REPORT
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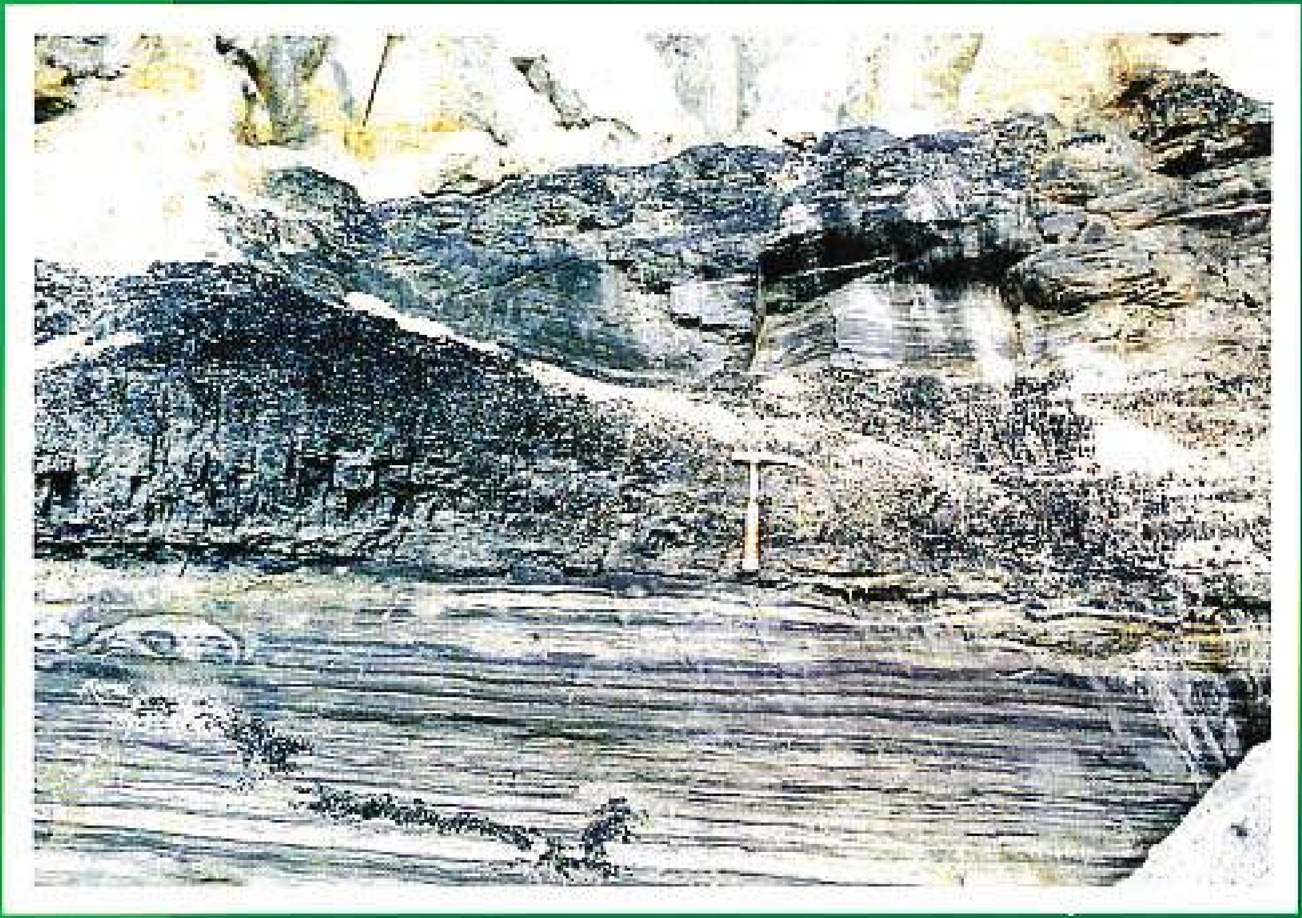
GEOLOGY AND PERMIAN COAL RESOURCES OF THE COLLIE BASIN WESTERN AUSTRALIA

by G. Le Blanc Smith



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 38

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G. Le Blanc Smith

Perth 1993

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Cover photograph:
Muja Coal Measures exposed in Muja Opencut showing Diana Seam underlain by wavy-laminated overbank fines and overlain by white channel-fill sandstone. A lenticular in-seam siltstone channel-fill unit splits the seam above the hammer

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Abstract

The Collie Basin is a fault-bounded, post-depositional pull-apart structure containing approximately 1200 m of generally southwesterly dipping Permian siliciclastics preserved as a consequence of right-lateral shear in a transtensional setting. Gravity and drilling data indicate the basin is 226 km^2 in area and that it comprises two weakly folded grabens striking northwest. The coal-bearing section reaches a maximum thickness of 900 m, of which up to 74 m consist of coal in 60 principal seams between 0.5 and 13 m thick.

Permian stratigraphy is revised: Collie Coal Measures and Stockton Formations are raised to group status; Cardiff, Collieburn and Chicken Creek Members are discarded; new formations include Muja Coal Measures, Allanson Sandstone, Westralia Sandstone, Moorhead and Shotts Formations; the Premier and Ewington Members are raised to the rank of coal measures. Lithostratigraphy is integrated with biostratigraphic palynomorph zones and includes deposits from Permo-Carboniferous to Early Kazanian in the Late Permian.

Significant tectonics in the Permian of Western Australia are inferred from vitrinite reflectance determinations, which indicate that maximum coal-burial depth approached 8 km. A suspected lacuna exists between the Muja Coal Measures and the underlying Premier Coal Measures, coincident with the appearance of *Didecitriletes ericianus* and a jump in vitrinite reflectance from 0.4 to 0.6%. The Permian strata are unconformably overlain by a veneer of Cretaceous (Neocomian) deposits.

The Ewington Coal Measures and underlying sediments constitute a broadly upward-coarsening glaciofluvial and glaciolacustrine deltaic succession that formed in response to climatic amelioration and glacial retreat of the Gondwana ice sheet; this constitutes Permian genetic Sequence 1 (P1). Fluvial to upper delta-plain alluvial coal deposition constitutes the balance of the succession.

Collie coal resources, determined in accordance with the *Australian code for reporting identified coal resources and reserves*, total 2400 Mt. Approximately 37% of the coal lies in the current opencut mining window. Maximum vitrinite reflectance averages 0.43 in the Muja Coal Measures and 0.60 in the deeper Premier and Ewington Coal Measures. On a modified Coded Commercial Classification System the coal *type* is *humic* with a range between code 2 (*vitric*) and code 7 (*inertic*) and reactives constituting up to 80%. The coal rank is (*meta*) *sub-bituminous* in the Muja Coal Measures and crosses the vitrinite reflectance boundary (0.5%) to (*hypo*) *bituminous* in the Ewington and Premier Coal Measures.

Tabulated qualities of Collie coal include proximate and specific energy, sulfur, ash fusion temperature, abrasiveness, Hardgrove grindability, ultimate, ash, trace element, petrographic and maceral analyses. Specific energy is 18.0–22.0 MJ/kg (as received) and 29.0 to 31.9 MJ/kg (dry ash free), moisture content is approximately 25% (ar), ash content is 3–10% (ar), volatile matter is 22–37 % (ar), fixed carbon is 37–50 % (ar) and 54–61% (daf), and sulfur is 0.29–0.49%.

Coal is mined in four opencut and three underground mines by two companies: The Griffin Coal Mining Company Proprietary Limited and Western Collieries Limited. In the past 100 years over 100 Mt has been produced. About 79% of Collie coal is purchased by the State Energy Commission for power stations; the balance is used for private power generation, cement manufacture, brick making, mineral sands processing and other industrial applications. A demonstrated potential exists for alternative coal utilization technologies including direct reduction of metal ores. There are currently no coal exports.

KEYWORDS: Coal, Collie Basin, Permian, Western Australia, stratigraphy, tectonics, sedimentology, resources, mining.

Introduction

The Collie Basin is located in Western Australia approximately 150 kilometres south of Perth, and 60 kilometres east of Bunbury (Fig. 1) and is a concealed, bilobate basin with axial dimensions of approximately 26 km in a northwesterly direction and 15 km across. The basic geometry of the basin was first determined by a gravity survey conducted by the Bureau of Mineral Resources (BMR) and the Geological Survey of Western Australia (GSWA) in 1946 (Lord, 1952a), and knowledge of the internal structure has been progressively refined by subsequent drilling and mining operations (Fig. 2). The Collie Basin comprises two principal grabens that strike northwest (Fig. 3), and in which Permian strata are weakly folded and plunge at a few degrees to the southwest. The sediments form an outlier on crystalline basement rocks of the Archaean Yilgarn Craton. Abundant intrabasinal faults parallel the graben axial trend, and transect low-amplitude folds. These factors have added complexity to the correlating of coal seams and the determination of mineable areas.

A stratigraphic section of approximately 1400 m of faulted Permian sediments is preserved, of which close to 1000 m is coal-bearing. The sedimentary succession contains about 60 significant, named coal seams (Fig. 4). Palynological work has identified that many seams have several names, depending on location, largely as a result of resource-block faulting. These seams range from 15 m to a few centimetres thick and are variably split into as many as 240 sub-seams and splits. The maximum cumulative coal thickness is 76 metres.

Coal fragments found in the bed of the Collie River led to the discovery of the basin and coalfield in 1883 by George Marsh and Arthur Perren. Following this discovery a number of small mining operations commenced and the town of Collie was founded. In 1991, the coalfield produced approximately 5 Mt of coal from six mines and a total of 100 Mt of coal has been produced to date (Fig. 5). Coal resources in situ are currently assessed at 2400 Mt and appear sufficient for domestic requirements for the foreseeable future.

In Western Australia the coal requirements are domestic, and presently serviced only by Collie coal. Collie coal was used principally for steam-raising on the railways in the early years. However, current applications are focused largely upon combustion, primarily to raise steam for electricity generation although subordinate applications include cement manufacture and mineral processing. Sub-bituminous and bituminous black coal is currently extracted from both opencut and underground operations. The Griffin Coal Mining Company Proprietary Limited (GCM) and Western Collieries Limited (WCL) operate collieries in the Basin.

Collie coal is categorized according to composition and end-usage. Coal characteristics are standardized under emerging international classification systems which integrate reporting, classification and utilization potential. Vitrinite reflectance values range from 0.41% at the top of the succession to 0.61% at the base; this characterizes the coal as transitional from sub-bituminous to bituminous. Using the modified Universal Classification for solid fuel, Collie coal *type* is *humic* and between code 2 (*vitric*) and code 7 (*inertic*); the coal rank is *(hypo) bituminous* in the Ewington and Premier Coal Measures and crosses the boundary (0.5%) to *(meta) sub-bituminous* in the Muja Coal Measures.

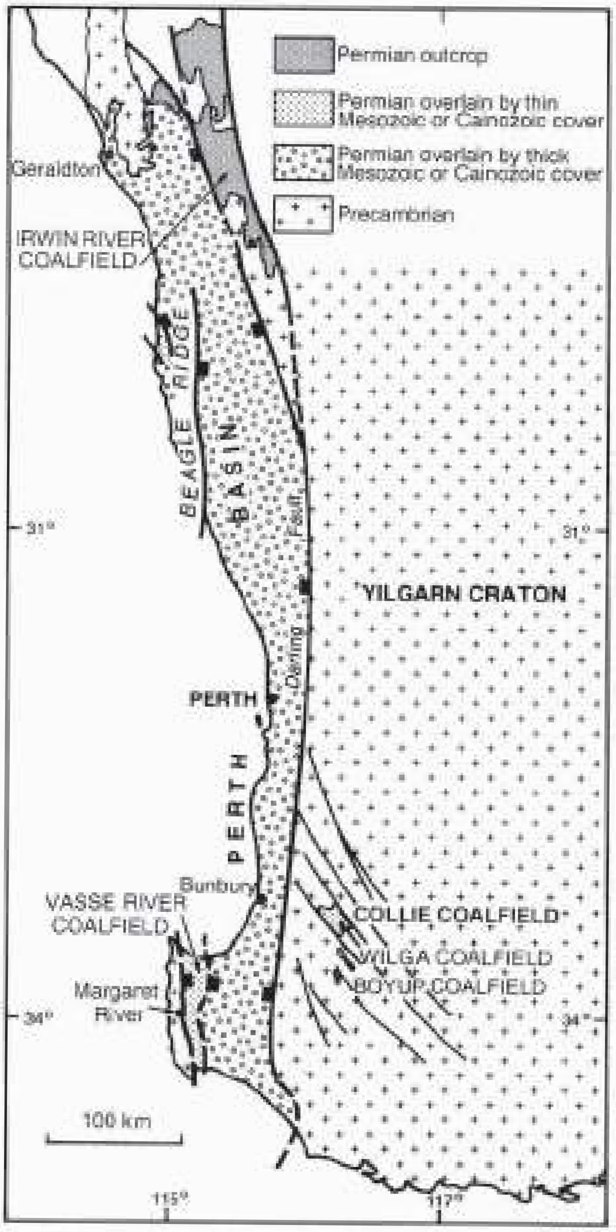


Figure 1. Location map of Collie Basin and Permian sediments at shallow depth in southwestern Western Australia

Exploration

Active exploitation of the Coalfield started in 1898. To date some thousands of drillholes have been bored to various depths within the coal-bearing strata. Many of

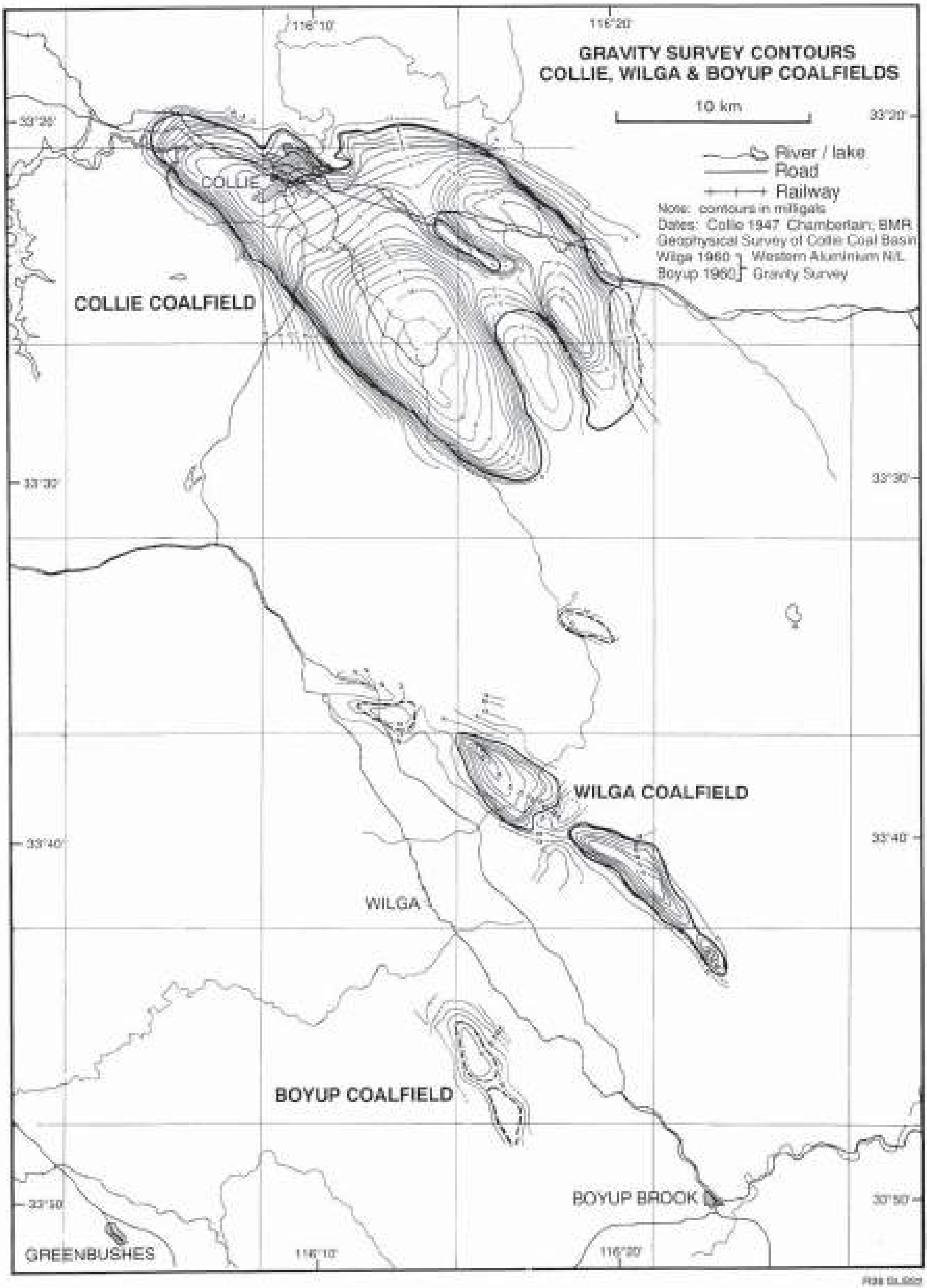
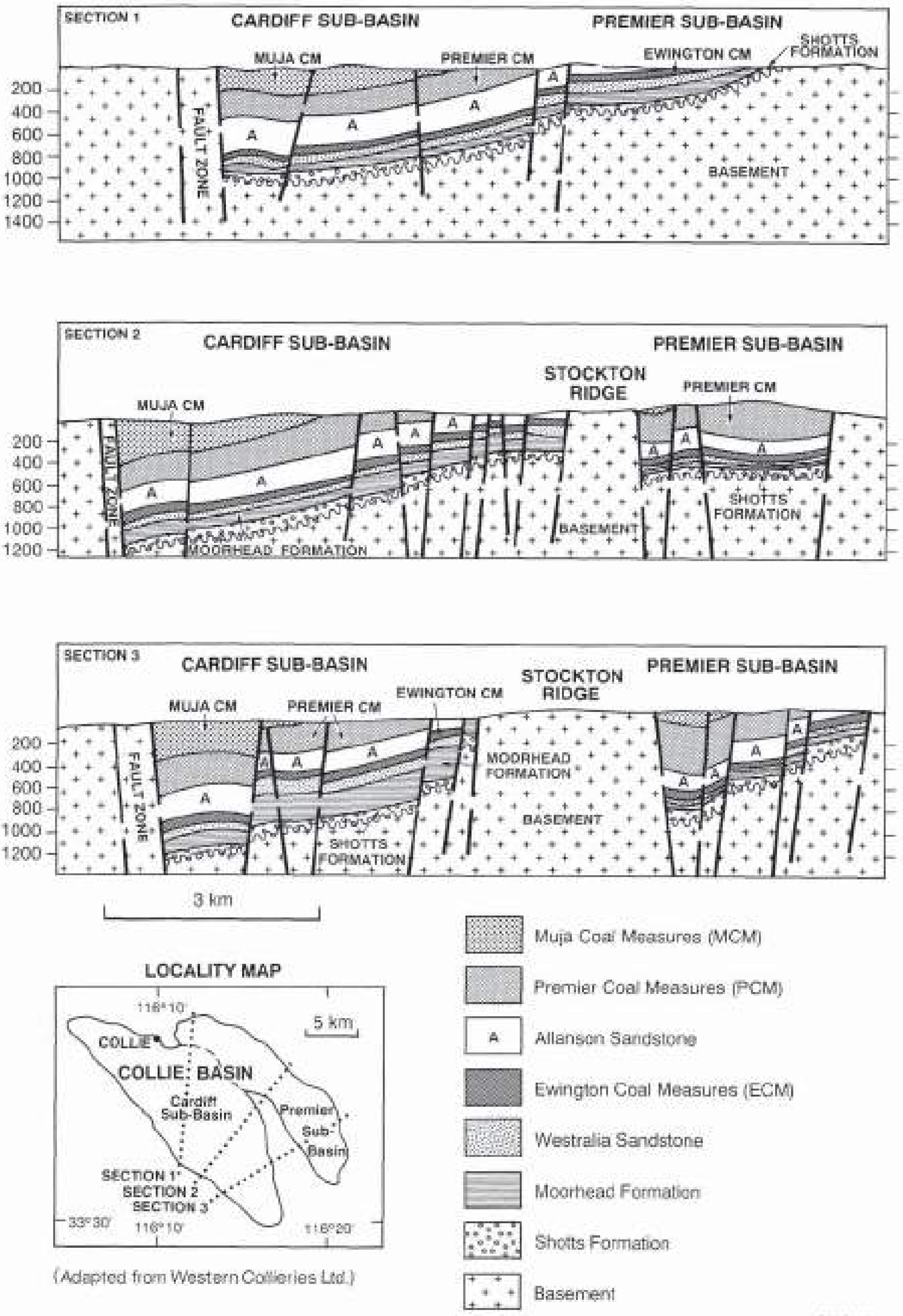


Figure 2. Location map of principal gravity anomalies; Collie, Wilga, and Boyup Basins



(Adapted from Western Collieries Ltd.)

