



Government of **Western Australia**
Department of **Mines, Industry Regulation**
and **Safety**

RECORD 2019/6

CENOZOIC COAL RESOURCES OF SOUTHERN WESTERN AUSTRALIA: EXPLORATION AND EVALUATION HISTORY

**by
SL Simons**



Geological Survey of Western Australia



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PERTH 2019



**Geological Survey of
Western Australia**

MINISTER FOR MINES AND PETROLEUM
Hon Bill Johnston MLA

DIRECTOR GENERAL, DEPARTMENT OF MINES, INDUSTRY REGULATION AND SAFETY
David Smith

EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY AND RESOURCE STRATEGY
Jeff Haworth

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Telephone: +61 8 9222 3459 Facsimile: +61 8 9222 3444
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Cover image: Sunset over the Yalgoo Mineral Field. Photograph by T Ivanic, DMIRS

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Cenozoic coal resources of southern Western Australia: exploration and evaluation history

by

SL Simons

Abstract

This Record collates the exploration and evaluation history of Cenozoic lignite resources in southern Western Australia, and accompanies a data package in which all available open-file data are compiled.

Cenozoic lignite occurs as part of a sequence of marine, marginal-marine to non-marine Eocene sedimentary paleochannel infill of the onshore western Eucla Basin. Numerous companies explored the broader area during the 1980s. Targeted exploration recommenced in the late 2000s and three deposits, Scaddan, Salmon Gums and Zanthus, have resource estimates reported according to the 2004 JORC Code. The Eucla Basin lignites are low-rank, low-grade fuel with high moisture and low heating value. The ash content varies between, as well as within, deposits and occurrences, and shows a range in reported values from 6 to 60%. The lignite has an average oil yield of 120 L/t and a large range of specific energy values, from 5 to 20 MJ/kg. The relative density of the lignite ranges from 1.2 to 1.4, and high salt content has been reported, with values ranging from 1.5 to 19%.

KEYWORDS: coal deposits, coal exploration, coal resources, Eocene, Eucla Basin, lignite

Introduction

Most of the Cenozoic coal in the southern half of the State is contained within the Eucla Basin. Brown coals, or lignites, occur in paleochannel successions within the onshore part of the western Eucla Basin (Holdgate and Clarke, 2000). Numerous companies explored the broader area during the 1980s; however, targeted exploration recommenced in the late 2000s and three deposits have resource estimates reported according to the 2004 JORC Code: Scaddan, Salmon Gums and Zanthus.

This Record collates the exploration and evaluation history of the Cenozoic lignite resources in the south of Western Australia (Fig. 1). Information for this Record was sourced from both published and unpublished data. Published information has been derived from Geological Survey of Western Australia (GSWA) Reports, Records, Bulletins and geological maps. Other published sources include scientific journal papers, conference proceedings, and company annual and quarterly reporting.

Unpublished information has been obtained from statutory exploration reports submitted to the Department of Mines, Industry Regulation and Safety (DMIRS) by mining and exploration companies, which are held within the Western Australian mineral exploration index (WAMEX) database and the Western Australian petroleum and geothermal information management system (WAPIMS). These exploration reports are supplemented by unpublished reports to the Australian Securities Exchange (ASX).

Due to the fluctuating nature of the extent of prospective areas and deposit boundaries over time, and the varying

names used to refer to prospects and deposits by different companies, for reporting accuracy prospects and deposits discussed in the text are referred to in the same terms as those used in the original reference. Drillhole details were extracted from open-file reports where available. Where collar coordinates are reported for historical drilling they have been converted to GDA94 using ArcGIS. Where collar coordinates were not available and only locations displayed on maps, the best-quality maps have been georeferenced in GDA94 in ArcGIS and the collar locations digitized. As the scale and quality of the original maps varies greatly, both over time and between companies, the accuracy of the collar locations is also highly variable and should be considered with caution. Drillhole locations and details are available from the DMIRS Data and Software Centre at <www.dmp.wa.gov.au/datacentre> as a data package associated with this Record. Figure 1 shows all of the drillholes collated for southern Western Australia.

The geological descriptions of the deposits and reported coal intersections have, in most cases, been taken directly from original exploration reports, as it was considered problematic to equate the use of terminology across different eras of exploration. Unless otherwise specifically stated, resource figures do not comply with the reporting requirements of the Joint Ore Reserves Committee Australian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (the JORC Code; Joint Ore Reserves Committee, 2012). If resources were originally reported as complying with an edition of the JORC Code prior to 2012 then the edition year has been stated. Further information on JORC reporting is given in the chapter on resources.

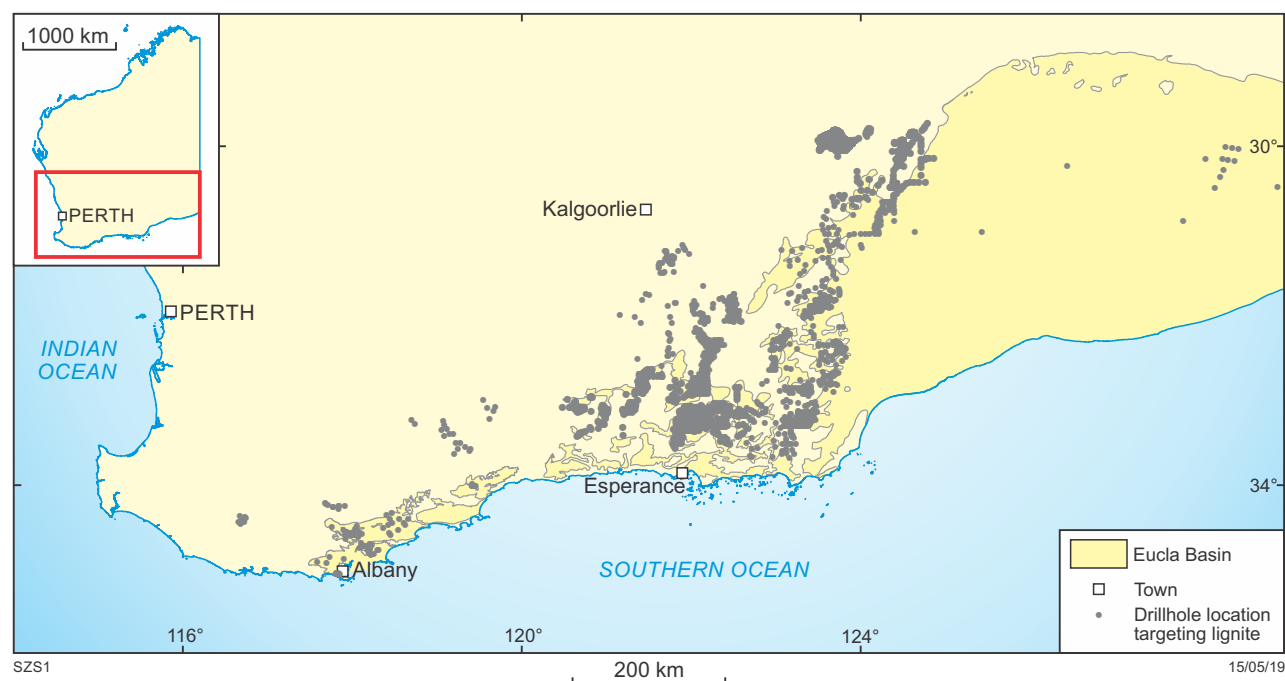


Figure 1. Distribution of drilling and location of the onshore Eucla Basin (after GSWA, 2017)

Previous exploration

Lignite from the Fitzgerald River area was first recorded in 1848 (Roe, 1852). Several early geologists examined the stratigraphy and quality of this lignite. GSWA reported a bore near Albany that intersected about 1 m of low-grade brown coal at a depth of 20 m, and noted that the hole collapsed before the full seam thickness was recovered (Maitland, 1900). The lignite was reported to contain 60% ash, 6.28% water and 18.84% volatile matter, and was described as compact, soft and friable, and was a dull, sooty black. In 1902, poor-quality lignite from the Fitzgerald River area was analysed by GSWA (Simpson, 1902). Poor-quality lignite was also noted by Simpson (1902) southeast of Coolgardie, where a seam of brown coal was struck in Olsen's claim at a depth of 65 ft (Table 1).

Campbell (1906) recorded a borehole in Lake Cowan that passed through soft 'bituminous mud' between 53.3 and 91.4 m. Further exploration was limited, although drilling by Carpentaria Exploration Company Pty Ltd in 1970 revealed thin discontinuous pockets of black bituminous clay underlying marine spongolite sands in a Cenozoic drainage channel near Widgiemooltha, north of Norseman (Sharples, 1981). Other intersections of lignite in this region included water bores drilled in 1977 in the Kumarl area (50 km south of Norseman) by the Department of Main Roads that intersected very high ash and peaty lignite (Loxton, 1978; Western Collieries Ltd and Mokey Pty Ltd, 1987), and drillholes east of Lake Gilmore and 22 km south of Norseman drilled by Australian Consolidated Minerals Ltd in 1977 that intersected 'brown coals with clay bands' and 'carbonaceous clays' (Bunting and Venning, 1982; Sharples, 1981).

Between 1980 and 1985, CRA Exploration Pty Limited, Western Collieries Ltd and Broken Hill Pty Co Ltd (BHP)

Table 1. Proximate analysis of lignites southeast of Coolgardie (from Simpson, 1902)

	Sample number		
	529	624	700
Moisture (%)	30.56	41.73	24.24
Volatile hydrocarbons and combined water (%)	23.62	19.35	29.81
Fixed carbon (%)	9.45	7.84	5.51
Ash (%)	36.37	31.08	40.44
Total	100	100	100
Specific gravity			1.493

each conducted large exploration programs that resulted in the delineation of several prospects of varying size throughout the Eucla Basin.

In 1980, BHP drilled over 2000 m of reconnaissance core during a regional search for oil shale covering from Salmon Gums to north of Norseman (Sharples, 1981; Bunting and Venning, 1982;). The drilling outlined an area of significant potential in a paleochannel southwest of Lake Gilmore. During the early 1980s, exploration increased after an announcement by Western Collieries that it had located a substantial deposit near Scaddan, north of Esperance. Kristensen and Wilson (1986) suggested that initial reports from other companies were optimistic regarding the quantity and quality of the lignite, and subsequent work had resulted in downward revisions of both. Although there was a range of lignite development projects, most occurrences were not of economic interest, and by mid-1985 only four tenement areas were maintained. By this time, the main thrust of company activity had moved from delineating deposits and quantifying tonnages to assessing the utilization potential of the resource.

Geology

The Eucla Basin lies on Australia's southern margin. In Western Australia, it is bounded by the Yilgarn Craton, Albany–Fraser Orogen, Canning Basin and South Australian Craton (Fig. 2). The main part of the basin covers an extensive area onshore and extends from Albany to the Western Australian border. It contains the most extensive onshore accumulation of Cenozoic marine sediments recorded globally (Clarke et al., 2003).

The formation of the Eucla Basin was predominantly controlled by long-wavelength plate flexure, sea-level change and local fault movement (Sandiford et al., 2009; Clark et al., 2012). Sediments were deposited over an extremely irregular surface of Precambrian rocks; consequently, paleogeography provides a strong control on lithologic variability and the thickness of depositional units (Clarke et al., 2003). The depth to basement is generally less than 1000 m (FROGTECH Geoscience, 2014).

The onshore Eucla Basin succession is dominated by Eocene and Oligocene to Miocene limestones, which grade laterally into siliciclastic rocks along the northern margin and south of both the Yilgarn Craton and Albany–Fraser Orogen (Plantagenet Group; Hocking and Martin, 2016). Correlative Eocene and Miocene valley-fill deposits are preserved in ancient drainage systems (paleochannels) across the Yilgarn Craton. These deposits are considered extensions of the Eucla Basin where they are in continuity with the main basin. Marine facies are recorded as

extending up these valleys as far as Norseman (Hocking and Martin, 2016). The marine and paralic sedimentary rocks of the onshore Eucla Basin are flat lying, with no faulting or folding known; therefore, there are no recognizable structural controls on sedimentation and lignite formation (Elms et al., 1995).

Paleochannels associated with the irregular topography of the Eucla Basin are widely distributed around the basin margins and have varying dimensions, with widths ranging from a few tens of metres to more than 30 km, depths of up to 100 m and main channel lengths typically extending 100–700 km into the hinterland. Each paleochannel represents a major drainage system comprising lakes, swamps and rivers active prior to the middle Miocene (van de Graaff et al., 1977). The principal direction of the paleodrainage flow was directly towards the basin from the continent, but paleochannels locally form a subdendritic pattern, typically with 'V-shaped' (mostly upper reaches), 'U-shaped' (mostly middle reaches) or 'W-shaped' (mostly lower reaches) cross-sections and very low gradients (0.01 – 0.008%) with total relief of 10–150 m (de Broekert, 2002; Hou et al., 2008). The modern topography of the region has been shown to largely reflect the pattern of Paleogene paleochannels (Hou et al., 2003, 2008; de Broekert and Sandiford, 2005), with the current-day chains of saline lakes (playas) marking the widest and presumably deepest parts of the ancient drainage systems. Prevailing easterly winds have resulted in the westerly migration of these lakes and, therefore, the deepest paleochannels are found east of modern lake centres (Hou et al., 2008).

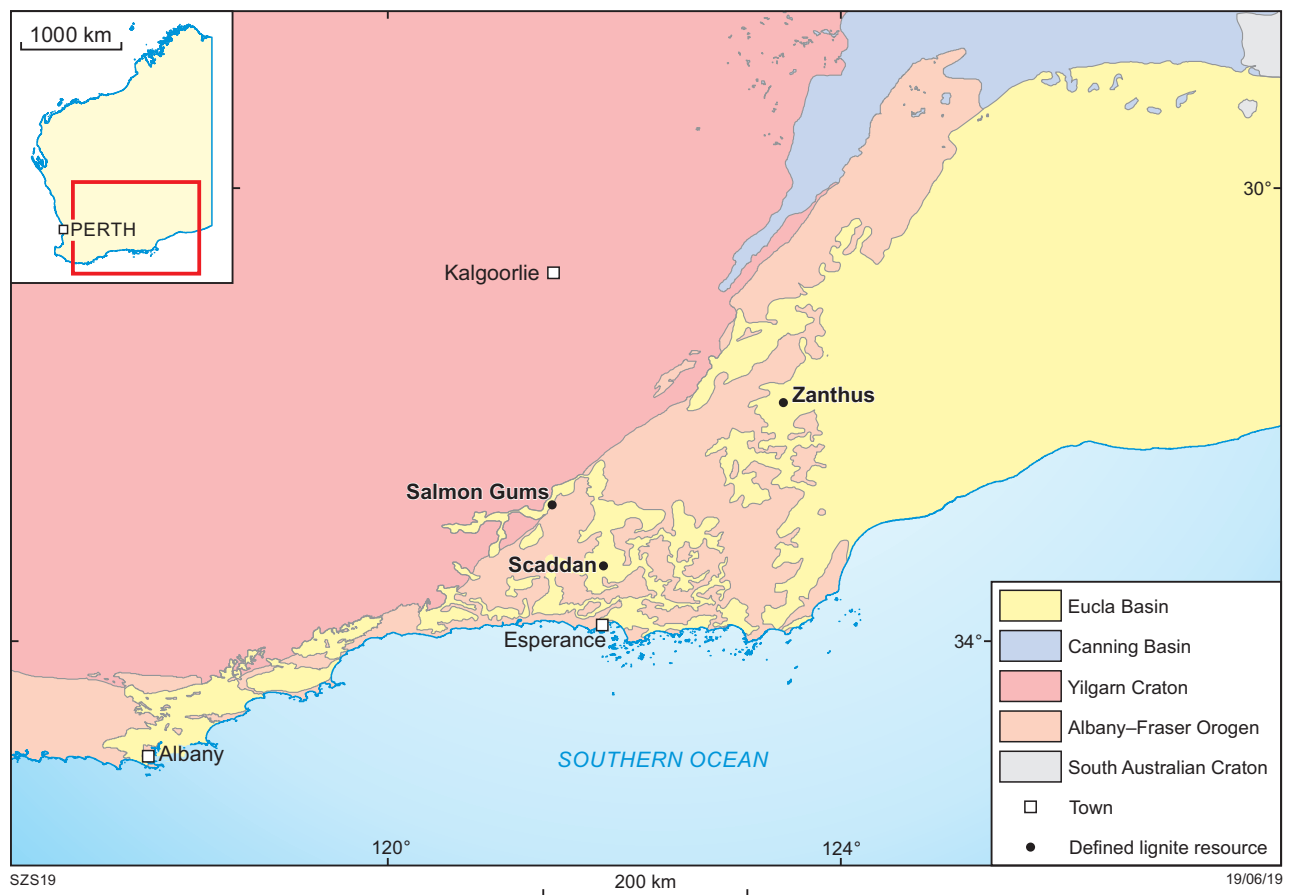


Figure 2. Location of the onshore Eucla Basin, Yilgarn Craton, Albany–Fraser Orogen, Canning Basin and South Australian Craton (after GSWA, 2017) and defined lignite resources

Paleochannel fill is generally dominated by Cenozoic sediments, with the major phases of deposition during the middle Eocene Wilson Bluff and Tortachilla transgressions and late Eocene Tuketja and Tuit transgressions (Clarke et al., 2003; Hou et al., 2008). However, distinct phases of paleochannel sedimentation have been identified in the early Eocene (fluvial sediments), middle Eocene (lagoonal carbonaceous limestone and estuarine–fluvial carbonaceous clastics), late Eocene (marginal-marine – fluvial carbonaceous clastics and estuarine clastics), middle Miocene to early Pliocene (lacustrine mudstones and dolomitic limestone and marginal marine–estuarine clastics) and Quaternary (regolith, lake sediments, eolian sands, calcrete, silcrete and ferricrete) (Clarke et al., 2003; Hou et al., 2003, 2006, 2008). Clarke et al. (2003) has reviewed the complete stratigraphy of these transgressions and the reader is directed to this paper for more detailed information (Hou et al., 2008).

