, which, based mainly on the work of the geologists at Grootegeluk Coal Mine, have been numbered as coal zones 5–11 (Alberts, 1982; Botha, 1984; De Jager, 1976). The coal deposits of the Grootegeluk Formation in the Waterberg Coalfield are typical of the thick interbedded seam deposit type as defined in SANS 10320 (2004). The vitrinite reflection of the Grootegeluk Formation (mean 0.72%) and palynological evidence indicate that the unit was subjected to post depositional temperatures of ±100 °C (Dreyer, 2011).

In the northern part of the Ellisras sub-basin the Goedgedacht Formation occurs between the Vryheid and Grootegeluk formations, and consists of mudstone, gritty mudstone and subordinate sandstone with only thin sub-economic coal seams present (Snyman, 1998). Beaufort Group equivalent strata however usually overly the Grootegeluk Formation. Beukes et al. (1991) describe this unit as their GIS 7 and note that it comprised dominantly of medium to light grey massive mudstones. Stormberg and Drakensberg group equivalent rocks also occur at surface within the coalfield. Whilst these units form the overburden and roof rocks to the coal seams they do not however contain any coals, and as such are not described here. For detailed descriptions of these lithologies the interested reader is referred to the works of Wakerman (2003), Johnson et al. (2006) and Bordy et al. (2010).

4.8.6. Coal seams

Unlike in the coalfields of the Witbank, Highveld and Ermelo coalfields, where five coal seams are present, and are restricted to the Vryheid Formation, in the Waterberg Coalfield eleven coal zones are identified, four of which occur in the Vryheid Formation, and the remaining seven in the overlying Grootegeluk Formation (Fig. 42).

4.8.6.1. Coal qualities. Little published information exists regarding the overall coal qualities of the Waterberg Coalfield, although it

is known that the coal rank increases steadily from west to east (De Jager, 1986). It is usually assumed that the qualities encountered at Grootegeluk Coal Mine are potentially representative of the entire coalfield, and these have been presented in the works of Alberts (1982) and Faure et al. (1996a) and in various conference presentations, including one of the most recent by Dreyer (2011).

In the Waterberg Coalfield there is no noticeable increase in rank with increasing depth. The air dried volatile content of the coal remains at 35–36% from the sub-outcrop to a depth of 400 m (Dreyer, 2011). The swelling indices (which show the potential of the semi-soft coking coal) are however strongly dependant on depth of weathering.

Zones 1 to 4 consist mostly of dull coal, with brighter coal at the base of each seam. There is however a large variation of coal qualities and thicknesses due to lateral facies changes. At Grootegeluk the Zone 1 coal is described as being a 1.55 m thick seam of dull coal with very few bright laminae and some thin mudstone intercalations (Alberts, 1982; Dreyer, 2011). Zone 2 is 3.73 m thick and described as a dull coal, with the note that the lower 2 m yields lower Ash coal. At 7.82 m Zone 3 is the thickest. It is described as a dull coal with bright laminae in the lower 1.8 m that yields a better lower Ash coal, which has some coking properties. Zone 4 is a composite zone (4A, interbeds and 4) around 10 m thick. Zone 4A is described as a dull coal with a few bright laminae and Zone 4 as a dull, heavy coal, with bright coal laminae in the lower 2 m that yields a coking fraction. In general however the lower zones at the Grootegeluk Mine have very little coking coal potential. Zones 1 and 2 do however have a low phosphorous content and coal from these zones can be used in the metallurgical industry. The Ash content of the four lower seams increases upward from approximately 20% to 45% and these lowermost coals are used primarily as a steam coal in the Matimba power station, without any beneficiation. The same zones can also be beneficiated to a 15% Ash content suitable as metallurgical coal for different markets (e.g. corex and char) depending on the phosphorous content. In the case of Coal Zones 2 and 3, in-seam selective mining is also possible to extract the basal portions of these coal zones with their lower phosphorous content.

The qualities in the upper seven zones (zones 5–11) are similar to one another, except for Zone 6, which can only be used for the production of thermal coal which has higher phosphorus content. Due to the high Ash content of the bright coal from coal zones 5–11 all the coal must be beneficiated (washed). The primary wash of these zones yields an excellent blend semi-soft coking coal of around 10.3% Ash content. The secondary wash produces a middling product of approximately 35% Ash content, which is suitable for power generation.

4.8.7. Structure and intrusions

The structural history of the Ellisras sub-basin has been well summarised by Mtimkulu (2009) and Fourie et al. (2009). The Waterberg Coalfield is heavily faulted, with major faults striking east–west and a conjugate set striking northwest–southeast (Snyman, 1998). The Eenzaamheid, Zoetfontein and Daarby faults (Fig. 40) control the regional fault pattern. The Daarby fault is the most significant fault structure and has caused displacements ranging from 240 to 300 m and effectively separates the coalfield into a shallow, potential opencast mine-able, and deep underground area (Fig. 40). It affects this by the juxtaposition of Ecca Group lithologies and the Clarens Formation, such that west of the fault strata of the Grootegeluk Formation are exposed at surface, whereas to the east of the fault the surface geology is dominated by rocks of the Stormberg Group.

As for the Springbok Flats Coalfield, but unlike the majority of the coalfields of South Africa, dolerite intrusions seem to be rare in the Waterberg Coalfield, with no sills yet reported and only a few narrow dykes documented.

4.9. Soutpansberg Coalfield (Mopane, Tshipise and Pafuri sub-basins)

4.9.1. Introduction

Sometimes referred to as the forgotten basin (Sparrow, 2012), with only one active colliery, which is winding down, the Soutpansberg Coalfield has recently become the focus of significant new exploration for both thermal and coking coal and CBM, with a number of new mines planned in the near future.

The Soutpansberg Coalfield may be sub-divided into three separate smaller sub-basins (sometime referred to as coalfields) namely the Pafuri (Eastern Soutpansberg), Tshipise (Central Soutpansberg) and Mopane (Western Soutpansberg) sub-basins (Fig. 1). Barker (1999) refers to these three sub-basins as the Venda–Pafuri, Mutamba and Mabelebele coalfields. Sparrow (2012) defines seven sub-basins for the Soutpansberg Coalfield, from west to east these being the Waterpoort, Mopane, Sand River, Mphefu, Tshipise South, Tshipise North and Pafuri sub-basins, however at present we have retained only the three better known sub-basins for the descriptions that follow.

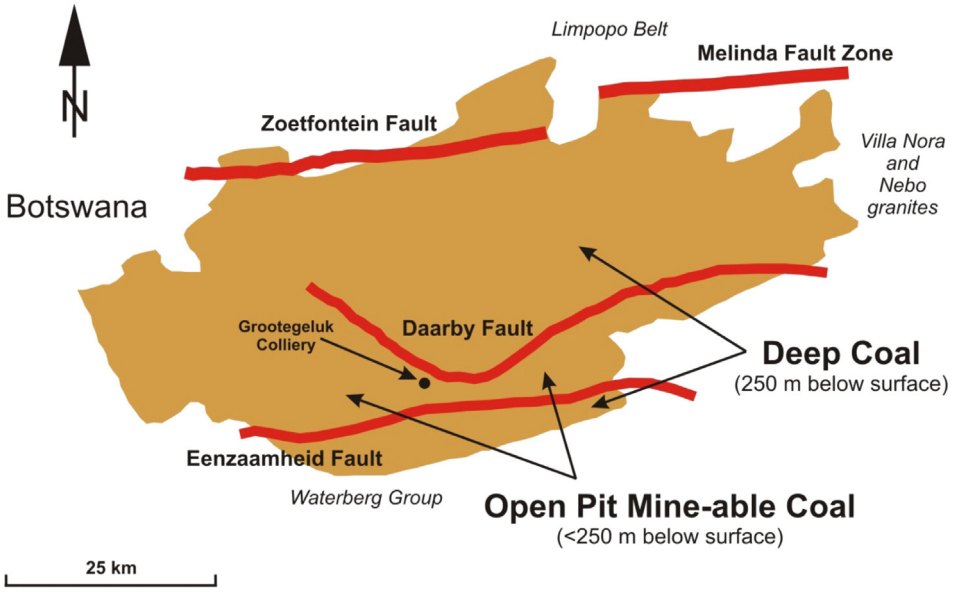

Fig. 40. Schematic overview of the extent of the Waterberg Coalfield showing the areas of shallow and deep coal and the main faults. After Jeffrey (2005b).

4.9.2. Location

The Soutpansberg Coalfield is situated to the north of the Soutpansberg Mountain Range in the Limpopo Province, extending for ±190 km from Waterpoort in the west, to the Kruger National Park in the east (Brandl, 1981). It lies between latitudes 22°S and 23°S and longitudes 28°E and 32°E (Malaza, 2013).

4.9.3. Exploration and exploitation history

The coalfield has been known since the late 1800s and commercial mining began in 1911 when the Messina Transvaal Copper Company developed the Lilliput Colliery to supply coal to the copper smelter in Messina. This mine was situated on the farm Cavan, and mining was terminated in 1918, leaving an inclined shaft system. The coal was sampled by the Fuels Research Foundation in 1947 and the report indicated that coal of "significant coking propensity" existed (Sparrow, 2012).

From the late 1950s to the late 1970s, the Tshipise Basin was fairly extensively prospected for coal by the Department of Mines of the Geological Survey (now the CGS) and Iscor (De Jager, 1976). During the 1970s to 1980s, Iscor undertook a detailed exploration of the whole of the Soutpansberg Coalfield, drilling in excess of 2000 boreholes. In 1978/79, Iscor developed the Fripp box cut to assess the coking coal resources. This project was however later shelved in favour of the Tshikondeni project.

Iscor further prepared a pre-feasibility document in 1983 for the Jutland project in the Mopane sub-basin for the underground mining of coking coal on the Middle Lower and Bottom Upper coal horizons. Trans-Natal was also active in the Mopane sub-basin, drilling in the region of 200 boreholes. Although the logs were submitted to the CGS, the coordinates were corrupted and it is not clear exactly where these boreholes were collared.

The underground Tshikondeni Mine is situated on the north-eastern edge of the Coalfield, some 140 km east of the town of Musina in Limpopo Province. It began operations in 1984 and is the only colliery currently operating in the Coalfield. It is currently owned by Arcellor Mittal (http://www.arcelormittalsa.com/) and operated under contract by Exxaro. The mine produces 316,000 tpa of premium hard coking coal (from between 500,000 and 580,000 tpa RoM) via conventional bord-and-pillar extraction methods. The coal is accessed by four surface declines, and is processed through a single coal preparation plant with an operating capacity of 75,000 tpm. The coal yields high-grade coking coal for Arcelor Mittal's steel mill in Vanderbijlpark. The mine is however near the end of its life with production scheduled to stop in 2015.

In 2002, Rio Tinto and Kwezi initiated an exploration project around the town of Waterpoort (the Chapudi Project) and drilled in excess of 140 boreholes (Sparrow, 2012). The Iscor dataset pertaining to the Tshipise sub-basin (containing information from 1250 boreholes) was purchased by Coal of Africa Limited (http://www.coalofafrica.com/) (CoAL) in 2007. CoAL started exploration drilling on the farm Fripp in 2007 and by February of 2010 a total of 144 boreholes had been completed, including 24 large diameter boreholes for bulk sampling purposes. To date CoAL has completed some 198 boreholes, a large-scale exploration sample pit, and various other exploration techniques.