Figure 3. Schematic structural cross sections through the Collie Basin

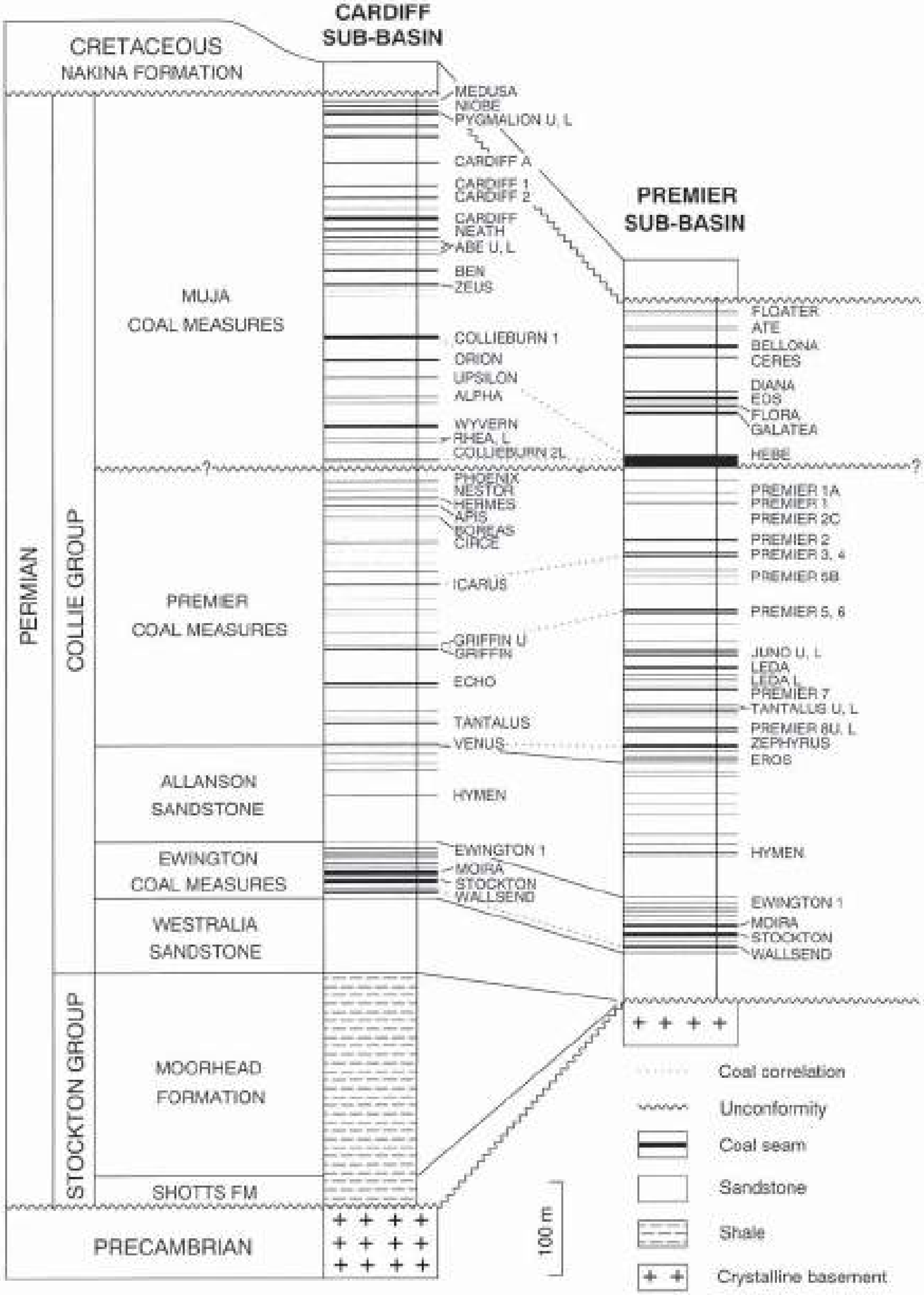


Figure 4. Principal coal seams and stratigraphy of the Collie Basin

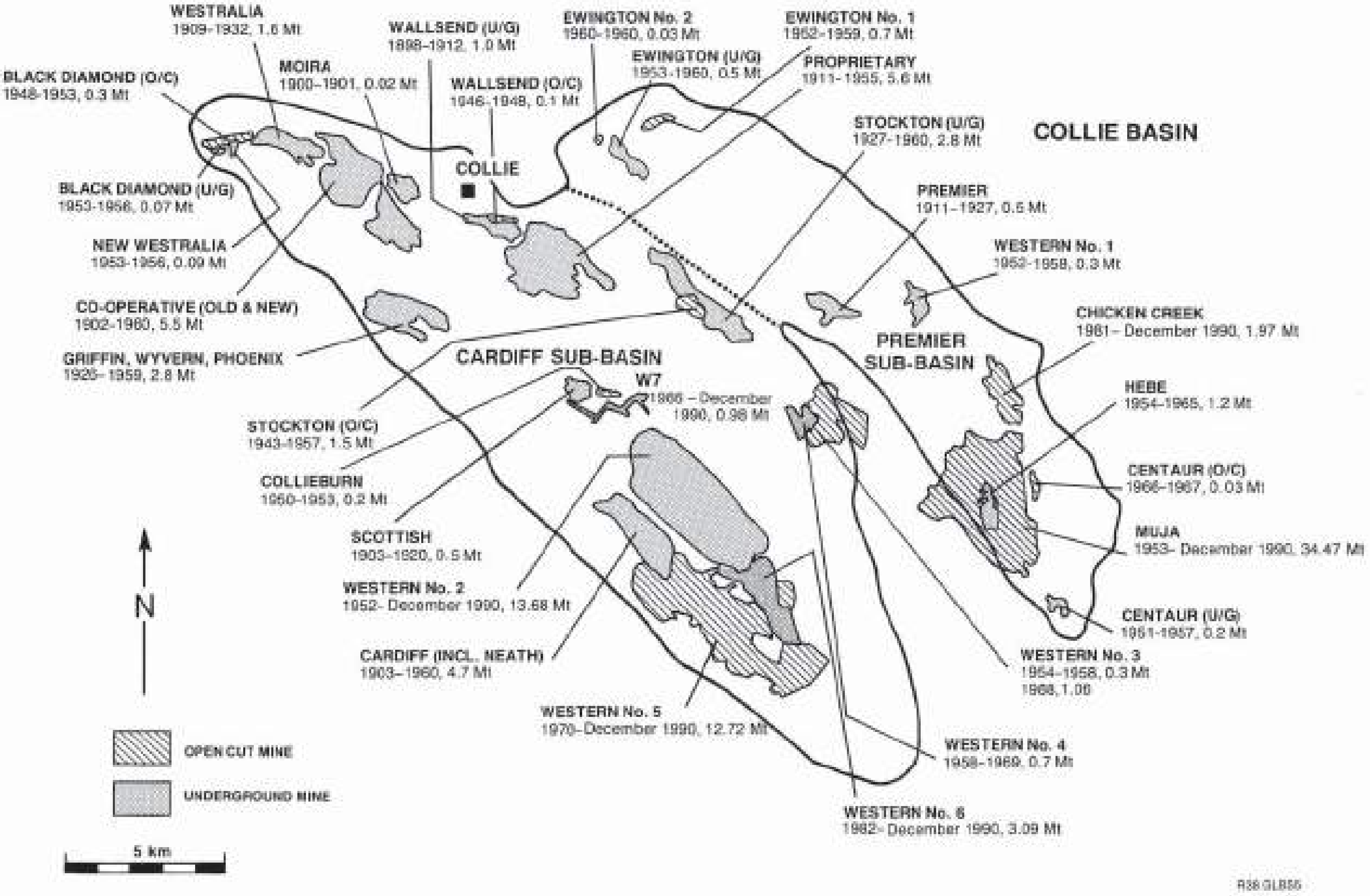


Figure 5. Map of minesites in the Collie Basin and their respective total coal production (by colliery) to 1990

these boreholes achieved very poor recoveries and were neither adequately surveyed nor unambiguously named. This has rendered many of the early data practically worthless. The high frequency of faulting and the presence of up to 240 seams and sub-seams within the succession make resource evaluation difficult. The coal seams lie at depths varying from the surface to over 900 metres. Substantial areas remain unexplored and unevaluated, particularly at depth, and the margins of the coalfield remain to be accurately defined. Most exploration has been based on drilling. Limited attempts have been made recently to apply high-resolution seismic and radar imaging techniques to resolve seam discontinuities.

History of exploration

A comprehensive overview of the historical development of the Collie Coalfield has been compiled by Stedman (1988). The history of coal exploration around Collie, and the geology, were discussed by Lord (1952a) and Ashton (1988) and the following outline is based on these accounts.

The 1880s: Coal was first discovered in the Collie Coalfield by George Marsh and Arthur Perren in 1883 in the bed of the Collie River. Subsequently, Messrs Hay and Dixon acquired large leases in the name of the Mineral Prospecting Machinery Co. and commenced active exploration of the prospective coalfield. The first success was the discovery of a coal seam in a pool on the Collie River. This was sampled by diving. The first public announcement of the coal discovery was in 1889 by Sir Frederick Broome at an exhibition burning, in Bunbury, of one ton of coal.

The 1890s: The initial phases of exploration work centred around the sinking of shafts near the Collie River coal intersection. The most successful intersection (of a 3.35 m seam) occurred upstream and on the south bank of the river. The Collie Commercial Coal Company was formed in May 1890 to exploit this discovery, but seam discontinuities curtailed these efforts.

The Government, encouraged by these early results, sent Harry Page Woodward to inspect the coalfield; this was the first official inspection of the coalfield by a qualified geologist. Woodward made a most encouraging appraisal, stating '...that this will be an extensive and important field in the future...' (Woodward, 1891). The saturated conditions of the sediments effectively precluded shaft-based exploration and Woodward recommended drilling as the most suitable exploration method. The coal quality was found to be suitable for furnace combustion, with low ash and an absence of clinker and slag formation.

In 1891, the Government sought to corroborate Woodward's findings and contracted Dr James Robertson for this task because of his experience in the New South Wales coalfields. Robertson was able to convince the Government that Woodward was accurate in his assessment of the coalfield's potential and that drilling was required for effective exploration.

Drilling by hand auger was implemented in 1892 under the guidance of W.B. Pendleton, a mining engineer and colliery manager with English and Australian experience. A program of 18 holes of 10 cm diameter was completed by 1893, with a total of 550 m of drilling. The bores were sited mainly around the coal subcrop and ranged in depth from 6 to 76 m.

Woodward mapped the basin boundary, on horseback, in 1892. Approximately 35.5 km of the basin boundary were defined before heavy rain and horsefeed problems curtailed the program.

The first coal bulk sample was raised from a small shaft in May 1893. This 16 tonne sample was successfully tested in the first official train to run on the newly constructed Perth–Bunbury railway. Under Pendleton's supervision, a 72.8 m drift was then excavated from which a further 169 tonnes of hard coal were produced with the assistance of blasting. This coal was found to be of high quality and the site was subsequently developed into the Government Mine.

In August of 1894, the first assessment of both the areal extent and extractable coal reserves was made by Woodward in conjunction with W.T. Atkinson, a coal-mining expert. They arrived at estimates of 259 km^2 and 1280 Mt respectively (Atkinson, 1894).

By 1895, the Government Mine had extended underground to a distance of 305 m and to a depth of 54 m (Woodward, 1896). This continued mining success led to the proclamation of the Coal Mining District on 20 February 1896 and open selection as of 23 March 1896. A total of 42 leases was granted in the vicinity of the Government Mine, over an area of 57 km^2 (Fig. 6). Logistical difficulties precluded significant development on these leases (Woodward, 1896). In 1897 the settlement of Collie was proclaimed a township. One year later the railway arrived at Collie as a spur to the Perth–Bunbury line. The railway was not only the major link between the Collie Coalfield and its markets, but became a major consumer of Collie coal for many decades.

Mining had stagnated by the end of 1898 and several mines closed. The Government decided to lease the Government Mine and the tender was won in April 1898 by Mr H.M. Deakin. He re-equipped the winder plant, pumped out the shaft and workings, and was in production within a month. The mine was renamed the Wallsend Mine, a name which survives to the present day.

The success of the Wallsend Mine operations contributed to a resurgence of activity by competitors in 1899. These operations included the Proprietary Company starting mine development, and the West Collie Company acquiring leases over the Westralia, Collieburn and Colliegrove areas. Active drilling and prospecting over these leases was rewarded by the intersection of a mineable seam 1.6 km to the west of Collie. Exploration at this time was being conducted by the Collie Trust on 4 leases to the south of Collie. Extensive drilling on 13 leases by the Collie Boulder Company put them in a position to commence development in the Collieburn area. In 1900 shallow mineable coal was discovered south of the Collie Boulder leases, and exploration was concentrated in this direction.

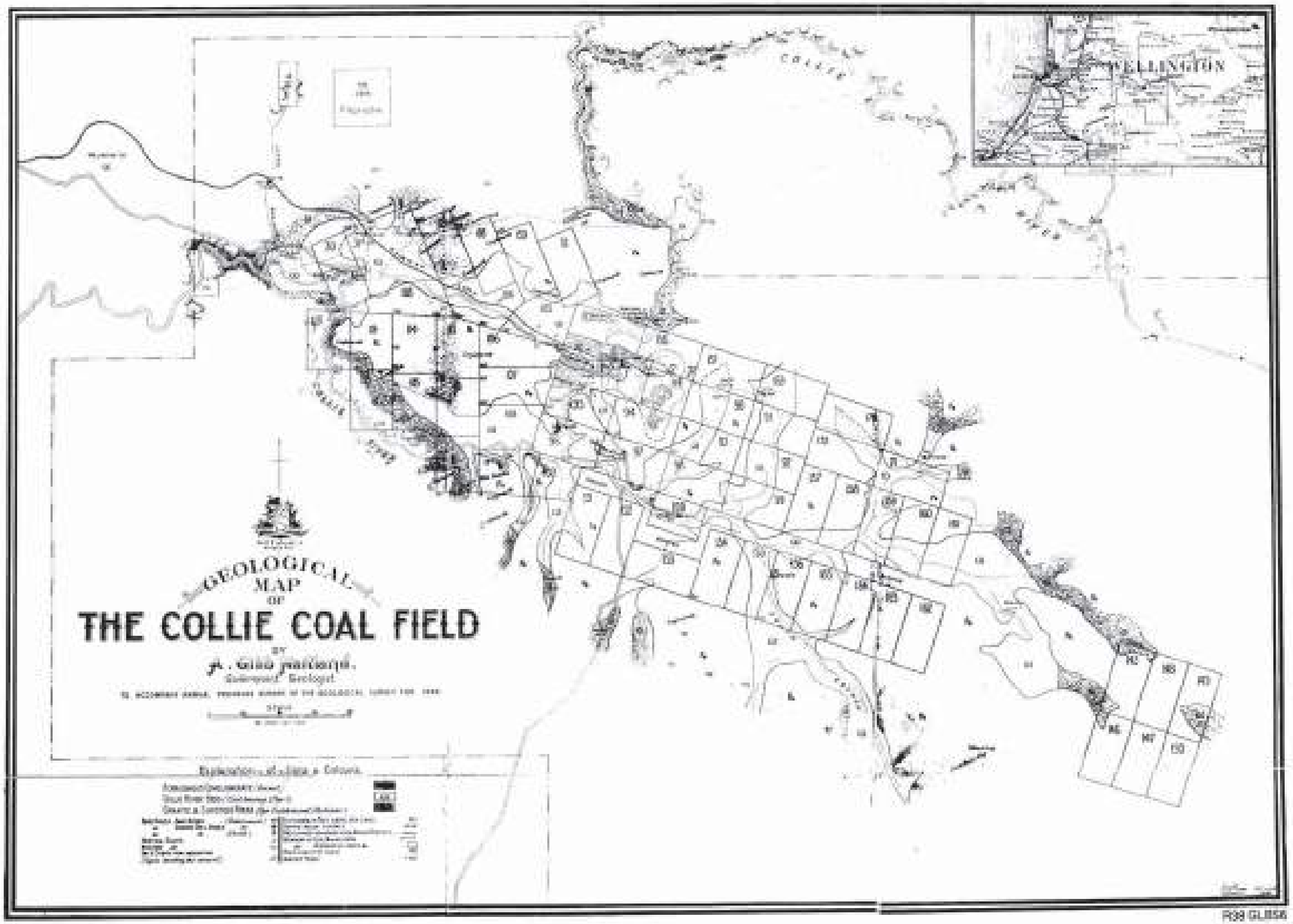


Figure 6. An 1899 map by Maitland of the proclaimed Collie coal mining district and tenements

The Early 1900s: In 1900 the Government published its first public summary of the geological and mining activities in the Collie Coalfield (Gee, 1900). Production had increased to 120 305 t by 1900. The Government-owned railways became the major consumer of Western Australian coal, despite railway officials' preference for imported, higher quality coal from New South Wales. This pattern of Government purchases commenced in 1901 when the first coal contract was granted to Wallsend Proprietary Company to supply 20 320 tonnes of coal annually for two years. This contract became the landmark of coal and energy policy with the Government becoming an active participant in supporting the local industry.

The Moira Colliery was forced to close in 1901 as a consequence of unprofitable operations. Exploration continued nonetheless on leases 70, 82 and 105 with calyx core drilling and hand boring. Ashton (1988) notes how close this exploration came to discovering the deposit exploited by the current Western No. 2 Colliery: 'The calyx bore on lease 82, drilled by W. D. Bedlington, sinker of the first shaft in Collie, was a little north of the current Western No. 2 workings and so just failed to identify the Wyvern Seam. The hole intersected 5.75 feet of weathered Wyvern coal which appeared not to have prompted further investigation. Fifty years passed before this area became of interest again'.

Further Government involvement with the fledgling coal industry occurred in 1901 with the establishment of the first Royal Commission into the Western Australian coal industry. The Collie coal miners initiated a strike in 1901 with the aim of increasing the hewing rate of coal from 4/- to 4/6 per tonne. The Coal Owners Association opposed the increase, stating that before hewing rates could be increased, the Government price for coal would have to increase from 9/7 to 14/- per tonne. The investigation by the Royal Commission was completed in a few weeks and its most significant finding was that the three coal-mining companies operating in the Collie Coalfield were running at a loss, with production costs higher than the Government coal price. Acting on this finding, the price of coal was increased to 13/- per tonne and the hewing rate was increased to 4/6 per tonne.

Attempts to improve logistics got underway in 1902, with the Collie Boulder Company undertaking development of a branch rail line to its workings in the Collieburn No.2 Seam. The Cardiff Coal Mining Company started access development into the 3 m thick Cardiff Seam. Production at both these sites commenced in 1903, with exploratory drilling continuing into 1904 when the first analytical information on the coal was published (Simpson, 1903).

Dr R. Logan Jack was appointed Royal Commissioner in 1905 to: 'undertake an investigation into all aspects of the Collie Coal Industry including geological considerations, working mines, transport to Perth and to the Goldfields, storage and economic use of the product, particularly in comparison with imported coal, on the Government railways'. The findings of this commission were reported in full in the newspaper as well as being published by the Government Printer (Jack, 1905). The commission was comprehensive, collating geological information, palaeontology, quality, origin and structure. The structural observations were most significant, indicating a faulted margin to the west and undisturbed northern and southeastern margins.

Controversy surrounded the age of the coal deposit. Etheridge (1891) worked on three small samples and determined the presence of *Glossopteris* or *Noeggerathia* fragments, indicative of a 'true Palaeozoic coal'. However, additional coal samples supplied in 1894 to Etheridge were interpreted as Mesozoic. This was apparently confirmed when *Sagenopteris* was wrongly identified in subsequent samples from the Moira, Cardiff and Collieburn areas. Later research by Chapman (1907) finally resolved the age as Permo-Carboniferous.

Extensive exploration was undertaken in 1907 under the direction of W. D. Bedlington, the manager of the Proprietary Coalfields and Scottish Collieries Company. Step-out drilling with a total of 18 boreholes defined an additional 30.5 Mt of extractable reserves. Multiple seams were intersected, the thickest of which attained 3.35 m of coal with superior quality attributes.

In late 1907, coal was intersected adjacent to the rail line 12.9 km to the east of Collie. This was the first record of coal in the eastern lobe of the Collie Coalfield and this locality was termed the Shotts Sub-basin.

Exploration in the Shotts area continued into 1908 and shafts intersected good-quality coal seams, which were too thin to be mined. Woodward (1909) recommended calyx drilling the area in response to requests from the prospectors who were seeking Government assistance to drill the area. There was concern that there would be insufficient capital to develop a new mine in the area, given the level of competition elsewhere in the Coalfield. The introduction of the bunkering trade allayed these fears.

The year 1908 saw a resurgence in prospecting with 2177 ha under additional prospecting licences. The persistence of the Shotts prospecting group was rewarded with the penetration of seven coal seams in a calyx bore. This result provided sufficient incentive to develop the area and the Premier Mine was started, coming into production in July 1911.

In 1912, the GSWA published two papers on the Collie Coalfield. Simpson (1912) provided data on the composition and properties of Collie Coal based upon face-sampling of the workings; Maitland and Montgomery (1912) assessed the aggregate reserves to be 310.68 Mt for six seams in a field bounded, 'with one exception', by faults. Woodward (1915) presented a paper on 'The Coal Resources of Western Australia' at the International Geological Congress, Canada, including the first published plan of coal subcrops and cross section.

A disastrous fire forced the closure of the Premier Colliery in early 1914 but triggered additional step-out exploration to define further reserves. Hand boring defined seam extensions, but attempts to sink a shaft into the seam failed owing to uncontrollable water-inflow. Prospecting shifted to the northwest with the intersection of a 2.74 m seam, but similar water-inflow problems at a depth of only 9 m thwarted shaft development.

The Collie Coal Company Limited undertook extensive and successful hand boring on Prospecting Area 19 and a shaft was sunk into what was considered the 'Wallsend Series' (Simms, 1917). The target seam was 3.2 m thick and displayed a remarkable similarity to the 'Allanson Seam' being worked by the Westralian Company. Simms concluded that this was the equivalent to the 'Co-operative Measures' displaced by the Wallsend Fault.

The Premier Company exploration had cut 610 m by hand boring and had finally located a suitable shaft site some 370 m to the southwest of the old entries. Tunnelling commenced, and by the end of 1916 had intersected coal of excellent quality.

Mapping of the Collie Coalfield was undertaken as part of the Woolnough Royal Commission in 1916 (Woolnough, 1916). The Stockton Ridge basement structure, to the south of the Premier Mine, was first identified at this stage by student mapper G. K. B. Hay. The interpretations proffered for this structure were that 'It may be either the top of what was an island in the Coal Measure swamp of Permo-Carboniferous time; or else the corner of a wedge-shaped block of granite, uplifted by faulting, from whose surface the Coal Measures have been denuded'.

In 1917, mine development in the Co-operative Colliery was piloted by 575 m of drilling in 18 hand bores.

The 1920s and 1930s: The East Collie Coal Mining, Briquetting & By-products Co. (1920) Limited drilled along the flanks of the Stockton Ridge on its ground south of the Premier Leases (PA 20). The drilling was supervised by J. Ewing, with the initial 13 bores sited to the west of the ridge and the balance being sited to the east of the ridge, 2.8 km to the southeast of the Premier Colliery. A total of 442 m was drilled in holes 35 to 46 m deep. The thickest of the seams intersected was 2.13 m.

In 1921, a further six hand bores were completed in the Premier area. The Griffin Syndicate drilled nine hand bores on its property, PA 24, and identified seams of mineable thickness and quality. The latter program completed approximately 183 m of drilling.

Step-out drilling on the Westralian Coal Mining Co. Limited lease extensions, into the Black Diamond area, was being evaluated during 1920. The major seams were intersected, confirming the extension, and a number of shafts were sunk to obtain bulk samples for analysis. The results confirmed good quality across a cumulative coal thickness of 15.24 m, with a reserve of approximately 5 Mt.

The Griffin Syndicate followed up its 1920 hand boring with a calyx drilling program assisted by the Department of Mines. Two holes showed mineable seams with a cumulative thickness of 8.23 m and reserves of 58.32 Mt.

In 1929, a series of seven calyx bores at Stockton proved substantial mineable reserves. This calyx program continued into 1930 with two more holes, and a further three holes in 1935 and 1936. The period from 1936 to 1947 saw over 130 hand bores drilled as reconnaissance for the Stockton workings.