On the western margin of the Eucla Basin, paleochannels often contain significant lignite deposits as part of the Cenozoic paleochannel fill. The carbonaceous sequences are generally thickest in the centre of the paleochannels and vary between 10 and 30 m. These lignite deposits are lenticular in one dimension and may be discontinuous along strike or parallel to the dendritic fluvial channels. Thick coal facies are rare in the upper reaches of the paleochannels but become more common downstream (Holdgate and Clarke, 2000), where the thickness of the seams ranges between 5 and 20 m. The top of the lignite is generally subhorizontal, whereas the base generally conforms to basement topography. The lignite itself is well gelified and contains abundant woody fragments. The lignite is described as soft, plastic, chocolate brown and earthy with rare globules of resin (Elms et al., 1995) and can have a kerogen smell. Pyrite is common, either as fine, disseminated grains or as coarse replacement of plant fossils.

Stratigraphy

Although stratigraphy varies across the western Eucla Basin, it reflects transitions from marine to non-marine sedimentation throughout the Cenozoic. Paleochannels are largely filled by a succession of Eocene non-marine to marine sediments where deposition was continuous (Clarke et al., 2003). The stratigraphy of the western Eucla Basin is summarized in Figure 3.

The basal North Royal Formation (previously known as the lower Werillup Formation in Clarke et al., 2003) was deposited in paleochannels incised into weathered Archean bedrock, and comprises lower–middle Eocene clastics and lignites, together with their lithified and weathered equivalents up to 50 m thick. These sediments were deposited in non-marine to marginal-marine environments along the margins of the western Eucla Basin, and are particularly common in older paleochannels (Clarke et al., 2003). The formation consists of an upwards-fining succession of basal sand and gravel grading into silt and then clay, with minor lignite in the upper part.

The Norseman Formation is a middle Eocene, cool-water carbonate and mixed carbonate–clastic unit that is widespread in the Cowan paleochannel, and was the innermost marine sediment deposited during the Eocene highstands (Clarke et al., 1996).

The upper Eocene Werillup Formation consists of an upwards-fining succession of basal sand and gravel, grading into silt and then clay, carbonaceous clay and lignite (Clarke et al., 2003). It was deposited in non-marine to marine environments along the western margin of the Eucla Basin, especially in the paleochannels. The Werillup Formation is more extensively distributed than the North Royal Formation (Clarke et al., 2003).

The Pallinup Formation (previously known as the ‘Pallinup Siltstone’, now superseded) includes all spicular marine sediments (spicular siltstone, sandstone and mudstone grading into spiculite) recorded along the margin of the western Eucla Basin (Clarke et al., 2003). Scattered outcrops of these lithologies occur almost continuously across the watershed between the south-draining Cowan paleochannel and east-draining Lefroy paleochannel (Clarke, 1994). Cyclic bedding is common throughout most of the unit, as is glaucony (Clarke et al., 2003). Included in the Pallinup Formation is the Princess Royal Member, a dark green, glauconitic spiculite unit (comprising <50% siliceous sponge spicules), which is the dominant lithology represented at the uppermost reaches of marine influence in the paleochannels.

Depositional environment

The properties of the Eucla Basin lignites (high ash, high salt and high oil yield) suggest that their deposition began at the start of the Eocene in a mature drainage system draining eastwards and northeastwards into the Eucla Basin. This system appears to have consisted of meandering fluvial systems and associated swamps, lakes and lagoons. Holdgate and Clarke (2000) suggest that coal was deposited in a variety of riverine and coastal plain environments with marine-influenced groundwater introduced during deposition or shallow burial, mainly controlled by eustatic changes in sea level (Elms et al., 1995). The high oil yield of these deposits further suggests a high proportion of brackish water algae and wax-rich cuticle material in the sediments (Clarke, 1994).

Age control

Palynology conducted by exploration companies was only conducted by early explorers. Palynological studies of lignites and related carbonaceous sediments in the western Eucla Basin reveal a range of ages extending from the late Paleocene to late Eocene (Bunting and Venning, 1982; Denman and Fewster, 1982b; Western Collieries Ltd and Mokey Pty Ltd, 1987).

Cenozoic palynology is poorly studied in Western Australia and most studies have been in informal reports by contractors and are difficult to find or access. This is particularly true for the Eucla Basin lignites, although Mack and Milne (2015) discuss Eocene palynology in southern Western Australia, and Milne (1988) covers palynology in detail from the Zanthus area.

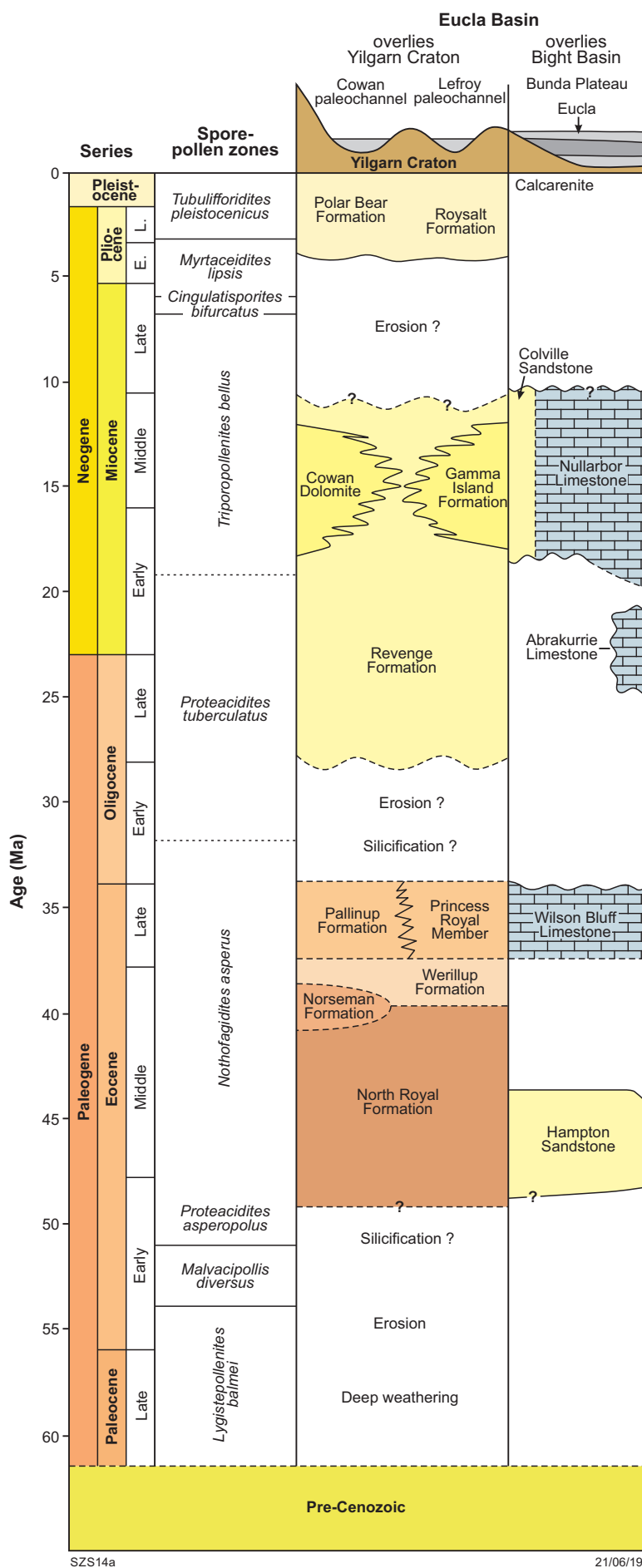


Figure 3. Stratigraphic correlation chart for the Eucla Basin and paleochannels overlying the Yilgarn Craton, with spore-pollen zones and ages (modified from Hou et al., 2008)

Geophysics

Early surface geophysical exploration of the area in the 1980s used methods such as gravity traverses, ground resistivity surveys and seismic traverses across regional gravity lows in parts of the drainage systems. These traverses provided information about the depth to basement and the shape of the drainage channels.

Airborne electromagnetic (EM) surveys have been instrumental in finding paleochannels, with surveys designed to map the thickness of electrically conductive sediments above resistive basement, and therefore to define the extent of the paleochannel, calculate the depth to basement and enable targeting of lignite deposits. Early explorers also used SIROTEM surveying (a time-domain electromagnetic technique) to delineate area underlain by thick lignite. Landsat TM and photogeological studies have also been used to define target paleochannels.

Most exploratory holes drilled in the region were accompanied by downhole geophysics, although rapid drillhole collapse prevented logging in some cases. High salt levels in the groundwater were found to affect the self-potential and resistivity readings, making these logs unreliable (Bunting and Venning, 1982). The density logs show pronounced changes between various sediment types, and are useful in defining lithological boundaries, with the lignite having higher density count rates (lower density) than other units. The density logs are especially useful in accurately identifying silt or sand interbeds and subtle changes in clay contents within the poorer quality lignite (Shearley and Denman, 2002). The gamma logs often show pronounced peaks at or near the top of the lignite seam and occasionally near the base of the seam, which most likely correspond to an increase in uranium at these levels. The gamma logs also clearly show clean lignite seams, as these give a very low gamma trace (Walsh, 1999).

Resources

There are three significant lignite deposits in the southeast of Western Australia, within the Eucla Basin — Scaddan, Salmon Gums (also referred to as the O'Sullivan's lignite deposit within some exploration reports) and Zanthus, all of which have resource estimates reported according to the JORC Code (2004; Fig. 4; Table 2). The current resource estimate for the Scaddan deposit is a Measured Resource of 80 Mt, Indicated Resource of 490 Mt and Inferred Resource of 470 Mt, totalling 1.04 Gt. The Salmon Gums deposit is estimated to contain Indicated Resources of 406.1 Mt and a further 470 Mt of Inferred Resources (Arndt, 2009). The Zanthus deposit contains an Inferred Resource of 350 Mt.

Coal quality

The coals of the Eucla Basin are classified as lignites due to their low rank. The moisture content is generally high and ranges from 38 to 60%, but averages 50–55% as received (ar). The ash content varies between, as well as within, deposits and shows a range in reported values from 6 to 60%; although, the ash content for the three JORC-compliant deposits (Salmon Gums, Scaddan and

Zanthus; reported according to the 2004 JORC Code) are reported as between 25–31% dry basis (db), 14.3% at 56% moisture basis, and 19.6% at 50% moisture basis, respectively. The reporting of volatile matter is often poor or incomplete, as are the sampling procedures used for analyses. The percentage of volatile matter at most other prospects is similar to that of JORC-compliant deposits such as Salmon Gums (approximately 40% [db]), Scaddan (17% at 56% moisture basis) and Zanthus (18.2% at 50% moisture basis). The oil yield of the lignite in this area is also variable but ranges between 40 and 240 L/t, with an average of 120 L/t; however, poor sampling may contribute to the large range. The reporting basis for specific energy values is commonly unknown. Specific energy values show a large range from 5 to 20 MJ/kg, with the high values likely to be on a dry basis. The relative density of the lignite ranges from 1.2 to 1.4 and the salt content has been reported as high, with values ranging from 1.5 to 19%.

Coal utilization

The Eucla Basin lignites are a low-grade fuel with high moisture and low heating value. Possible uses for the lignite include a fuel source for power generation, a feedstock for oil refinery (coal to liquids), gasification (coal to gas) and synthesis, a petrochemical feedstock and a source of montan wax. Potential utilization issues with the lignite include high salt and ash contents.

Coal deposits, prospects, projects and occurrences

Salmon Gums

The Salmon Gums deposit (also referred to as the O'Sullivan's lignite deposit within some exploration reports) contains significant lignite and related carbonaceous sediments within a paleochannel, which explorers refer to as the Gilmore paleochannel, approximately 100 km north of Esperance (Fig. 4).

Within the paleochannel, a horizontal Eocene sequence of initially fluvial and later transgressive marine carbonaceous clay and lignite passes up into lacustrine clays and sands (Fig. 5, Table 3). The sediments unconformably overlie the Archean basement and can be up to 40 m thick. The western and northern margins are defined by subcropping granitic rocks but the eastern margin is poorly defined.

The uppermost part of the granitic basement is strongly weathered and consists of several metres of white clay containing coarse quartz crystals. This is overlain by an unconsolidated, fine to coarse, arkosic, quartz sand unit with both angular and rounded grains, which is water filled with the water under subartesian pressure. It commonly shows a sharp contact with the overlying footwall carbonaceous clay, a brown plastic clay unit between 1 and 10 m thick; however, this carbonaceous clay layer is not present everywhere. This is overlain by lignite (Crowe and Archer, 2001), which is in turn conformably overlain by thin (up to 5 m thick) carbonaceous clay followed by a glauconitic and/or spicular claystone, locally known as

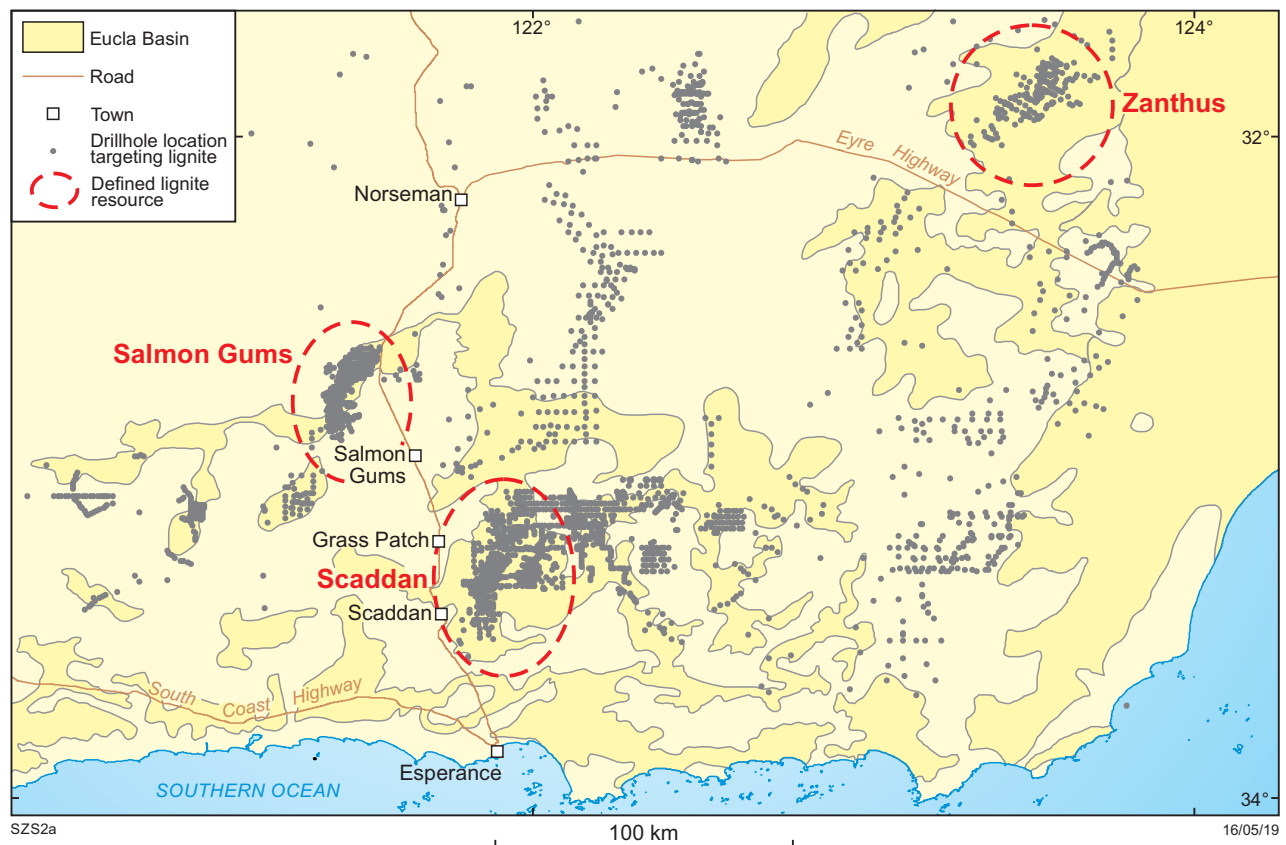


Figure 4. Distribution of drilling and location of JORC-compliant lignite resources within the Eucla Basin, Western Australia