CoAL's Makhado Project is now an advanced feasibility-stage project with a 344.8 Mt MTIS resource. This resource is to be extracted by opencast methods and should allow for a 16 year LoM at an extraction rate of 12.6 Mtpa RoM coal (yielding 2.3 Mtpa) hard coking coal and 3.2 Mtpa thermal coal for domestic or export markets.

4.9.4. Research history

The most detailed published work directly concerning the geology of the Soutpansberg Coalfield are those of McCourt and Brandl (1980), Brandl (1981) and Van der Berg (1980). This work was followed by the likes of De Jager (1986), Sullivan (1995) and Thabo and Sullivan (2000). The descriptions which follow utilise these works. Bordy (2006) notes, that the work of McCourt and Brandl (1980) was based on limited borehole and outcrop data from the eastern extreme (Pafuri sub-basin) and that it may not be applicable to the basin as a whole.

4.9.5. Geology

Like the other northern coalfields the Soutpansberg Coalfield is preserved within various down-faulted, half-grabens, at the north-eastern edge of the Kaapvaal Craton (Fig. 43). McCourt and Brandl (1980) recognised that the location and shape of the Soutpansberg Coalfield were controlled by east-northwest and west-southwest orientated faults that follow the trend of the Limpopo Mobile Belt. The coal-bearing Karoo Supergroup rocks dip between 3 and 20° northwards, terminating against east–west trending strike faults on the northern margin (Brandl, 1981). Even within a particular sub-basin, coal-bearing strata may occur in separate areas (termed Valleys by Telfer and Njowa, 2012) (Fig. 43).

The Karoo aged rocks, containing the Soutpansberg Coalfield, overly the ±1850 Ma Soutpansberg Group (Malaza, 2013) and rock of the Beit Bridge Complex. The full stratigraphy of the Karoo Supergroup is preserved, although in a much reduced form from than in the MKB. The descriptions and formational nomenclature below follows that of McCourt and Brandl (1980), and Brandl (1981). It should be pointed out however that Bordy (2006) notes that detailed geological studies by Van der Berg (1980) in the Soutpansberg Coalfield seem to indicate that the applicability of this lithostratigraphic nomenclature is limited, as the various formations are not mappable in all parts of the coalfield. For this reason she suggested a practical informal subdivision, which places all the lower Karoo Supergroup strata (below the regionally traceable Fripp Formation) in the Basal Unit (which would include the Tshidzi, Madzaringwe and Mikambeni formations as described below).

Like elsewhere in South Africa the basal part of the Karoo succession is formed by Dwyka Group equivalents. In the Soutpansberg Coalfield these are referred to as the Tshidzi Formation and occur as a unit between 5 and 20 m in thickness. It is composed of diamictite and coarse-grained sandstone. According to McCourt and Brandl (1980) these deposits reflect glacial and fluvioglacial depositional environments. The upper contact of the Tshidzi Formation is currently defined as being gradational into the overlying Madzaringwe Formation, which forms the basal part of the Ecca Group in the coalfield.

The Madzaringwe Formation comprises up to 200 m of alternating feldspathic, often cross-bedded sandstone, siltstone and shale containing coal seams (Brandl, 1981). The basal part of the formation consists of a 30 m thick unit of carbonaceous siltstone and mudstone, shaly coal and thin coal seams. This unit is overlain by a succession of alternating layers of coal, grey black siltstone and carbonaceous mudstone, and very fine- to medium-grained sandstone. In the upper third of the formation prominent coal seams occur interlayered with carbonaceous mudstone (Malaza, 2013).

The Madzaringwe Formation is overlain by the Mikambeni Formation, which attains a thickness of between 20 and 150 m, and is composed predominantly of medium to dark grey siltstone, minor carbonaceous mudstone and khaki-red to grey sandstone. Scattered thin coal seams occur throughout.

The overlying Fripp Formation is the subject of some debate considering its equivalency in the MKB. McCourt and Brandl (1980) equate it to the lowermost Beaufort Group, a correlation followed by Malaza (2013). According to Van der Berg (1980) the Fripp Formation should be correlated with the Molteno Formation, both on lithological and palaeontological grounds. The Fripp Formation is up to 110 m thick and comprises medium- to coarse-grained feldspathic sandstones with thin pebble layers. The sandstone is interbedded with thin siltstone and mudstone and trough cross-stratification is present. The sandstones were probably deposited by braided river systems flowing towards the northwest and west (McCourt and Brandl, 1980).

The overlying Solitude Formation generally consists of purple to grey mudstones with a maximum thickness of approximately 170 m. At the

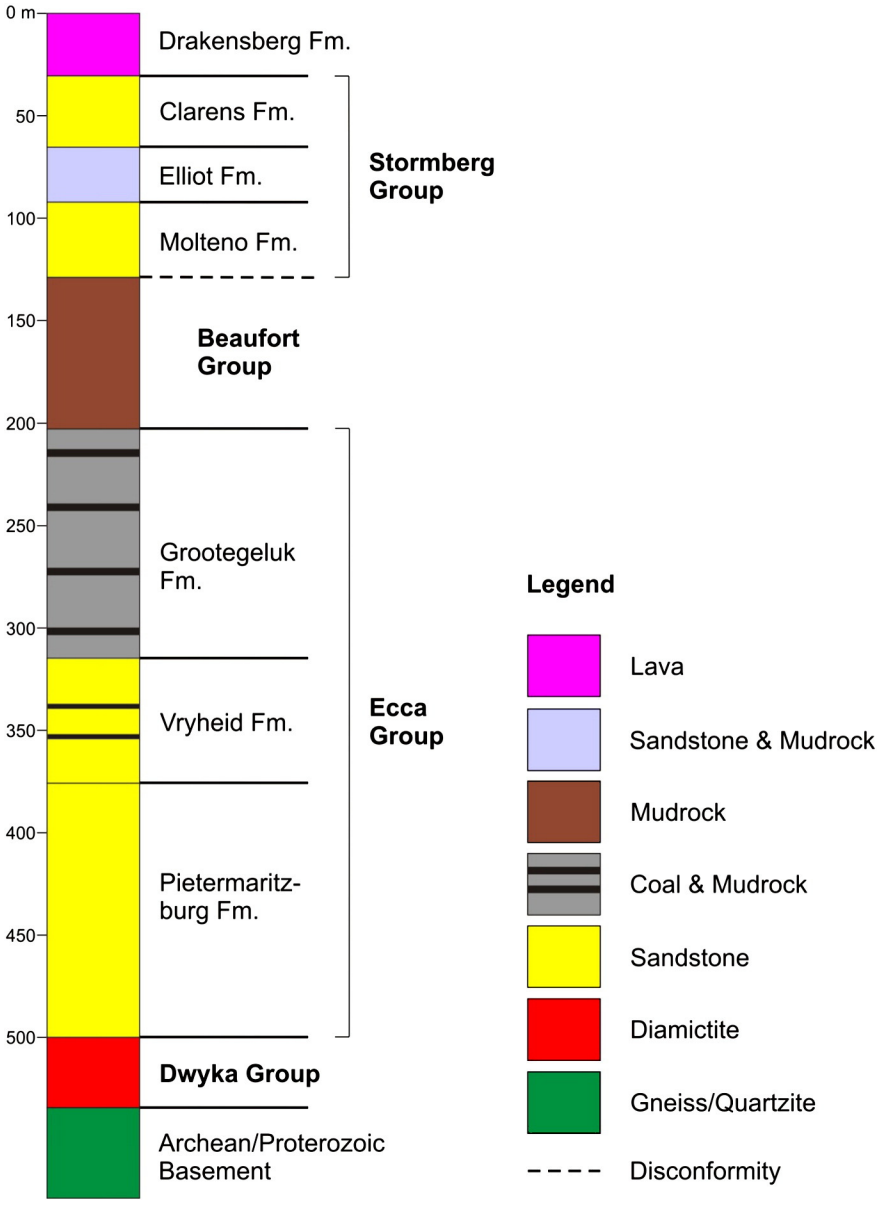

Fig. 41. Stratigraphic column of the geology of the Waterberg Coalfield. Fm. = Formation. Modified from Faure et al. (1996a).

type locality on the farm Solitude 30 m of grey shale is overlain by 80 m of alternating purple and grey mudstone with three intercalated siltstone units. In other parts of the basin, the lower unit of the formation may consist of black shale with occasional bands of bright coal and greenish or reddish fine- to coarse-grained sandstone up to 5 m thick (Johnson et al., 2006). The formation represents the overbank deposits of meandering rivers with extensive floodplains. The dark shale and associated coals accumulated in flood basins and marshes under reducing conditions (McCourt and Brandl, 1980).

The Klopperfontein Formation disconformably overlies the uppermost Solitude Formation, with a prominent erosional surface in places. The formation attains a maximum thickness of 20 m (Brandl, 2002) and comprises medium- to coarse-grained, cross-stratified, feldspathic sandstones. According to McCourt and Brandl (1980) deposition was from braided river channels. This unit has previously been equated to the Late Triassic Molteno Formation in the MKB, but this assignation is obviously questionable if the work of Van der Berg (1980) is accepted.

The overlying Bosbokpoort Formation comprises up to 100 m of mainly red mudstones to very fine-grained sandstones. The red colours and abundance of concretions suggest deposition on the floodplains of meandering rivers under dry oxidising conditions. This unit is generally equated to the Elliot Formation in the MKB and is overlain by typical Clarens Formation sandstone.

The Clarens Formation has been divided into the Red Sandstone Member and Tshipise Member. The Red Member forms an up to 150 m thick unit of very fine to fine-grained light red sandstone, with occasional irregular patches and thin cream-coloured sandstone layers. The Tshipise Member consists of fine-grained, well sorted, white or cream-coloured sandstone (Brandl, 1981). The Clarens Formation is considered to be aeolian, but water-lain deposits may be present in the lower part of the succession (McCourt and Brandl, 1980). The Clarens Formation is overlain by volcanics of the Letaba and Jozini formations. The Letaba Formation is composed of basaltic lava with subordinate andesite, and rhyolite flows and tuffs. The Jozini Formation is composed of pink to reddish rhyolite (Brandl, 1981).

4.9.6. Coal seams

The nature of the coal deposits gradually changes from a multi-seam coal-mudstone association, approximately 40 m thick in the west and comprising up to seven discrete coal seams (Mopane Coalfield in the Waterpoort area), to two individual seams in the east (Pafuri Coalfield in the Tshikondeni area), with a 3 m thick Upper Seam and a 2 m thick Lower Seam approximately 100 m deeper. The transition from multi-seam to discrete is very sudden adjacent to the farm Gaandrik 162MT, with argillaceous rocks to the west and arenaceous lithologies to the east (Sparrow, pers. comm.).