Kent (1939) published an extensive summary of the constitution of the Collie coals, including petrographic and chemical analyses.

The 1940s: In 1940, a Royal Commission was appointed to investigate 'creep' at the Proprietary Colliery and to study available coal supplies and future development. The Commission estimated the coalfield to extend over 129.5 km^2 and to contain over 600 m of coal-bearing sediments with an aggregate thickness of 38.71 m. The reserve total was estimated at 240 Mt. The Commission further indicated the belief that the coalfield was preserved as a consequence of being faulted down into Precambrian rocks, and that it originally covered a very much larger area.

The Commission concluded by recommending that Amalgamated Collieries embark on a five-year drilling program to define a six-year coal supply and a further four years of proven reserves. In the case of the Griffin Coal Mine, a one-year drilling program was considered sufficient to prove a two-year reserve supply.

Wilson (1944) delivered the Presidential Address to the Royal Society of Western Australia entitled 'The Collie Coalfield, its Problems and its Economic Importance'. Wilson provided a figure of 1521 Mt of coal 'reserves' in the well-prospected areas of the basin. This was a qualified figure and included only seams thicker than 1.5 m. This halved the previous estimates made by Woolnough (1916). Following revised calculations this figure was further reduced to 800 Mt in 1947.

The first geologist from the GSWA to work at Collie on a permanent basis was J. H. Lord (1947a,b, 1948, 1949a,b,c, 1950a,b,c, 1951, 1952a–g, 1975). Government technical and financial commitment to the Collie Coalfield was substantially expanded in 1946 with the commencement of a basinwide geological and geophysical investigation.

The BMR, in conjunction with the GSWA undertook a gravity survey in June 1946 (Chamberlain, 1947). The basin was traversed using available roads and tracks, and 767 gravity stations were established. These data were used to construct a contour map which clearly shows the major basinal shape (Fig. 2). Unfortunately, the original gravity-station data from this survey have been lost and only the interpretative contour data survive.

In March 1946, the Government embarked on a program to increase coal production and acquired the options over the four leases constituting the Ewington area from the Ewington Syndicate. Exploration drilling commenced immediately under the supervision of Mr R. A. Hobson of the GSWA, and a small coal reserve was eventually delineated. Amalgamated Collieries subsequently acquired this area and continued exploration over the years 1946–1960. In total, 531 boreholes were drilled.

In 1947, plans were underway for a deep-drilling program to follow up the gravity survey. Lord recommended that the Government purchase a drilling rig, and proposed drilling 12 holes totalling some 7224 metres. Lord's argument for core drilling prevailed and the then Minister for Mines granted £75 000 for this 'Deep Drilling Program'. In March of 1947, the State Energy Commission (SEC) resumed the Black Diamond Leases from Amalgamated Collieries. This was in order to obtain 'sufficient coal supplies at a reasonable price'. The SEC further evaluated this resource by drilling 48 bores by the end of the year.

The Goldfields Syndicate was actively drilling in 1948. A total of 17 percussion holes was completed with drilling during the latter phases moving to the west side of the Stockton Ridge.

The proposed Government Deep Drilling Program had a poor start in a bid to test the Collieburn area for a deep colliery. The three cored holes planned were not completed. Core recovery was abysmal — ranging from 3 to 20%. The contractors had insufficient experience to deal with the poorly consolidated ground conditions typical of the Collie strata and were relieved of the contract.

The Department of Mines set about resolving this dilemma and ordered a deep-drilling rig from Canada in 1948. This rig arrived in May of 1949 and the project recommenced with the drilling of Mining Leases (MLs) 49 and 50, adjacent to the Collieburn townsite. The aim was to confirm the potential for opencut coal, as indicated by Amalgamated Collieries 1946 exploration program. This drilling was successful, and a small opencut mine — the Collieburn Opencut (the Blue Pool) — was subsequently established. This mine contained only 110 kt at a 6:1 stripping ratio.

In 1949, the Goldfields Coal Syndicate reconstituted under the corporate title of Western Collieries Limited and has continued to play a major role in the development and exploitation of the coalfield to the present day. At this time, the newly formed company planned to mine underground at Western No. 1 and by opencut at Collieburn. A contract was entered into with the Government for the supply of 100 kt of coal from underground and 100 kt of coal from opencut mines over a two-year period.

The 1950s: The Government Deep Drilling Program commenced in January 1950 with the new rig — a Boyles Bros BBS-4 — having an NX capacity of 1500 m. The rig operators used bentonite mud and casing to improve core recovery and prevent caving in of the poorly consolidated strata. The drilling was contracted to Australian Drillers Pty Limited who used Canadian drilling crews experienced with the equipment and techniques.

GCM was having difficulty finding resources for future mining development. Lord recommended that GCM apply for Prospect Areas (PAs) 55 and 56, which lay to the south of the Muja and Buckingham areas. Any northward expansion was effectively blocked by WCL, who held PA 53 immediately to the north. These PAs were duly secured by GCM and exploration drilling was rewarded in December 1950 with intersections of a 3 m seam with good quality coal in the southern extremity of the eastern lobe of the coalfield. This discovery was developed into the Centaur Colliery, which commenced production in 1951.

In 1951, Lord supervised the WCL drilling of 18 holes to establish underground mineable coal resources in the Rifle Range area. Reserves were estimated at 7 Mt measured and 6 Mt inferred of low-ash (4.4%) coal at 20% moisture and specific energy of 22 MJ/kg. These encouraging results promoted the development of the Western No. 2 Colliery.

The Government was placed under increasing pressure during 1950, by the mining companies and the Collie Miners Union, to divert the efforts of the Deep Drilling Program into reconnaissance drilling ahead of the current workings in the Proprietary, Wyvern and Stockton Collieries. This work necessitated a light and more mobile drilling-rig configuration, and the Government ordered a 'Failing M1' rig from England for this purpose. The reconnaissance drilling program was completed in September 1951 with an average 62% core recovery; an improvement of 10% over the Deep Drilling program. Detailed coal analyses were carried out on many of the samples.

The first Bulletin on the geology and mineral resources of the Collie Mineral Field was published by the GSWA in 1952 (Lord, 1952a). Glover (1952) investigated the petrology of the Permian and Tertiary deposits in the basin. Palynological determination of the coal and shaly units was conducted by Balme (1952) and assisted in seam correlations in the highly faulted basin.

G. H. Low supervised the Failing rig's core-drilling program over the next few years. Seventeen holes were completed in the first 20 months of operation at a rate of 230 m per month. The first of the Failing coreholes was drilled at the Cooperative Colliery and thereafter the rig was moved to the eastern lobe of the basin. A re-evaluation of the Centaur area (in the south) commenced with three holes. The results established that the Centaur seam was not part of the Ewington Member coals as had been previously thought.

The Deep Drilling Program continued with the Boyles rig moving into the Muja area and drilling Site D in 1953. This corehole was an outstanding success, intersecting the previously unknown Muja Member coals, which proved substantial. The Site D hole finished in basement at 627 m, having intersected a series of thick coal seams including the 11 m Hebe Seam, the thickest in the coalfield. Following the discovery of the Muja Member, the Failing rig was assigned to determining the extent of the Muja Member. Low detailed the geology and formalized the stratigraphic succession and nomenclature of the Muja Sub-basin (Low, 1954a–e, 1957, 1958a–e, 1964a,b, 1970, 1975). The stratigraphy was termed, from the top, the 'Muja', 'Chicken Creek' and 'Ewington' Horizons; these were determined to contain respective average coal thicknesses of 27, 17, and 6 metres.

GCM wasted little time in exploiting the Government's discovery of coal on its leases. The Muja Colliery opencut commenced operations in 1953, and the underground Hebe Colliery started in late 1954. GCM recruited Lord in February 1953, making him the first Mine Geologist employed at Collie. Between October 1952 and July 1955, GCM drilled a series of holes, mainly seeking southeastern extensions of the Wyvern Colliery.

The Government Failing rig was used in 1954 to evaluate roof and floor conditions for the Centaur and Western No. 2 Collieries. A serious fall at the Centaur Colliery in June 1953, followed by a slurry run, highlighted the lack of geotechnical information about areas ahead of the workings. The Geological Survey was asked to drill three holes to evaluate future roof and floor conditions. Recoveries were poor, ranging from 38 to 40%. Faulting and poor mining conditions continued to plague GCM's Centaur operations, and exploration efforts were targeted towards predicting mining conditions.

The WCL operations at Western No. 2 were similarly plagued by poor mining conditions, an unwelcome feature of which included slurry runs from 'washouts' in the main south headings. The assistance of the Geological Survey was sought, and in 1954 Low recommended drilling ahead of the workings. A total of nine holes was subsequently drilled on a 50% subsidized basis, and these indicated the most favourable development direction.

The final and deepest Government Deep Drilling Program hole was commenced in December 1953 and completed in July 1954. The hole was drilled down-dip from the Western No. 2 Colliery's entry to a depth of 853 m and penetrated into the Stockton Formation. This hole was typical of the series, reflecting a total core recovery of 73% with practically no recovery in the first 60 m.

Once the Government-assisted programs at Western Nos 2, 3, and 4 were completed, WCL spent little on further exploration drilling.

By 1957, conditions in the Western No. 2 Mine had improved and the Government signed a three-year contract with WCL for coal supplies.

Amalgamated Collieries actively explored the areas to the southeast of the Western No. 2 Mine between May 1958 and May 1959. A total of 95 holes was drilled, with an aggregate intersection of 2725 m.

The GSWA published Part 2 of Bulletin 105 (Low, 1958e) in which the results of the Government Drilling Programs were summarized together with an overview of basinal geology and reserves determined from some 1700 boreholes (Low, 1958e, figure 12). Coalfield resources were estimated with a degree of precision for the first time and included quality appraisals (Low, 1958e). Approximately 111 Mt of the total resources of 1877 Mt were considered extractable reserves.

The 1960s: Tenders were let in 1960 for the supply of coal for Government requirements, which were principally for power generation under the auspices of the State Energy Commission (SEC). GCM and WCL were successful. Amalgamated Collieries closed operations following this process. The surviving mining operations were the Muja Opencut and the Western No. 2, No. 4, and Hebe Collieries.

The new SEC contract prompted considerable drilling by GCM. This program commenced in August 1961 with shallow development drilling around the Muja Opencut. A total of 155 holes was drilled by December 1961. A second exploration core-drilling program of 140 holes commenced in July 1962 and was completed in October 1969; the results aided seam correlation, structural interpretation, and reserves determination.

In 1964, Low supervised an exploratory drilling program, financed by the SEC, in which 17 coreholes were sited in the Muja Sub-basin. D. L. Rowston, the GSWA geophysicist, piloted the use of downhole geophysical methods in the coalfield and conducted point-resistivity and self-potential tests down borehole S17. The results were encouraging, showing that remote-logging methods could be used to determine seam depths and thickness. Rowston was ahead of his time and, regrettably, it was another 14 years before the value of downhole geophysics became widely recognized and adopted in the coalfield.

In March 1965, disaster struck the Hebe Colliery. The workings intersected borehole S2 (which had deviated from vertical) and water then cascaded into the workings causing a slurry run and mine flooding. Operations ceased and expansion of the Muja Opencut workings was expedited.

WCL stepped up its exploration effort in May 1967 in an attempt to locate additional opencut reserves in the 'Cardiff Member' in the southern portions of the Cardiff Sub-basin (the western lobe of the Coalfield). A total of 132 holes was drilled with an aggregate intersection of 2847 m. This drilling culminated in the definition of substantial opencut reserves and the opening of the Western No. 5 Opencut in December 1969. Subsequent drilling has been mainly for mine development.

In 1969, the Government commissioned Messrs Menzies and Hanrahan (1969) to investigate the potential of the Collie Coalfield to sustain an output of up to 5 Mt per annum. The results from this study were positive and a drilling program was recommended. The Department of Mines funded the program as part of the State Mineral Resources Investigation Program. The GSWA supervised the drilling which was focused on structural resolution in the Ewington and Collieburn areas. Work commenced in April 1970 using a Mayhew 2000 rig. The main coal seams were cored, together with adjacent strata, and downhole geophysical logs were run.

The Collieburn area was assessed, with four holes to a depth of 300 m indicating an estimated 121.8 Mt resource of which 60.8 Mt were deemed extractable. The deeper areas were estimated to contain a resource of 23.8 Mt with 11.9 Mt being extractable.

The 1970s: In late 1971, WCL and Peabody (an American coal-mining company) formed a joint venture to undertake detailed exploration in the Collie Basin. The program concentrated on the Premier, Muja, and Western

Nos 2, 3, and 5 areas. These areas were drilled to determine structure and resource geometry. This was an extremely comprehensive program, and 868 holes were drilled totalling 10 180 m. A total of 121 holes was drilled for structure, 307 for crop-line resolution, and 23 coreholes for coal sampling and geotechnical analysis. This period set the trend, and WCL continued over the next 15 years with a steady exploration of areas of high potential, drilling a total of 130 000 m.

WCL conducted detailed structural drilling and crop definition in the Cardiff Sub-basin during 1974 to 1977. The emphasis in 1975 was on the Cardiff and Neath Seams in the Western No. 5 area.

In September 1974, GCM was granted a Temporary Reserve (TR 5943 H) covering 24 km^2 of Crown Land lying to the northeast of the old Stockton Opencut. In 1975, GCM commenced a drilling program of 120 holes to define the area, including 10 coreholes to determine coal and rock quality. The results were most encouraging and defined a substantial, largely undisturbed resource of opencut coal. A second program was commissioned in 1977–78 and the holes were geophysically logged. Two areas of mineable coal were resolved: the first, a deposit with opencut potential in the 'Ewington Member' to the north, and a second with underground potential in the stratigraphically lower 'Premier Member' to the south.

The degree of understanding of the coalfield's geology and coal quality had improved to such a level that in 1978 GCM signed a 21-year contract with the SEC to supply coal from the Muja Opencut Mine for power-generation purposes. Mine-development drilling, planning and implementation ensued and continues to the present.

GCM appointed W. J. Park as a full-time geologist and conducted exploratory drilling in the Buckingham area to the northwest of the Muja Mine where three seams of potentially mineable thickness were intersected.

WCL was taken over by CSR in 1978, and the period between 1978 and 1980 saw the pursuit of further opencut areas with detailed drilling in the vicinity of the Western No. 3 Mine.

The 1980s: In 1980, Peabody's interests at Collie were sold to Dampier Mining, a subsidiary of BHP. The leases subsequently became known as the Western Collieries and Dampier (WCD) leases.

In 1980, both GCM and WCL recognized the need for site-based geological staff and reorganized to establish permanent geological and mine-site offices at Collie. By mid-1980, geological resource calculations for the WCL leases were revised to 233 Mt measured, 224 Mt indicated and 630 Mt inferred, totalling 1087 Mt (Ashton, 1988). The extractable reserves were placed at 82.8 Mt for underground mining and 65.8 Mt for opencut.

During the 1980–81 period, GCM secured coal markets beyond State fuel supply, which prompted further exploration in the northern Chicken Creek area. The aim was to build up reserves from the 8 Mt already defined. A total of 245 holes was drilled of which 18 were cored for coal and geotechnical analysis. GCM completed a further 307 holes to depths between 20 and 228 m in the Muja Opencut development, including 85 for groundwater monitoring, dewatering, and control. Groundwater control was recognized as a major feature for a successful coal-exploitation strategy within the coalfield. GCM's dewatering operations within the Muja Mine include depressurization of 10 aquifers across a succession exceeding 250 m in thickness (Jones, 1986). Footwall depressurization is required to stop floor heave during mining. The old underground workings within the Hebe Seam are now used as a sump, and the water is removed and supplied at 15 ML per day to the SEC's Muja Power Station.

GCM developed the Chicken Creek Mine in 1981, and over the following two years continued exploration to assess mining potential in the adjacent Buckingham area. Geophysical wireline logging, by now standard practice, ensured reliable identification of coal seams. A reserve of approximately 4.2 Mt of potential opencut Ewington Member coal was defined to the east of the Chicken Creek Mine. Further reserves appear to exist to the southeast of the mine.

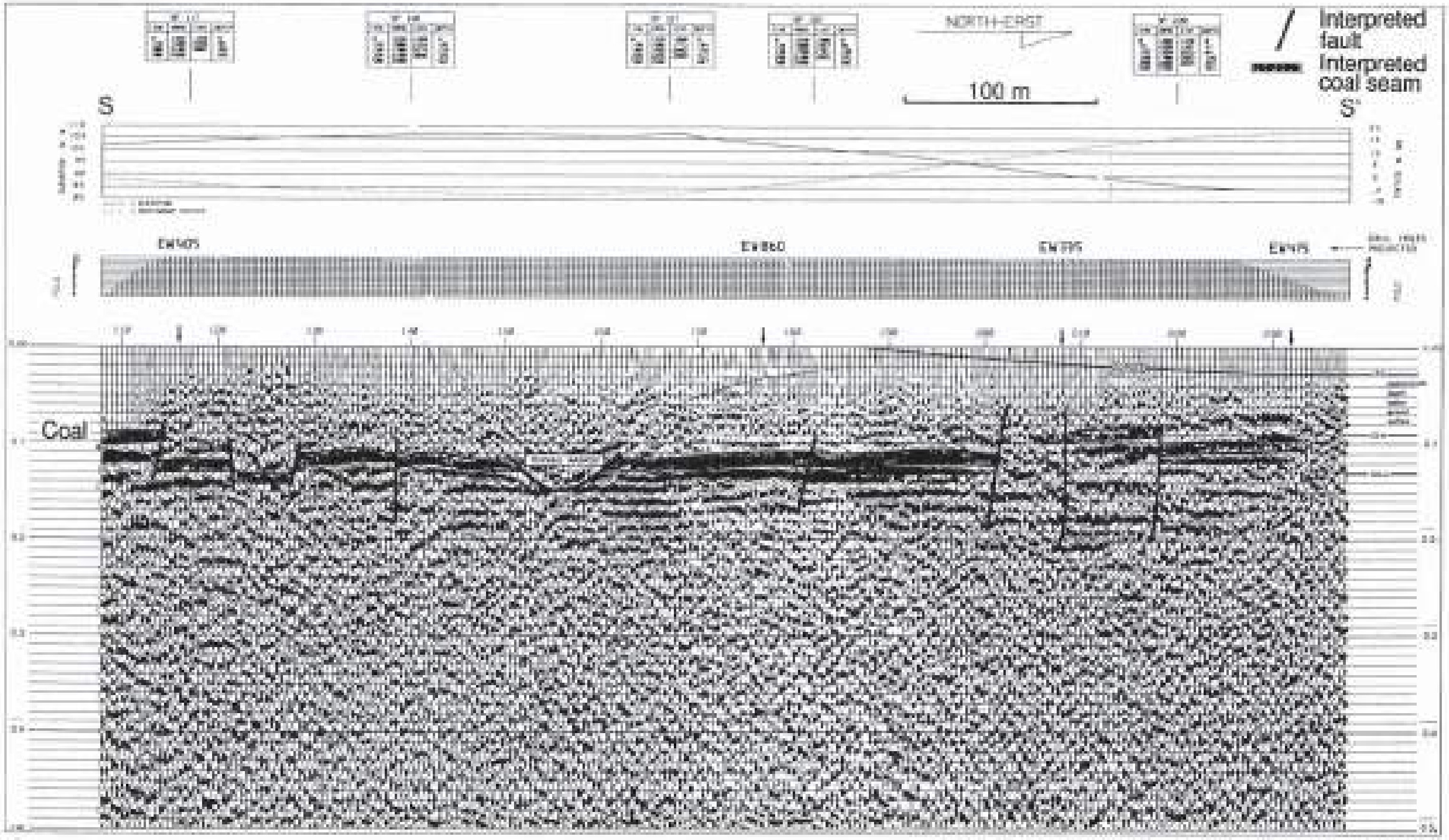
In 1981, WCL and GCM jointly contracted for routine wireline geophysical logging of their drillholes. The main tools used for coal identification include the gamma, density, neutron, resistivity, focused electric, resistance, sonic, verticality, and caliper. Sappal (1986) performed a detailed petrographic analysis on coals selected from a number of the mining faces.

The use of palynology in determining the correlation of coal seams and shales in the highly faulted basin was demonstrated by the early work of Balme (1948) and has been continued by Backhouse (1990, 1991).

Analyses of coal ash and trace elements were reported by Davy and Wilson (1989, 1990), although no clear trends emerged from the study. Subsequent neutron-activation studies on the coal have been attempted by Davy (1991, pers. comm.), although the latter technique is very time consuming and expensive.

Faulting and seam discontinuities continue to afflict the coal-mining industry at Collie. Attempts have been made by both GCM and WCL to use alternative technologies to facilitate drilling, including seismic methods. The earliest rigorous attempts at seismic structural determination were conducted by GCM in 1983, using the Mini Sosie method. However, to date these attempts have met with varying success owing to the poorly consolidated nature of the sediments. The best results were obtained from the Ewington Coal Measures where good resolution of small-scale faulting (Ashton, 1988) and seam washouts was obtained (Fig. 7). It appears that, as with the introduction of downhole geophysics, it will take many years before seismic methods are seriously adopted at Collie.

GCM became a private company in 1986 and changed its name to The Griffin Coal Mining Company Pty Ltd.



(Modified from Griffin Coal Mining Company Pty. Ltd.)

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Figure 7. Seismic section showing coal seam discontinuities across faults and a washout. Location S — S' on Plate 2.

During the 1980s, there has been an ever-increasing awareness of environmental and landuse planning issues, particularly in the context of the future development of the Collie Coalfield. To this end, Government undertook a comprehensive evaluation which detailed multiple landuse options and recommendations (Gee, 1987) and subsequently established the 'Collie Basin Management and Planning Group' to coordinate the development of the coalfield in accordance with a ranked list of priorities. A comprehensive map detailing the interrelationships of these various multiple landuse interests has been produced by the Department of State Development. This map is based on the distribution of shallow, potentially mineable coal, and the locations of mine workings (Plate 1).