Table 2. Current JORC (2004) resource estimates for the Scaddan, Salmon Gums and Zanthus deposits

Deposit	JORC category		
	Measured (Mt)	Indicated (Mt)	Inferred (Mt)
Scaddan	80	490	470
Salmon Gums		406.1	470
Zanthus			350

the Princess Royal Member (formally the 'Princess Royal Spongolite', now obsolete), up to 20 m thick. The lower part of this unit is typically spongolitic and occurs in an elongated, marine inlet erosional channel believed to be penecontemporaneous with the lignite. The upper part of the Princess Royal Member is glauconitic and appears to have resulted from a marine transgression that terminated lignite formation. Younger spongolite and sand-filled marine channels cut the deposit and can result in the absence of lignite from the sequence or present at a reduced thickness. The marine clays are overlain by a sequence of terrestrial clays — red to brown to yellow to white — that contain one or two thick (up to 2.0 m) carbonaceous clay layers close to the base of the terrestrial clay unit, and may contain discontinuous lignite beds up to 1 m thick. These terrestrial clays commonly contain fine to coarse quartz sand and are covered by eluvial soils with some silcrete and calcrete. The post-Eocene sediments, mainly sand and salt lake deposits, are thin, ranging in thickness from 2 to 5 m.

Oil is present in the form of kerogen; however, there are significant concentrations of waxes (montan wax), resins, phenols, cresols and other aromatic compounds. The average calorific value of the deposit is 22 MJ/kg ([db]; Bruno Sceresini Holdings Pty Ltd, 1998). Analysis showed the main compounds present in the ash were sodium chloride, silicon dioxide, iron oxide (hematite and magnetite), calcium and sodium sulfate, and various silicates of aluminium, calcium and magnesium (Herman Research Laboratory, 1996).

Exploration of this area started in the 1980s by BHP during a regional exploration program targeting oil shale. Sixty holes were drilled within the deposit during this initial exploration, with over half intersecting oil-yielding carbonaceous material, the thickest lignite intersection being 20 m (Bunting and Venning, 1982; Sharples, 1981). At this time, the deposit was estimated to contain 2.7 Gt of lignite with an average of 70 L/t of oil (Bunting, 1982). Bunting (1982) reported high moisture (average 55%), salt (7–19%) and sulfur (about 5% [db]) contents with some samples containing up to 8.6% (db) pyritic sulfur and variable ash yield, from 18–48% (db) with an average of 28%.

BHP withdrew in 1983 and the deposit was taken up in 1992–95 by the O'Sullivan's Group, in agreement with Trans Global Resources NL. Trans Global recognized a major marine Eocene channel (1.0 – 1.5 km wide) transecting the previously estimated lignite resource. Thirty shallow aircore holes were drilled across the paleochannel, showing a reasonably continuous lignite seam up to 18 m thick under approximately 20 m of overburden (Lewis

and Symons, 1995). Trans Global also drilled ten 6-inch diameter cores to provide a bulk lignite sample for detailed analysis aimed at determining the power generation properties of the lignite (Lewis and Symons, 1995). Their estimate of an inferred resource was split into two areas, together totalling 390 Mt (Lewis and Symons, 1995).

During 1998–99, Australian Power and Energy, with Hillcrest NL, conducted further drilling and analysis to investigate the area's oil production potential (Crowe and Archer, 2001). A major outcome of this program was a Synfuel test in 1990 by Texaco in the US, which concluded that the lignite was suitable as feed for a 'Texaco gasifier' (Walsh, 1999). Their average oil yield using a 70 L/t cut-off was 119.4 L/t (Walsh, 1999).

Portman Ltd entered into a joint venture over the project in 2001, with an interest in using the lignite to upgrade iron ore from its Koolyanobbing deposit through the production of 'iron-char'. The exploration program consisted of 110 aircore holes on a ~1 km grid, two bulk samples of lignite core and ten core holes (Shearley and Denman, 2002). In 2002, Portman reported a total resource of 508 Mt (in situ moisture basis) at a 5 m cut-off, and 290 Mt (in situ moisture basis) at a 10 m cut-off (Shearley and Denman, 2002). Analysis confirmed that the lignite contained approximately 20–30 % ash (db) and an oil yield range for seams of at least 10 m thick of 103–154 L/t (Shearley and Denman, 2002). The average relative density for the full seam ranged from 1.22 to 1.31 at in situ moisture. The oil yield from the Fischer Assay shows a considerable range within the lignite section, from above 100 L/t and up to 177 L/t but can be as low as 20 L/t in lignitic clays.

In 2006, Hurricane Energy Limited conducted a major review of the lignite and processing technology aimed at

maximizing the production of liquid fuels from the lignite. Hurricane Energy estimated the inferred lignite resource at 519 Mt at 5 m cut-off and 312 Mt (including a 5 m cut-off) at a 10 m cut-off, both at in situ moisture basis (Denman, 2006).

From 2007 to 2010, Spitfire Oil Limited conducted geophysical interpretations of an airborne EM survey, flew light detection and ranging (LiDAR) air photography, and undertook approximately 21 000 m of drilling with downhole geophysical logging. They reported that the lignite seam (informally referred to as the Gilmore lignite unit) is divided into three broad zones in the Salmon Gums area — GL1, GL2 and GL4, in ascending stratigraphic order (Figs 6, 7). The basal GL1 seam is erratic, restricted to the far western section of the deposit and coincides with persistent regional depocentres. The seam rarely exceeds 2 m in thickness and is interpreted to represent early stage peat accumulation within the paleochannel, likely in local topographic lows. The intermediate GL2 seam reflects more extensive peat accumulation, although it was reported that it is restricted to the western and central parts of the paleochannel. Seam thickness locally exceeds 3 m and in the far west it coalesces with the GL4 seam. The GL2 seam is typically parting free. The uppermost GL4 seam represents the most extensive phase of peat accumulation and occupies much of the paleochannel. The best development occurs on the western side, where it locally exceeds 15 m thick. The GL2 and GL4 seams coalesce near the western limit of the deposit to form a single, largely parting-free seam reaching a maximum of approximately 20 m thick. The GL4 Seam is commonly parting free, although thin clastic horizons are occasionally present in the upper portion. Parting frequency increases to the east (i.e. away from the westerly located seam depocentre; Arndt, 2009).

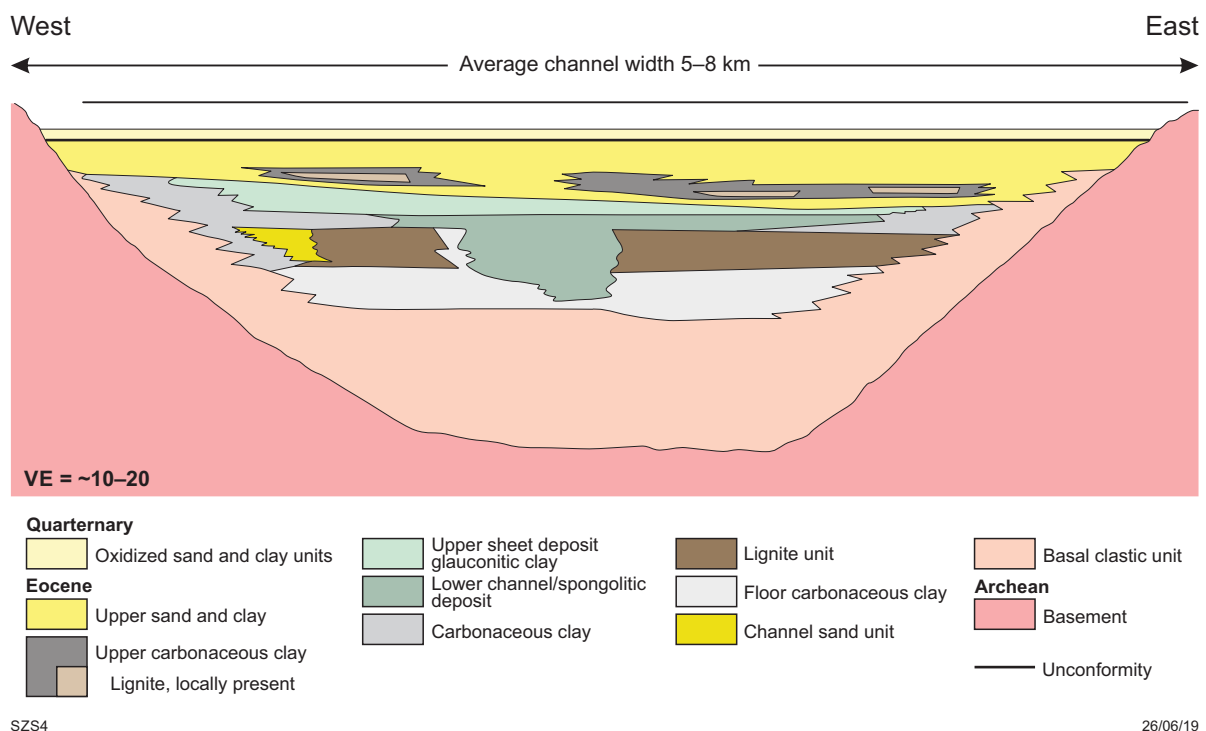


Figure 5. Schematic cross-section through the Salmon Gums lignite deposit within the Gilmore paleochannel, showing lateral variation and local defined stratigraphy (modified from Arndt, 2009). Abbreviation: VE, vertical exaggeration

Table 3. Stratigraphy of the Salmon Gums lignite deposit showing the Gilmore lignite unit (in bold text; modified from Shearley and Denman, 2002)

Age	Unit	Approximate thickness (m)	Description
Quaternary	Sand and clay	0–10+	Mainly pale white–yellow–orange, red, most often sandy clay or eolian sand, oxidized
Eocene	Unconformity		
	Upper sand and minor clay	1–10+	Tan to orange
	Upper carbonaceous clay	0–5	Generally black to grey
	Lignite	0–1	Black, thin, locally developed 'upper lignite unit'
	'Princess Royal Spongolite', upper sheet deposit	0–20	Flat, non-erosive base, olive green, glauconitic clay, open marine depositional environment, may be spongolitic, occurs above ?200 mRL
	'Princess Royal Spongolite', lower channel/inlet	0–25	Highly erosive, grey–green, sand texture, occurs below +220 mRL
	Roof carbonaceous clay	0–5	Thin, black–grey, carbonaceous, marks a change in depositional environment from swamp to marine
	Gilmore lignite unit 'floats'	0–22	Higher quality, low ash, black–brown, floats in glycerine
	Gilmore lignite unit 'sinks'	0–20+	Lower quality, higher ash, more argillaceous, clayey, sinks in glycerine
	Gilmore lignite unit, sand	0–3	Yellow to grey–black, occurs as channel deposits within the lignite
	Gilmore lignite unit, clay	0–3	Black–grey, argillaceous facies that forms interbeds within the lignite, often laterally discontinuous and grades into the lignitic clay facies
	Floor carbonaceous clay	1–10+	Black, represents decreasing energy in the depositional environment with the onset of swampier conditions
	Local channel sand	0–10+	Cream to grey, possibly earlier than or equivalent to the Princess Royal spongolite (lower unit) and predates the Princess Royal spongolite (upper unit)
	Basal clastic unit	0–30+	Pale, yellow–white, commonly arkosic, rounded quartz grains, interpreted to be thinner along valley margins and thickest in the centre
Inferred unconformity			
Archean	Basement		Granite and gneiss, strongly weathered in uppermost parts

Arndt (2009) reported that the lignite was low in rank, containing high moisture (~55%), sulfur (2–7%), sodium (3–8%) and chlorine (4–12%), all db. The lignite contains an average ash value of 25% (db) and average volatile matter of 43% (db). Relative density ranges between 1.31 and 1.22 at in situ moisture (Denman, 2007). Oil yields of ~120 L/t have been recorded using standard Fischer Assay (Arndt, 2009). In 2008 and 2009, drill out of the tenements was completed and a JORC (2004) resource (at 4 m coal thickness and 45% ash cut-off) was reported with an Indicated Resource of 406 Mt and Inferred Resource of 470 Mt, totalling 876 Mt (Table 4).

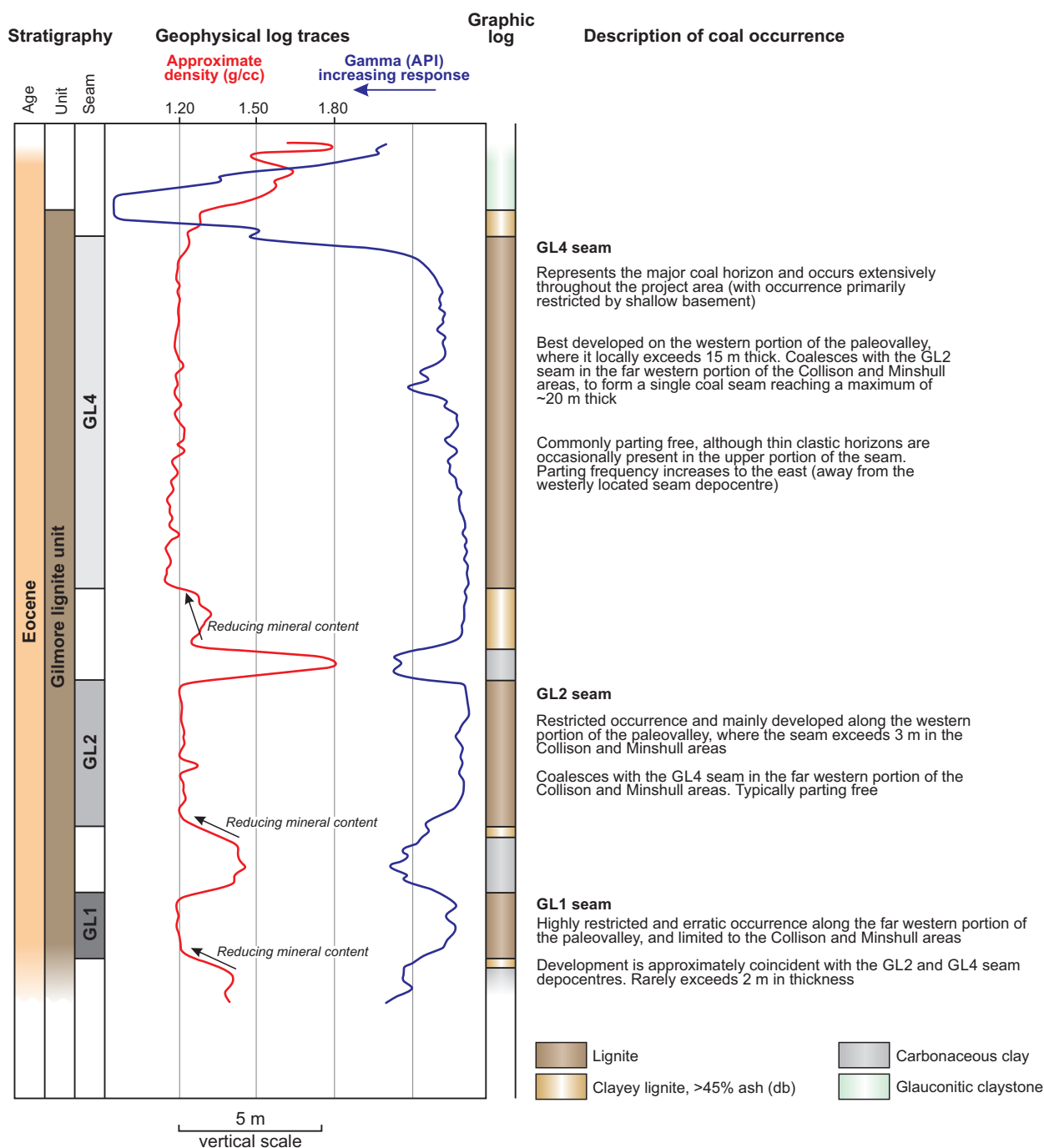
Scaddan

The Scaddan lignite project is located approximately 10 km east of the Norseman–Esperance Highway between the towns of Grass Patch and Scaddan (Fig. 4). The Scaddan lignite resource is made up of two main lignite bodies (Scaddan East and West) in an approximately 5 km-wide, north–south trending paleochannel surrounded and underlain by Precambrian granitic basement (Lippie and Wadley, 2009; Figs 8, 9). Sediments have a maximum recorded thickness of 60–70 m, although this can be

reduced locally near the edges of the paleochannel and by topographic highs in the basement (Miles, 2012b). In both Scaddan East and West, the lignite occurs at depths ranging from 20 to 40 m, and ranges in thickness from 0 to 17 m, with an average of 10 m (Chapman, 1989; Lippie and Wadley, 2009).