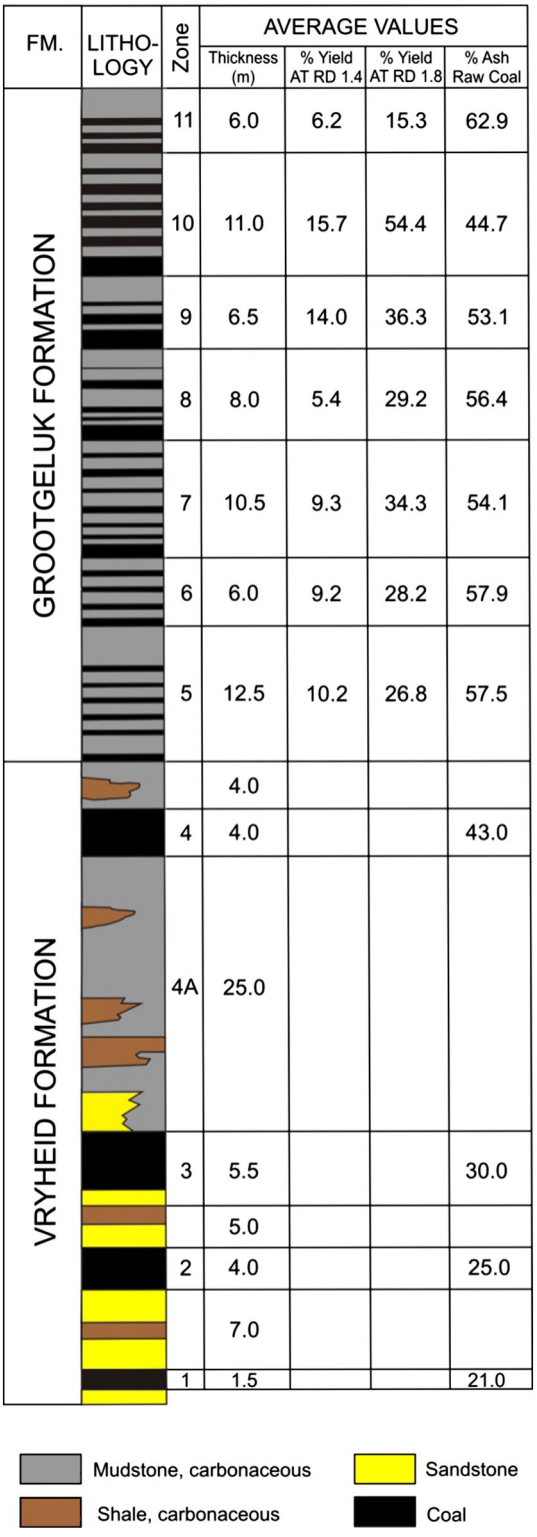

Fig. 42. Stratigraphic column of the geology of the coal-bearing sequences of the Waterberg Coalfield showing the nature and coal qualities of the 11 coal zones. Modified from Botha (1984).

4.9.6.1. Coal qualities. Where developed, the coal is generally bright and high in vitrinite and the coal rank increases towards the east, as does the coke strength after reaction and yield (Sparrow, 2012). Dull coal occurs locally at the base of the multi-seam coal–mudstone association in the Waterpoort area as well as in the upper part of the lower seam at Tshikondeni. The volatile content in the west (Waterpoort) is approximately 35% which decreases to 25% in the east (Tshikondeni).

4.9.7. Structure and intrusions

The region is faulted, becoming more severe in the far east, and has throws of between 60 m and 200 m, leading to the formation of horst and graben structures. A further subordinate set of faults, orientated at right angles to that mentioned above, subdivides the eastern portion of the Soutpansberg Coalfield region into a set of irregular blocks. Brandl (1981) documents three notable faults within the Soutpansberg Coalfield, these being the Tshipise, Klein Tshipise and Bosbokpoort faults. All the faults which affect the coalfield appear to be normal and probably of post-Karoo age (Brandl, 1981).

4.9.8. Sub-basins

4.9.8.1. Mopane sub-basin. The Mopane sub-basin is the most westerly of the three recognised depositories, being situated northwest of Waterpoort. The area is 140 km from east to west and is 26 km from north to south at its widest. There has never been any commercial mining within the Mopane Coalfield, and the fill of the sub-basin is best known from the Chapudi Project (Bordy, 2006) and the reader interested in a detailed description of this succession is referred to this paper. In 2008 this project made headlines when Rio Tinto released an open-pit Measured and Indicated Resource of 1.04 Gt.

The Mopane Coalfield comprises a number of east–west trending half-graben structures in which upper Ecca Group sedimentary rocks are preserved. The geology is generally broken up into fault blocks by a number of parallel strike faults (Telfer and Njowa, 2012). Rocks of the Karoo Supergroup strike east–west and dip towards the north at angles of up to 12°. The area has been broken up into fault blocks into a number of strike faults. South of the area the Karoo rocks are absent due to uplift and erosion, leaving Beit Bridge Complex and Waterberg Group rocks exposed at surface.

Bordy (2006) notes that three of the boreholes in her study intersected the basal Tshidzi Formation, which in the Chapudi Project area comprises mostly clast- and matrix-supported breccias and conglomerates, with a maximum recorded thickness of 4.62 m. Note should be made however that none of the boreholes in her study were drilled through to the basement. She felt that the peculiar soft sediment deformations observed around the clasts of the matrix-supported breccias and conglomerates may be taken as a reliable evidence of the glacial origin, and that the presence of dropstones clearly suggests a landscape probably dotted by glacial lakes.

Bordy (2006) further notes that based on the limited number of boreholes available for the study, the coal-bearing strata of the Chapudi area are on average ±130 m thick. Two major lithofacies associations were identified, these being a subordinate arenaceous facies and a dominant argillaceous facies. She felt that the application of the formal lithostratigraphic subdivision of the coal-bearing strata into the Madzaringwe and Mikambeni formations was impossible in this area, as the lithological properties of the mudstones are identical throughout the sequence, and the sandstones that occasionally divide the mudstones into a relatively coal-rich lower interval, and a less carbonaceous, upper mudstone interval, are not developed in the area.

The coal-bearing succession is regionally overlain by texturally submature sandstones of the Fripp Formation, which comprises at least two distinct cycles of fining-upward successions in the Chapudi area (Bordy, 2006).

4.9.8.2. Tshipise sub-basin. The Tshipise sub-basin stretches from east of Mopane to the area of the town of Tshipise. This sub-basin is best known form the work undertaken at CoAL's Makhado Project (Fig. 44).

Outcrops of Soutpansberg Group metaquartzites and Beit Bridge Complex rocks occur in the middle of the Tshipise sub-basin area, and these rocks are known to make up the immediate floor to the Karoo sedimentary succession. The best exposures of Dwyka Group equivalents (Tshidzi Formation) occur on the farm Bluebell 480 MS (Brandl, 2002) where the succession is around 5 m thick, with a basal unit consisting of angular to rounded clasts up to 0.5 m in diameter set in a sandy matrix.

Based on the work undertaken at CoAL's Makhado Project six potentially mineable composite coal seams (or zones) have been identified within a 30–40 m thick carbonaceous zone of the Madzaringwe Formation. These are named from the bottom up the Bottom Lower Seam, Bottom Middle Seam, Bottom Upper Seam, Middle Lower Seam, Middle Upper Seam and Upper Seam. The seams comprise interbanded carbonaceous mudstones and coal. The coal component is usually bright and brittle and contains a high proportion of vitrinite. The coal bands exhibit the same trend of decreasing vitrinite content (from 80 to 90%) with increasing depth as for the Mopane sub-basin. The raw coal has an Ash content of approximately 25%. Seam dips average 12° and a number of major faults have been identified.

4.9.8.3. Pafuri sub-basin. The Pafuri sub-basin extends from a point midway between the towns of Makhado and Musina eastwards, terminating at the northern limit of the Kruger National Park (KNP) in the east. The area is 109 km from east to west and is 26 km from north to south at its widest. The eastern boundary beneath the KNP is with the border with Mozambique. The Pafuri sub-basin is home to Exxaro's Tshikondeni Colliery and the geology of the area is best known from work associated with this mine. The basement in the area is formed by rocks of the Soutpansberg Group. The overlying basal part of the Karoo succession is formed by diamictites of the Tshidzi Formation.

Within the coal-bearing Madzaringwe Formation (Ecca Group), two coal seams are locally developed. At Tshikondeni, the seams are referred to as the Main Coal Seam and the Lower Coal Seam (Fig. 45). Due to its good coking properties and medium phosphorous content, the 2.6 m thick Main Seam (sample 7B and 7C) has been exploited at Tshikondeni. The Lower Seam also has coking properties, but the high phosphorus content renders the coal unacceptable to steel manufacturers.

At Tshikondeni the Main Seam dips relatively steeply at between 2° and 18° to the north. Although mining has followed the seam down to a maximum of 350 m at the Nyala Shaft, most mining takes place in difficult conditions at depths of between 200 and 300 m.

Structurally, the Tshikondeni Mine is very complex, with faulting and dolerite intrusions having a significant impact on mining in terms of displacement and devolatilisation of the coal. Steps and grabens delineate mining blocks and dykes and sills have been identified as having thicknesses of up to 15 m to 30 m, respectively. The Mutale sill in the northern areas of the mining authorisation has devolatilised large areas of the coal as it closely follows the dip of the Main Seam.

4.10. Limpopo (Tuli) Coalfield

4.10.1. Introduction

The Limpopo Coalfield is the northernmost coalfield in South Africa (Fig. 1). It generally hosts a higher-grade coal than the coalfields of the MKB, containing a valuable percentage of South Africa's coking coal, which is important for the country's metallurgical and steel industries. Although the Limpopo Coalfield has been known since 1895 and some small exploration shafts were sunk on the Zimbabwean side of the Limpopo in the 1920s, it took well over a century for this coalfield to become a producer, and currently only one mine, CoAL's opencast Vele colliery, is in operation.

4.10.2. Location

The Limpopo Coalfield is situated in the northernmost extremity of the Limpopo Province, some 70 km west of the town of Messina. The coalfield has an east–west strike length of ±80 km, extending from Pontdrif in the west, to Beit Bridge in the east. It is small relative to most of the other coalfields of South Africa and rocks of the Karoo Supergroup cover an area of about 120,000 ha of which about 11,000 ha on the southern limb are considered to be underlain by workable coal-bearing horizons (Ortlepp, 1986).

Geologically the Limpopo Coalfield forms part of the greater Tuli Coalfield (greater Tuli block/Bubye River Coalfield) that extends northwards from South Africa into Zimbabwe and Botswana (Fig. 1). It is represented in South Africa by only a relatively narrow deposit of Karoo Supergroup rocks on the right hand bank of the Limpopo River between latitudes 21.80°S and 22.50°S and longitudes 29°E and 30°E (Malaza, 2013).

4.10.3. Exploration and exploitation history

No real systematic exploration of the Limpopo Coalfield occurred until the 1960s and 1970s. Exploration work on the then AngloCoal owned portion of the Limpopo Coalfield started in the 1960s (Ortlepp, 1986). Reconnaissance drilling was conducted in an area 15 km by 15 km, with subsequent detailed exploration confined to an area approximately 15 km by 10 km in the eastern part of the coalfield. A total of 160 boreholes were drilled and detailed surface mapping and ground magnetometer surveys over the many intrusive dykes were undertaken. The prospecting phase culminated in 1970 with the sinking of a prospect shaft from which a bulk sample of 12 tonnes was obtained. This material was sent to Japan for beneficiation test work and coking coal analysis.

Southern Sphere Mining and Development (a division of Utah Mining) undertook a detailed exploration programme in the late 1970s and early 1980s. This exploration took the form of cored and percussion drilling, down-hole geophysical logging and airborne magnetic and gravity surveys. During the period 1979 to 1983 Southern Sphere Mining and Development drilled a total of 61 boreholes on the farms Overvlakte 125 MS and Almond 120 MS. Other exploration programmes in the 1980s were undertaken by AAC and Union Carbide.

CoAL commenced exploration on their Vele Project in January of 2008 and by 2010 a total of 188 slim core boreholes and 28 large diameter boreholes had been completed. Aerial magnetic and radiometric surveys have also been undertaken. The mine opened in 2011 on a JORC compliant 362.5 Mt mineable tonnes in situ (MTIS) resource.