Basin setting

Overview

The Collie Basin, bilobate in shape with axial dimensions of 26 kilometres (northwesterly) and 15 kilometres, is filled with Permian and Cretaceous sediments which form an outlier within crystalline basement rocks of the Archaean Yilgarn Craton. The Collie Basin was named by Woodward (1915), and its basic bilobate form was first determined by a gravity survey (Fig. 2) conducted by the BMR (Chamberlain, 1947). Historically, the basin has been subdivided a number of different ways, each with its own stratigraphic scheme. Lord (1952a) termed the western area the 'Main Basin' and assigned the sediments northeast of the Stockton Ridge to the 'North Eastern Basin'. Playford et al. (1975) recognized three sub-basins; the 'Shotts, Muja and Cardiff Sub-basins'. Present data show that the Collie Basin comprises two principal grabens striking northwest in which Permian strata are weakly folded. The western graben is named the Cardiff Sub-basin (Playford et al., 1975) in which strata dip at a few degrees to the southwest. The Cardiff Sub-basin is separated by a medial basement horst, the Stockton Ridge, from the eastern graben named the Premier Sub-basin (Wilson, 1990), which in turn includes the 'Muja' and 'Shotts' Sub-basins. Low-angle stratal dips to the southwest occur in the southern areas at the Premier Sub-basin but dip at shallow angles to the northeast in the northern areas (Plate 2).

Abundant intrabasinal faults parallel the graben axial trend to the northwest and transect low-amplitude folds. In some instances the fold trains are out of phase causing discontinuous faults with variable throw and instances of scissoring (Plate 2). These factors have contributed to the difficulty in correlating the coal seams and determining mineable areas.

The coals show a range of maturity: the stratigraphically highest are sub-bituminous (ASTM) black coals with vitrinite reflectance values in the region of 0.41; reflectance increases to 0.61 for the deeper coals (Sappal, 1986). The burial depth can be calculated by assessing the rank of coal against the effects of geothermal gradient and maturation time, and this indicates a maximum burial depth of several kilometres.

Historically, two models have been proposed for the origin of the basin:

(a) The formation by erosional processes of a depression that was subsequently infilled by coal-bearing sediments, and

(b) Initial deposition of coal-bearing strata followed by later down-faulting and preservation. A variant of this model includes syn-depositional faulting.

Maitland (1899) initially believed that the coal measures accumulated in a 'comparatively unsymmetrical shallow basin of erosion' within which the strata were apparently unaffected by serious disturbance. The low dip (southwest) was attributed in part to 'consolidation and the settling of the strata' (differential compaction) that produced 'rolls' (small open folds) and small faults. Jack (1905) reported, without elaboration, that the coalfield boundary was defined by faults with the exception of the northern boundary, and that the southwestern boundary fault had a downthrow to the northeast in excess of 650 m. Woolnough (1916) and Maitland (1919) expanded on this and envisaged a formerly extensive sedimentary sheet that had been locally preserved from erosion by down-faulting. Montgomery (1925) noted the considerable similarity between the coal stratigraphy and setting at both the Wilga and Collie Coalfields (Fig. 1) and was the most explicit stating:

> It is rather likely that considerable faults will exist, as the whole coal-bearing area, as at Collie, owes its preservation to its having been faulted down into a deep 'grave' or 'sunkland' in the granite. The Collie and Wilga coal patches indicate that at one time the granite plateau of the Darling Range was overlaid by a thick and extensive series of Permo-Carboniferous strata, quite probably extending continuously to connect with the similar ones in the vicinity of the Irwin River and well over 2000 feet in thickness. Subsequent violent movements of the earth's crust led to extensive rending of the country and dislocation of the ruptured blocks, allowing some to subside into trough-like depressions between portions of the bed-rock thrust upwards, and thus dropping areas of the superficial strata into troughs in the old hard rocks which have preserved them from removal by erosion.

Present data support this view.

Lord (1947a) stated that there was no definite evidence to support either the erosional-basin or the down-faulted model, but supported Maitland's (1899) contention that the faults in the mines appeared to be the result of differential compaction. Lord (1952) discarded the down-faulted theory, citing lack of hard evidence, and reverted to the topographic-erosion basin theory as outlined in Maitland and Jackson (1904).

The State Government's deep-drilling program of the 1950s confirmed that glacial processes had been active in the basin when tillite was intersected overlying striated crystalline basement (Low, 1958e). This appeared to reinforce the theory that glacial erosion processes formed the basin.

Lowry (1976) favoured the tectonic origin, invoked a modified syn-sedimentary faulted-basin theory based on indirect sedimentological evidence, and indicated that regional tectonic events clearly played a significant role in promoting the net subsidence required to accumulate and preserve peats in the Collie Group. However, the existence of significant local syn-sedimentary faulting is in doubt for several reasons; the faulted strata display a sharp-edged brittle fracture, and seam attributes such as thickness and bedding are consistent and continuous across faults. These features are interpreted as indicative of post-depositional displacement.

Finkl and Fairbridge (1979) again proposed a glacial-scour depression for the origin of the Collie Basin. They further concluded that since the Proterozoic peneplanation, there had been a high degree of stability in the 'Yilgarn section of the West Australian craton' with very low denudation rates as had prevailed over hundreds of millions of years. Van de Graaff (1981) presented reasoned arguments to disprove this hypothesis and concluded that: denudation rates on the 'Yilgarn Block' during most of the Mesozoic were in the order of 4.5–5 metres/million years (m/Ma) as a minimum; rates in the Late Cretaceous–Early Tertiary were still as high as 1.5–2 m/Ma; at least 500 m of cover rock was eroded; preservation of a pre-Permian land surface was virtually impossible. Van de Graaff (1981) agreed with Lowry (1976) that the Collie Basin was essentially a tectonic feature.

Park (1982) described the dip-slip Muja Fault (exposed in the Muja Opencut) on the western boundary of the Premier Sub-basin, and interpreted the highly sheared basement as an Archaean shear zone along which the Muja Fault acted. The Muja Fault is overlain by undisturbed Cretaceous Nakina Formation (Fig. 8), which indicates faulting had ceased by the early Aptian. Le Blanc Smith (1989) assessed the sedimentology and the fault and fold patterns and concurred with the tectonic model for basin preservation, concluding that the Collie, Wilga and Boyup Basins are extensional (pull-apart) basins. The basins formed as a consequence of strike-slip movement on ancient transcurrent faults. Segments of an areally extensive Permian sedimentary platform were preserved and the pattern of faulting and folding (Plate 2) is indicative of post-depositional transtensional (dextral) tectonics.

From consultation studies of mine exposures, the geotechnical analyses and mapping of Joass (1990) and drillhole core, Bogacz (1992) confirmed that the overall basin structure was associated with basement fault movement that was predominantly normal-slip, with a dextral horizontal component which could be ascribed to dextral transtension along the northwesterly basement faults.

Stratigraphy of the Collie Basin

Permian rocks of the Collie Basin lie concealed beneath a veneer of Cretaceous and younger sediments. The Permian sedimentary succession is approximately 1400 metres thick and lies unconformably on Archaean crystalline rocks. Sandstone dominates the succession with subordinate amounts of siltstone, mudstone, and coal. The base of the succession is marked by an irregular diamictite unit (Stockton Group) and coals occur within the top 1000 m of the Permian stratigraphic section (Collie Group). There are approximately 60 principal coal seams and these are locally split by stone partings into as many as 244 named splits. Coal seams vary from 15 m to a few centimetres in thickness (Fig. 3).

Early attempts to derive a coalfield stratigraphy were complicated by the high number of coal seams and a proliferation of seam-splits in a succession that is cut by frequent faults. Historically, many seams have inadvertently been given duplicate names as a consequence of the geological complexity, and because mines developed in physical isolation from each other. Several increments have been recognized as containing coals of mineable thickness, and these have been given stratigraphic names with the relatively barren intervals being unnamed.

Woolnough (1916) recognized three 'phases' in what he termed the Collie Coal Measures, applying the names 'Lower or Collie Phase', 'Middle or Collieburn Phase' and 'Upper or Cardiff Phase'. Maitland (1919) accepted this three-fold division.

Lord (1952a) called the 'Phases' of Woolnough (1916) 'Horizons' and added 'Ewington' and 'Premier' Horizons to the stratigraphy, which was summarized as a tabulated succession with approximate thickness in each sub-basin. However, type sections for these units were still not defined. Fairbridge (1952, p. 143) renamed the 'Collie Coal Measures' the Collie Group and amended Woolnough's (1916) terms to 'Collie Formation', 'Collieburn Formation', and 'Cardiff Formation'. Lord (1953, 1955) subsequently named the 'Muja Horizon' and 'Stockton Formation'. McWhae et al. (1958) doubted that these units could be regarded as formally established as neither type sections nor the upper and lower limits of any of the proposed formations were clearly designated. Playford et al. (1975) proposed recognizing these units as members and selected type sections.

This study provides a revised stratigraphy for the basin as a consequence of the improved stratigraphic resolution from extensive mining and exploration drilling. This subdivision is developing at several levels: lithostratigraphic, biostratigraphic and genetic–stratigraphic.

Balme (1952) was the first to recognize and apply biostratigraphy with a comprehensive analysis of the palynomorphs in the basin. More recently, Backhouse (1990, 1991) has sequentially subdivided the Permian succession at Collie using a series of cryptic biohorizons based on first appearances of selected spore and pollen taxa.

The genetic approach to stratigraphy is dependent on the resolution of 'increments and sequences of strata' (Busch, 1971) that were deposited in specific depositional environments and which may be readily recognized using the depositional modelling concepts of modern sedimentology. The concept has proved very effective

Table 1. Evolution of Permian lithostratigraphic terminology for the Collie Basin

Woolnough (1918)	*Lord (1952a)*		*Fairbridge (1952)*	*Playford et al. (1975)*		*Le Blanc Smith (this Report)*	
Collie Basin	*Main Basin*	*NE Basin*	*Collie Basin*	*Cardiff Sub-basin*	*Muja Sub-basin*	*COLLIE BASIN*	
Upper or Cardiff Phase	Upper or Collie Cardiff Horizon	Muja Horizon (Lord, 1953)	Cardiff Formation	Cardiff Member	Muja Member	MUJA COAL MEASURES	COLLIE GROUP
Middle or Collie Burn Phase	Middle or Collie Burn Horizon	Middle or Premier Horizon	Collie Burn Formation	Collieburn Member	Premier Member	PREMIER COAL MEASURES	
unnamed	unnamed	unnamed	unnamed	unnamed	unnamed	ALLANSON SANDSTONE	
Lower or Collie Phase	Lower or Collie Horizon	Lower or Ewington Horizon	Collie Formation	Ewington Member	Ewington Member	EWINGTON COAL MEASURES	
unnamed	unnamed					WESTRALIA SANDSTONE	
						MOORHEAD FORMATION	STOCKTON GROUP
		Stockton Formation (Lord, 1955)	unnamed	Stockton Formation	Stockton Formation	SHOTTS FORMATION	
Archaean basement							

in exploration for coal (Le Blanc Smith, 1980a,b; Winter et al., 1987; Ardito, 1991) and oil (Busch, 1974), and is being developed for the Collie Basin, where three genetic sequences have been identified.

Lithostratigraphy

The historical stratigraphy was based largely on lithology derived from Government deep core drilling and hinged on the relative abundance and thickness of coal seams. The succession was resolved into an alternation of apparently 'barren' units and 'coal bearing' units. The evolution of the lithostratigraphy is given in Table 1.

Substantial exploration and mine-development drilling has been systematically undertaken in the coalfield, particularly over the past ten years. Most of the boreholes were very shallow, localized, and focused on facilitating mine extensions with a consequently restricted stratigraphic section. The majority of the newer drillholes have been air cored and rely principally on remote-sensing methods (such as wireline logs) to target seam intersections. Many of these data are thus inferential in type. A substantial database of both observed and inferential data now exists and has been computerized (available in electronic format) and this forms the basis for the refinement of the stratigraphy.

The revised stratigraphic nomenclature is given in Table 2 and reference sections on Plate 3.

Precambrian

The basement and rocks surrounding the basin are part of the Yilgarn Craton. Lord (1952a) provided early information from the vicinity of the basin, and this was substantially extended through the mapping of Wilde and Walker (1982).

The bulk of the rocks in the vicinity of the Collie Basin are Archaean, comprising: granitic units in the granodiorite–adamellite–granite range from the southern extension of a major plutonic complex; the Darling Range Batholith; and metamorphic rocks consisting of ortho- and paragneiss, metasediments, and some mafic and ultramafic intrusions of the Balingup Metamorphic Belt. Younger mafic dykes of late Precambrian age are tholeiitic quartz dolerite intrusives which have a northwesterly trend.

The basin is bisected by a horst structure named the Stockton Ridge (Fig. 3). This is composed of granitic basement rocks that contain numerous dykes; the best exposures occur to the south of the Shotts townsite (Lord, 1952a, figure 41). The western margin of the Muja opencut mine abuts against the Stockton Ridge along the Muja Fault. In 1989, along this fault, the mine exposed fresh basement comprising olive green, near-vertically dipping phyllonite, dolerite dykes, and granite gneiss (Park, 1982). The phyllonite is mostly chlorite but contains infrequent white lenses of quartz up to five centimetres long.

Some of the deep coreholes have intersected dolerite basement. Approximately half of the corehole intersections of basement penetrate mafic rock, an indication of its abundance. Lord (1952a) noted that the intrusives appear mostly to be located to the east of the western boundary fault of the Basin. This observation may be indicative of movement along ancient shears, which juxtaposed differing terranes.

Table 2. Revised Collie Basin lithostratigraphy

Age	*Group*	*Formation*
CRETACEOUS		Nakina Formation
	Unconformity	
PERMIAN	Collie Group	Muja Coal Measures
		?lacuna
		Premier Coal Measures Allanson Sandstone Ewington Coal Measures Westralia Sandstone
	Stockton Group	Moorhead Formation Shotts Formation
	Unconformity	
ARCHAEAN BASEMENT		

Reconstruction of the syn-sedimentary basement topography reveals an undulating terrain, with a vertical relief of over 500 m, overlain unconformably by the Permian strata. The palaeotopography was lowest in the west of the basin and several hundred metres higher to the east. The Stockton Ridge formed within the basin a palaeotopographic basement high which was flanked to the west by the deeper palaeovalley.

Permian

Stockton Group

Definition: This was defined by Lord (1955) as the 'Stockton Formation' and a reference section was selected by Playford et al. (1975). Since distinct diamictite and argillaceous lithologies with regional significance can be identified within the unit, the rank is here raised to group level. The Stockton Group is defined as comprising the Shotts Formation and Moorhead Formation. Thickness ranges from over 250 m along the axial portions of the Cardiff Sub-basin (Plate 4) to a few tens of metres in the vicinity of the Stockton Ridge and in the Premier Sub-basin (Plate 5). The Stockton Group was deposited in a glacial to proglacial setting associated with the climatic amelioration and glacial retreat of the Gondwana ice sheet.

An Early Permian age is assigned to the Stockton Group as it contains palynoflora from upper Stage 2 (Backhouse, 1991) and is in part correlatable with the upper portion with the *Granulatisporites confluens* Oppel-zone of Foster and Waterhouse (1988). The unit starts below the Asselian *Pseudoreticulatispora confluens* Zone

Table 3. Stockton Group lithostratigraphy with palynostratigraphic zones; Collie Basin

Formation	*Cardiff Sub-basin*	*Premier Sub-basin* *North–Central*	 *South*
Moorhead Formation	No seams	No seams	No seams
Base of *Pseudoreticulatispora confluens* Zone (Asselian–?Tastubian)			
Shotts Formation	No seams	No seams	No seams
Base of Stage 2 (Asselian)			

of Foster and Waterhouse (1988) and the lower part may extend into the Carboniferous (Table 3).

Shotts Formation

Definition: The Shotts Formation is a diamictite with polymictic extrabasinal clasts, clast-supported conglomerate, poorly sorted pebbly sandstone, and thin shale that rests unconformably on crystalline rocks of the Yilgarn Craton. It is overlain conformably by the Moorhead Formation. In areas where the Moorhead Formation is absent, such as in palaeotopographically high areas, the Shotts Formation is conformably overlain by the Westralia Sandstone. The type section is from 629–665 m in the Government corehole GOV-DD-A (33°22' 00"S, 116° 08' 00"E), a total thickness of 36 metres (Plate 3). No core is available from this hole. There is a partial core from the Shotts Formation in drillhole GOV-MH4, which was drilled in the eastern lobe of the Basin in 1970; this core is stored at the GSWA core library. The diamictite has been observed to overlie striated basement (Low, 1958e). The Shotts Formation is named after the village of Shotts in the Premier Sub-basin.

Lithology: The Shotts Formation is principally a diamictite with a matrix that is pale grey with a bluish to greenish tinge. The matrix is predominantly a structure-less silty mudstone which supports extrabasinal polymictic conglomerate clasts of granitic, mafic, and metamorphic rock. The unit is a few metres thick; however, the range of thickness is unknown as the unit lies substantially below the economic coal-bearing strata and there have thus been very few drillhole intersections. The diamictite has been observed to overlie striated basement (Low, 1958e). At some locations the diamictite is overlain by crudely stratified clast-supported conglomerate and pebbly sandstone units a few metres thick. These units generally fine upwards over a few metres into dark-grey to brownish interlaminated siltstone and mudstone units of the Moorhead Formation.

Stratigraphic relationships: The Shotts Formation can be readily correlated to equivalent units in the Wilga, Boyup, and Perth Basins. The diamictites and clast-supported conglomerate lithofacies correlate regionally with the Nangetty Formation in the Perth Basin, the Paterson Formation in the Officer Basin, the Lyons Group in the Carnarvon Basin, and the Grant Group in the Canning Basin.

Fossils and age: Backhouse (1991) has identified palynomorphs from Stage 2 in this unit, placing the age at Early Permian — Asselian and earlier — because it lies below the Asselian *Pseudoreticulatispora confluens* Zone of Foster and Waterhouse (1988). This places the formation at the Carboniferous–Permian boundary.

Depositional environment: The Shotts Formation was deposited in a glacial to proglacial setting associated with the climatic amelioration and glacial retreat of the Gondwana ice sheet. The diamictite is a tillite.

Moorhead Formation

Definition: The Moorhead Formation is defined as the unit of pale-grey laminated claystone with subordinate thin beds of buff-coloured siltstone, fine-grained sandstone, and rare limestone lenses, which rests conformably on the Shotts Formation and is overlain conformably by the Westralia Sandstone. The formation contains occasional extrabasinal polymictic clasts up to cobble size. The type section (Plate 3) is 213 m thick and is taken between 416 and 629 m in corehole GOV-DD-A (33° 22' 00"S, 116° 08' 00"E). This hole was drilled in the north of the western graben of the basin in the early 1950s (Low, 1958e). No core from this corehole survives. The Moorhead Formation is named after a railway siding on the Collie–Wagin line.

Lithology: The Moorhead Formation conformably overlies the Shotts Formation with a gradational contact spanning several metres across which the coarse-grained sediments of the Shotts Formation fine upwards into dark-grey to brownish interlaminated sandy-siltstone and mudstone units. The siltstone and mudstone units contain a variety of dispersed extrabasinal clasts up to cobble size, and infrequent lenses of fine-grained, buff-coloured sandstone. These fine-grained sandstone units may display soft-sediment deformation structures. Occasional thin, sandy limestone beds occur, from which Chapman (1907) reported 'dwarfed' foraminifers (Lord, 1952). The Moorhead Formation displays a transitional contact with the conformably overlying Westralia Sandstone. This contact is characterized by an increase in the sand fraction at the expense of siltstone and shale.

The thickest section of the Moorhead Formation is 230 m in an incomplete penetration by corehole GOV-GF28. The Moorhead Formation shows a substantial variation in thickness throughout the basin, ranging from nil over much of the eastern lobe to over 230 m in the western lobe (Plate 4: Government coreholes GOV-DD-A and GOV-GF28; Low, 1958e).

Stratigraphic relationships: The Moorhead Formation can be readily correlated with equivalent units in the Wilga, Boyup, and southern Perth Basins, and with the Holmwood Shale of the northern Perth Basin.

Fossils and age: Backhouse (1991) has identified the palynomorphs *Brevitriletes parmatus* and *Jayantisporites pseudosonatus* from Stage 2 in these rocks, yielding an Early Permian age of Asselian–?Tastubian or earlier because it lies below the Asselian *Pseudoreticulatispora confluens* Zone of Foster and Waterhouse (1988). This places the formation at the Carboniferous–Permian boundary. Crespin (1958) did not regard the record of dwarfed foraminifers as authentic, and the specimens cannot now be found in the Museum of Victoria (Cockbain, A. E., 1992, pers. comm.).

Depositional environment: The Moorhead Formation was deposited in a proglacial lacustrine setting associated with the climatic amelioration and glacial retreat of the Gondwana ice sheet. The palaeoenvironmental model envisaged is similar to that outlined by Le Blanc Smith and Eriksson (1979).

Collie Group

Definition: The previous usage of 'Collie Coal Measures' was as a formation and has been in use since the 1800s (Maitland, 1899). Current studies indicate the 'Collie Coal Measures' contains a number of distinct units and it is proposed to redefine it as the Collie Group. The Collie Group comprises the:

Muja Coal Measures
Premier Coal Measures
Allanson Sandstone
Ewington Coal Measures
Westralia Sandstone

The Collie Group incorporates a stratigraphic section (Plate 3) of approximately 900 m of coal-bearing siliclastic sedimentary rocks, and conformably overlies the Stockton Group. Sandstone predominates with lesser conglomerate, siltstone, mudstone, and coal seams. The most common depositional motif comprises stacked upward-fining cycles that are frequently coal capped, and subordinate upward-coarsening cycles. The Collie Group is unconformably overlain by the Nakina Formation (Fig. 9). The group name is derived from the Collie River, which traverses the basin.

A number of increments within the Collie Group have been recognized as containing coals of mineable thickness (Table 4). As a consequence various names have historically been given to these potentially mine-able portions (Table 1), leaving the intervening 'barren' sections unnamed. However, inspection of several thousand drillhole logs shows that while the so-called barren sections do not contain coal seams of current economic significance they do contain numerous seams ranging in thickness from a few tens of centimetres to over 1.5 metres. This had been overlooked during the development of the early lithostratigraphy, particularly when contrasting the east and west areas of the basin. The distinction between the 'Cardiff' and 'Collieburn' Members is essentially an artefact of mining convention rather than lithostratigraphy, and there is no significant difference in the lithostratigraphic character between the members and the unnamed unit between them.

Traditionally, the 'Muja' and 'Cardiff' Members have been correlated (Playford et al., 1975). However, using coal-seam palynology (Backhouse, 1990, 1991) and sedimentology, the 'Muja Member' correlates with both the 'Cardiff Member' and a substantial portion of the 'Collieburn Member'. The *Didecitriletes ericianus* Zone (Backhouse, 1991) contains major economic coal seams from both the 'Muja' and 'Collieburn' Members. The 13 m-thick Hebe Seam, together with the subordinate Iona Seam in the 'Muja Member', correlates with the section containing the Collieburn 1, Alpha, Wyvern, and Collieburn 2 Seams from the 'Collieburn Member'. The so-called barren section that traditionally has been used to separate the 'Cardiff–Collieburn' and the 'Muja–Premier' (see Kristensen and Wilson, 1985; Wilson 1990) is inconsistent as a boundary unit. However, the correlation appears valid between the stratigraphically highest coal seams of both the 'Muja Member' (Ate–Galatea seams) and the 'Cardiff Member' (Neath and various Cardiff seams).