The upper surface of the lignite in the Scaddan area is relatively flat, whereas the base conforms to the basement topography, sitting upon a well-developed basement saprolite up to 20 m thick (Elms et al., 1995). The upper portion of the lignite can contain one or more discontinuous, thin (<10 cm) layers of silicified lignite. The lignite is approximately horizontal and in a consistent stratigraphic position within the unit; the beds are split in some locations, although this does not persist for more than 1 or 2 km (Western Collieries Ltd and Mokey Pty Ltd, 1987).

The lignite is dull, earthy, chocolate brown in colour and contains wood fragments, pyrite and rare globules of resin (Fig. 10). The huminite group of macerals typically comprise approximately 80% of the organic matter present. Of these, densinite and attrinite are most abundant macerals, with textinite, ulminite, gelinite and corpohuminite together making up 15% of that 80%.



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Figure 6. Downhole geophysical log including density and gamma (in American Petroleum Institute units [API]) correlated with coal stratigraphy with detailed coal descriptions from the Salmon Gums lignite deposit (Arndt, 2009)

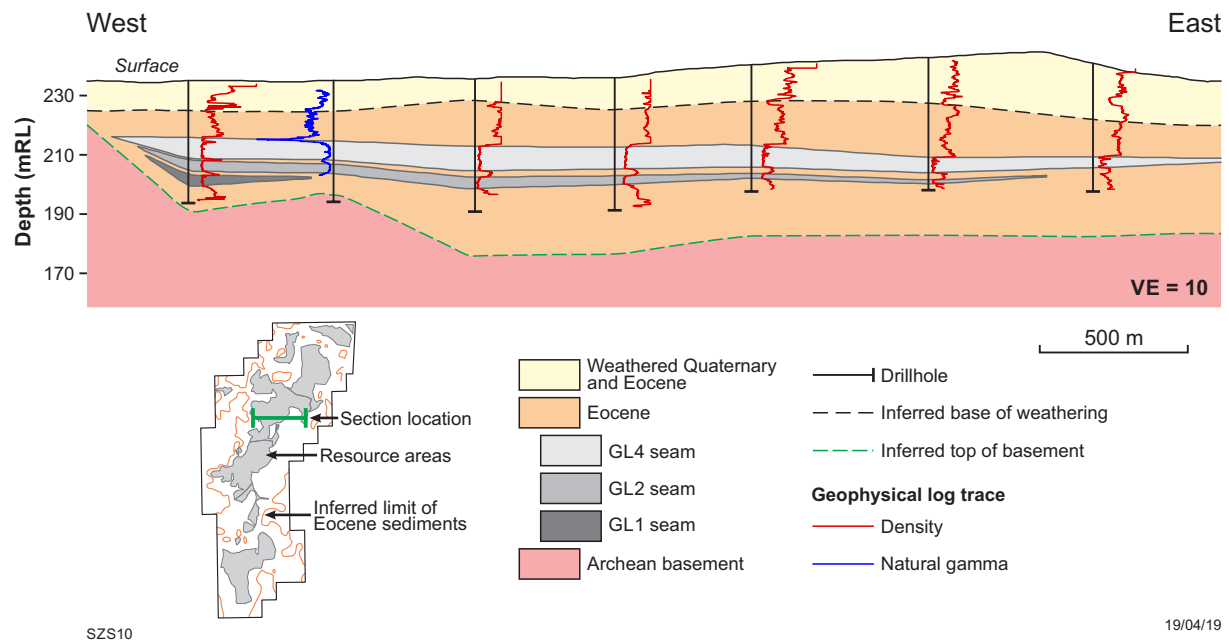


Figure 7. Cross-section through the Salmon Gums lignite deposit showing coal stratigraphy and downhole geophysical logs (Arndt, 2009). Abbreviation: mRL, reduced level above or below sea level, in metres

The liptinite maceral group may comprise up to 10% of the organic matter, with sporinite, cutinite, resinite and suberinite occurring in varying proportions. Suberinite may comprise up to 50% of the liptinite, although sporinite and cutinite are dominant elsewhere. Inertinite macerals are common but not abundant, and are dominated by sclerotinite with macrinite and fusinite also noted. Apart from quartz and pyrite, the main mineral matter is clay minerals and phyllosilicates, sulfides, halite and gypsum, which are intimately associated, and generally interstitial, with organic matter. Pyrite and quartz make up approximately 5% of the coal (Western Collieries Ltd and Mokey Pty Ltd, 1987).

The lignite appears to have two types of occurrence: D1, which is lignite, and D2, which is interbedded carbonaceous or lignitic claystone and lignite. Both types can be present up to 10 m thick. The upper part of this lignite sequence, commonly lignitic claystone, may be a separate stratigraphic unit above the lignite (Miles, 2012b; Lipple and Wadley, 2009). Marine green clays are sporadically present in the sediments above the lignite. Overlying the marine sediments are sand, silt and clay beds up to about 20 m thickness. The post-Eocene sediments, mainly sand, minor silt and clay with scattered salt lake deposits, are thin, in the range of 0–5 m (Miles, 2012b; Lipple and Wadley, 2009).

The Scaddan deposit was discovered in 1980 by Western Collieries, during their regional search for oil shale (Western Collieries Ltd, 1987). By the end of 1982, a large lignite resource had been delineated within the project area, which totalled 614.8 Mt of in situ lignite in what they termed the ‘measured category’ and a further 760 Mt in their ‘inferred category’ (Chapman, 1982). Western Collieries reported that the lignite was fairly well gelified with a high ash and salt content, contained in seams up to 10 m thick with 20–40 m of overburden (Western Collieries Ltd and Mokey Pty Ltd, 1987).

Drilling for brown coal in the Scaddan area, undertaken in the early 1980s by CRA Exploration, resulted in a potential lignite resource of 100 Mt, delineated from three holes which intersected a lignite seam ranging in thickness from 3.50 to 10.0 m (Muggeridge, 1981). The average Fischer oil yield was 87.0 L/t and the average ash content (db) was 32.3% (Muggeridge, 1981).

In 2005, Wesfarmers Premier Coal Limited calculated a Measured coal Resource of 487 Mt at 18% ash cut-off, an Inferred coal Resource of 181 Mt at 18% ash cut-off, and 193 Mt of Inventory coal (Inferred) at 20% ash cut-off (Chapman, 2006). This was revised in 2008, in accordance with the JORC Code (2004), to 700 Mt of brown coal based on a 60% moisture basis and an approximate relative density of 1.2 (310 Mt in the Indicated category, 390 Mt in the Inferred category and an additional non-JORC 200–300 Mt of Inventory coal; Horn, 2009).

Blackham Resources Limited updated the resource details in 2010 to a total of 860 Mt (40 Mt as Measured, 460 Mt as Indicated and 360 Mt as Inferred). Following the completion of further drilling programs, an upgraded resource and geological model was completed in June 2011. Under this model, a total of 1.04 Gt was estimated in accordance with the 2004 JORC Code (80 Mt as Measured, 490 Mt as Indicated, 470 Mt as Inferred), with 200–320 Mt as non-JORC inventory coal (Miles, 2012a). The estimated lignite qualities are listed in Table 5.

In 2007–08, Lignite Pty Ltd explored for lignite in subsidiary branches on the flank of the main paleochannel that hosts the Scaddan lignite deposit (Lipple and Wadley, 2009). Lignite in this area was up to 11 m thick, with 20–40 m overburden (Lipple and Wadley, 2009). An independent assessment by CSA Global for Lignite Pty Ltd suggested that the total resource potential for this target would be in the range of 50–100 Mt, with a possible upper limit of 200 Mt (Lipple and Wadley, 2009).

Table 4. Summary of lignite quality of core from each area of the Salmon Gums deposit (indicative best-quality seam for each area at a minimum of 10 m thickness; Arndt, 2009)

Resource block	Seam interval (cumulative thickness) (m)	Seam	Resource class	Average seam thickness (m)	Average relative density	Average ash (% [db])	Average oil yield (LTOM @ 15°C)	Average total moisture (% [ar])	Average volatile matter (% [db])	Area (m ² *10 ³)	Indicated Resource (Mt)	Inferred Resource (Mt)
Far North	>4	GL4	Inferred	7.3	1.20	26.1	107	58.4	41.5	19 173.5		168.2
		GL2	Inferred	0.6	1.23	30.6	102	58.6	38.3	2354.2		1.8
Minshull	>4	GL4	Indicated	7.7	1.21	27.6	123	57.4	42.0	18 472.2	171.6	
		GL4	Indicated	2.6	1.21	26.9	121	57.2	42.1	14 268.2	45	
		GL4	Inferred	6.5	1.20	26.7	114	57.6	41.9	7443.5		58.1
		GL2	Inferred	1.8	1.20	25.2	126	57.6	42.6	2156.1		4.6
		GL1	Inferred	1.0	1.21					1452		1.7
Collison	>4	GL4	Indicated	8.5	1.22	29.2	107	53.5	39.6	16 349.1	169.4	
		GL2	Indicated	2.0	1.22	29.8	119	50.6	40.2	8310.8	20.1	
		GL4	Inferred	6.3	1.22	29.1	111	55.0	40.0	4277.9		32.8
		GL2	Inferred	1.3	1.23	31.2	124	51.7	40.3	1721.5		2.8
		GL1	Inferred	1.0	1.21					940.6		1.2
Pixie	>4	GL4	Inferred	7.1	1.20	25.2	128	53.3	42.4	21 616.1		183.2
		GL2	Inferred	1.3	1.23	31.2	115	52.3	39.6	9146.4		14.9
Total											406.1	~470

Note: Abbreviations: ar, as received; db, dry basis; LTOM, L/t at 0% moisture

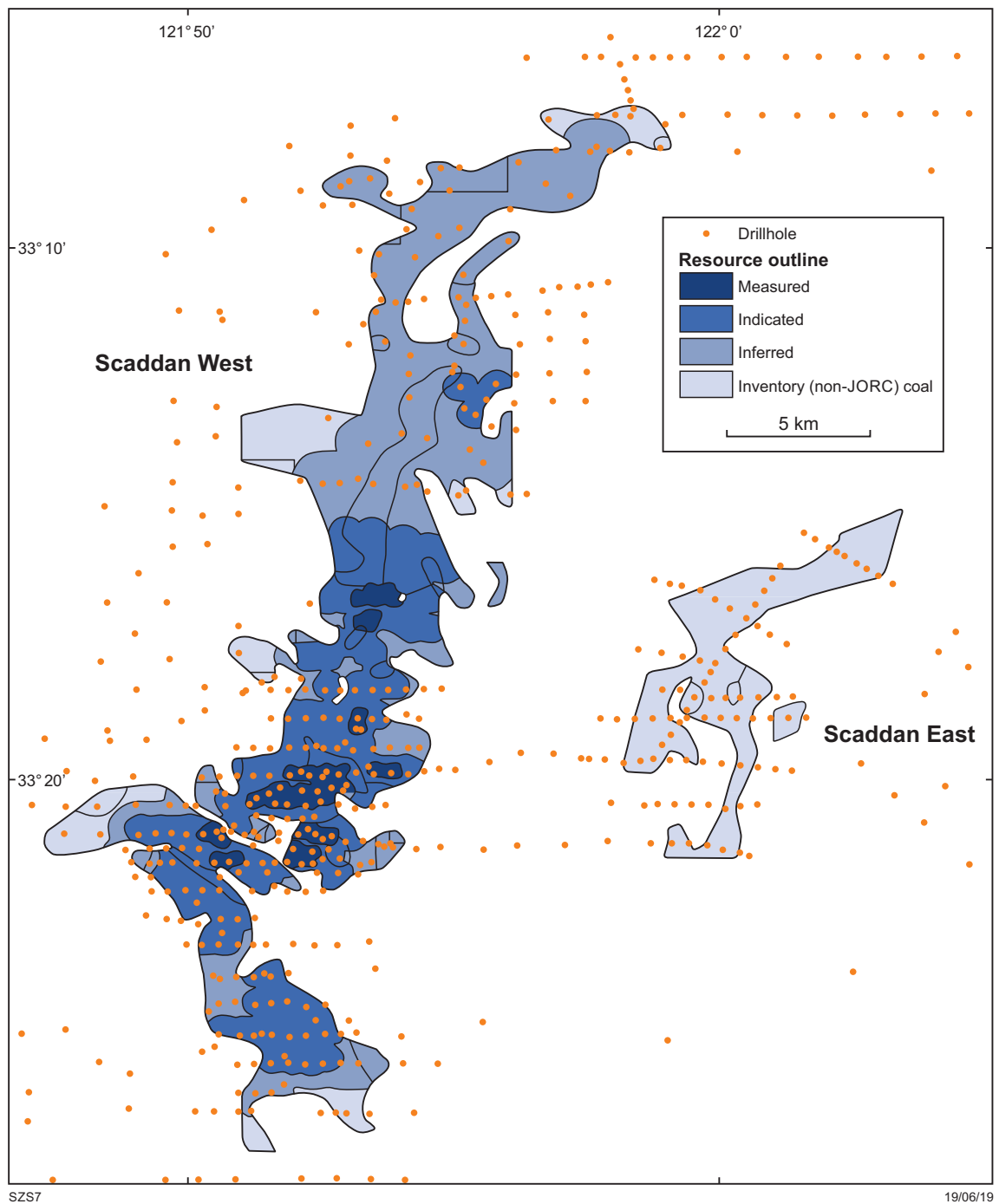
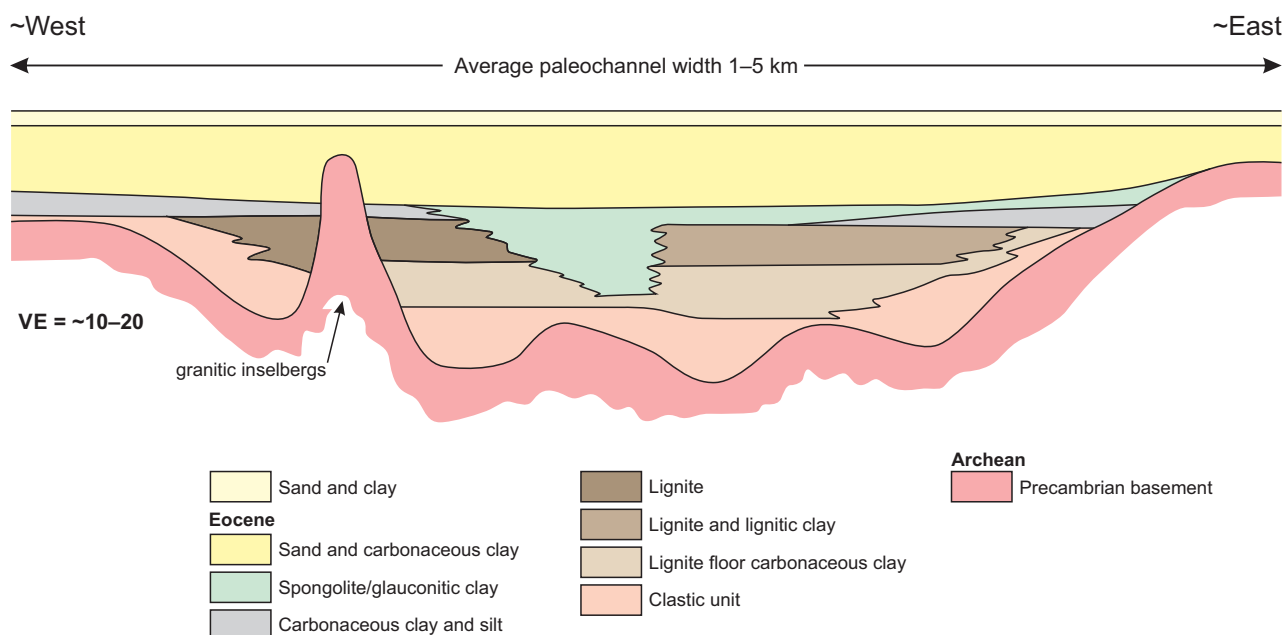