4.10.4. Research history

The Karoo aged rocks of the Limpopo Basin were first described by Trevor and Mellor (1908) following a reconnaissance of the region in 1907. At this time however the presence of coal remained undetected. General geological work in the Limpopo Coalfield has subsequently been undertaken by Chidley (1985), Brandl (2002), Bordy (2000) and Bordy and Catuneanu (2001, 2002a,b,c). Most of what is currently known about the Limpopo Coalfield comes from this work and from various reports and presentations concerning CoAL's Vele Project.

Bordy and Catuneanu (2001) investigated the sedimentology of the fluvial upper unit, which they felt was correlatable to the alternating sequences of fine- to medium-grained sandstones and argillaceous beds of the Elliot Formation in the MKB. Bordy et al. (2004a) document Early Jurassic termite nests from the Clarens Formation in the Limpopo Basin.

4.10.5. Geology

The pre-Karoo basement to the Limpopo Coalfield consists of the metamorphic and meta-sedimentary rocks of the Limpopo Mobile Belt. Deposition of the Karoo sediments occurred with concurrent movement on the pre-existing fault planes. This has resulted in a highly truncated sequence (to that encountered in the MKB) of the Ecca and Beaufort groups, as well as of the Molteno Formation (Fig. 46), with a maximum thickness estimated at between 450 and 500 m.

Various authors have used various nomenclatures for the stratigraphic succession in the Limpopo Coalfield. Until new formal nomenclature is accepted for the coalfield we here prefer to follow Chidley (1985), Johnson et al. (1996) and Malaza (2013), and retain the same stratigraphic nomenclature as for the Soutpansberg Coalfield (McCourt and Brandl, 1980). It should however be noted that Bordy (2000) and Bordy and Catuneanu (2001, 2002a,b,c) do not follow this approach for reasons provided in these references.

The pre-Karoo Basement surface was scoured during the Dwyka glaciation creating a rugged palaeotopography, which coupled to the load release from the melting ice (which re-activated basement faults) had a strong control on the subsequent sedimentary fills. Like in the Soutpansberg Coalfield, the basal part of the Karoo succession generally comprises diamictite interbedded with relatively coarse-grained sandstones in places (Chidley, 1985). The overlying Madzaringwe Formation comprises up to 120 m of alternating feldspathic, cross-stratified sandstone, and siltstone and shale containing thin coal seams. Three distinct coal horizons are developed within the 15 m thick Main Coal Zone. They occur at depths varying from a few metres in the far south of the basin, to over 300 m northwards towards the Limpopo River. All three coal horizons are interbedded coal and clastic units, with varying coal percentages. Within the coal horizons the coal thicknesses are generally greater than the clastic partings, and the interburden thickness are significantly greater than the thickness of the individual coal horizons.

The overlying Mikambeni Formation attains a thickness of about 80 m and consists of alternating black shale, sandstone and coal (Chidley, 1985). The Fripp Formation comprises 5–10 m of well-sorted, medium- to coarse-grained, white, arkosic sandstone and course conglomerates (Chidley, 1985). The Solitude Formation consists of siltstones and very fine sandstones with grey mudstones. Its maximum thickness is about 25 m in the western part of the Limpopo Coalfield, but in some places is only 3.5 m thick (Chidley, 1985). Shallow cross-lamination is common in the siltstones. The Klopperfontein Formation comprises coarse sandstone and subordinate conglomerate. It is only present in the central part of the coalfield and attains a maximum thickness of 10–12 m. The Bosbokpoort Formation consists of red to purple mudstones with subordinate white siltstone layers and some occasional conglomerates. It attains a thickness of up to 60 m (Chidley, 1985).

The Clarens Formation is subdivided into a lower Red Rocks Member and an upper Tshipise Member. The Red Rocks Member is composed of very fine to fine-grained, pinkish to red, argillaceous sandstones and attains a maximum thickness of about 60 m. The Tshipise Member has a thickness which ranges from 5 to 140 m and consists of fine to very fine-grained, khaki to yellowish sandstones.

4.10.6. Coal seams

In the area of exploitable coal three distinct coal horizons are developed in the Madzaringwe Formation. Ortlepp (1986) refers to them as the Basal, Middle and Upper sections. We here follow CoAL's terminology and name the seams the Bottom, Middle and Top Seam Coal (Fig. 47). The Top and Bottom Seams can be further differentiated into sub-seams, these being the Bottom Lower, Bottom Upper, Top Lower (TL), Top Middle (TM) and Top Upper (TU).

All three coal horizons are interlaminated carbonaceous mudstones and coal in varying proportions. The dip of the coal seams is generally gentle (1° to 2°) towards the north and northwest, but may increase up to 10° in the vicinity of faults. Steeper dips are also encountered close to the edge of the basin in the south and southeast. The Main Coal Zone is located at depths of less than 50 m along the southern margin, but attains a depth of over 300 m near the Limpopo River, and this depth probably increases to the north of the river.

The base of the 1.5–3.5 m thick Bottom Seam tends to be best developed in the palaeovalleys and mirrors the pre-Karoo basement topography, generally occurring within 5–15 m of the pre-Karoo basement. It usually consists of between 65 and 80% of coal. The overlying 3–5.5 m thick Middle Seam is the most consistent of the three coal zones and is the main economic target and normally tends to consist of between 20 and 45% coal. The Top Coal, which is 2–3 m thick, is more sporadically developed and generally tends to consist of between 55 and 65% of coal. The predominant coal maceral occurring in the coal horizons is vitrinite, which gives rise to the high reflectance and Free Swelling Index of the coals.

In general individual seams and sub-seams can be correlated over the entire area, however significant drilling is usually required to confirm the correlation of the Top Coal Zone. Correlation is aided by the presence of a distinct bioturbated marker band which occurs between the Bottom and Middle Seams and also by the position of the Bottom Lower Seam which immediately overlies glaciogenic sediments of the Dwyka-age Tshidzi Formation or, where the latter is absent, granites and gneisses of the pre-Karoo basement.

4.10.6.1. Coal qualities. According to Ortlepp (1986) the clean coal has the following characteristics (Table 20).

The raw coal contains about 7% vitrinite, 3% exinite, 7–14% and 16% visible mineral matter. When crushed to 3 mm the vitrinite content of

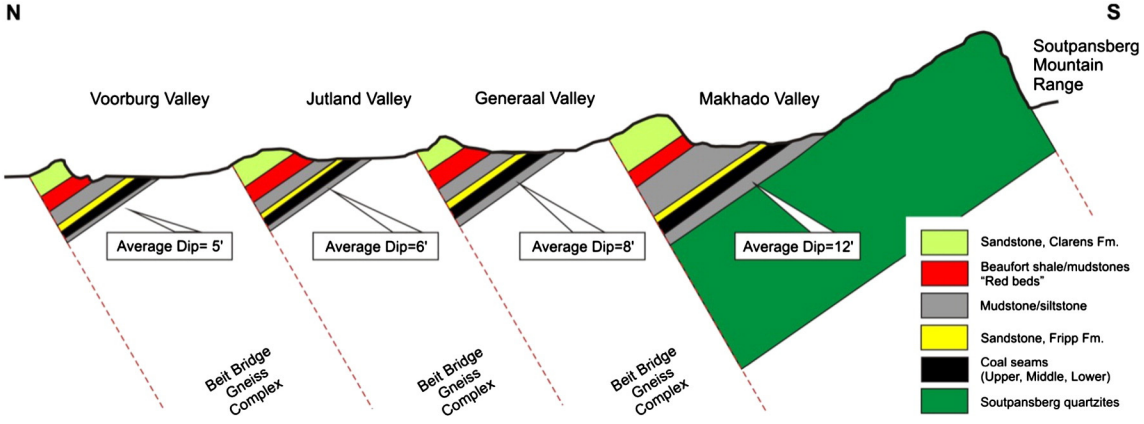

Fig. 43. Schematic cross section through the greater Soutpansberg Coalfield. From Sparrow (2012).

the washed coal is greatly increased, and the exinite, inertinite and mineral matter decreases. According to Sparrow et al. (2013) the vitrinite content of the 10% Ash product is in the order of 86%. These authors also showed that reactivation of faulting post coalification generated pseudo-vitrinite in close proximity to the faults.

4.10.7. Structure and intrusions

The Limpopo Coalfield is structurally controlled. The southern edge of the basin is defined by a large basin edge normal fault, which has a general west–east trend and a dip to the north. This fault has also resulted in a number of sympathetic faults with smaller throws. The trend of the sympathetic faulting is generally northeast to southwest. According to Smith (1984) a half-graben structure for the Tuli Basin is suggested by the general gentle (<5°) northward dips of the Karoo Supergroup beds, coupled to the nature of the northern boundary fault, which is a major, east-northeast trending tectonic line. Watkeys and Sweeney (1988) however define the entire Tuli Basin as a pull-apart rhombochasm. Generally the basin has a broad plunging synclinal nature with the axis of the syncline trending northwest with a bearing of 312°.

The Karoo strata are intruded by dolerite and porphyritic andesite dykes of Jurassic age. Ortlepp (1986) notes that a number of large dykes (some 15–17 m wide), strike east–west across the coalfield and that the larger dykes are porphyritic andesites containing large feldspar phenocrysts. There does not appear to be any significant displacement associated with the dykes. Coal occurring in proximity to the intrusions is however invariably devolatilised. At the Vele Colliery a 15 m thick dolerite intrusive has a metamorphic aureole of only 3 m (Sparrow, pers. comm.). Interpretation of the regional magnetics indicates that the majority of the fault planes are expected to carry dolerite intrusions. A number of independent dykes have also been interpreted from ground magnetics and they tend to have an east to west trend.

4.11. Molteno Coalfield

4.11.1. Introduction

Unlike all of the other coalfields discussed in this paper the Molteno Coalfield is Triassic in age (Fig. 1). It was one of the earliest coalfields exploited and was South Africa's principal coal supplier from 1900 to 1904, becoming abandoned with the discoveries of better quality coal in KZN and the Free State, and Gauteng. With the development of high efficiency circulating fluidized-bed (CFB) technology, the low grade Molteno coal seams have again become attractive for a range of industrial and power generation applications. Recently a small operation has been established near the town of Indwe, which at present is the only operational mine in the coalfield. The Molteno Coalfield is also actively being explored for its CBM potential.

4.11.2. Location

The Molteno Coalfield extends in an arc from Aliwal North and Jamestown in the west, through Molteno, Dordrecht, Indwe and Elliot, to north of Maclear in the east (Fig. 48) and covers an aerial extent of some 13,000,000 ha (Christie, 1986; MacDonald, 1993) making it the largest single coalfield in South Africa. The majority of the coalfield falls within the Eastern Cape Province.

4.11.3. Exploration and exploitation history

Driven by the need for coal in the Cape Colony (and a reward of £100), coal was first discovered in the Molteno Coalfield on the farm Cyphergat in 1860 by a Mr. George Vice. In 1864 Vice formed his own mining company and commenced the sinking of the Penshaw Mine, from where he started shipping wagons of coal to Cradock and Kimberley. Soon afterwards other mining companies sprang-up in the area. These included The Great Stormberg Coal Company and Cape Collieries Limited. Full scale commercial mining for coal in the Indwe area began in 1895 and the town of Indwe was formally laid out in 1896. Production peaked at about 175,000 tpa between 1900 and 1904. After 1904 production declined, mainly due to the discovery of better coals in KZN and the Free State. The Cape Collieries closed in 1905, whilst the Penshaw Mine stayed in production until 1913. By 1917 production from this coalfield had fallen to only 7500 tpa. Prior to its recent revival, the last recorded historic production in the Molteno Coalfield was in 1948. A contributing factor to the closure of this coalfield was the inferior quality of its coal compared to that from other of South Africa's coalfields.