Similarly, the 'Premier Member', as intersected in the Premier Sub-basin in the east, contains coal seams that correlate with the lower 'Collieburn Member' and with the upper portion of the unnamed 'barren' units of the Cardiff Sub-basin to the west.

Consequently, it is proposed to drop the terms 'Collieburn Member', 'Cardiff Member' and 'Chicken Creek Member', upgrade the 'Ewington', 'Premier' and 'Muja' Members to formation rank, and formally name the 'barren' intervals.

Westralia Sandstone

Definition: The Westralia Sandstone comprises the predominantly sandstone succession that lies beneath the stratigraphically lowest occurring coal seam in the Ewington Coal Measures.

The name is taken from the early mine site, rail siding, and forestry and conservation management area in the northwest of the coalfield. The type section of the Westralia Sandstone is the interval 337 m to 416 m (a total thickness of 79 m) in corehole GOV-DD-A (33° 22' 00"S, 116° 08' 00"E; Plate 3).

Lithology: The succession shows a broad upward coarsening and predominance of sandstone over argillite. The lower units are composites of interbedded, deformed, and ripple cross-stratified fine- to medium-grained sandstone, which is in turn interbedded with sub-ordinate, laminated, pale-brownish siltstone. These units coarsen upwards with an increasing frequency of medium- to coarse-grained, cross-stratified sandstone units in the upper section. The fine-grained sandstone units may display soft-sediment deformation structures. The coarser upper units feature up to 60 m of stacked, upward-fining cycles. The typical cycle comprises, in depositional order:

(a) erosively based, poorly sorted, coarse- to fine-grained, buff-coloured subarkosic sandstone a few metres thick that contains stacked cross-bed cosets;

(b) a relatively abrupt upward gradation (over a few tens of centimetres) into rippled fine- to medium-grained pale, buff-coloured sandstone, the upper portions of which may feature interlamination with dark-grey siltstone; and

(c) laminated grey siltstone that is capped by a thin (centimetre scale), dark-grey carbonaceous shale.

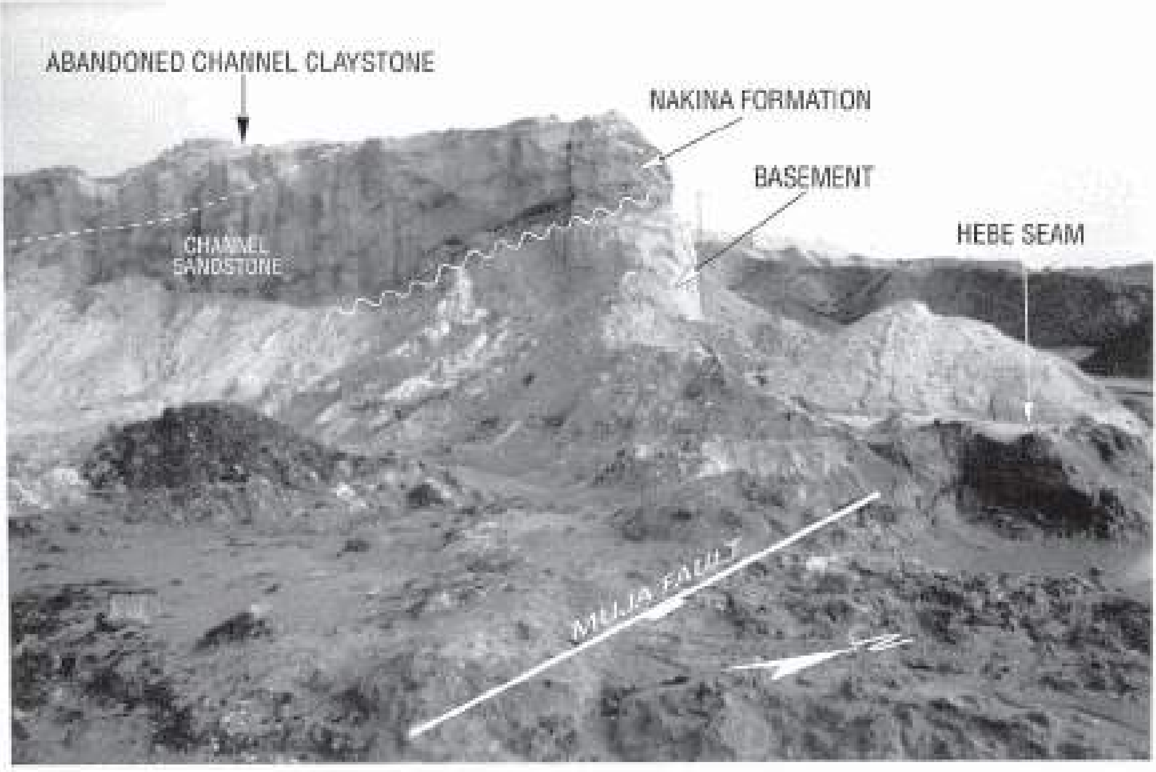


Figure 8. Nakina Formation overlying basement and Permian sediments above the Muja Fault

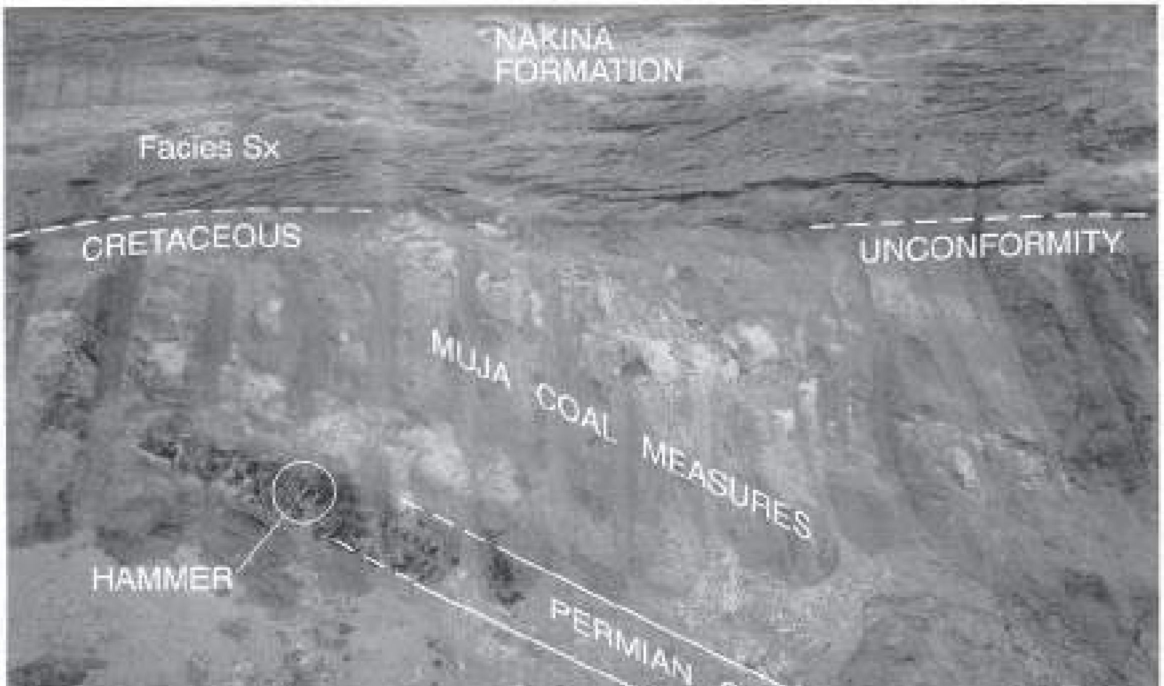


Figure 9. Permian–Cretaceous horizontal angular unconformity between the Collie Group and the overlying Nakina Formation, Muja Opencut north face.

Table 4. **Collie Group lithostratigraphy, correlation of principal seams, and palynostratigraphic zones**

Formation	*Cardiff Sub-basin*	*Premier Sub-basin*	
		North–Central	*South*
Muja Coal Measures	Bacchus		
	Echo		
	Medusa		Floater Upper
	Niobe		Floater Middle
	Pygmalion Upper		
	Pygmalion		Floater Lower
	Cardiff A		Ate
	Cardiff 1 Upper		
	Cardiff 1		Bellona
	Cardiff 2 Upper		
	Cardiff 2		Ceres
	Minos		
	Cardiff Upper		Diana
	Cardiff		Eos
	Neath		Flora
	Abe		Flora
	Ben Upper		Galatea
	Ben Lower		Galatea
Base of *Protohaploxypinus rugatus* Zone (?Kungurian–Ufimian)			
	Collieburn1		Hebe
	Collieburn 1 Lower		Hebe
	Orion		Hebe
	Upsilon		Hebe
	Alpha		Hebe
	Wyvern		Hebe
	Wyvern Lower		Hebe
	Rhea		Hebe
	Rhea Lower		Hebe
	Collieburn 2 Upper		Hebe
	Collieburn 2 Lower		Hebe
	Janus		Iona
Base of *Didecitriletes ericianus* Zone (?Kungurian–Ufimian)			
Premier Coal Measures	Phoenix	Premier 0 Upper	
		Premier 0	
		Premier 1 Upper	
		Premier 1	Apis
	Nestor Upper	Premier 2c	
	Nestor Lower	Premier 2b	
	Hermes	Premier 2a	
	Acis	Premier 2	Uraeus
	Boreas	Premier 3	Unicorn
	Circe	Premier 4 Upper	
	Icarus	Premier 4	Pegasus
		Premier 5a	
		Premier 5b	
		Premier 5c	
Base of *Dulhuntyispora granulata* Zone (?Kungurian)			
	Griffin Upper	Premier 5	Hydra
	Griffin	Premier 6	Briareus
		Juno Upper	Gryps
	Erato (Echo)	Juno Lower	Chiron
	Demeter Upper	Pan Upper	
	Demeter	Pan Lower	
	Tantalus Upper	Leda Upper	
	Tantalus Lower	Leda Lower	
	Venus	Premier 7	Centaur
		Tethys Upper	
		Tethys Lower	
Base of *Microbaculispora villosa* Zone (Baigendzhinian)			

Table 4. *(continued)*

Formation	*Cardiff Sub-basin*	*Premier Sub-basin* *North–Central*	 *South*
Premier Coal Measures (continued)		Premier 8 Upper Premier 8 Lower Zephyrus Upper Zephyrus Lower Serapis Eros Upper Eros Lower	unnamed seams
Allanson Sandstone	Hymen	Hymen	Hymen
Base of *Praecolpatites sinuosus* Zone (Early Baigendzhinian)			
Ewington Coal Measures	Ewington 1 Ewington 2 Moira	Ewington 2 Moira Stockton	3 unnamed seams
Base of *Microbaculispora trisina* Zone (Aktastinian)			
	Stockton Wallsend	Wallsend	Achilles Ajax Ares
Base of *Striatopodocarpites fusus* Zone (Early Aktastinian–Sterlitamakinian)			
Westralia Sandstone	No seams	No seams	No seams
Base of *Pseudoreticulatispora pseudoreticulata* Zone (?Tastubian)			
	No seams	No seams	No seams
Base of *Pseudoreticulatispora confluens* Zone (Asselian–?Tastubian)			

Important diagnostics are considered to be firstly, the predominance of sandstone and the absence of coal seams of significant thickness and areal extent and secondly, a carbonaceous content in the subordinate dark-grey to black siltstone and mudstone units. The basal contact of the cycle may be erosional and associated with intraformational conglomerate characterized by rip-up clasts of siltstone and infrequent macerated carbonaceous detritus.

Stratigraphic relationships: The Westralia Sandstone can be correlated with equivalent units in the Wilga, Boyup, and southern Perth Basins and with the High Cliff Sandstone of the northern Perth Basin (Irwin River Coalfield).

Fossils and age: The Westralia Sandstone is Early Permian. Backhouse (1991) has identified the palynomorphs *Pseudoreticulatispora pseudoreticulata* and *Striatopodocarpites fusus* in these sediments, indicating a range in age from Asselian to ?Tastubian at the base to Early Aktastinian–Sterlitamakian at the top.

Depositional environment: The Westralia Sandstone was deposited in a proglacial lacustrine delta setting associated with the climatic amelioration and glacial retreat of the Gondwana ice sheet. The palaeo-environmental model envisaged is similar to that outlined by Le Blanc Smith and Eriksson (1979).

Ewington Coal Measures

Definition: The Ewington Coal Measures ('Ewington' and 'Collie' Horizons of Lord, 1952a; 'Ewington Member' of Playford et al., 1975) is the oldest coal-bearing unit in the Collie Basin. The Ewington Coal Measures lies conformably above the Westralia Sandstone and is conformably overlain by the Allanson Sandstone. The unit consists of interbedded poorly sorted feldspathic sandstone, carbonaceous shale, clast-supported conglomerate, and coal.

The type section of the Ewington Coal Measures is the interval between 336 and 393 m (a total thickness of 57 m) in Stockton Diamond Drillhole No. 3 (Site J) (Playford et al., 1975), which is now known as GOV-DD-J (33° 24' 00"S, 116° 13' 30"E). Core from this hole was discarded. Western Collieries Limited have contributed reference coreholes WCL-P-D226 (33° 24' 22"E, 116° 15' 49"E; Plate3), in which the Ewington Coal Measures occurs from 41 to 101 m, and WCL-P-D224 (33° 24' 34"S, 116° 17' 17"E; Plate 3) from 69 to 128 m.

The Ewington Coal Measures is the most areally extensive coal-bearing unit in the basin and can be correlated across the whole coalfield and into the adjacent basins, including the Perth Basin.

Lithology: The unit comprises a cluster of relatively thick coal seams intercalated with sandstone and siltstone over a vertical interval of approximately 60 to 80 m (Plates 4 and 5). The succession shows marked similarity to the underlying Westralia Sandstone, with the exception that it contains substantial coal seams. The depositional motif is predominantly stacked, coal capped, upward-fining cycles. There is a predominance of sandstone over argillaceous rock. The ideal cycle comprises, from the base upwards:

(a) sandstone, a few metres thick, that is erosively based, poorly sorted, coarse to fine grained, buff coloured and subarkosic containing stacked cross-bed cosets;

(b) a relatively abrupt upward gradation, over a few tens of centimetres, into rippled fine- to medium-grained, pale-grey to buff-coloured sandstone. The upper portions become interlaminated over a few tens of centimetres with dark-grey carbonaceous siltstone;

(c) laminated dark-grey siltstone, with occasional plant fossils, that is capped by up to a metre of dark, brown-grey carbonaceous mudstone which may host frequent sub-vertical carbonaceous to coaly filaments;

(d) coal, from a few centimetres to 5 m thick. The coal is black, bituminous and predominantly banded with a blocky cleat. Dull to lustrous coal predominates with vitrinite generally confined to sparse bands up to 3 cm thick.

The basal contact of the cycle may be strongly erosional into the underlying unit and associated with intraformational conglomerate characterized by clasts of siltstone and infrequent macerated carbonaceous detritus.

The cumulative coal thickness in the Ewington Coal Measures is approximately 12 metres. There are three principal coal seams (Moira, Stockton, and Wallsend) and a number of lesser seams and local seamlets. Sandstone units cause these seams to split and coalesce across the coalfield, with individual seam thicknesses varying from over 5 m to less than a metre.

The naming of seams is inconsistent. The principal seams are known by different names depending on the location and mining history. Seam splitting is complex in some areas and, consequently, a plethora of names and correlations has evolved across the coalfield. The most widely used names in the Ewington Coal Measures are given in Table 5.

Stratigraphic relationships: The Ewington Coal Measures can be correlated with equivalent units in the Wilga, Boyup, and southern Perth Basins (Fig. 1), and with the Irwin River Coal Measures of the northern Perth Basin.

Fossils and age: The Ewington Coal Measures are Early Permian (Artinskian), and lie beneath the Early Baigendzhinian *Praecolpatites sinuosus* Zone, span the Aktastinian *Microbaculispora trisina* Zone and lie above the Early Aktastinian–Sterlitamakinian *Striatopodocarpites fusus* Zone, as identified by Backhouse (1991) (Table 4).

Depositional environment: The Ewington Coal Measures were deposited in a proglacial lacustrine-delta platform setting associated with the climatic amelioration and glacial retreat of the Gondwana ice sheet. The palaeoenvironmental model envisaged is similar to that outlined by Le Blanc Smith and Eriksson (1979) and Le Blanc Smith (1980a) for the situation occurring near the margin of an interior sag basin.

Table 5. Examples of principal seam names in the Ewington Coal Measures; Collie Basin

Principal seams	*Other names*	*Company code-names*	
Ewington Upper		E1U	E05
Ewington 1		E1S	E06
Ewington 1 Lower		E1L	E07
Iris		IS	E08
Ewington 2		E2S	E09
Priam		PRS	
Moira	Achilles	MS	E10
Moira Lower	Achilles Lower	MSL	
Stockton	Ajax	SS	
Stockton Lower	Ajax Lower	SL	
Homer		HOS	E20
Wallsend	Ares	WLS	E30
Wallsend Lower	Ares Lower	WL	E32
Ewington 5			

Allanson Sandstone

Definition: The Allanson Sandstone is a unit of poorly sorted cross-bedded feldspathic sandstone, subordinate small-pebble conglomerate, siltstone, carbonaceous shale, and sporadic coal, which lies conformably above the Ewington Coal Measures and is conformably overlain by the Premier Coal Measures. The unit is approximately 125 m thick and essentially barren of substantial coals, but coal is nonetheless present in numerous seams that range from a few tens of centimetres to over 1.5 m thick in the Hymen Seam (Plates 4 and 5). The type section of the Allanson Sandstone is the interval 285 to 441 m (a total thickness of 156 m) in diamond drillhole WCL-P-1008 (33° 22' 37"S, 116° 16' 58"E; Plate 3). The Allanson Sandstone is named after the town of Allanson in the northwest of the basin.

Lithology: The section is composed of numerous upward-fining cycles (dominated by sandstone) in which the ideal cycle comprises, from the base upwards:

(a) Sandstone that is generally cross-bedded, very poorly sorted with a subarkosic composition, medium to very coarse grained with beds of small-pebble conglomerate. The basal contact frequently shows erosional characteristics, displaying an angular contact associated with very coarse grainsize and occasional armouring with a pebble lag. Where the cycle overlies a siltstone or carbonaceous shale, the matrix in the 30 cm above the contact is frequently darker than elsewhere and may contain shale-clast intraformational conglomerate. The coarser grained material of the cycle base fines upward gradationally, yet relatively abruptly, into

(b) Sandstone that is of similar composition to (a) but cross-laminated and medium to fine grained. There is generally an upward transition where the size of the cross-stratification set diminishes. This unit is relatively thin, generally not exceeding 3 m, and most often less than a metre thick. The cycle fines upward into

(c) Siltstone that is generally under a metre thick, light grey, laminated, and which may contain thin fine- to very fine-grained sandstone laminae and occasional lenses that diminish in thickness and frequency upwards, and

(d) Mudstone a few tens of centimetres thick that is dark grey, laminated and carbonaceous with occasional plant fossils, and

(e) Rarely, coal a few centimetres thick. Occasionally a seam over 1 m thick may be developed, as in the case of the Hymen Seam.

These argillaceous and coaly units are observed less frequently; this is attributed to a lower preservation potential than the basal portions of the cycle.

Stratigraphic relationships: The Allanson Sandstone can be correlated to equivalent units in the Wilga, Boyup, and southern Perth Basins.

Fossils and age: The Allanson Sandstone is Early Permian (Artinskian) and lies within the Early Baigendzhinian *Praecolpatites sinuosus* Zone of Backhouse (1991) (Table 4).

Depositional environment: The Allanson Sandstone was deposited in an alluvial plain–upper wet fan-delta platform near the margin of an interior sag basin in a cold-temperate climatic setting.

Premier Coal Measures

Definition: The Premier Coal Measures ('Premier Member' of Playford et al., 1975) consists of interbedded poorly sorted feldspathic sandstone, carbonaceous shale, clast-supported small-pebble conglomerate, and coal. The unit lies conformably above the Allanson Sandstone and is overlain, apparently conformably, by the Muja Coal Measures: the upper contact is the base of the Iona Coal Seam. Interpretation of vitrinite reflectance data suggests there may be a lacuna at the contact. The most common depositional motif comprises stacked upward-fining sandstone to siltstone cycles, which are commonly coal capped. The cycles become more argillaceous towards the top of the Premier Coal Measures.

The 'Premier Member', 'Chicken Creek Member', and 'Collieburn Member' (Playford 1975) now appear to be vertically overlapping stratigraphic units and it is proposed that the terms 'Chicken Creek Member' and 'Collieburn Member' be abandoned. The Premier Coal Measures includes strata from the 'Premier Member' and lower portions of the 'Collieburn Member' as defined in Playford et al. (1975). A reference section of the Premier Coal Measures in the Premier Sub-basin (Plate 3) is a composite of two intervals: (a) the interval between 7 and 68 m (a total thickness of 61 m) in drillhole WCL-F-1031 (33° 22' 30"S, 116° 17' 19"E), which links downwards at the top of the Premier 2 coal seam to (b) the interval between 18 and 265 m (247 m) in drillhole WCL-P-D230 (33° 22' 28"S, 116° 16' 42"E). The reference section can be correlated by a marker coal seam common to the two respective drillholes.

Core from these former coreholes is stored at the WCL core store at Collie.

An additional reference section for the Premier Coal Measures is proposed for the Cardiff Sub-basin (Plate 3) and is taken as the interval between 145 and 325 m (180 m) in drillhole WCL-P-D236 (33° 25' 56"S, 116° 13' 24"E), and linking downwards at the base of the Griffin seam to the interval between 355 and 458 m (103 m) in drillhole GOV-DD-B (33° 26' 18"S, 116° 13' 42"E).

The Premier Coal Measures are up to 320 m thick and are best preserved in the southern portions of the basin (Plates 4 and 5).