Figure 8. JORC-compliant resource outline and drillhole locations at Blackham Resources' Scaddan lignite deposit (Blackham Resources Limited, 2011)

Table 5. Estimated lignite quality at specified moisture basis for the Scaddan deposit (Blackham Resources Limited, 2011)

Deposit	Moisture basis (%)	Ash (%)	Volatile (%)	Fixed carbon (%)	Total sulfur (%)	Specific energy (MJ/kg)
Scaddan	56	14.3	17.0	12.8	2.2	7.9



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Figure 9. Schematic cross-section through the Scaddan lignite deposit, showing the stratigraphic units and rock relationships (Lipple and Wadley, 2009)



Figure 10. Typical portion of lignite core showing a fracture along the bedding plane and plant fossils, including a leaf impression and wood fragments (Detheridge, 2011a)

In 2009, Bronzewing Gold Ltd drilled 32 holes to test ground east of the main deposit, which at the time was held by Blackham Resources. In this area, the lignite has a large clay and sand component and sits on well-developed basement saprolite up to 20 m thick. Drilling from this program identified two 'lignite-like' seams; an upper seam typically 4 m thick between 6–14 m deep and a thicker lower seam between 4 and 10 m thick from 15 to 25 m deep (Ryall, 2010). Composite samples from 31 holes showed approximately 50% moisture, 60% ash and a dry calorific value of 9.9 MJ/kg (wet calorific values of 4.9 MJ/kg; Ryall, 2010).

Grass Patch

In 1981, Centamin Ltd intersected significant intervals of shallow, dry, finely granulated brown coal in six drillholes on the northeastern fringe of the main Scaddan deposit, near the town of Grass Patch (Centamin Ltd, 1981; Fig. 11). The seam ranged in thickness from 2 to 7 m. Only two lignite samples were analysed and showed moisture of 21.8 and 27.3% as analysed basis, ash content of 15.9% and 20.2% as analysed basis, and specific energy on a dry ash-free (daf) basis of 24 and 26.34 MJ/kg, respectively (Centamin Ltd, 1981; Lipple and Wadley, 2009).

In 2000–01, as part of later exploration for zinc, lead and silver mineralization in the area by BHP, Eocene carbonaceous to lignitic clay and sand, often with thin bands of pure lignite, were intersected immediately above the unconformity with the basement (White, 2001; Fig. 12).

In 2010, Blackham Resources completed a small exploration program over the Grass Patch area, with results indicating that the western portion has no major paleochannels and is barren of lignite. The lignite was considered more likely to be striking in a northerly or northeasterly orientation from the main Scaddan lignite resource into the area. Regional digital terrain modelling also shows that the western portion of the area is topographically higher than the eastern portion, which is more likely to host paleochannels of significant depth (Blackham Resources Limited, 2010).

Zanthus

The Zanthus prospect is located approximately 150 km east of Norseman and covers part of the western margin of the Eucla Basin (Fig. 4). The lignite is confined to one or more southwest–northeast trending paleochannels that shallow to the southwest and are traversed by drainage channels

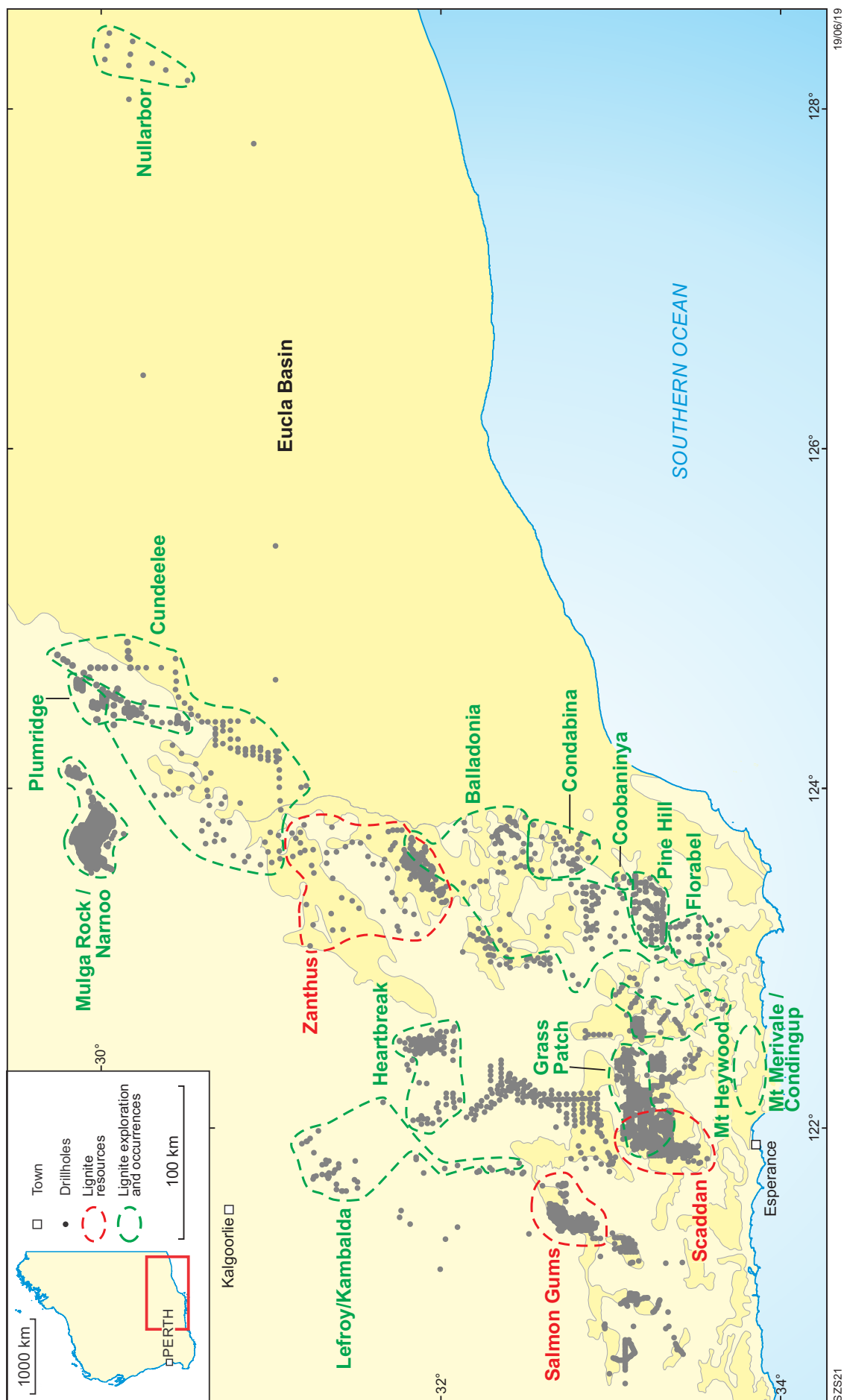


Figure 11. Distribution of lignite resources and occurrences on the eastern side of the study area, over 1:500 000 tectonic units (modified after GSWA, 2017)

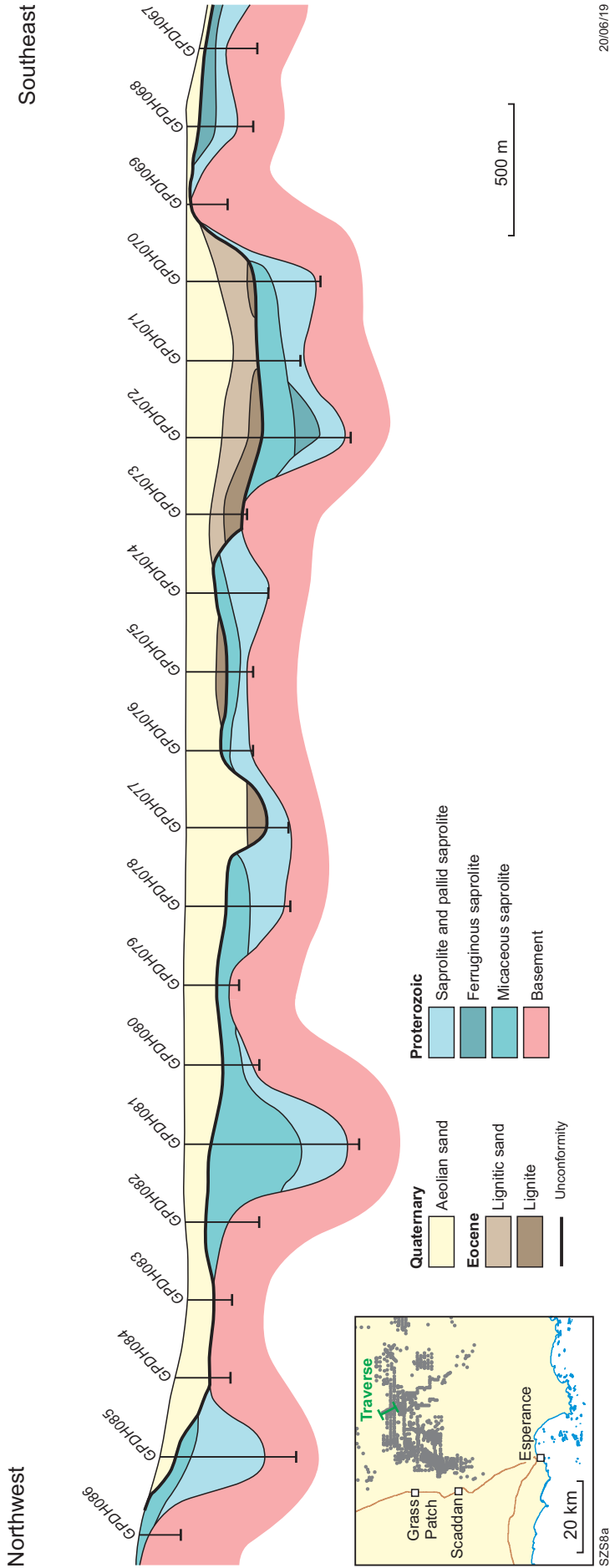


Figure 12. Schematic cross-section of a traverse through the Grass Patch area by BHP in 2000–01, showing lignite in the paleochannel and rock relationships (White, 2001)

that cut through the lignite body in places (Denman and Fewster, 1982b). The basement is generally shallow, being about 40 m below the surface.

The lignite occurs as a single sinuous body over 30 km long, 400–1000 m wide and up to 15 m thick. It lies 15–20 m below the surface in the southwest, and up to 50 m deep in the northeast (Reindler, 1990; Fewster, 1990). The full seam has an average thickness of 10 to 13 m and includes lignite, clayey lignite and lignitic banded claystone. The lignite component of the deposit is usually 4–6 m thick, although it can be up to 12 m thick.

The quality of the lignite varies laterally throughout the deposit and vertically through the seam, and is related to the different depositional environments. Middleton (1996) proposed that a marginal-marine environment occurred in the northeast of the deposit area and peat accumulation commenced in a partly oxidized forest association, and progressively passed through reducing non-marine conditions to marginal marine and terminated in marine open water. The upstream part of the drainage system accumulated peat in the same sequence but peat deposition was not terminated by the second marine transgression. In this upstream area, the lignite seam is thicker (Middleton, 1996).

The basal unit overlying the Proterozoic Fraser Range Metamorphics consists of 10 m thick, very coarse, upwards-fining sandstone with minor conglomeratic pebble bands and pyritic growths. In the northern part of the deposit area, the basal unit is overlain by a sequence of sands, siltstone and claystone. In the south, the main lignite seam conformably overlies the basal unit. Marine sediments comprising moderately sorted glauconitic sandstones and sporadic calcareous claystones disconformably overlie the fluvial sequence containing the lignitic beds. This Eocene sequence is overlain by Miocene fluvial and marine sediments (Middleton, 1996).

Initially explored by Griffin Coal Mining Company Ltd in 1980–88 for oil shale, a total lignite resource of over 1000 Mt was consequently reported, with 400 Mt having an ash content of less than 30% ([db]; Denman and Fewster, 1984b; Middleton, 1996). The proximate analysis indicates that the coal is relatively low quality with high ash and sulfur contents, with only moderate heating value (Denman and Fewster, 1982b).

Beacon Mining Pty Ltd and Brunswick Oil NL concurrently explored the eastern margin of the Zanthus deposit between 1980 and 1983, both suggesting the presence of several hundred million tonnes of lignite material (Reindler, 1990).

In 1990, C Reindler and Eaglefield Holdings Pty Ltd conducted an exploration program in the Zanthus area to test the potential for a Montan wax resource (Reindler, 1990). Limited oil yield assays on the lignite showed that it is uniformly anomalous in solid hydrocarbon content, likely in the form of Montan wax. One sample yielded a solid hydrocarbon content of approximately 10% ([db]; Reindler, 1990).

In 1990, Sabminco NL acquired the Zanthus prospect, and through further drilling and reinterpretation of the Griffin dataset, calculated an inferred resource of 350 to 500 Mt

of lignite, of which 60–70% had an ash content of less than 30% ([db]; Robinson, 1993). Sabminco also assessed the Montan wax potential of the lignite (Table 6).

In 2005, MBA Petroleum Consultants (Anderson, 2005), commissioned by Renaissance Corporation Pty Ltd, calculated a new in situ Inferred Resource of between 186 and 323 Mt of lignite, according to the JORC Code 2005 [sic], with an ash content of less than 30% ([db]; which they defined as Class 1 lignite). Anderson (2007) estimated the oil content of this Class 1 lignite as between 70–80 L/t average ([db]; 34–40 L/t at 50% moisture). The total Zanthus seam tonnage was calculated to be 772 Mt in situ.

In 2011, Blackham Resources reported an Inferred Resource estimate (JORC Code, 2004) of 350 Mt, and non-JORC Inventory coal of 460–760 Mt for Zanthus (Thom, 2012). These resource estimates are on a 56% moisture basis and approximate relative density of 1.2 (Blackham Resources Limited, 2011).

Blackham Resources concluded that the lignite is discontinuous through the inferred resource zone and that the lignite quality is variable (Table 7). Their best lignite intersection returned 9 m at 17.2% ash ([db]; Detheridge, 2011b).

Cundeelee

The Cundeelee deposit is located northeast of the Zanthus deposit (Fig. 11). The Cretaceous Madura Formation contains some rare, local, highly carbonaceous beds that gave low oil yields (Denman and Fewster, 1982a). In the area tested by CRA Exploration, a thin veneer of upper Eocene fluviochannel and lacustrine sedimentary rocks, including sandstone, siltstone and claystone, were present. CRA Exploration notes that no marine sedimentary material was observed (Rickards, 1982b).

Between 1977 and 1979, AFMECO Pty Ltd conducted drilling for uranium mineralization in the Cundeelee area and some holes were reported to have intersected lignite and black claystone (Rickards, 1982b). Griffin and CRA Exploration completed a significant amount of drilling for coal in the Cundeelee area between 1981 and 1984. The majority of the Griffin drillholes did not contain any carbonaceous material and no coal was intersected (Denman, 1981); however, CRA Exploration intersected two lignite horizons in a single hole. One horizon was 31–35 m deep, and the other was 37–50 m deep. The upper horizon was assayed and returned 54% ash and 72 L/t of oil, and the lower horizon returned 39% ash and 147 L/t of oil ([db]; Rickards, 1982b). CRA Exploration calculated a maximum in situ reserve of 48 Mt of lignite based on the single lignite intersection and historic AFMECO drilling results (Rickards, 1982b).