From 1942 to 1944 B.J. Botha carried out fieldwork for the Geological Survey in the Molteno–Sterkstroom area. This was followed by Geological Survey drilling between 1944 and 1947, with 12 boreholes drilled at the town of Molteno, two at Elliot, and one each at Indwe and Sterkstroom. These results were summarised in a report by Van der Westhuizen (1948). In 1960 Federale Mynbou Bpk prospected from Dordrecht eastwards and concluded that only coal in the Guba Sector was of economic value. Interest in the Molteno Coalfield was renewed in the 1980s (MacDonald and Bredell, 1984) and led to the 1985/86 drilling programme undertaken by the Geological Survey in the Molteno, Dordrecht and Indwe sectors of the coalfield. Concurrently (1985–1988), the Transkei Mining Corporation (TMC) conducted extensive drilling in the Guba Sector of the coalfield. This work is described in MacDonald (1988a,b).

Intensive studies from 2000 to 2004 led to the conclusion that the Indwe/Dordrecht area would sustain a viable long-term coal mining programme to fuel a new IPP. A rigorous drilling programme was mounted in 2006 to prove the resource in accordance with internationally accepted reporting codes, with over 50,000 m drilled by 2008. This year saw the official re-opening of the Molteno Coalfield for commercial production, with the start of a small scale mine at Indwe (http://www.elitheni.co.za/).

4.11.4. Research history

Surprisingly, given the poor quality of its contained coals, the Molteno Coalfield has been the subject of a fairly large body of academic work. The oldest records of prospecting in the Molteno area refer to a somewhat discouraging report on the coal deposits by the government geologist A.J. Wyley (Wyley, 1856). Dunn (1873, 1878) referred to more promising coal occurrences near the town of Indwe. Green (1883) presented a pessimistic assessment of the coal, however Galloway (1889) recommended the opening of a colliery at Indwe, which subsequently took place. From 1902 to 1929 A.L. du Toit carried out extensive research from Dordrecht eastwards towards Elliot and Maclear, undertaking a special survey of the Indwe Sector (Du Toit, 1905, 1954).

Rust (1959) investigated the Molteno Formation in the vicinity of the town of Molteno and provides a detailed description of the stratigraphy exposed in the Old Bushmanshoek Pass, where the Bamboesberg Member is at its thickest. Ryan (1963) utilised the results from the Federale Mynbou exploration in the compilation of his work on the geology of the Indwe area. Further mapping was undertaken by B.J. Brits in the Molteno District in 1965 and in 1966 by C.B. Coetzee and was used to compile an unpublished report on the economic potential of the north-eastern Cape's mineral resources (Coetzee, 1966).

Between 1965 and 1967 Turner researched the coal potential of the northern-eastern Cape (Turner, 1969a,b), and this led to a Geological Survey Bulletin of the geology and coal resources of the north-eastern Cape Province (Turner, 1971), which included a review on the early investigations undertaken between 1856 and 1948, as well as work carried out by Federale Mynbou in 1960–61, and the Geological Survey between 1965 and 1967. Turner's work culminated in a PhD study (Turner, 1975) which covered aspects of the entire Molteno Formation outcrop area, as well as the stratigraphy of the Bamboesberg Member.

Christie (1981) further investigated the stratigraphy and sedimentology of the Bamboesberg Member (and its contained coals) in the Indwe and Elliot areas and erected an informal stratigraphic subdivision for the Formation. Christie (1986) also covered the Molteno Coalfield for the Mineral deposits of southern Africa volume.

The TMC drilling formed the basis of a study of the Molteno coal seams in what was then the independent homeland of the Transkei (Heinemann, 1988). This work suggested that there were sufficient coal resources to power a small power station for twenty five years.

MacDonald (1993) undertook a re-assessment of the coal resources in the western part of the Molteno Coalfield, including the area around the towns of Molteno, Dordrecht and Indwe. This work was based to a large extent on the work previously undertaken by the Geological Survey, coupled to the results of the 1985–86 drilling project, and provides detailed descriptions of both the Indwe and Guba seams, including tables of the cumulative yields at various RDs. Hancox (1998) covers aspects of the Bamboesberg and Indwe members of the Molteno Formation, including the nature of the basal contact, palaeontology, sedimentology, stratigraphy, coal seam nomenclature and spatial and temporal variability.

4.11.5. Geology

The general geology of the Molteno Formation is covered in a previous section and is not repeated here. This section therefore concentrates on the nature and nomenclature of the economic coal seams within the Bamboesberg Member. The Bamboesberg Member (SACS, 1980; Turner, 1975) is named after the Bamboesberg Mountains in the Eastern Cape Province and is the basal member of the Molteno Formation. It lies stratigraphically between the Burgersdorp Formation (Beaufort Group) and the Indwe Sandstone Member of the Molteno Formation. The type locality for the Bamboesberg Member is situated in the hills above Grootdoringhoek Pass (Turner, 1975). A neostratotype for the Bamboesberg Member was proposed and the member was formally defined in Hancox (1998).

Where the Bamboesberg Member is preserved to its maximum extent, the basal contact with the Burgersdorp Formation is usually sharp and erosional. The top contact is at all localities marked by the base of the overlying Indwe Sandstone Member and in many places coincides with a concentration of extra-formational clasts informally named the "Kolo Pebble Bed" (Turner, 1975). The erosive nature of this basal contact has a strong control on the thickness of the Guba Seam. A description of the sedimentology of the Bamboesberg Member at the type locality is given by Turner (1975) and for the area around Indwe and Cala by Christie (1981). Hancox (1998) provides a more detailed description of the member over its entire outcrop area.

Lithologically the Bamboesberg Member is composed of up to five stacked fining-upward sequences, each of which is composed of laterally extensive sandstones, capped by thin lenticular siltstones, mudstones and more rarely, coal. Well preserved fossil plant remains, including silicified tree trunks, are frequently concentrated on bedding plains, as well as randomly interspersed within the siltstones and mudstones.

4.11.6. Coal seams

Six coal seams are sporadically developed in the Molteno Formation over a vertical interval of some 400 m (Fig. 49). These have previously been recorded and described by Du Toit (1905), Turner (1971, 1975), Christie (1981), Heinemann (1988), Thamm (1998), MacDonald (1993) and Hancox (1998).

All the seams cap upward-fining fluvial sequences of sandstone and mudstone and only the three lower seams are reasonably persistent. Of these six seams only two are considered to be economic. Both occur within the Bamboesberg Member and have had a complex historic nomenclature and correlation history (Fig. 50). We here follow the nomenclature of Christie (1981, 1986) and MacDonald (1993), as it is the most entrenched in the literature. It should however be noted that the Indwe Seam should not be renamed. This is due to the fact that the use of the same geographic name to describe two lithological units of different status within the same formation is at odds with international stratigraphic nomenclature. Confusion may also be created due to the fact that the Indwe Seam actually occurs within the Bamboesberg Member, and the fact that this seam does not actually even underlie the Indwe Sandstone Member.

The coal seams of the Bamboesberg Member are typically horizontally zonated, with bands of dull (inertinite/fusinite) and bright (vitrinite) coal alternating with carbonaceous siltstone and mudstone. The Indwe Seam varies in lithology and thickness over short distances and is a composite seam consisting of alternating coal and shale, of which the coal percentage varies between 30 and 65%. It attains a maximum thickness of 4.5 m at the town of Indwe (Christie, 1981). Christie (1986) notes that it is not a laterally continuous seam, but rather a number of coals formed in discrete settings at the same stratigraphic horizon. The Guba Seam is also a composite seam but generally contains

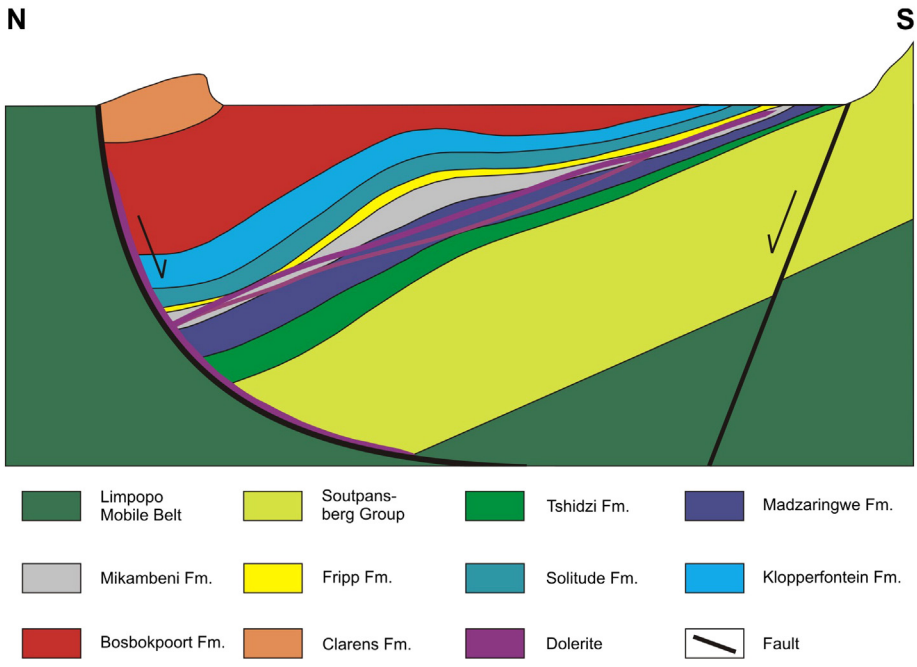

Fig. 44. North–south cross section through CoAL's Makhado Project showing the northerly dip and structural control to the hosting sub-basin.

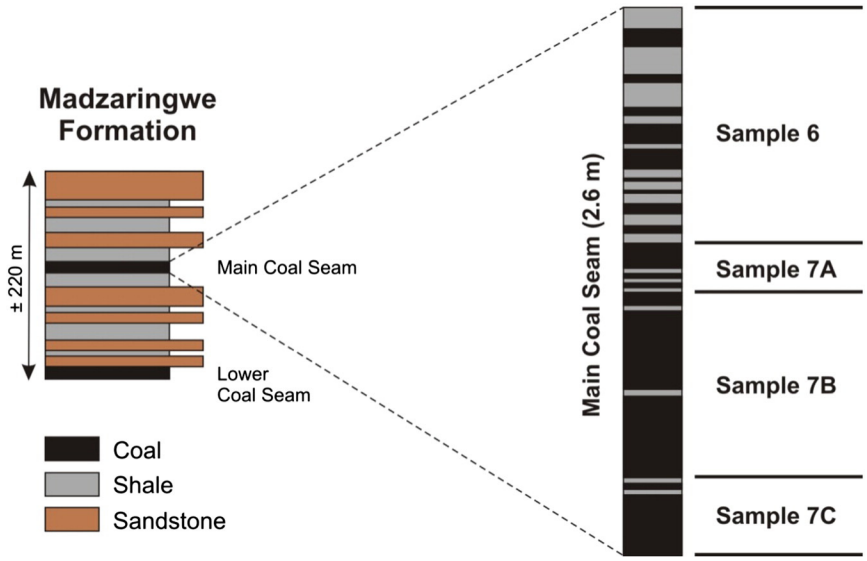

Fig. 45. General profile through the mining cut of the Main Seam at Tshikondeni. After Sullivan et al. (1994).

fewer mudstone partings than the Indwe Seam. It varies considerably in thickness across the coalfield, attaining a maximum height of about 3 m. This thickness variability is due mainly to the fact that the upper portion of the seam has frequently been eroded away by the overlying Indwe Sandstone Member. Whilst forming a competent roof, this unit causes extreme roof rolls in places, effectively compartmentalising coal resources.