Lithology: The unit consists of a multitude of thick and thin coal seams, with intercalated sandstone and siltstone, prevailing over a vertical interval of approximately 320 m (Plates 4 and 5). The succession shows a similarity to the underlying Allanson Sandstone, with the exception that it contains substantial coal seams. The depositional motif is predominantly stacked, coal capped, upward-fining sandstone–siltstone cycles, but there are local upward-coarsening increments. At the base there is a predominance of sandstone over argillaceous units; however, the argillaceous units are thicker and more numerous than those in the underlying Allanson Sandstone, particularly towards the top of the unit. The ideal cycle comprises, in order of deposition:

(a) Sandstone, generally between one and ten metres thick, that is erosively based, poorly sorted, angular, pebbly coarse to fine grained, buff coloured and subarkosic with a kaolinitic-clay matrix. The dominant structure is cross-bedding with sets up to a metre thick. This unit undergoes a relatively abrupt upward gradation over a few tens of centimetres into

(b) Sandstone, usually less than a metre thick, that is ripple cross-laminated, fine to medium grained, pale grey to buff coloured with a similar subarkosic composition to the underlying unit. The cycle fines upward into

(c) Wavy- and lenticular-laminated sandstone in dark-grey siltstone between a few tens of centimetres and several metres thick. The sandstone, which may contain abundant carbonaceous detritus on the bedding surfaces, is light grey, poorly sorted, and medium to very fine grained. The unit grades upwards into

(d) Laminated dark-grey silty mudstone, ranging from a few tens of centimetres to a metre thick, that is carbonaceous with occasional plant fossils. This unit frequently hosts subvertical carbonaceous to coaly filaments (rootlets) in which case it is characterized by a dark brown-grey colour and most often overlain by

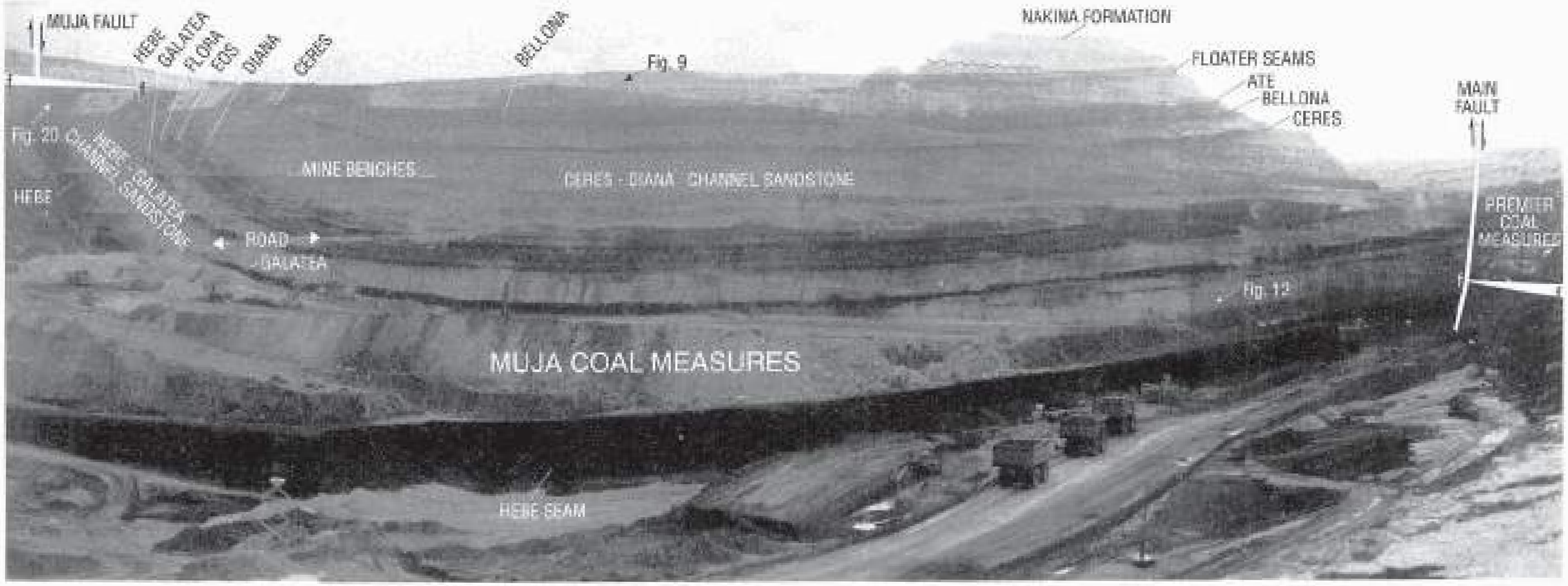


Figure 10. Muja Coal Measures exposed in montage of Muja mine north highwall showing large syncline with steeply dipping southwest limb.

(e) A coal seam from a few centimetres to up to 4 m thick. The coal is black, bituminous to sub-bituminous, predominantly banded bright with lustrous, and has a blocky cleat. Some seams contain over 70% vitrinite.

The basal contact of the cycle may be strongly erosional into the underlying unit, and may also be associated with intraformational conglomerate characterized by rip-up clasts of siltstone and sporadic black macerated carbonaceous detritus. The thinner coal seams commonly shale-out laterally into grey-black carbonaceous shale.

Stratigraphic relationships: The Premier Coal Measures can be correlated to equivalent units in the Wilga and southern Perth Basins (Fig. 1). The most widely used names in the Premier Coal Measures are shown in Table 4.

Fossils and age: The Premier Coal Measures is Early Permian (Late Artinskian to Kungurian). It spans the upper portion of the Early Baigendzhinian *Praecolpatites sinuosus* Zone, extends upwards through the Baigendzhinian *Microbaculispora villosa* and ?Kungurian *Dulhuntyispora granulata* Zones of Backhouse (1991), but lies beneath the ?Kungurian–Ufimian *Didecitriletes ericianus* Zone (Table 4).

Depositional environment: The Premier Coal Measures was deposited in an alluvial plain–upper wet fan-delta platform near the margin of an interior sag basin under cold-temperate climatic conditions.

Muja Coal Measures

Definition: The Muja Coal Measures ('Muja Member' of Playford et al., 1975) consists of interbedded poorly sorted feldspathic sandstone, carbonaceous shale, clast-supported small-pebble conglomerate, and coal. This unit lies apparently conformably above the Premier Coal Measures and is unconformably overlain by the Nakina Formation. The most common depositional motif is stacked upward-fining cycles and subordinate upward-coarsening cycles. These cycles are commonly coal capped. This unit contains the thickest coal seams in the Collie Group (Table 4).

The Muja Coal Measures includes strata from the 'Cardiff Member' and upper portions of the 'Collieburn Member' as defined in Playford et al. (1975) and (Wilson, 1990, figure 4-172) and it is proposed that these terms be abandoned. The Muja Coal Measures contains nine principal seams of economic interest (Fig. 10; Plate 3). The seams range in thickness from around a metre to a maximum of 13 m in the Hebe Seam.

The type section of the former 'Muja Member' is between 21 and 162 m (141 m) in State Electricity Commission drillhole SEC S12 (33° 26' 00"S, 116° 18' 30"E). A reference section of the Muja Coal Measures in the Cardiff Sub-basin (Plate 3) comprises (a) the interval between 12 and 76 m (64 m) in drillhole WCL-W-W653 (33° 26' 36"S, 116° 12' 24"E) which is linked downwards at the top of the Cardiff A seam to (b) the interval between 12 and 92 m (80 m) in WCL-P-D218 (33° 27' 03"S, 116° 12' 43"E), which in turn links downwards at the Abe Upper Seam (split) to (c) the interval between 158 and 307 m (149 m) in drillhole WCL-P-D86 (33° 27' 52"S, 116° 13' 17"E), which is then linked downwards at the top of the Upsilon seam to (d) the interval between 35 and 133 m (98 m) in WCL-P-D236. Core from these coreholes is stored at the WCL core store at Collie.

The reference sections may be correlated by a common marker coal seam encountered in the two respective drillholes.

A reference section of the Muja Coal Measures is proposed for the Premier Sub-basin (Plate 3) and is taken as the interval between 23 and 186 m (163 m) in drillhole WCL-F-1021 (33° 25' 17"S, 116° 18' 13"E).

The Muja Coal Measures is best preserved in the southwestern portions of the sub-basins (Plates 4 and 5).

Lithology: The unit comprises numerous thick coal seams that are intercalated with small-pebble conglomerate, sandstone, and siltstone over a vertical interval of approximately 450 m (Plates 4 and 5). The succession shows marked similarity to the underlying Premier Coal Measures, with the exception that it contains substantially thicker sandstones and thicker coal seams; up to 13 m thick in the case of the Hebe Seam. The depositional motif is predominantly stacked, coal capped, upward-fining sandstone–siltstone cycles, but there are significant upward-coarsening increments above the Hebe Seam (Plate 3). There is a predominance of sandstone. The ideal upward-fining cycle comprises, in depositional order:

(a) Sandstone that is poorly sorted, angular, pebbly, coarse to fine grained, buff coloured and subarkosic and is weakly cemented by a white kaolinitic matrix. Thickness ranges from less than a metre to 30 metres. The basal contact of the cycle may be erosional into the underlying unit and associated with intraformational conglomerate containing rip-up clasts of siltstone and coal (Fig. 11). The most common structure is cross-bedding with set size generally under a metre and arranged in coset stacks up to 30 m thick. This unit undergoes a relatively abrupt upward gradation, over a few tens of centimetres, into

(b) Sandstone, usually less than a metre thick, that is ripple cross-laminated, fine to medium grained, pale grey to buff coloured, but with a subarkosic composition similar to the underlying unit. The cycle fines upward into

(c) Wavy- and lenticular-laminated sandstone in dark-grey siltstone between a few tens of centimetres and several metres thick. The sandstone is light grey, poorly sorted, medium to very fine grained and may contain abundant carbonaceous detritus on the bedding surfaces. The unit grades upwards into

(d) Laminated dark-grey silty mudstone, ranging from a few tens of centimetres to a metre thick, which is carbonaceous with occasional plant fossils. This unit frequently hosts subvertical carbonaceous to coaly filaments (rootlets) in which case it is characterized by a dark brown-grey colour and most often overlain by

(e) Coal from a few centimetres up to 15 m thick. The coal is black, sub-bituminous, predominantly banded bright with lustrous, and has a blocky cleat. Vitrinite content commonly ranges between 40 and 60%.

The upward-coarsening increments of strata, such as are found between the Hebe Seam and the overlying Galatea Seam, (Fig. 12) comprise basal, grey, carbonaceous, sandy siltstone overlain by interlaminated rippled sandstone and carbonaceous siltstone in which the argillite diminishes upwards and the sandstone content, grainsize, and set width increases. The cycle culminates with deposition of several metres of coarse-grained cross-bedded sandstone.

Stratigraphic relationships: The Muja Coal Measures can be correlated with equivalent units in the south Perth Basin. The most widely used names in the Muja Coal Measures are shown in Table 4.

Fossils and age: The Muja Coal Measures is Late Permian, probably Ufimian or younger, and spans the ?Kungurian–Ufimian *Didecitriletes ericianus* Zone and parts of the ?Kungurian–Ufimian *Protohaploxypinus rugatus* Zone of Backhouse (1991) (Table 4).

Depositional environment: The Muja Coal Measures was deposited in an alluvial plain–upper wet fan-delta platform near the margin of an interior sag basin under cool-temperate climatic conditions.

Cretaceous

Nakina Formation

Definition: The Nakina Formation (Playford et al., 1975), or 'Collie Lake Beds' of Maitland (1919), consists of weakly lithified claystone, conglomerate, and sandstone and rests unconformably on the Collie Group (Fig. 9). The name is taken from the railway siding on the Collie–Wagin line, and the type section (9.8 m thick) at the top of the abandoned Western No. 3 open cut, 4.4 km southwest of the siding (33° 25' 02"S, 116° 15' 36"E), has been mined out. The Nakina formation unconform-ably overlies the Moira Seam of the Ewington Coal Measures, and is overlain by laterite. The thickest section exposed is about 20 m at the northern end of the Muja Opencut.

Lithology: The Nakina Formation comprises weakly lithified claystone, conglomerate, and sandstone arranged in a broadly upward-fining cycle, commonly with a strongly erosional base. The formation has cut down into the Collie Group and contains rip-up clasts of this underlying unit. The thicker sections in the Muja opencut highwall have a basal unit that comprises a pale-grey, very poorly sorted, very coarse-grained sandstone or sandy small-pebble conglomerate with medium and large trough and planar cross-bedding stacked in cosets up to 6 m thick and of westerly orientation. Reactivation surfaces are common and are generally marked by finer grained silty drapes on the foresets. Set size diminishes upwards and grades into micaceous, horizontally intercalated sandstone, siltstone, and grey claystone up to 6 m thick.

Figure 11. Channel sandstone showing erosive basal contact cut into the Diana Seam; Muja Opencut

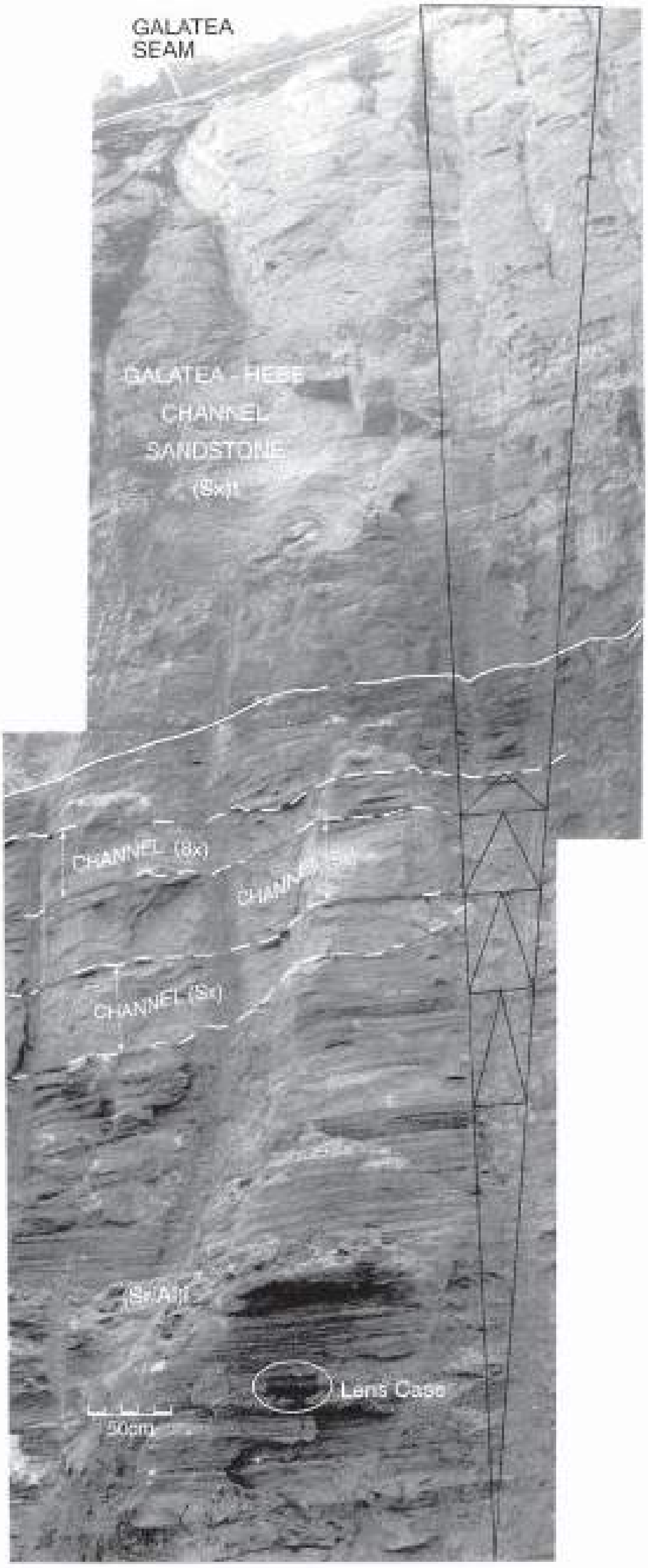


Figure 12. Upward-coarsening section of strata between the underlying Hebe Seam and the Galatea Seam, Muja Opencut northern highwall

Stratigraphic relationships: The Nakina Formation is approximately equivalent to the Donnybrook Sandstone and Leederville Formation and possibly the 'Maxicar Beds' of the Perth Basin (Backhouse and Wilson, 1989).

Fossils and age: The Nakina Formation contains reworked Permian palynomorphs and an assemblage of Cretaceous miospores, acritarchs, and algal cysts and is of Cretaceous age, probably Barremian to early Aptian (Backhouse and Wilson, 1989).

Depositional environment: The Nakina Formation shows evidence of deposition in high-energy channels, and overbank and ponded settings in what was possibly a freshwater fluviolacustrine environment.

Tertiary

Laterite

Laterite covers a large portion of the Collie Basin; in general, it caps all the ridges. The laterite over the coalfield is generally lower in both iron and alumina (bauxite) content than that over the adjacent basement areas (Lord, 1952a).

Biostratigraphy

The first comprehensive analysis of the palynomorphs in the Collie Basin was by Balme (1952). More recently Backhouse (1990, 1991) has sequentially divided the Permian succession at Collie using biohorizons based on first appearances of selected spore and pollen taxa. These taxa were selected to conform where possible with those previously used to define palynostratigraphic units in eastern Australia (see Kemp et al., 1977; Price, 1983). These subdivisions are correlated with the lithostratigraphic units of the Collie Basin in Figure 13.

Within the small area that comprises the Collie Basin these biohorizons can be viewed as chronohorizons. A palynostratigraphic range chart for the Collie Basin is contained in Backhouse (1991), and general geological timescales are provided by Harland et al. (1989) and Archbold and Dickins (1991).

Tectonics

Fracturing and controls on fracture distribution

Recent drilling and structural mapping in the mines has confirmed the presence of extensively faulted margins to the basin, against which coal seams are locally folded and abruptly truncated (Fig. 14; Plate 2).

Archaean basement adjacent to the boundary faults, as observed in opencuts and in drillhole core, displays intense metamorphic foliation and fracturing (Fig. 15). Bogacz (1992) determined that the maximum concentration of surfaces strikes northwest at around 210–230° (Fo1) with congruent patterns between the metamorphic foliation and the shear, fault, and joint surfaces.

Most of the fracturing in the basin displays an orthogonal relationship between specific steep to vertical sets of joints and cleats (Bogacz, 1992, figs 10, 11 and 12). The geometry of the J1–J2 (longitudinal) and J3–J4 (transverse) joint sets indicates dominant northwesterly and northeasterly structural trends, whereas the cleat in the coals displays a predominantly northerly trend with a subordinate westerly trend (Bogacz, 1992, figs 10 and 11).

Specific minor structures on joint and shear surfaces reflect phases in the development of the basin's structural regime. Figure 16 shows how they can be arranged in a sequence which reflects the development of the increasing role played by the shear component during the process of failure (Bogacz, 1992). Initial failure was tensile/shear related with an axis of failure in the horizontal plane as interpreted from small en echelon fractures, fringe structures, tectonic ribs, and slickensided slip surfaces with initial horizontal tectonic scratching. Shear forces increased, with a change in shear failure to a vertical plane with the development of tectonic ribs and step-like breaks with vertical tectonic scratching. These minor structures indicate that initiation of joint formation was associated with horizontal extensional to extensional/shear stresses due to the strike-slip component of movement. The onset of northwesterly trending faulting was associated with relatively high confining pressure due to depth of burial, and higher normal forces which promoted normal-slip shearing associated with diagenesis and compaction.

Exposures in mine opencuts show that low-angle dipping structures display normal-slip kinematics, whereas high-angle dipping structures are reverse-slip shear/fault structures. Bogacz (1992) interpreted these structures as the result of vertical movement of basement with a diagnostic pattern indicative of the sense of movement (Fig. 17).

Folding and fold-related features

Several orders of weak folding are present in the basin. The largest is on the basinal scale and has an axis that plunges at a few degrees to the southwest and essentially constitutes the basin itself, with each sub-basin half-graben preserving a portion of this broad, plunging synclinal structure. The northern and southern limbs dip at approximately 6° towards the sub-basin centres. The wavelength of this fold structure is greater than 25 km.

The second order of folding is essentially at the sub-basinal level with fold axes that generally parallel the northwesterly basin axis. The limbs are asymmetric with steep, short southwest limbs and essentially flat-lying, extensive northeasterly limbs. The steepest folds are associated with the basin boundary faults and display high drag with intensive extension and elongation of the sequence. An example is the large northwesterly trending syncline exposed in the Muja Opencut in the Premier Sub-basin, between the Muja Fault (western boundary fault) and the intrabasinal Eastern Fault (Fig. 10). The Muja and

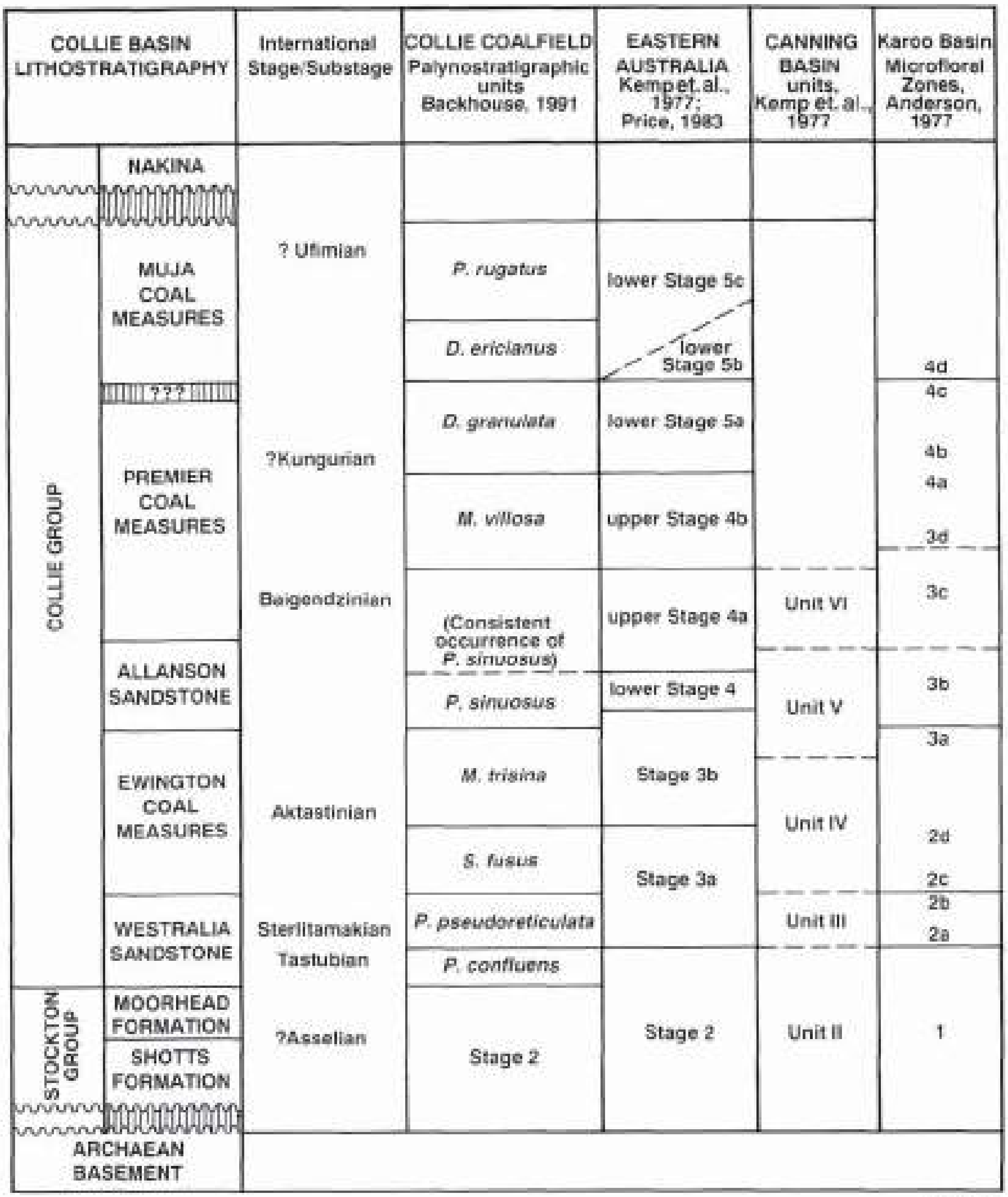


Figure 13. Suggested correlation of Collie Basin ages, lithology and palynostratigraphy with other Gondwana palynostratigraphic schemes

Premier Coal Measures are folded up against the near vertical Muja Fault at angles up to 75° (Fig. 14). The northeasterly dip in the southwestern limb diminishes eastwards into the sub-basin and reverses to a dip of a few degrees southwest in the opposing limb (Fig. 18). This feature is interpreted as a drag fold associated principally with post-depositional tectonics early in the diagenetic history.