Balladonia

In 1981, Beacon Mining and Brunswick Oil completed a drilling program east of the Zanthus deposit and discovered several million tonnes of lignite material (Beacon Mining Pty Ltd, 1982) (Fig. 11).

Table 6. Montan wax content of lignite at the Zanthus deposit (Robinson, 1993)

<i>Drillhole</i>	<i>Interval (m)</i>	<i>Total moisture (%)</i>	<i>Wax (% [db])</i>	<i>Ash (% [db])</i>
ZNR64	28–33	47.8	3.86	15.9
ZNR65	28–34	46.8	4.29	22.3

Table 7. Estimated lignite quality at specified moisture basis for the Zanthus deposit (Blackham Resources Limited, 2011)

<i>Deposit</i>	<i>Moisture basis (%)</i>	<i>Ash (%)</i>	<i>Volatile (%)</i>	<i>Fixed carbon (%)</i>	<i>Total sulfur (%)</i>	<i>Specific energy (MJ/kg)</i>
Zanthus	50	19.6	18.2	12.3	2.1	7.1

Between 1981 and 1982, Mokey and Western Collieries carried out an extensive drilling program in the Dundas Mineral Field, with one section of the program covering the Balladonia area (Harms Lake, Mount Andrew, Pine Hill, Condabina Tank and Curnadina Rock areas). They recorded thin, low-quality lignite, which is poorly developed at the base of the succession, over shallow basement (Western Collieries Ltd, 1982). In 1982, CRA Exploration completed a drilling program in three areas within 20 km of the Balladonia Hotel. The area to the northeast contains only minor lignite, but the areas to the south and southeast contain relatively thick (average seam thickness of 6 m) but deep (average overburden thickness of 50 m) lignite (Fig. 13) that extends over an area of 100 km² (Parker, 1982b). The lignite from areas around Balladonia have a range in total moisture from 43 to 68%, ash ranging from 21 to 51% (db) and an oil yield ranging from 68 to 200 L/t (daf; Parker, 1982b). Other minor occurrences of lignite in the region were limited in thickness and extent or too deep to warrant further evaluation.

In 2008, Heron Resources Limited and Epsilon Energy Limited undertook a drilling program near Balladonia for lignite and mineral sands. One drillhole (BLAC20) intersected 15 m of lignite and analysis showed that total moisture ranges between 20 and 48% (ar), ash between 33 and 89% (ad), and volatile matter between 9 and 34% (ad; Eddison, 2009). A modified Fischer Assay was also conducted on a single sample of this lignite and reported an oil yield of 89.1 LTOM (L/t at 0% moisture) at 15°C (Table 8).

Table 8. Modified Fischer Assay for lignite sample 357072 from drillhole BLAC20, Balladonia area (Eddison, 2009)

<i>Analysis</i>	<i>Sample 357072</i>
Free moisture (%)	13.8
Total water, mass (%)	5.0
Oil, mass (%)	8.1
Spent shale, mass (%)	78.6
Gas + loss, mass (%)	8.4
Oil density (g/mL @ 15°C)	0.9538
Oil yield (LTOM @ 15°C)	89.1

Lignite intersections 1–6 m thick have been encountered at a depth of 56–80 m (Shelverton, 2007). The lignite seams are overlain by a predominantly marine sequence of white, yellow, red and blue-grey clays and sandy clays of the Werillup Formation, which are commonly oxidized and up to 28 m in thickness. The lignite deposits are lenticular in one dimension and may also be discontinuous along strike or parallel to the dendritic fluvial channels. The top of the lignite is subhorizontal, whilst the base generally conforms to the basement topography. The lignite itself is well gelified and contains abundant woody fragments. The colour varies from pale to medium brown, which probably reflects a moderate to high proportion of liptinite in the lignite (Eddison, 2009).

Heartbreak

CRA Exploration conducted an exploration program for brown coal at prospects Heartbreak 1 to 4, approximately 50 km east of Norseman (Fig. 11) between 1980 and 1981 (Ferguson, 1982a,b). Their analysis of the lignite at Heartbreak 1, 2 and 3 showed approximately 50–60% moisture, an average oil yield of 90 L/t with a range of 38–159 L/t (db) and an ash content of approximately 40–50% ([db]; Ferguson, 1982b). The thickness of the coal seam is less than 10 m and depth to basement varies from 0 to 81 m (Ferguson, 1982b). Heartbreak 2 and 3 were determined to have lignite in shallow, discontinuous irregular paleochannels. The lignite seams are thin, sporadic and of poor quality (Rickards, 1986b,c). Lignite intervals at Heartbreak 4 average 5 m thick, with an ash content of approximately 55% (db) and an oil yield ranging from 15 to 73 L/t ([db]; Ferguson, 1982a).

In 1982, CRA Exploration completed exploration at Heartbreak 7, where lignite seams up to 15 m thick were intersected below 3–60 m of overburden, and an in situ reserve of 200 Mt of lignite was calculated with oil yields up to 240 L/t ([db]; Ellis, 1982a). This estimate was based on an average lignite thickness of 10 m in two drillholes, and the assumption that this total seam thickness is developed over one-third of the paleochannel. Heartbreak 9 was also explored by CRA Exploration in 1982 and significant seams of lignite up to 9 m thick were intersected (Fig. 14). A possible resource of 700 Mt was estimated for this area. Oil yield was determined to be up to

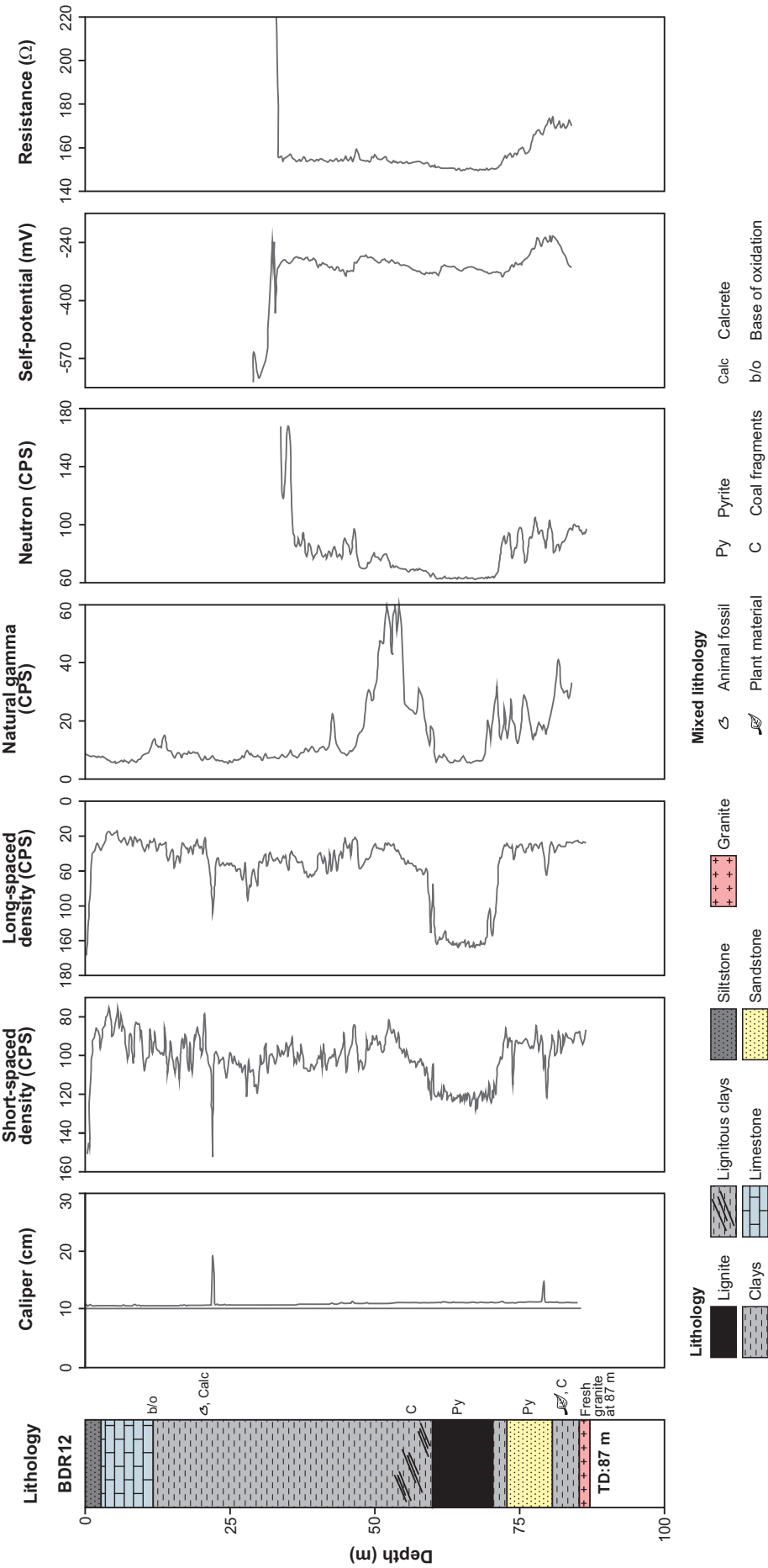


Figure 13. Example of a downhole geophysical log from the Balladonia area, showing caliper, short-spaced density, long-spaced density, natural gamma, neutron, self-potential and resistance with lithology (Parker, 1982b). Abbreviation: CPS, counts per second

115 L/t (Rickards, 1982a). CRA Exploration also drilled at Heartbreak 5 and 6; however, only thin, high-ash lignitious clay bands were observed (Parker, 1982c).

In 1983, CRA Exploration calculated a total in situ inferred resource of 2500 Mt for Heartbreak 1, 2 and 3, of which 860 Mt were determined to be superior quality at a 1:1 overburden ratio (Ellis, 1983).

At Heartbreak 1, CRA Exploration identified two areas of lignite development that contain 30 Mt of inferred coal reserves and 115 Mt of inferior lignite (Ellis, 1984b). The lignite in this area is up to 12 m thick and occurs at shallow depths; however, better quality lignite seams are less than 5 m thick (Ellis, 1984b). Oil yield at Heartbreak 1 is low, averaging 41 L/t ([db]; Ellis, 1984b). Heartbreak 2 and 3 had a maximum seam thickness of 36 m, with the lignite having high moisture, salt and ash, a low specific energy of 6.65 MJ/kg and a moderately high oil yield of 116 L/t ([db]; Ellis, 1984a). Although the coal quality is low at Heartbreak 2 and 3, with an average ash content of about 30% (db), total moisture of 57% (Ellis, 1984a) and high sodium, chlorine and sulfur contents, a reserve was estimated at approximately 900 Mt (Ellis, 1985a). In 1985, CRA Exploration reviewed the Heartbreak 2 and 3 lignite deposit and reduced the reserve figure to 480 Mt of better quality lignite (Rickards, 1986a).

CRA Exploration highlighted a distinct difference in the petrographic composition of the lignite between the northern and southern parts of the Heartbreak 2 and 3 deposits; the coal in the south has a higher liptinite content and high atomic hydrogen/carbon ratios, and the coal in the

north has lower chlorine, sulfur and mineral matter content (Kristensen, 1993). These observations are consistent with the concept of the deposit resulting from a northwards marine transgression (Kristensen, 1993). Despite the perhydrous nature of the coal, the lignite has low oil yields with an aromatic rather than aliphatic composition (Kristensen, 1993).

In 1984, CRA exploration determined that Heartbreak 9 has higher quality lignites than other deposits in the area with lower moisture (43–53%), high specific energy (9.9 MJ/kg) and high oil yields (167 L/t), but has a higher overburden ratio than the rest of the main deposit (Ellis, 1984c). Two areas of lignite development were recognized to contain inferred coal reserves of 128 Mt (Ellis, 1984c). In 1985, CRA Exploration reported that Heartbreak 9 lignite deposit thins rapidly to the east and becomes interbedded with clays. The resource was downgraded to an estimated 70 Mt at a 3.5:1 overburden ratio (Ellis, 1985b).

In 1999, Kaiser Engineers were commissioned by Heron Resources NL to complete a desktop scoping study on limited historic data for the Balladonia oil shale project (Kaiser Engineers, 2005). The area covered Heartbreak 1, 2, 3, 4, 7 and 9 and they reported a total of 649 Mt of lignite and an average of 116 L/t for this area (Perger, 2005).

The lignite deposit trends north–south through a 50 km paleochannel underlain by the steep undulating topography of the Archean Yilgarn Craton. The lignite deposits are lenticular in one direction and can be discontinuous along strike or parallel to dendritic fluvial channels (Perger, 2005). Ellis (1985b) suggests that that lignite was deposited

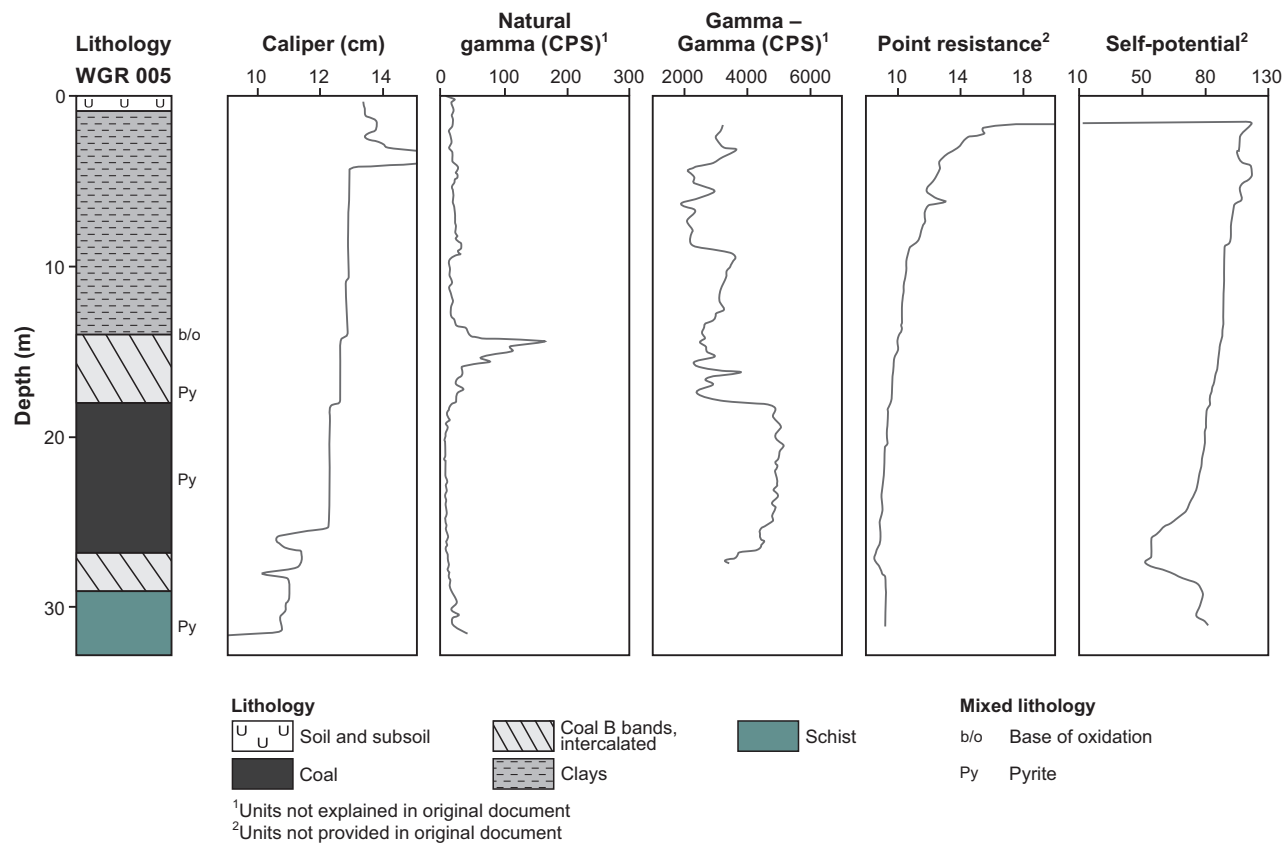


Figure 14. Example of a downhole geophysical log at Heartbreak 9 showing natural gamma, gamma, point resistance, self-potential and caliper with lithology (modified after Rickards, 1982a)

in a drowned fluvial system strongly controlled by the north–south trending alignment of the resistant Archean metamorphic rocks. This resulted in subhorizontal lignite beds conformable with the marine overburden sediment, but unconformable at the base (Ellis, 1985b). Although the deposits are discontinuous, the seam plies are isochronous and correlatable between channel-like sub-basins separated by ‘islands’ of Archean rock. The lignite horizon at Heartbreak consists of upper and lower plies which split, diverge and thin to the east (Ellis, 1985b). The lignite is well gelified and the colour varies from pale to medium brown (Perger, 2005).