4.11.6.1. Coal qualities. The rank of coals in the Molteno Coalfield generally increases from west to east and also fluctuates on a local scale according to proximity to igneous intrusions (Saggerson, 1991). High volatile bituminous coals are present but sparse in the west, with the coals in the east more commonly being low volatile bituminous to anthracitic.

The following coal properties are compiled from reports by Christie (1981), Heinemann (1988) and MacDonald (1993). The coals are durain to cladodurain rich, with high Ash values, ranging from 30 to 85% for the raw material. The mineral component consists of clay, calcium and magnesium carbonates, pyrite, marcasite and trace amounts of chloride, fluoride and phosphorous (Turner, 1971). They range in rank from low-volatile bituminous to anthracite and are generally fairly vitrinite rich. The fixed carbon content ranges from 30 to 41% (MacDonald, 1993). Analyses show that the Indwe and Guba seams have high raw Ash contents of between 31 and 51% (and between 26 and 27% when washed), high IM content of 7–11% and low VM of 7 to 12% (Prevost, 2002). They have the highest phosphorous levels of any South African coal (Turner, 1971). Generalised coal characteristics of the Molteno Formation, washed at a RD of 1.8, are provided in Table 21.

4.11.7. Structure and intrusions

As for most of the other coalfields in South Africa numerous Jurassic aged dolerite dykes and sills intrude the Molteno Formation, effectively dividing the coalfield into a western and eastern sector in the area of Penhoek Pass.

5. Coals as palaeoclimate archives

Other than being used by industry, coal deposits are also unique sedimentary archives of climate change and the coal-bearing formations of the Karoo Basin of South Africa play a crucial role in the study and interpretation of Gondwana's climate history and biodiversity. A continuous climate amelioration succeeding the Permo-Carboniferous glaciation was first inferred from palynological data by Falcon et al. (1984) and Falcon (1986c), showing that subsequent to the melting of the Dwyka ice sheets, cold to cool-temperate climate conditions prevailed during the Early Permian, with a continuous change to hot and dry climate conditions occurred during the Late Permian and Triassic (Fig. 51).

So far, palaeofloral evidence of climate change during the Permo-Triassic is based on data from these few sources (for a review see Falcon, 1989). Whereas new palynostratigraphic zonation schemes were established in other parts of southern Africa (D'Engelbronner, 1996; Modie and Le Hérissé, 2009; Nyambe and Utting, 1997; Stephenson and McLean, 1999), no recent works address high-resolution palynostratigraphy of the Permian–Triassic coal-bearing formations in South Africa and our knowledge of the Permian and Triassic palynology of the Karoo Basin is based on fundamental research carried out in the 1970s and 1980s by J. M. Anderson (1977) and Falcon (1989). Later, palynological studies were carried out only in a few selected sites of Early and Middle Permian age in the Waterberg and Pafuri coal basins (MacRae, 1988), the Witbank and Highveld coalfields (Aitken, 1994, 1998), and near Vereeniging (Millsteed, 1994, 1999). From this limited background, our understanding of vegetational changes related to climate change is still very poor, and the study of the palynological record of coal seams with respect to establishing a high-resolution climate history of the Permo-Triassic of the Karoo is a challenge for the future.

One milestone in deciphering high temporal resolution climate change was achieved by a recent study of the No. 2 Seam of the Witbank Coalfield (Götz and Ruckwied, 2014), which documents the switch from icehouse to greenhouse conditions in the Early Permian, and the use of palynological data and their climatic signatures for cross-basin correlations (Ruckwied et al., 2014). The most striking signal is the change from a horsetail/fern spore and gymnospermous monosaccate pollen grains dominated assemblage of No. 2L Seam, to a gymnospermous bisaccate (taeniate and non-taeniate) pollen grains dominated assemblage of the No. 2U Seam. This change in the palynomorph assemblages indicates a change in vegetation from a horsetail/fern wetland community (together with an upland conifer community dominated by monosaccate-producers) to one replaced by cycad-like and lycopsid lowland vegetation and a gymnospermous upland flora of bisaccate-producers. This change is interpreted to document a shift from cold to cool-temperate climate conditions. Previously, the precise stratigraphic position of this shift within the Early Permian was not identified due to the lack of high-resolution palynological analyses of key sections in the MKB.

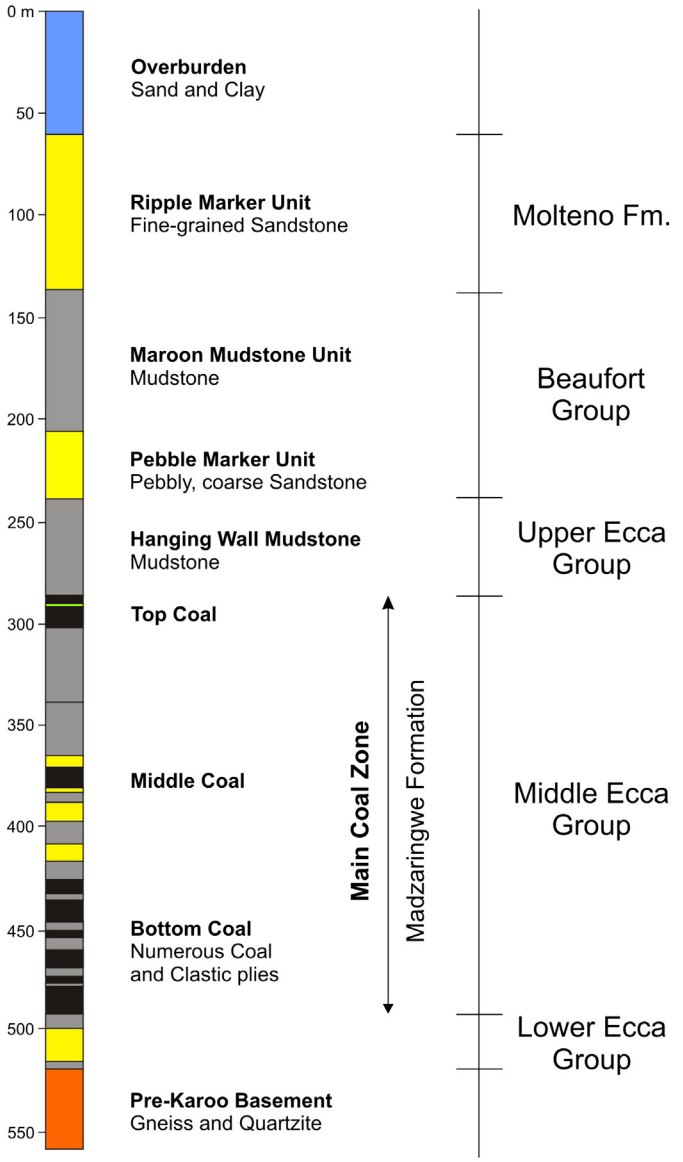

Fig. 46. Generalised stratigraphic column for the Karoo Supergroup in the Limpopo Coalfield.
After Sparrow (2006).

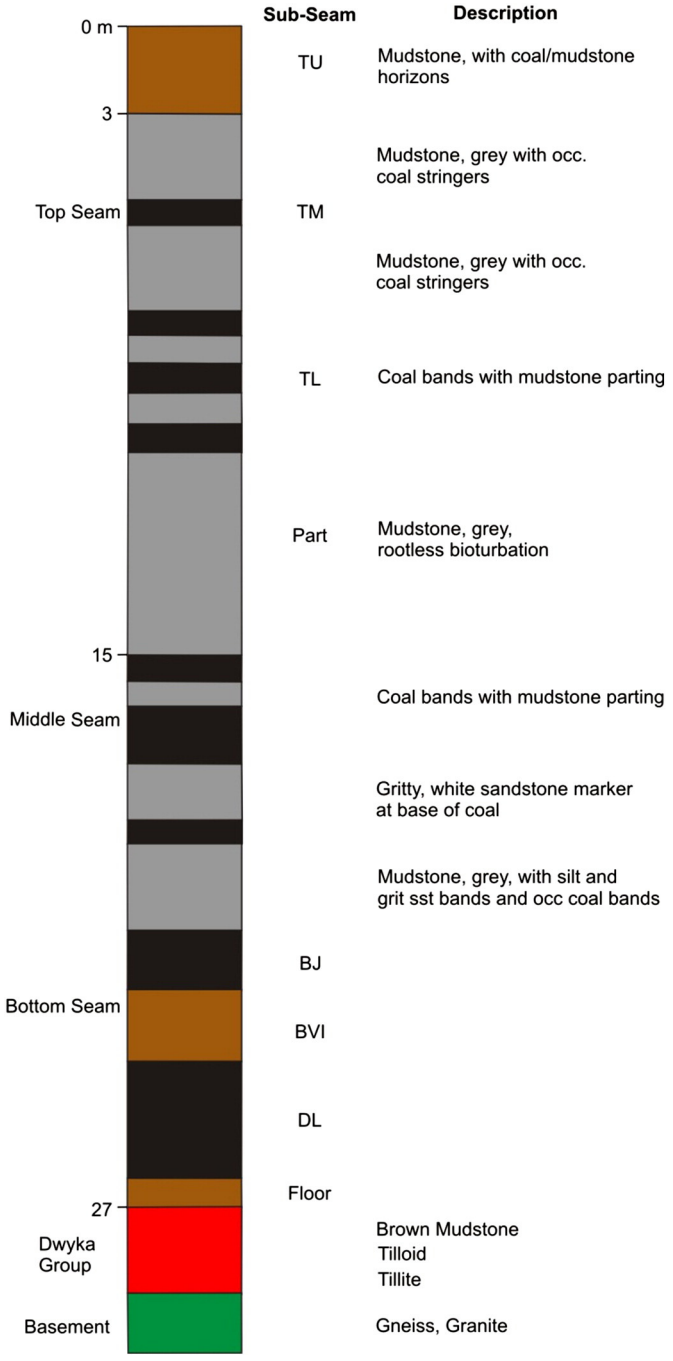

Fig. 47. General stratigraphy as encountered at CoAL's Vele Colliery.
From Sparrow (2012).

The potential of palynology applied to correlation by climatic signatures of different assemblages from different sub-basins was proved for the first time by the recent study of Ruckwied et al. (2014). Samples from a drill core in the northern MKB yielded the first palynological data of the upper Prince Albert and Whitehill formations, pointing to a late Early Permian to early Middle Permian age. This allows for direct temporal correlation between the uppermost Prince Albert and Whitehill formations with the Vryheid Formation. This new palynostratigraphic data will strongly effect the interpretation of the Permian basin-fill history of the MKB, the intercontinental comparison of palaeofloral diversity patterns in adjacent sub-basins (e.g., Botswana, Mozambique; Götz, 2014b), and intra-Gondwanan correlations of coal-bearing basins (e.g., Australia, Brazil).

6. Discussion and conclusions

6.1. Nomenclature

Most of the coalfields of South Africa are named for a major town in the area, the area itself or the Province (and as such are geographically linked). Whilst not in itself a problem, some of these names are also taken by formal lithostratigraphic units, which creates confusion in the literature, and in electronic search engines. For this reason, whilst it was not the purpose of this review, this work has highlighted some

Table 20
Coal qualities for the Limpopo Basin.
From Ortlepp (1986).