These folds are interpreted as having formed during faulting and rotation of basement blocks. A characteristic series of extensional normal-slip faults was thus produced in the sedimentary strata (Fig. 17) together with weak folds with flat to moderately inclined limbs. These account for a large part of the tectonic transport and corresponding tectonic shortening of the sequence (Bogacz, 1992). Figure 19 shows a mechanism whereby such folds were formed by flexural-slip, with tectonic transport along the existing bedding surfaces being a consequence of basement faulting and block rotation. This mechanism produced reverse-slip shearing along bedding surfaces and contributed to the tectonic shortening.

There are two populations of synclinal structure (Plate 2). One population has an axis azimuth that lies at a low (oblique) angle to the principal faults, is generally asymmetric and is associated with dip-slip movement; the other population is oriented at a high angle to the fault

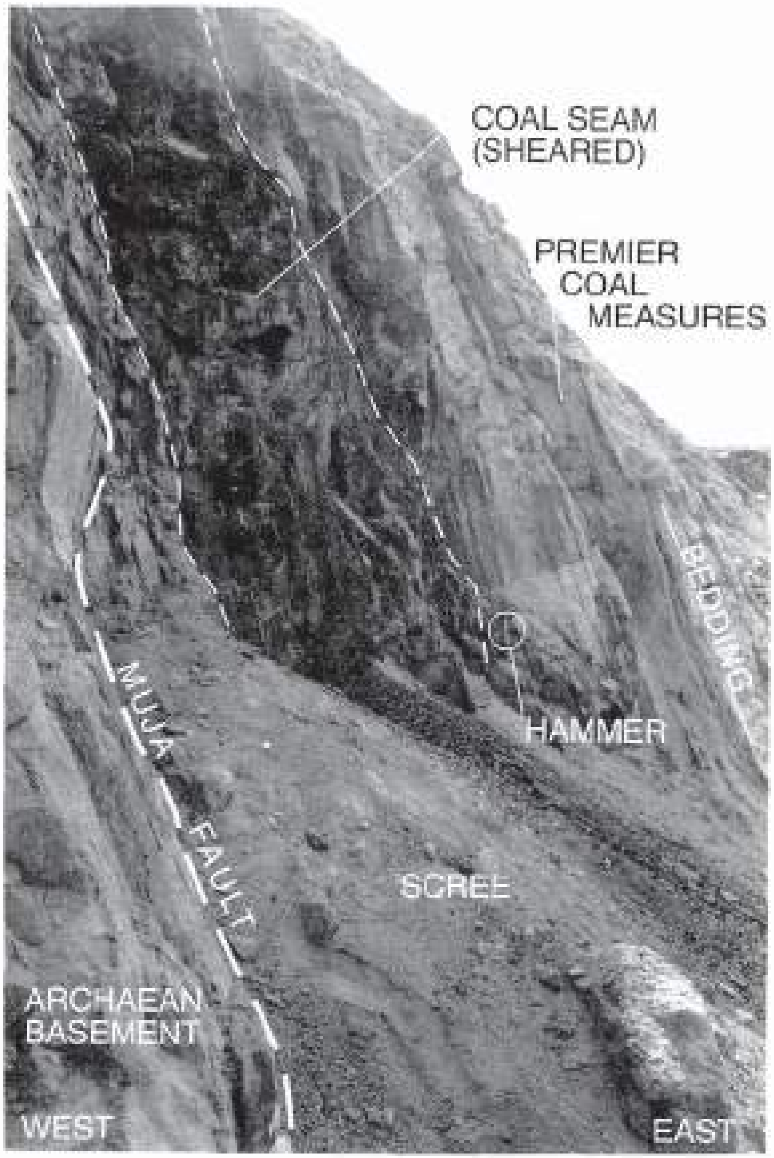


Figure 14. Northwesterly view of steeply dipping coal seam from the Premier Coal Measures abutting basement on the Muja Fault in the west highwall of the Muja Opencut. The Muja Fault at this site has a dip-slip displacement of over 800 m

planes, is more symmetric, commonly occurs in fold trains, and is interpreted as being generated by a component of strike-slip movement on the faults.

A pattern of smaller en echelon weak folds occurs adjacent to the steep dip-slip faults (Plate 2). In some instances the fold trains are out of phase, producing discontinuous faults with variable throws and instances of scissoring. There appears to be no clearly preferred fold orientation although a number of domains are present which may be interpreted respectively as left-lateral (e.g. eastern boundary fault; Premier Sub-basin) and right-lateral (e.g. north Premier Sub-basin) simple shear processes (Sylvester, 1988, fig. 16). This may indicate that, at this scale, there was a number of principal displacement zones and several phases of deformation.

Faulting and fault-related structures

Most of the intra-basinal faulting that displaces the coal strata has a northwesterly strike which broadly subparallels both the basinal axis and the major basin-bounding faults (Plate 2). These intra-basinal faults commonly impinge at a low angle onto the basin-bounding faults and display a highly variable dip-slip component which, at some locations, can range from zero to over two hundred metres within a strike length of a kilometre. A

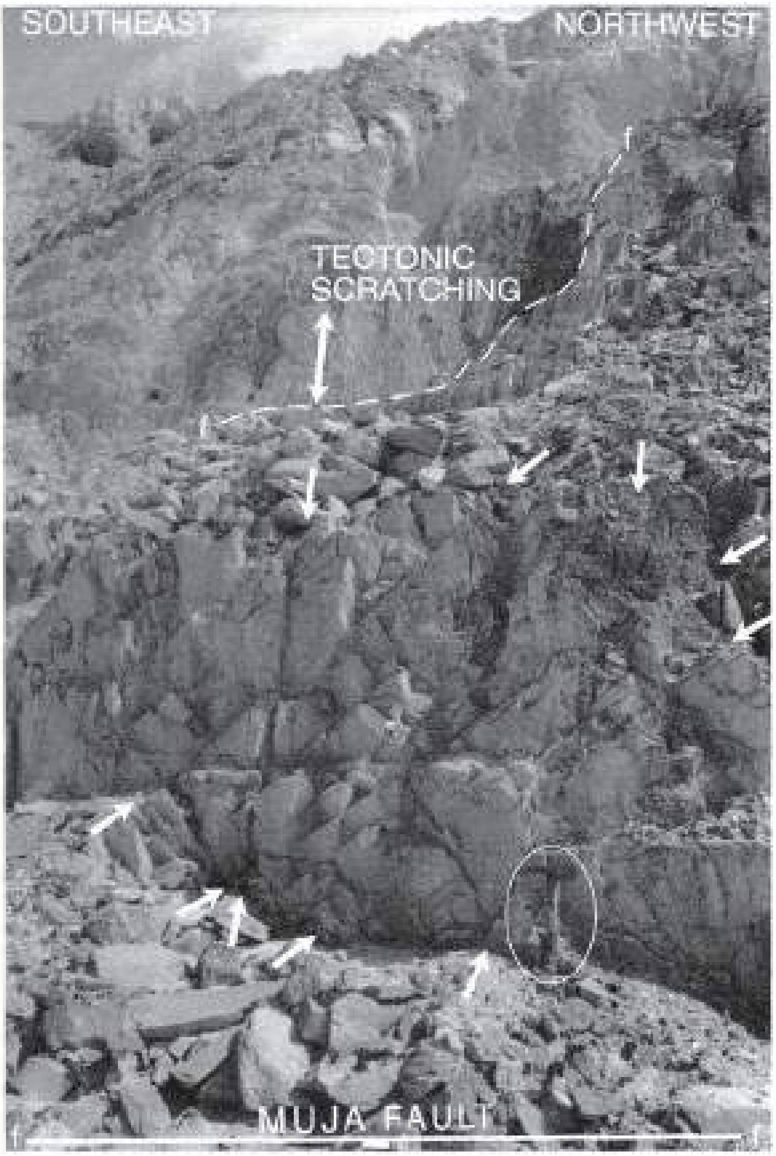
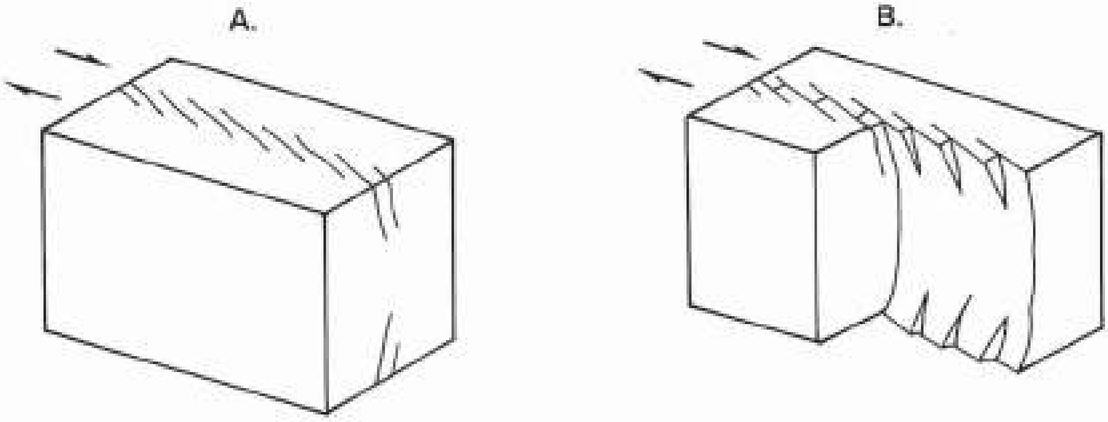


Figure 15. Extensional fractures and metamorphic foliation in crystalline basement exposed along the Muja Fault, west highwall Muja Mine Opencut

number of faults display dip-slip reversals along strike. Fault bifurcation, en echelon faults, and folds are common. Many of the variations in dip-slip movement are associated with low-amplitude folding within the coal-bearing strata.

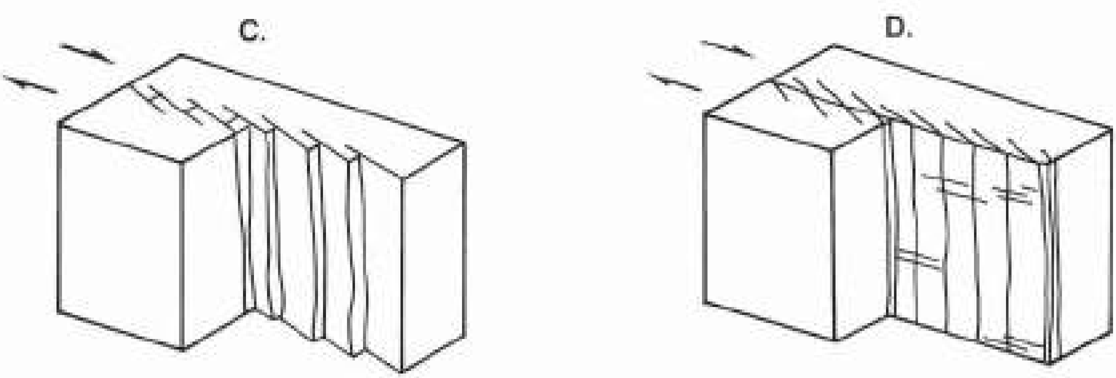
The dominant kind of faulting in the basin is steep dip-slip with dip angles of 60–90°. For example, the Muja Fault contact between the Collie Group and basement has a maximum dip-slip of over 800 m and strikes northwest with a northeast dip of approximately 80°. The Muja Fault is abutted on the one side by basement characterized by intense metamorphic foliation and fracturing, with near-vertical chloritic phyllonite, small dolerite dykes, and gneiss. On the other side, the fault is abutted by coal-bearing strata inclined at up to 75° with many small-scale high-angle faults and fractures, but no soft-sediment deformation (Fig. 20). The prevalence of steep dip-faults is greatest in areas with large basement movements. Splay faults are a common feature in the proximity of the Muja Fault. The splay faults are characterized by steep dips (70–80°), small displacements (5–50 m), and tectonic ribs indicative of a right-lateral shear component (Fig. 21). The faulted contacts are sharp with no evidence of seam splitting, quality degradation, or significant variation in bedding or thickness as could be expected adjacent to a syn-depositional fault. Small in-seam sandstone lenses (anastomosed channel sandstones) occur locally in the Hebe Seam but display the same bedding orientation as the seam bedding plies, which are inclined at a high angle adjacent to the Muja Fault. The lack of soft-sediment deformation in the vicinity of faults strongly indicates post-depositional displacement.

Sporadic exposures (e.g. Stockton Colliery shaft) reveal reverse-throw faulting with displacements of the order of a few metres. The strike of the reverse faulting



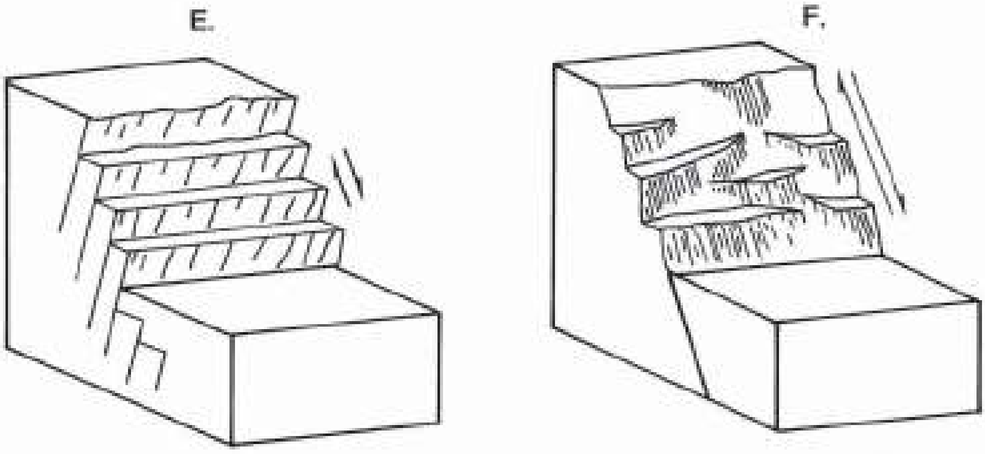
Series of en echelon fractures

Fringe structures



Tectonic ribs

Slickensided slip surface
with first tectonic scratches



Tectonic ribs with
vertical tectonic scratching

Tectonic scratches and step-like breaks

Structures are propagated in horizontal (A–D) or vertical (E–F) plane

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Figure 16. Schematic geometry and pattern of minor right-lateral extensional shear (A–D) and normal-slip shear (E–F) structures observed in the Collis Basin (adapted from Bogacz, 1992)

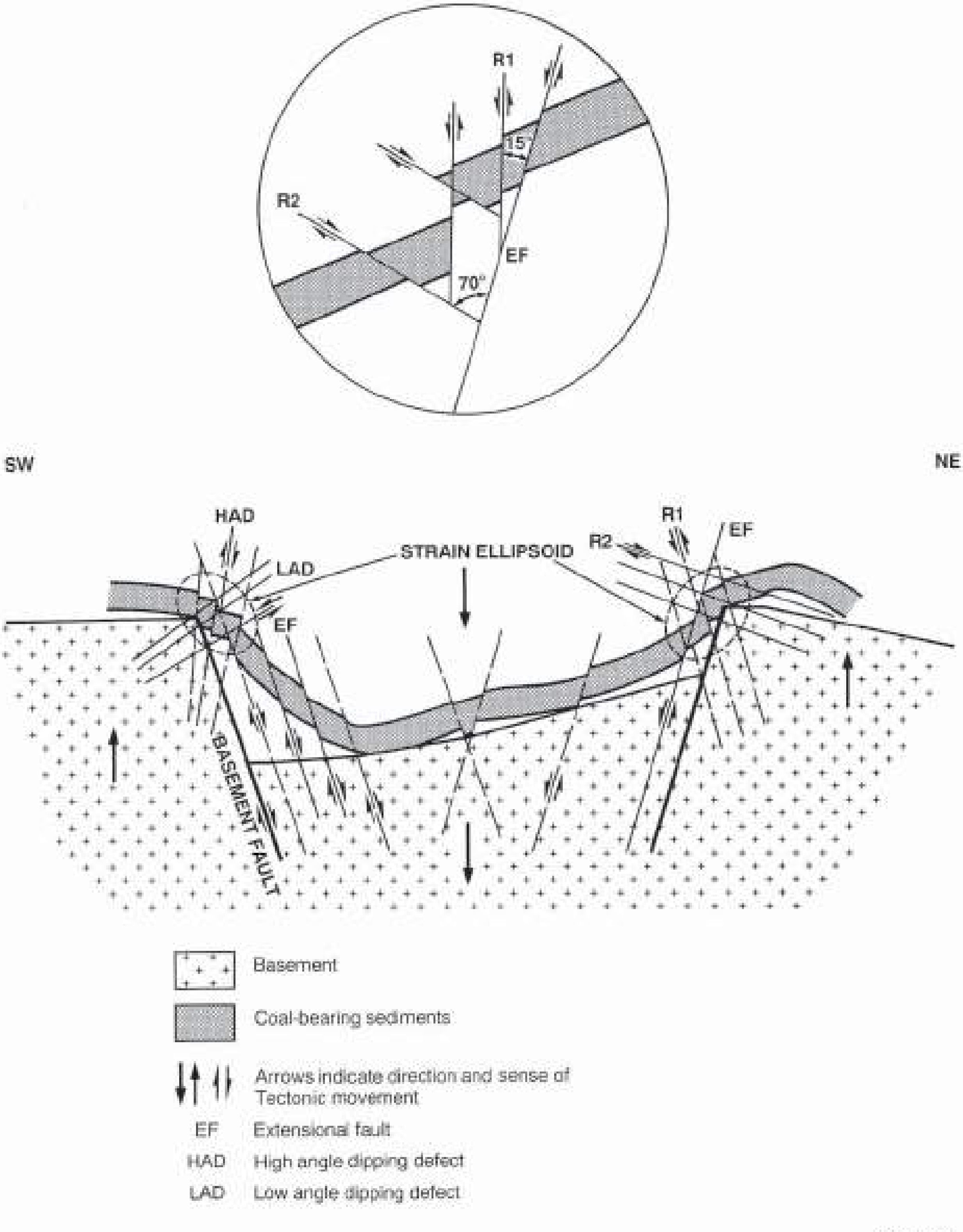


Figure 17. Tectogenetic explanation of the major structural features observed in the Collie Basin (after Bogacz, 1992)

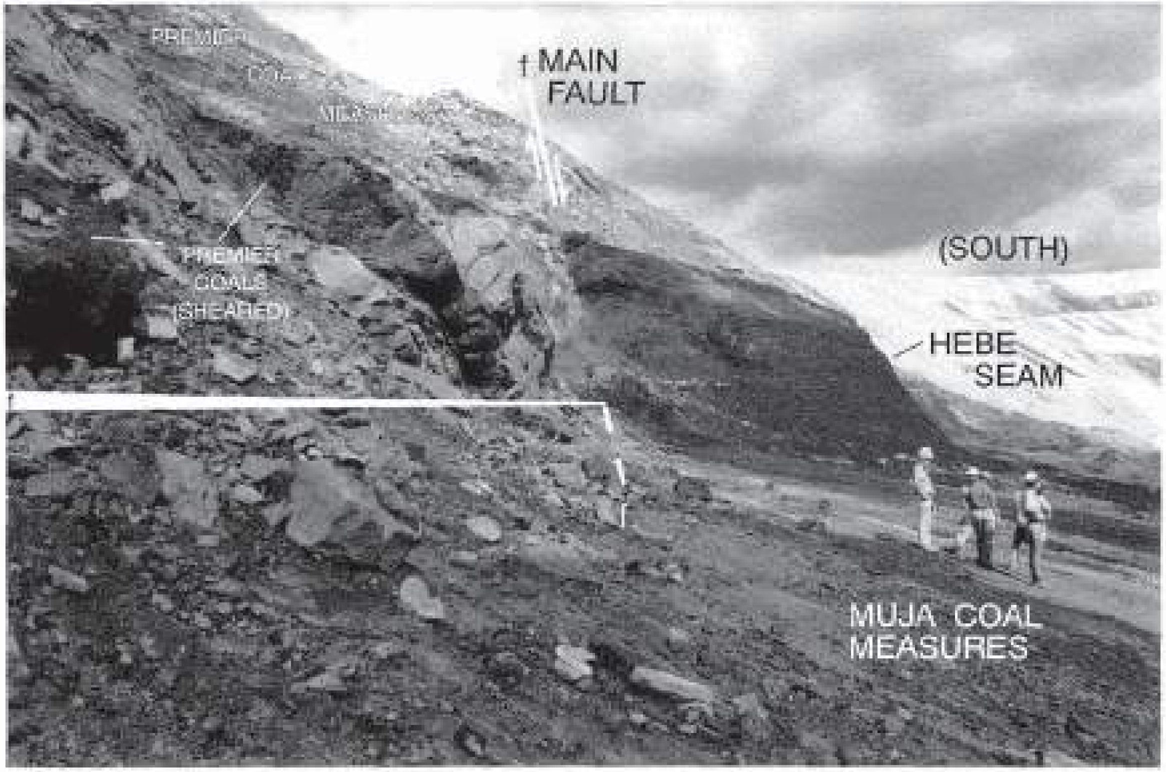


Figure 18. Exposure of the steep intrabasinal Main Fault contact between the westerly dipping Hebe Seam in the eastern fold limb of the Muja Syncline and the Premier Coal Measures; Muja Opencut

is northeasterly and essentially normal to the basinal long axis.