The Werillup Formation overlies the basement in this area and consists of thin basal sands on which lignite and carbonaceous clays, and foraminiferal clayey sandstones developed. The Pallinup Formation conformably overlies the Werillup Formation and comprises mainly silts, clays and calcareous sediments with bryozoan calcarenites developed in thin bands near the top. The middle Miocene Nullarbor Limestone unconformably overlies the Pallinup Formation siltstone and is a white, unfossiliferous, amorphous limestone between 5 and 20 m thick (Rickards, 1982a; Ellis, 1982a).

Lefroy/Kambalda

From 1980 to 1981, Western Collieries explored for oil shale in a number of paleochannels near Lake Lefroy, discovering large thicknesses of high oil-yielding sediments (Fig. 11). Two holes intersected significant lignite, with one hole intersecting 22 m of lignite yielding 88 L/t of oil and some samples from this hole exceeding 120 L/t. The other hole intersected 13 m of lignite and yielded 46 L/t. The lignite was intersected at depths between 20 and 35 m, and the lignite seam comprises lignite, sub-lignite, lignitic clays and carbonaceous clays. Ash is high at 44–66% and specific energies are low at 11.2 – 5.3 MJ/kg (Green, 1982).

Using several Western Mining Corporation Limited gold and nickel exploration drillholes that intersected lignite, Clarke (1993) later described in detail the stratigraphy of Lakes Lefroy, Cowan and Dundas, and their adjacent areas; however, no further studies were done on the lignite.

Condabina, Coobaninya and Florabel

A total of three lignite occurrences are located or in close vicinity to, Mount Coobaninya, from north to south: Condabina, Coobaninya and Florabel, respectively (Fig. 11). Paleochannels in the Condabina, Coobaninya and Florabel areas comprise the middle to late Eocene, dominantly argillaceous, lacustrine Werillup Formation; the younger, upper Eocene marine Pallinup Formation siltstone; and the middle Miocene Nullarbor Limestone (Eddison, 2009).

The Werillup Formation at Florabel comprises highly carbonaceous siltstones and claystone often containing lignite seams (Muggeridge and Parker, 1981). This is overlain by the Pallinup Formation, which is dominantly marine, highly fossiliferous and consists of highly glauconitic siltstones, claystone, calcarenites, calcilutites and crystalline limestones, with minor beds

of carbonaceous material. Fine-grained, well-rounded quartz sandstones also occur with occasional spongolites (Muggeridge and Parker, 1981).

At Condabina, the Werillup Formation consists of carbonaceous argillaceous sediments, minor quartz sandstone and lignite, and is generally less than 20 m thick. Conformably overlying the Werillup Formation is the Pallinup Formation (referred to as Pallinup siltstone in Rickards, 1982c), which consists exclusively of marine, highly fossiliferous calcareous sediments. The sediments are highly glauconitic siltstone, claystone, calcarenite, calcilutite and lesser crystalline limestone (Rickards, 1982c). The Pallinup Formation is about 50 m thick in this area. Unconformably overlying the Pallinup Formation is the middle Miocene Nullarbor Limestone, which is a pale grey, hard, laminated crystalline limestone with indistinct fossils (Rickards, 1982c).

The Werillup Formation at Coobaninya comprises interbedded clays and quartz sands overlain by a carbonaceous interval. The clays and quartz sand beds vary between 1 and 6 m in thickness and grade into the carbonaceous material, which ranges from lignitous clay to lignite (Parker, 1982a). The formation varies from 2 to 23 m in thickness, and the thickest lignite intersection without a major parting is 6 m. The lignite grades into a predominantly marine sequence considered to be the Pallinup Formation (referred to in the text as the Pallinup siltstone equivalent). It is up to 45 m thick and graduates from grey–green, highly glauconitic silty clays and sands into a fossiliferous and glauconitic limestone with coquina layers. Unconformably overlying the Pallinup Formation is the Miocene Nullarbor Limestone, which consists of up to 7 m of yellow-white or red, oxidized, silty clays with amorphous white limestone chips that passes upwards into a 5–12 m-thick hard, white, amorphous crystalline limestone with no fossils (Parker, 1982a).

Between 1981 and 1983, CRA Exploration encountered lignite at Condabina, 20 km south of Balladonia. A ‘reserve’ estimate of 1000 Mt of low-grade lignite was outlined with a high overburden ratio of 5:1 (Fitton, 1984b). The lignite seam was reported to be between 1 and 10 m thick, with an average of 6 m thick down to a depth of 85 m and extending over an area of 100 km² (Parker, 1982b; Rickards, 1982c). Compared to other lignite in the general Esperance region, the Condabina deposit has a relatively low salt content, moderate ash content of approximately 30% ash (db) and relatively high oil yield (Fitton, 1984b). The average gross dry specific energy of the Condabina coal is 21.7 MJ/kg and average oil yield by modified Fischer Assays is 158 L/t (Fitton, 1984b).

Four exploration holes were drilled at Coobaninya in 1981 by CRA Exploration (Parker, 1982a). One drillhole (MCR004) revealed a 6 m-thick lignite seam at a depth of 67 m within the Werillup Formation. Subsequently, a resource of 270 Mt of lignite was estimated; however, the lignite is low grade and has an average overburden ratio of 7:1 (Fitton, 1984a). The lignite from Coobaninya has relatively low ash (23% [db]), salt levels and high oil yield (161 L/t) compared to other lignites in the general Esperance area (Parker, 1982a; Fitton, 1984a). A specific energy of 21.8 MJ/kg was reported by CRA Exploration (Fitton, 1984a), which suggested that Mount Coobaninya deposit was possibly an extension of the Florabel deposit to the southwest.

In 1981, exploration drillholes by CRA Exploration in the Florabel area intersected a huminite-rich brown coal seam of averaging 7 m thick (maximum thickness of 11 m) at depths of 50–55 m just above the basement. The coal seam is reported to contain about 50% moisture, approximately 25% ash, approximately 44% volatiles and have a specific energy of 22 MJ/kg ([db]; Muggeridge and Parker, 1981; Fitton, 1984c). CRA Exploration reported oil yields of up to 78 L/t (average 50 L/t); however, this was from only one drillhole (Parker, 1981; Fitton, 1984c). A resource potential for the Florabel deposit was calculated to be 650 Mt (Muggeridge and Parker, 1981), based on the assumption of continuity of the coal seam between their widely spaced drillholes.

Pine Hill

The Pine Hill area lies between Mount Coobaninya and Condabina Tank (Fig. 11). Drilling in the area was completed between 1980 and 1982 by Western Collieries, who reported the presence of thin, low-quality, poorly developed lignite in the Werillup Formation (Western Collieries Ltd, 1982). The Werillup Formation in the Pine Hill area consists of basal sand, thin lignite and lignitic and carbonaceous clays. The overlying Pallinup Formation is 50–80 m thick and consists of glauconitic fossiliferous clays and siltstones and white–yellow limestone with minor interbedded clay (Lippie and Ellis, 1994).

Mount Merivale / Condingup

The area between Mount Merivale and Condingup Peak (Fig. 11) is named ‘Esperance’ by Elms et al. (1995), who described a typical sedimentary sequence in this area as consisting of a ‘laterite capping up to 1.5 m thick overlying the Pallinup Formation, which is up to 80 m thick and consists largely of siltstone with (fossiliferous, glauconitic, micaceous) sandstone, marl-limestone and minor conglomerate. This rests unconformably on basement or on a thin Werillup Formation sequence, typically consisting of 4–5 m of lignite, carbonaceous siltstone and sandstone, and pyritic fossiliferous sandstone.’ There are no drillhole data from this area held in GSWA databases to support these geological observations, and Elms et al. (1995) do not provide information on the source for this statement.

Mount Heywood

Between 1982 and 1984, Griffin conducted a small exploration program confirming that a minor Eocene paleochannel, probably a tributary to a more major system, existed between Mount Heywood and Mount Beaumont (Fig. 11). As no true lignite was intersected in this paleochannel, with only minor lignitic material intersected west and south of Mount Beaumont, it was concluded that the paleochannel was not sufficient in depth or width to host a significant lignite deposit (Denman and Fewster, 1984a).

Western Collieries later conducted an exploration program about 20 km north of Mount Heywood, reporting that they intersected lignite up to 4.5 m thick (referred to as Mount Hey in Elms, 1981; Elms et al., 1995); however, GSWA has

no record of this drilling. The Pallinup Formation in this area is generally between 0 and 10 m thick; however, one Western Collieries hole found up to 20 m of sand, silt and glauconitic clay directly over basement (Elms et al., 1995). The underlying Werillup Formation includes lignite as well as carbonaceous sand and clay with a coarse basal sand accumulation (Elms et al., 1995) and is up to 12 m thick (Elms, 1981; Ellis, 1981c; Elms et al., 1995).

Nullarbor

In 1982, CRA Exploration (Ellis, 1982b) drilled nine boreholes within a paleochannel (Fig. 11). Only one of these drillholes intersected channel coal or oil shale, between 77 and 80 m depth. Analysis of the 3 m intersection averaged 56% total moisture, 54% ash and oil yields of 79–113 L/t ([db]; Ellis, 1982b).

Plumridge

Plumridge Gold Pty Ltd explored for lignitic coal approximately 250 km east of Kalgoorlie (Fig. 11); however, exploration drilling in the area did not intersect any lignite (Du and Schwertfeger, 2012; Wilson, 2013).

Lake Muir

In 1981, BHP drilled two scout holes in the Lake Muir area (Fig. 15), of which one hole showed 4.25 m of lignite (Bunting and Sharples, 1982). A further six holes were drilled, and three of these encountered several lignite horizons interbedded with carbonaceous clays up to 5 m thick. Fischer Assays gave oil yields of up to 75 L/t and proximate analysis indicated that the lignite is poor quality with high ash, low specific energy, and a moisture range of about 30–50% (Bunting and Sharples, 1982). The lignite and lignitic clay were intersected at depths of about 25–30 m. BHP noted that the potential lateral extent of the lignite is very small and confined by surrounding granite hills, although there may be several similar small deposits (Bunting and Sharples, 1982). The paleochannel in this area is partly filled with a late Eocene sequence of sands, clays and carbonaceous units up to 70 m thick and underlain by Precambrian basement (Bunting and Sharples, 1982).

Green Range / Manypeaks

BHP drilled seven holes in the Manypeaks area in 1981, where the sediments are in excess of 100 m thick and infill the deep valleys between granite outcrops (Fig. 15). Only occasional thin (<1.2 m) lignite bands were intersected at the base of the carbonaceous clay, which mostly occurred between 80 and 100 m depth (Westblade, 1982). Analysis of these lignite bands showed 42–43% moisture, >10% ash, <12 MJ/kg of specific energy (ad), and oil yields of up to 60 L/t (Westblade, 1982).

CRA Exploration carried out coal exploration in the northern Green Range area in 1981, and intersected coal over a strike length of 20 km (Ellis, 1981c; Wolstencroft, 2001). All of the holes drilled in the Green Range area intersected lignite 0.2 – 5.7 m thick (Ellis, 1981d). The lignite has a high moisture content (average 57.8%),

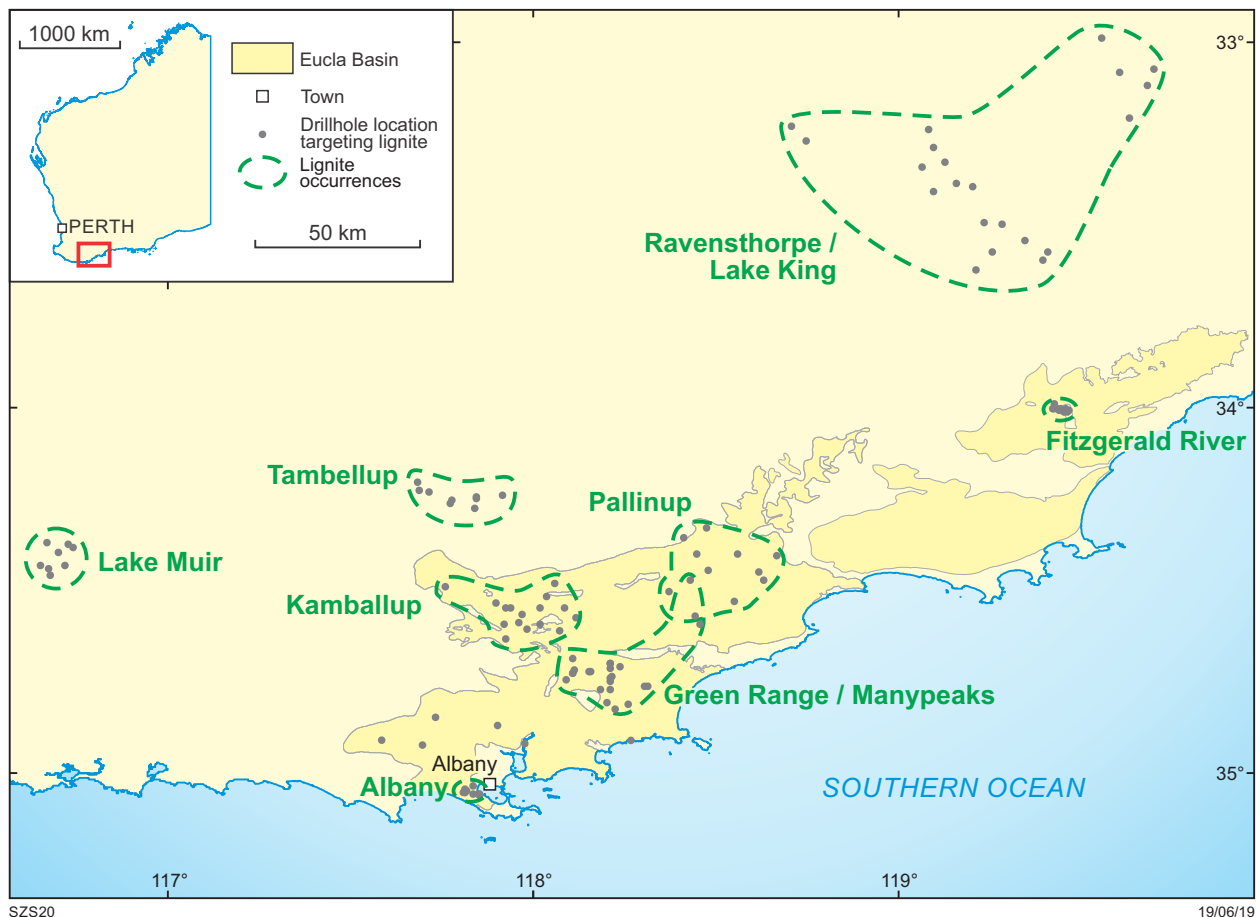


Figure 15. Distribution of lignite occurrences on the western side of the study area, over 1:500 000 tectonic units (modified after GSWA, 2017)

a medium ash content (18.6% [db]), low specific energy (average 6.5 MJ/kg) and low to average oil yields (66 L/t [db]; Wolstencroft, 2001). CRA Exploration subsequently estimated an inferred in situ reserve of 1000 Mt (Ellis, 1981d). In 1983, holes were drilled in the western part of Green Range; however, no significant thicknesses of lignite were encountered. A revised 'in situ reserve estimate of up to 500 Mt was inferred at a stripping ratio of 10:1' for this area (Ellis, 1981b,d).

In 2001, Phanerozoic Energy Pty Ltd carried out a small exploration program in the Green Range area consisting of seven drillholes. Coal seams of greater than 1.5 m and up to 5 m were intersected in four of the holes. Phanerozoic Energy noted an increase in depth to basement from north to south across the basin, from 45 m to more than 70 m, and that the coal increases in thickness from north to south. The lignite in the northern part of Green Range is well developed and rests directly on the basement, whereas in the southern area is not well developed and consists of carbonaceous sandstone, siltstone and clay with thin lignite bands that do not rest on the basement. The lignite in the southern area is also reported to be deeper and has a thicker zone of carbonaceous sediment (Table 9; Wolstencroft, 2001). Phanerozoic Energy also tested the lignite for coal seam methane potential; however, the results were too low, with the highest result being 0.05 cubic m/t (Wolstencroft, 2001).