Relative density	Yield %	Ash (%)	VM (%)	TS %	Swell index
1.43	47	10.0	36.5	1.1	8.5
1.46	50	11.0	36.0	1.1	8.5
1.49	53	12.0	35.5	1.2	8

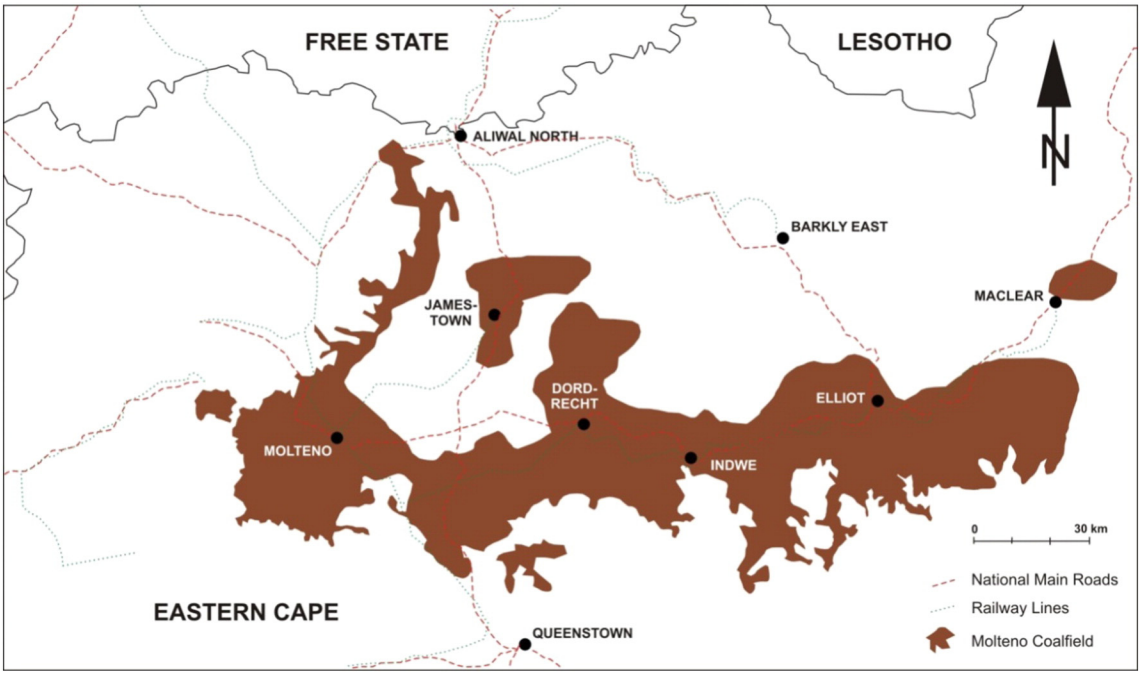

Fig. 48. Map of the extent of the Molteno Coalfield in the Eastern Cape Province. After Barker (1999).

of the inconsistencies of nomenclature used for the various coalfields. New names should be sought for the Free State, Waterberg, Soutpansberg, Limpopo and Molteno coalfields in particular, with the proviso that any new geographic names have not been used for any previously named stratigraphic unit. Use of a purely numerical system (with No. 1 at the base) creates correlation issues and confusion between coalfields, especially where the basal seam is not the same. Robust stratigraphies and seam nomenclature for each coalfield should be established and preferably formalised.

6.2. The role of the basement

This review has hopefully shown that an understanding of the nature of the pre-Karoo basement and its control on palaeotopography is critical to understanding various aspects of the sedimentary fill and coal qualities of many of the coalfields under discussion. This is particularly the case where palaeotopography has created anomalous accommodation space and thicker sedimentary profiles, or where palaeohighs have precluded deposition or created increased dips. Identifying major palaeovalleys is important as they acted as conduits for fluvial activity and it is within their axes that coal seams will be the subject of more intra-seam partings, with the concomitant drop in qualities. Irregular basement topography may also play a role in the position of later igneous intrusions.

6.3. The role of sedimentology

Autocyclic variability is to be expected in sedimentologically complex depositional environments such as braided rivers, deltas and peat swamps, and fluvial input into the peat mire may cause depositional hiatuses, pinch-outs, and seam-splitting and peat erosion. Understanding this variability and the nature of the depositional system is a crucial aspect of understanding the history of the seam development, although an aspect that seems to have been forgotten following on the heydays of academic research in the 1980s. It is not only the coal seams that are of importance — understanding the intra-seam successions are just as important, especially the roof and floors to the seams.

6.4. Correlation of the various coal-bearing horizons

6.4.1. Main Karoo Basin

The present literature is split on the question of whether or not the various coal-bearing successions in the MKB can be correlated, with authors such as Van Vuuren and Cole (1979), Cadle (1982), Van Vuuren (1981), Falcon (1986a,b,c), Cadle et al. (1993) and Catuneanu et al. (2002) believing that they can be, and Tavener-Smith (1983) questioning the validity of using coal seams for correlation. The senior author is of the opinion that Van Vuuren and Cole (1979) and Van Vuuren (1981) have however shown that detailed sedimentological and stratigraphic research, coupled with palynological and petrographic data, allows for informative and useful seam correlations. By relating the various allocyclic controlled transgressions (and their transgressive surfaces) these authors showed that correlation between the various coalfields of the MKB was indeed possible.

Whilst autocyclic variability is the norm rather than the exception, allocyclic variability is much less so, and given the strong allocyclic control on the nature of the deposits, such genetically related sequences should indeed be correlatable. The numbering, naming and correlation of the seams does however still need to be addressed as disparate nomenclature has previously led to the concept that the geology of the various coalfields differs significantly from one another, which is not necessarily true Prevost (2011). A precise correlation of coal-bearing horizons of the different coalfields can however only be performed once a high-resolution palynostratigraphy is established for the Permo-Triassic successions in the South African MKB. In this context, recent studies on palynofacies patterns and palaeoclimate signatures recorded in palynomorph assemblages proved to be a powerful tool for cross-basin correlation (Götz and Ruckwied, 2014; Ruckwied et al., 2014).

6.4.2. Northern basins

Due to the difference in the tectonic development of the containing basins, the Karoo Supergroup sedimentary succession in the northern basins of South Africa is much thinner than in the MKB, and correlation is often difficult across the region. The senior author is however of the

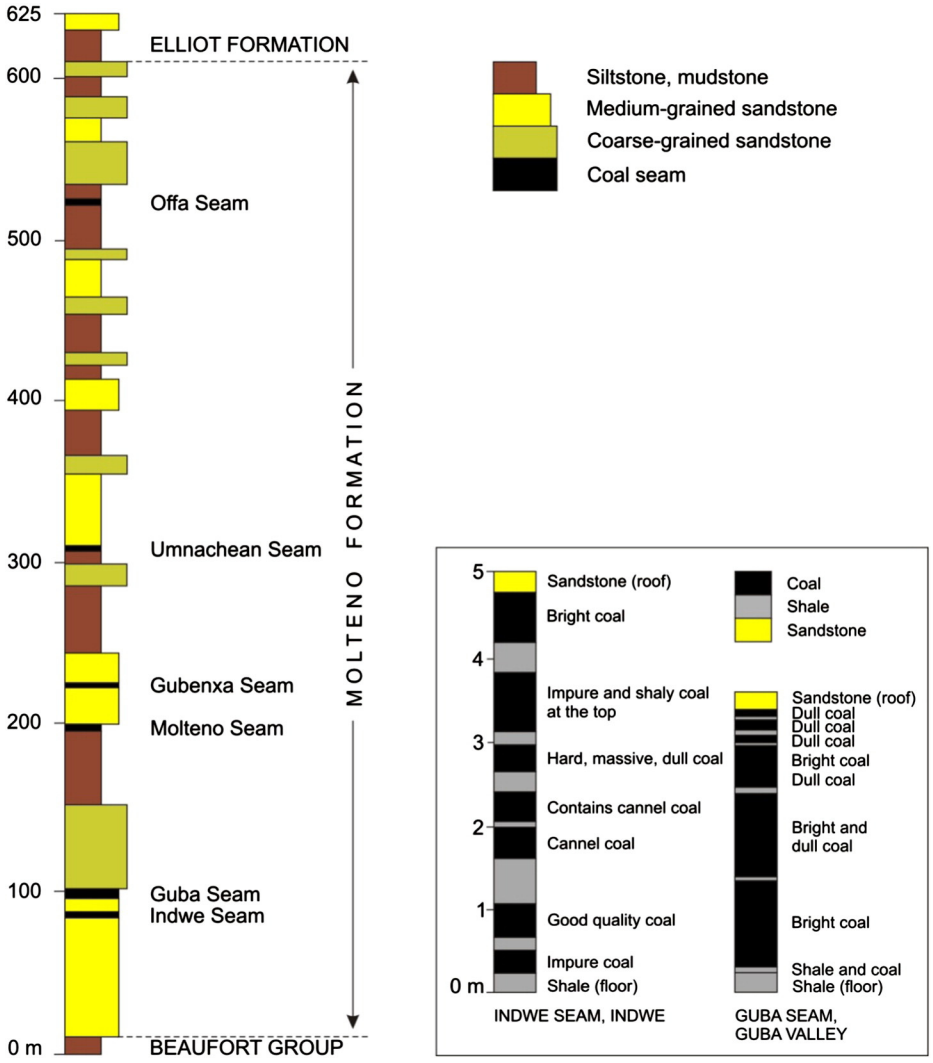

Fig. 49. Composite stratigraphic column for the Molteno Formation between Elliot and Indwe. After Christie (1986).

opinion that there is a linkage between the tectonics affecting the MKB and the northern basins, and that the stratigraphic nomenclature as applied to the MKB may in fact be applied throughout the northern basins as well.

6.5. Sequence stratigraphy

Whilst sequence stratigraphic principles for non-marine and marginal marine successions are now firmly entrenched (Catuneanu, 2006; Catuneanu et al., 2009), in South Africa only two papers have considered this aspect of coal seam development (Catuneanu et al., 2002; Tovela, 2011). If the various depositional successions can indeed be correlated as discussed above, then sequence stratigraphic principles for the fills of the MKB may be applied to all of these coalfields.

Catuneanu et al. (2002) undertook a third-order sequence stratigraphic analysis of the Early Permian marine to continental facies of the northern margin of the MKB. These authors document a succession of five basin-wide regressive systems tracts, with each regressive systems tract (RST) terminated by a basin-wide transgressive systems tract (TST). In terms of this model the evolution of the transgressive–regressive cycles was controlled by normal (sediment supply driven) regressions in the distal shorelines of the Ecca interior seaway. Tovela (2011) utilised boreholes and outcrop studies to fit the coal seams of the Emakwezeni Formation of the Somkhele Coalfield into a sequence stratigraphic framework, placing the Emakwezeni depositional cycles as fourth-order cycles.

The senior author has been involved in a number of studies on projects in the far western region of the Witbank Coalfield that has shown that the various plies that compose the seams in this area may be analysed in a sequence stratigraphic framework. The basal plies of both the No. 2 and No. 4 seams have the maximum aerial extent during the TST, with the upper plies being far less aerially developed and much more fragmented in their distribution. This is believed to be a response to the rate of base level rise beginning to increase (lowering the water table and causing fluvial incision) as one reaches the top of the TST. Whilst this data cannot be made public at present it is an avenue of research which should be looked into.

6.6. Impact on exploration practices

This work has shown that one needs to understand the nature of the pre-Karoo basement if one is to understand the nature of the early accommodation space created, the sedimentary fill and subsequent coal formation. Due to cost implications, too many exploration boreholes stop short of the basement. It is however vitally important to fully understand the palaeotopography (and its controls on the succession), not only for sedimentological work, but also for geotechnical

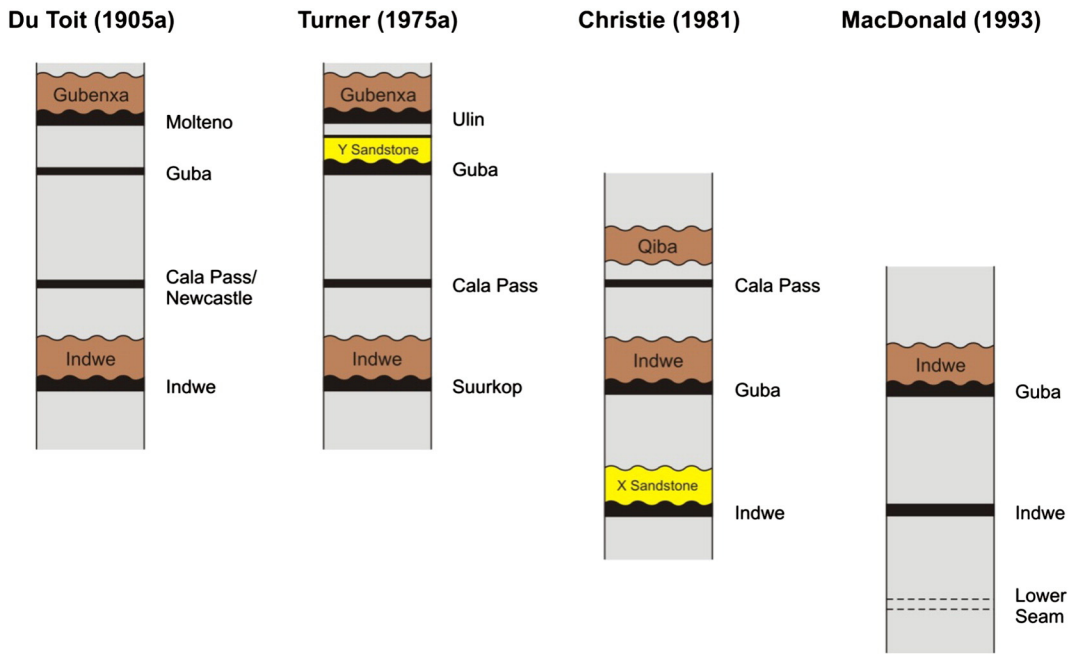

Fig. 50. Comparison of the nomenclature and stratigraphic placement of the coal seams in the Bamboesberg Member. From Hancox (1998).

considerations and in modelling (both for dolerites and basement elevations).

This work has also highlighted the need for exploration geologists to get back to the basics of sedimentology (not just seam and interburden logging). Detailed sedimentological logging and facies interpretations allow for an understanding of the depositional environment and aid in the interpretation of the geotechnical environment, allowing for better understanding of the rock mass behaviour during mining operations (Van Heerden, 2004a). It is the senior author's experience that far too few borehole logs have sufficient detail to correctly interpret the depositional environment.

As the entire coal seam is sampled and most exploration boreholes for coal are not retained, high-resolution photography is a crucial element of the documentation of the core. Too often this aspect of the core description is either not undertaken, or undertaken poorly.

Coal has anomalously low density compared to its host rock successions and down the hole geophysical readings should be routinely taken, primarily to check for coal recoveries. The full suite may include three-arm calliper, gamma, density, P-wave sonic, neutron, resistivity, dipmeter and acoustic scanner (Jeffrey, 2004). Van Heerden (2004b) has shown that only three probes, density, optical televiewer and acoustic televiewer are required in order to identify geotechnical features, and that non-orientated core only really allows for an assessment of rock quality data (RQD). Both the optical and acoustic televiewer produce a 360° orientated image of the borehole wall. The optical televiewer works only in air, and the acoustic televiewer only in water filled holes. In the Springbok Flats Coalfield the use of the gamma probe may also be used to delineate the co-occurrence of uranium.

This review has shown that two major styles of coal seams are developed in South Africa, which SANS (10320) refers to as multiple seam and thick interbedded deposits. These two styles require different exploration techniques to be applied. By way of example it is noted that in the Limpopo Coalfield both down the hole wireline and televiewer is required for positive correlation. Borehole core sizes must also be adequately matched to the type of coals being explored for, with larger diameter holes required for vitrinite-rich successions.

Except in the Springbok Flats and Waterberg coalfields the presence of dolerites is ubiquitous. They occur as both magnetic sills and magnetic and non-magnetic dykes. Their presence may hamper exploration drilling, with issues ranging from access to scree-covered rubble slopes, through to difficult drilling conditions including poor core recoveries due to faulted and fractured ground and baked and metamorphosed contacts. These dolerite intrusions have devolatilised and in places burnt the coal seams, impacting on their qualities. Furthermore they are often the cause of gas and water issues. A thorough understanding of their occurrence and morphology is therefore critical to any exploration project. During exploration it is also important to document the contact angles of the intrusions and to state the degree of weathering of any dolerites encountered in the borehole as this is important from a structural and mining perspective. A standardisation of the nomenclature for the dolerite sills of the MKB would also be of practical use.

6.7. Impact on exploitation practices

The thickness of the seam, its ply qualities, the nature of the roof and floor, and the style of coal (multi-seam or thick interbedded) all have a significant impact on the method and rate of extraction, and on the beneficiation requirements. A thorough understanding of each of these areas will allow for the selection of the correct mining cut as well as for the correct exploitation method. For example floor rolls in thin seam heights preclude the effective use of continuous mining equipment.

The five coalfields containing thick interbedded coal seams require the beneficiation of the intercalated fine carbonaceous material, with the associated materials handling issues. Underground extraction of these coal zones will remain a serious challenge for the future. Underground extraction in the Somkhele and Limpopo coalfields will probably not happen due to the high dips encountered. Meaningful structural and geotechnical data may only be acquired from televiewers (Van Heerden,

Table 21
Generalised coal characteristics of the Molteno Formation, washed at a RD of 1.8. From Thamm (1998).

Seam	CV (MJ/kg)	Ash (%)	VM (%)	IM (%)	FC (%)	TS (%)
Guba	21.25	32.45	8.87	2.22	40.03	0.64
Indwe	23.25	30.06	14.89	1.65	53.40	0.45

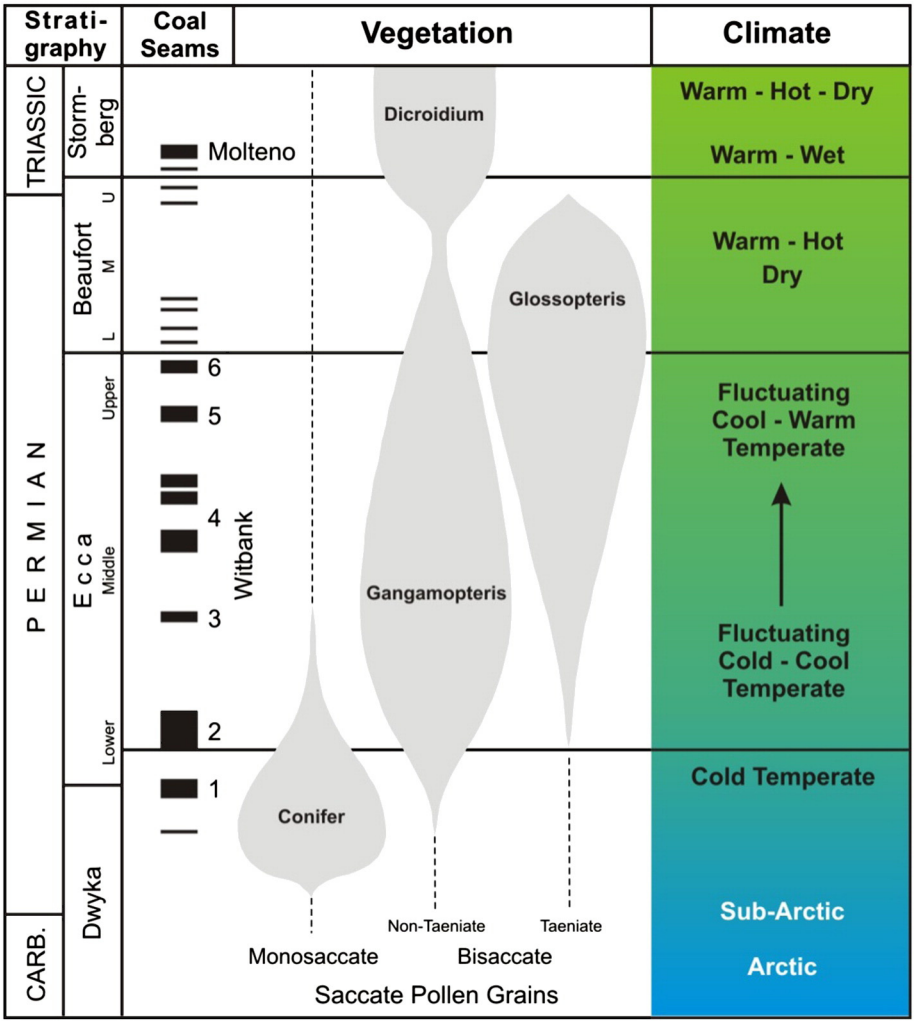

Fig. 51. Gondwana's climate history inferred from the palynological record of the Karoo coal-bearing deposits. The switch from Icehouse to Greenhouse is documented in the No. 2 Coal Seam (Lower Ecca Group), reflected by a major vegetational change (Götz and Ruckwied, 2014).
Modified from Falcon (1986c).

2004b); data which are crucial in understanding the nature of high and low wall stability during mining.

6.8. Impact on utilisation

All of the qualities of the various coals impact on the utilisation or potential utilisation, and the exploration geologist and coal resource estimator should be aware of the potential markets and their constraints, both technical and economic. The phosphorous percentage, for example, is a critical factor in the marketing of metallurgical coals and one must understand the product phosphorous. Due to its environmental impact the sulphur percentage is an important criterion in most contracts, and the form and species of the sulphur needs to be understood in order to understand the beneficiation characteristics.

6.9. The future role of coal mining for South Africa's energy mix

Although it is never a good idea to predict the future, it would seem that for the next 40–50 years, and barring some major other energy breakthroughs, coal will continue to dominate South Africa's energy mix. Large resources of high Ash, low volatile coal exist that need to be brought to account. The primary challenges for the unlocking of the resource potential of all of South Africa's coalfields are similar. Geologically these include that the remaining resources are more marginal in quality than those historically mined, and are also often more geologically complex, requiring additional exploration work and closer spacing of points of observation. These lower quality coals also often require beneficiation even to make local power market specifications. Coal will also only fulfil its role with social and environmental buy-in, and issues such as the handling of legislative, environmental and community matters are common to all the coalfields, as are the real infrastructural and logistical constraints.

Acknowledgements

A review of this nature draws on many different sources and people that are too numerous to be individually listed and our indebtedness to these colleagues is noted en masse. The authors would however like to thank various individuals and companies: Sasol for permission to incorporate Fig. 22; Keaton Energy Holdings for permission to publish various photographs; Dr. Johann Neveling and Lorraine van der Merwe (Council for Geoscience) for sourcing various open file reports and for providing the senior author with copies of Anderson's reports; Peet Meyer for providing hard to find references on the Kangwane Coalfield; John Sparrow for providing various images for the Soutpansburg and Limpopo coalfields and for proof reading these sections; Yeolanda

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