The lignite in this area contains abundant huminite and fusinite (Lipple and Ellis, 1994), and is also abnormally

rich in resinite, the latter occurring as large, precipitated balls up to 3 cm in diameter (Ellis, 1981d). The Werillup Formation, which contains the lignite, generally consists of dark-coloured clay, siltstone and sandstone (Wolstencroft, 2001). It is reported to be up to 46 m thick, with up to 5 m of lignite at the base lying unconformably on kaolinitized granite basement. The lignite is overlain by 5 m of brown, carbonaceous claystone, which is in turn overlain by 36 m of well-sorted sandstone in varying colours (Elms et al., 1995). The Pallinup Formation conformably overlies the Werillup Formation or rests on the Proterozoic basement, is about 30 m thick and consists of white, brown or red siltstone and spongolite (Wolstencroft, 2001).

Pallinup

In 1981, BHP commenced wide-spaced drilling in the Pallinup area in search for oil shale (Fig. 15). Although 4 of the 11 holes drilled in the area intersected shallow basement, the remaining holes intersected carbonaceous intervals 30–50 m thick, with some holes also intersecting thin lignite bands at >50 m depth. Thin lignite bands of 1–2 m thick were intersected near the base of the carbonaceous unit in two holes (Westblade, 1982). One sample from this area was submitted for analysis and showed high water content (42–43%), >10 % ash (unknown basis) and <12 MJ/kg of specific energy ([ad]; Westblade, 1982).

Table 9. Phanerozoic Energy drillhole assay results from the Green Range / Manypeaks area (Wolstencroft, 2001)

Drillhole number	Depth to basement (m)	Significant coal intersections (m)			Specific energy (MJ/kg; gross dry)	H ₂ O (%)	Ash (%)	Volatiles (%)	Fixed carbon (%)
		From	To	Width					
PHGR1A	55.8	no significant coal intersections							
PHGR1B	55.8	no significant coal intersections							
PHGR2	83	80	83	3	16.49	19.1	35.7	43.1	21.2
PHGR3	61.35	no significant coal intersections							
PHGR4	71.25	65	65.6	0.6	12.17	10.4	49.9	28.2	21.9
PHGR4		66.3	71.25	4.95	23.69	13.3	12.7	46.9	40.4
PHGR5	92.85	87.45	88.4	0.95	15.58	14.1	38.5	34.5	27
PHGR5		88.57	91	2.43	14.9	6.9	34.5	37.8	26.2
PHGR5		91.55	92.85	1.3	12.36	13.1	50.1	27.7	22.2
PHGR6	80.15	76.65	78.5	1.85	24.25	13.5	12.1	47.4	40.5

Fitzgerald River

The first analysis of the lignite from the Fitzgerald River area was completed by Simpson (1902) and returned 22% moisture, 37.32% volatiles and 12.84% ash. Cockbain and van de Graaff (1973) later completed a comprehensive investigation of the lignite in this area (Fig. 15), including a 15-hole drilling program, of which two holes intersected lignite at approximately 15 m deep. The lignite occurs in the Werillup Formation, which is overlain by the spongolite-bearing Pallinup Formation and underlain by granite. The Werillup Formation consists of dark brown to black clay, loose sand to friable sandstone and lignite (Cockbain and van de Graaff, 1973). The lignite is 3–4 m thick with an average specific gravity of 1.3. Specific energy ranges from 5.5 to 10.5 MJ/kg and crude oil is 0.3 barrels/t. Moisture is about 50%, volatile matter approximately 20–30%, and ash ranging from 6 to 40% (Cockbain and van de Graaff, 1973). Cockbain and van de Graaff (1973) inferred 1.1 Mt of lignite in this area with a moisture content of 50% and 15 000 t of Montan wax.

Tambellup

Tambellup (also reported as Camel Lake) is located approximately 90 km north of Albany and 20 km northeast of Cranbrook (Fig. 15).

Lignite occurrences in this area were discovered in 1981 during reconnaissance mud rotary drilling by CRA Exploration (Ellis, 1984a,b). Drillhole TRH 1 intersected a 12 m unit of lignite and clay between 13 and 24 m, which had a high ash content (approximately 42.5% [ad]) but moderately high oil yield (75 L/t full Fischer analysis [db]). CRA Exploration estimated a ‘reserve’ of 500 Mt at shallow depths (Ellis, 1981e).

CRA Exploration drilled an additional five holes in 1983, and lignite was intersected in two holes with seams between 14 and 21 m thick, which were of poor quality and interbedded with carbonaceous claystone (Ellis, 1981a). Analysis of the lignite indicated high moisture, ash, sulfur and salt content, and low specific energy and oil yield (Lipple and Ellis, 1994). The best interval returned 43% ash, 13.42 MJ/kg gross specific energy and 87 L/t of oil by

Fischer Assay (db). Subsequently total ‘in situ reserves’ of inferior lignite (35–50% ash) were estimated at 100 Mt (Lipple, 2013; Lipple and Ellis, 1994; Ellis, 1981e).

Although Western Collieries apparently drilled in the area in the early 1980s (Elms, 1981), GSWA (WAMEX) has no record of this drilling. Elms (1981) reports proximate analysis (60% moisture basis) from the Western Collieries drilling of 9.4% ash, 16.3% volatiles, 1.7% sulfur and 4.1% NaCl with 8.5 MJ/kg net specific energy. A resource of over 100 Mt (average seam thickness 7 m and overburden ratio of 1.6:1) was reported by Elms (1981).

Sediments at Tambellup (referred to as Cranbrook in Elms et al., 1995) occur in a shallow east–west oriented meandering channel approximately 5 km wide and over 50 km long. The lowermost unit of the Werillup Formation is a coarse, unsorted, unlithified sand of fluvial origin. Overlying this is a unit of lignite and lignitic clay, followed by silty, sandy clay of the Pallinup Formation between 2 and 20 m thick (Elms et al., 1995). The lignite occurs in localized patches within the main channel, and the main deposit has an average thickness of 7.2 m with a depth of cover between 6 to 16 m (Elms et al., 1995).

The interpreted geological cross-section of the Tambellup area (Fig. 16) is based on CRA Exploration 1981 drilling in the area which revealed at least 15 m of Werillup Formation resting on granitic basement and overlain by up to 20 m of sand and clay which may be the Pallinup Formation siltstone (Lipple, 2013).

Kamballup

Silfar Oil and Gas Search Co. drilled petroleum well Kendenup 1 near Kendenup in 1973. No oil or gas was encountered but minor lignite occurred between 52–60 m (Berven, 1974; Morgan, 1994).

In 1981, BHP commenced wide-spaced drilling in the Kamballup area in a search for oil shale (Fig. 15). Of the 15 holes drilled, minor thin lignite bands were observed in two holes, and shallow granite was intersected in six others (Westblade, 1982). Lignite-bearing sediments of the Werillup Formation averaged about 60 m thick; however,

carbonaceous clay intersections in this basin were generally about 10 m thick. The Pallinup Formation siltstone was interpreted to occur at the top of the carbonaceous clays of the Werillup Formation (Westblade, 1982). The coal in this area was suggested to have been deposited in a small cut-off embayment within the larger Eucla basin.

Albany

In 1900, GSWA reported a bore near Albany that intersected about 1 m of low-grade brown coal at a depth of 20 m (Maitland, 1900). Maitland (1900) noted that the hole collapsed before the full seam thickness was recovered. The lignite was described as a dull, sooty black and was compact, soft and friable. Lignite analysis yielded 60% ash, 6.28% water and 18.84% volatile matter.

In 1967, GSWA drilled seven water bores near Albany, each of which intersected a maximum of 8 m of peat (lignite) resting unconformably on the basement and overlain by clays, grey to green pyritic silt with some interbedded, coarse-grained, poorly sorted sand and sandy lignite (Probert, 1968). According to Elms (1981) 'Esso/Eagle' drilled two core holes in 1981 north of Albany and intersected a thick (1.5 m) poor-quality lignite seam separated from the basement by a thick (0.5 m) transitional conglomerate. In 1981, CRA Exploration drilled six holes in the Albany area at Redmond and South Stirling (Fig. 15; Ellis, 1981c). Minor coal horizons were identified in the Werillup Formation in the Redmond area; however, no coal was encountered in the South Stirling area.

The type section for the Werillup Formation is GSWA borehole W3, where it consists of 40 m of grey and black clay, siltstone, sandstone, lignite and carbonaceous siltstone, although the formation reaches a maximum basin-wide thickness of approximately 50 m. In the Albany area, the Pallinup Formation overlies the Werillup Formation and consists of up to 60 m of brown clay and siltstone (Cockbain, 1968).

Lake King

In 1981, Conex Australia NL drilled through significant intersections of lignite in three holes in the area between Salmon Gums and Lake King (Fig. 15), with lignite intersections ranging from 1 to 5 m thick beneath 23–28 m of overburden. The lignite seam is overlain by brown carbonaceous clay ranging from 10 to 16 m thick, and unconformably overlies weathered basement. The proximate analysis (ar) is shown in Table 10 (Earth Energy Resource Consultants, 1981).

In 1982, Western Collieries and Mokey conducted an exploration program in the same area, with several holes intersecting lignite up to 11 m thick. The lignite often sits unconformably on granite basement with dark brown clay as the roof. Lignitic clays and lignitic sands can also be present (Western Collieries Ltd, 1982). Uranex NL report that Griffin drilled 13 auger holes south of Lake Tay and west of Pyramid Lake in search of lignite; however, drillhole locations and corresponding information is unavailable (Robinson, 2010; Haber, 2011).

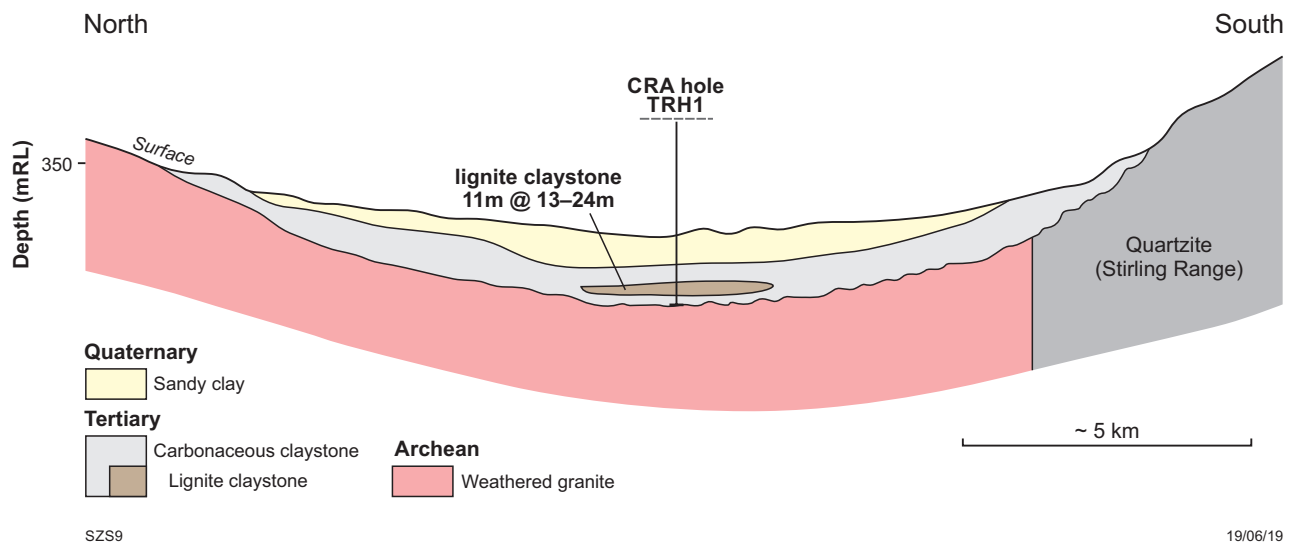


Figure 16. Schematic geological cross-section of the Camel Lake (Tambellup) project area (Lipple, 2013). Abbreviation: CRAE, CRA Exploration

Table 10. Proximate analysis of Lake King lignite drillholes 103A–C from north of Rollands Road for Conex (Earth Energy Resource Consultants, 1981)

Drillhole	Thickness (m)	Moisture (%)	Volatiles (%)	Ash (%)	Fixed carbon (%)	Specific energy (MJ/kg)
103A	5	41.15	24.11	19.39	15.27	9.14
103B	1	55.09	21.85	9.14	13.91	8.86
103C	4	38.71	22.72	21.55	17.02	9.38

Uranex in 2008–11 explored for uranium and drilled 18 holes that intersected lignite. One drillhole (BBAC153) intersected lignite between 16 and 25 m. A composite sample from lignite samples from this hole (BBAC153) gave an oil yield of 141 L/t, total moisture of 56%, ash yield of 30.9% (db) and gross dry calorific value of 19 MJ/kg (Table 11; Haber, 2011).

The lignite beds and associated sediments intersected in these drillholes are considered to fall within the Werillup Formation (Earth Energy Resource Consultants, 1981), which consists of dark brown to black clays, loose sands and friable sandstones. The overlying Pallinup Formation consists of pale brown to creamy white spongolite-bearing siltstones.

Ravensthorpe / Lake King

In 1981, Conex drilled two holes in the Lake King / Ravensthorpe area (Fig. 15); however, only brown carbonaceous sands about 20–24 m thick were intersected. CRA Exploration also drilled 19 holes in the area in 1981, but no lignite was intersected.

Mulga Rock / Narnoo

Mulga Rock / Narnoo (Fig. 11) is a uranium-bearing base metal sulfide deposit that also hosted some lignite; however, it is not discussed further as the main commodity is not lignite (Fig. 11).

Summary

Lignite resources in the south of Western Australia occur in paleochannel successions within the onshore part of the western Eucla Basin (Holdgate and Clarke, 2000). They are low rank with a high moisture and ash content, and variable oil yield and specific energy.

One of the first recordings of lignite in area was in 1848, and limited occurrences were noted in the early 1900s. Concentrated exploration for lignite began in the late 1970s to early 1980s, when several companies conducted large-scale drilling programs. More recently, exploration in the late 2000s focused on defining the resources of specific deposits.

Thorough examination of historical exploration for lignite in southeastern Western Australia shows that there are significant lignite deposits that have resource estimates reported according to the JORC Code (2004) — Scaddan, Salmon Gums and Zanthus. Scaddan has a Measured Resource of 80 Mt, an Indicated Resource of 490 Mt and an Inferred Resource of 470 Mt, totalling 1.04 Gt; the Salmon Gums deposit contains Indicated Resources of 406.1 Mt and a further 470 Mt of Inferred Resources; and the Zanthus deposit contains an Inferred Resource of 350 Mt.

Table 11. Results of lignite analyses of composite sample from BBAC153, Lake King area (Haber, 2011)

<i>Proximate analysis</i>		<i>Ultimate analysis (mass % [db])</i>		<i>Calorific value (MJ/kg)</i>	
Total moisture (%)	56.0	Carbon	45.8	Gross dry	19.0
Ash (% [db])	30.9	Hydrogen	4.3	Gross wet	8.4
Volatile matter (% [db])	44.7	Nitrogen	0.33	Net wet	6.7
Fixed carbon (% [db])	24.4	Organic sulfur	6.1		
		Oxygen, by difference	43.5		

<i>Ash composition (%)</i>		<i>Forms of sulfur (% [db])</i>		<i>NaCl content (% [db])</i>	<i>Modified Fischer Assay</i>	
SiO ₂	42.0	Total	6.5	10.4	Free moisture (%)	10.6
Al ₂ O ₃	25.1	Sulfate	0.7		Total water, mass (%)	8.3
Fe ₂ O ₃	5.0	Pyritic	1.8		Oil, mass (%)	12.6
TiO ₂	1.2	Inorganic	2.5		Spent shale, mass (%)	61.6
K ₂ O	0.4	Organic	4.0		Gas + loss, mass (%)	17.5
MgO	6.2				Oil yield (LTOM @ 15°C)	141
Na ₂ O	5.8				Oil density (g/mL @ 15°C)	0.977
CaO	2.0					
SO ₃	7.9					
P ₂ O ₅	0.06					

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