The presence of near-vertically oriented phyllonite along the Muja Fault can be interpreted as evidence that the major fault planes are associated with a reactivation of ancient shear planes, which are probably related to strike-slip faults in an extensional (transtensional) setting. High-angle dip-slip faulting is indicative of high load and extensional conditions (F1>F2>>F3) exerted by movements in the crystalline basement (Bogacz, 1992), and signifies that a substantial thickness of sedimentary cover existed at the onset of tectonic movements. The interplay among the intrabasinal faults outlines domains of uplift and subsidence within the basin. Secondary pull-aparts in the basin form unconnected domains of local subsidence which, taken in combination, impart an intense, wholesale subsidence to the entire basin (Fig. 22).

These structures in combination form patterns that can possibly be divided into domains and interpreted in the context of right- and left-lateral shear as depicted in Sylvester (1988, fig. 12). The structures in the Collie Basin can also be studied by fault-azimuth analysis (Lowell, 1985). The fault azimuths in the Collie Basin are oriented in a northwesterly direction in a tight envelope (Plate 2) and strongly suggest that wrench (strike-slip) tectonics influenced the development of the basin. Fault-trend analysis shows that the dominant fault trend parallels the Zenith–Wallaby Fracture Zone (Marshall and Lee, 1988), which delineates the direction of continental breakup between Australia and Greater India during the Cretaceous.

The available data suggest that the Collie Basin was deformed by northwesterly movements (Le Blanc Smith, 1989), possibly right-lateral, which had a low displacement and high drag (Middleton, M. F., 1990, pers. comm.). The process preserved an extensional basin in a transtensional setting. Bogacz (1992) interpreted the movement process as producing a normal stress field that was slightly oblique. This gave a dextral horizontal component which significantly influenced the pattern, type, and geometry of the faults in the basin. Thus, the basement blocks in the basin moved downward along the northwesterly trend, with a concurrent tilting of the blocks towards the southwest. These movements produced the asymmetry of the sub-basins and resulted in zoned structural development associated with intensive extensional movement. Concomitant faulting and shearing, particularly on the steeper fold limbs, is associated with the basin-bounding faults. These movements also produced a set of conditions suitable for the development of extension-compensating structures which include flat folding, and reverse-slip and thrust shearing although these are less commonly observed.

There is an angular unconformity separating the Cretaceous Nakina Formation (Backhouse and Wilson, 1989) from the weakly folded Permian (Fig. 9) and this sets the youngest time limit on the deformation. The Nakina Formation displays a number of sedimentary

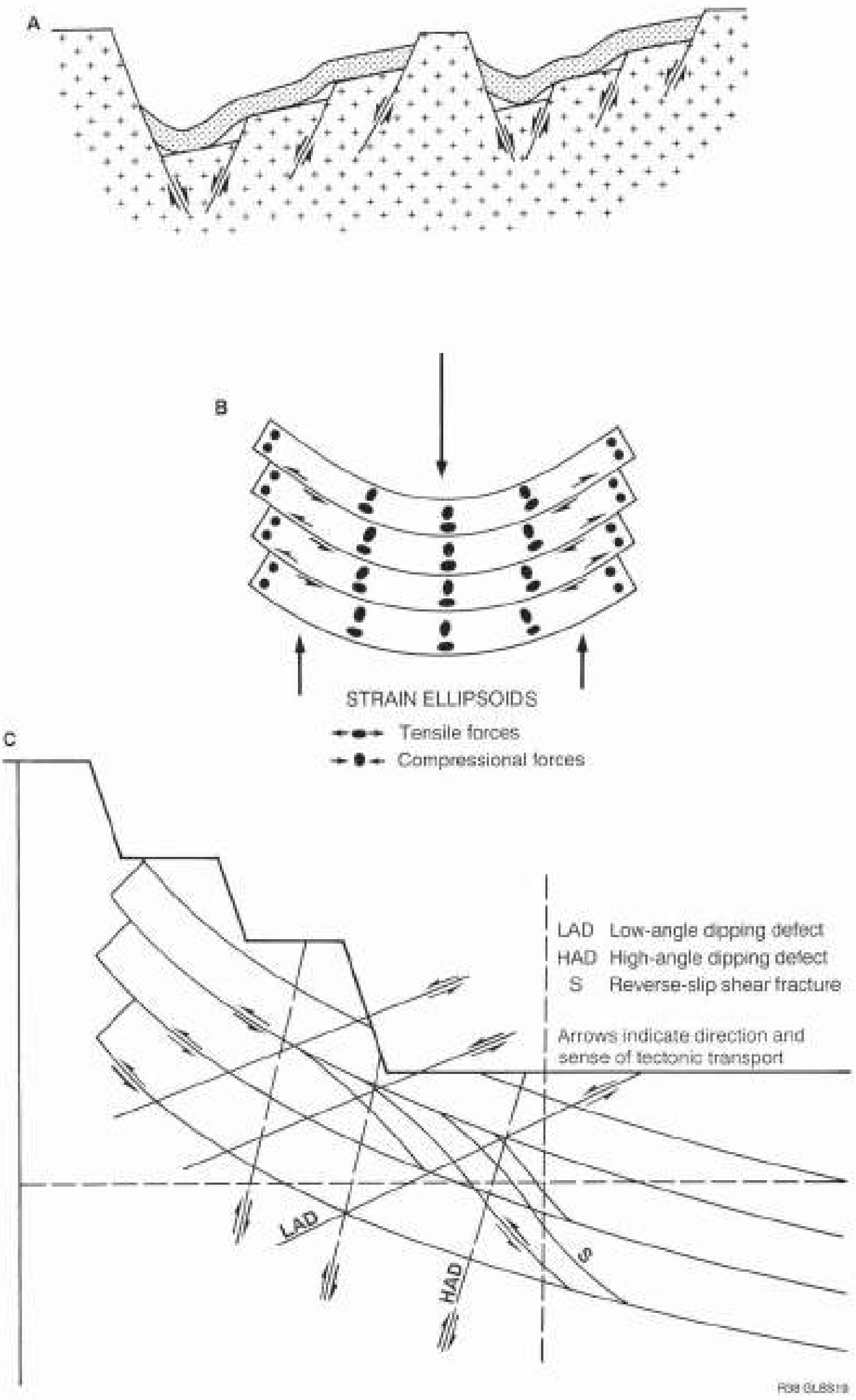


Figure 19. Conceptual folding mechanism for Collie Basin. (a) Tilting of basement blocks along northwesterly trending faults, (b) Flexural slip on bedding in overlying sedimentary strata, (c) Development of associated defect and fracture pattern in the strata (after Bogacz, 1992)

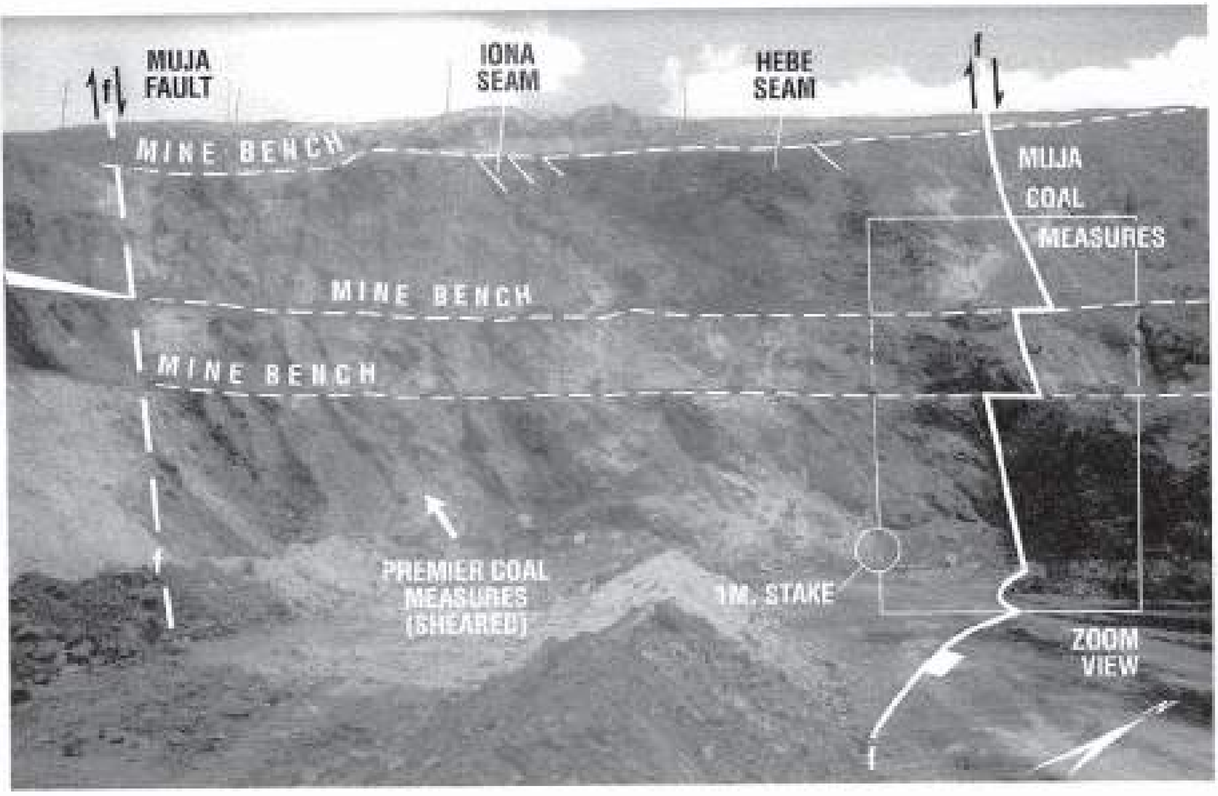


Figure 20. Tectonic structures exposed adjacent to Muja Fault, north highwall Muja Opencut. Windowed area is enlarged as Figure 21

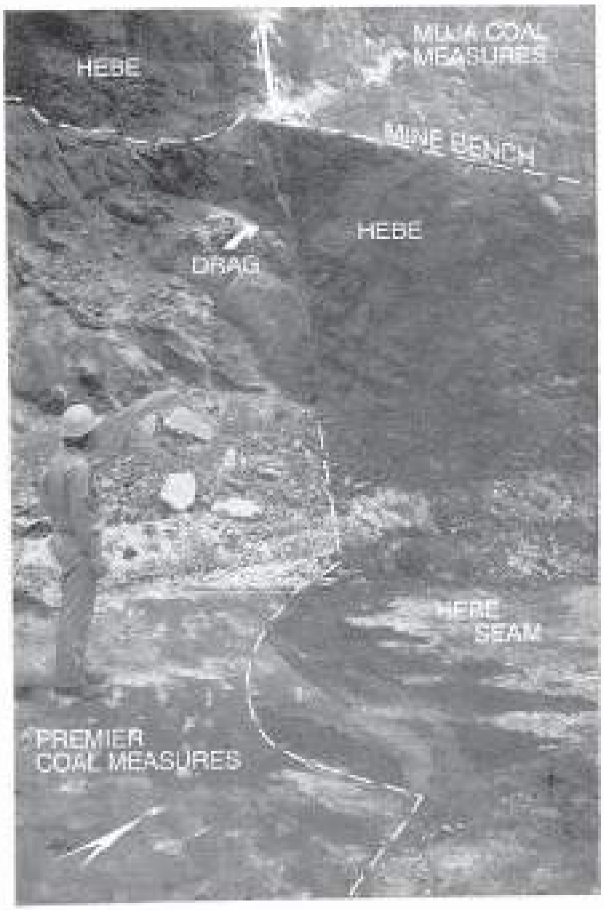


Figure 21. Hebe Seam displaced by a steep, small-scale, dip-slip splay fault, with right-lateral tectonic rib

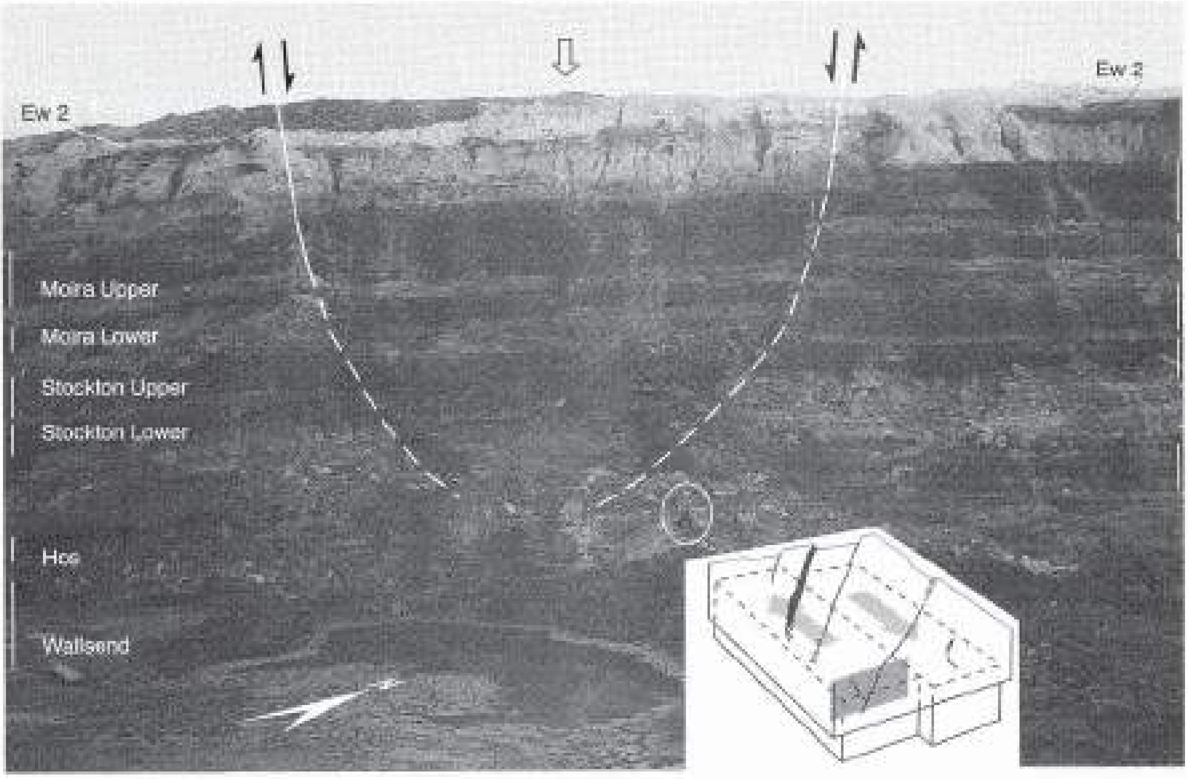


Figure 22. Small graben exposed in northeastern highwall of Western 3 Opencut illustrates extensional nature of basin and the scale of local subsidence domains

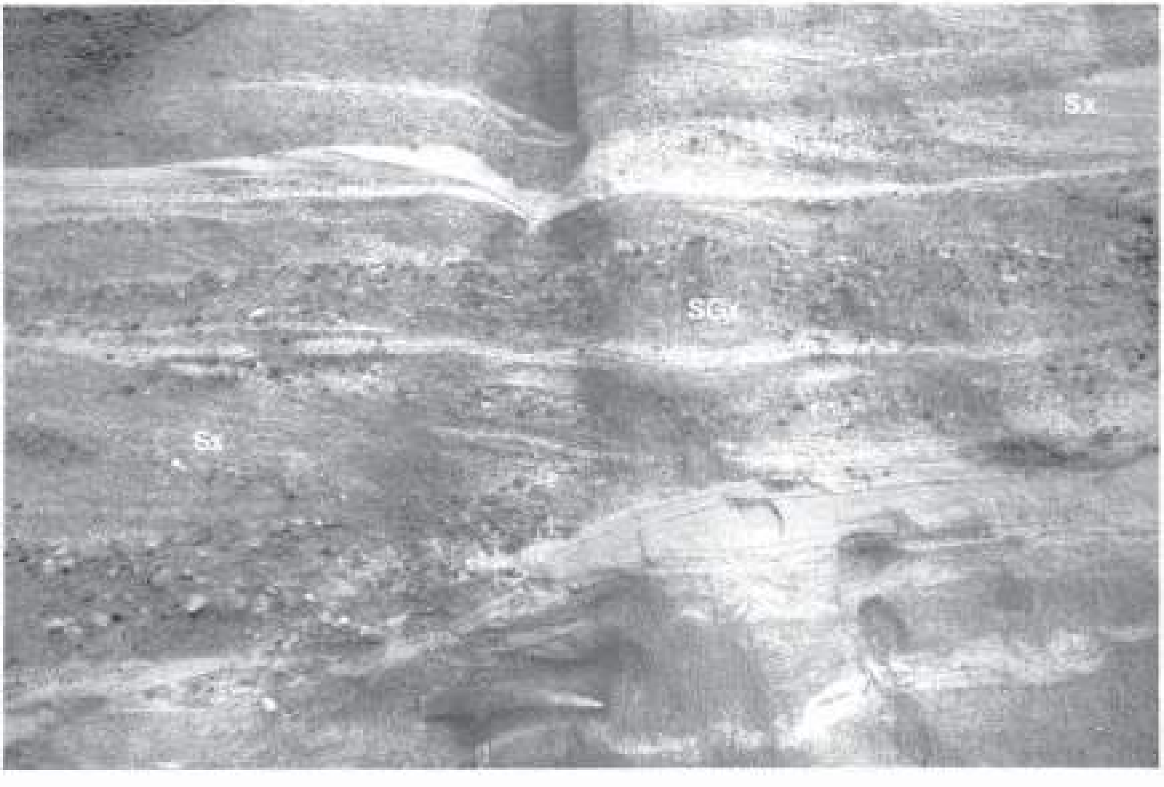


Figure 23. Channel architectural element (*CH*) consisting of Facies *SG* pebbly sandstone and Facies *Sx* cross-bedded sandstone; between Ceres and Diana seams, Muja Opencut

structures including large, westerly trending planar and trough cross-bedding (Facies *Sx*), and scour-and-fill structures with abundant rip-up clasts of Permian sediments (including coal). The westerly orientation of the Cretaceous palaeocurrents is in marked contrast to the northwesterly orientation of the underlying Permian strata measured by Wild and Walker (1978) and Wilson (1989).

This is interpreted as showing that following peat formation, preservation, and maturation the succession was faulted, folded, uplifted, and eroded. The uplift appears to have been substantial and of the order of 6.5 km (based on modelling of the vitrinite reflectance data). The folding events (probably more than one) were syn-tectonic with the faulting and predate the Cretaceous unconformity. The regional palaeodrainage flow direction changed from northeasterly in the Permian (Wilde and Walker, 1978; Wilson, 1989) to westerly in the Cretaceous, reflecting a regional tilting probably associated with the breakup of Gondwana in the Neocomian.

Tectonic and thermal history

The high frequency of coals spread through 1 km of Permian succession is indicative of sustained subsidence in the Permian. Episodic pulses of accelerated deposition caused innundation and burial of peats. The generally low ash content (below 10%) of the coals is attributed to relatively rapid peat accumulation and consequent low oxidation rates with minimal enrichment of mineral matter (ash). The low vitrinite contents of the coals low in the succession is indicative of lower subsidence rates and higher oxidation of the peats prior to preservation. The coals higher in the succession have significantly greater vitrinite contents (up to 80%) indicative of reduced oxidation and more rapid preservation.

Organic accumulation rates of between 0.5 and 1 mm per annum are considered normal in cool temperate settings (Stach et al., 1982). Other factors contributing to the rate of peat/coal formation are losses through oxidation during dry spells (inertinite), and compaction/compression effects. Stach et al. (1982) point out that the compression ratio varies from 7:1 up to the coking-coal stage in pteridosperm peats in the Upper Carboniferous, whereas Carboniferous gyttja-durites can compact by as much as 20:1. A ratio of 6:3:1 is suggested for the transition from peat to brown coal to black coal. Thus a minimum of approximately 6000–9000 years are required per metre of Collie coal, although this may contain hiatuses (inertinite bands).

Petrographically determined vitrinite reflectance data from the Collie Basin (Sappal, 1986) is sparse, although vitrinite is found in all the coal seams at Collie. Data are predominantly from the stratigraphically highest coal seams in the Muja Coal Measures, and there is a paucity for the deeper coals (Table 6).

A number of deductions may be drawn from the vitrinite reflectance data. Vitrinite reflectance is very sensitive to heat and shows a quantifiable response to heating over time (Hood et al., 1975), but is essentially unaffected by pressure, notwithstanding anisotropy (Stach et al., 1982). Using assumptions of the geothermal gradient, the burial depth of the coals can be estimated and have been calculated for a variety of geothermal gradients from vitrinite reflectance formulae derived from Iasky (1990a,b) and Stach et al. (1982). This forms a basis for assessing the coalfield's geohistory and depths at which peats were buried to form coal.

No maturation correction for geological time has been used (although such relationships have been demonstrated by Hood et al., 1975) as it is difficult to estimate how long the organic material was subjected to temperatures within 15°C of the maximum (burial) temperature. However, the effect of an increased maturation time would be a reduction in the calculated burial depth, as lower temperatures would be required to achieve an equivalent vitrinite reflectance value.

Present-day geothermal gradients have been determined from hydrogeological wells (Boyanup Line) in the adjacent Perth Basin (Commander, D. P., 1990, pers. comm.) and these lie between 21 and 31°C/km. The minimum apparent depth of burial is associated in inverse relationship with the highest geothermal gradient. A geothermal gradient of 20°C/km fits the observed variation in vitrinite reflectance over the coal-bearing vertical interval of 975 metres. The vitrinite reflectance varies over this interval from 0.41 at the top of the succession to 0.61 near the base. However, there appear to be two discrete coal populations in the basin:

1. Seams lying within the Muja Coal Measures (youngest) have the lowest reflectance of approximately 0.43, and

2. Seams lying within the Premier Coal Measures and the top of the Ewington Coal Measures have a distinctly higher rank, with reflectance of approximately 0.60.

The transition between these two populations is abrupt and occurs throughout the basin. In the Cardiff Sub-basin it occurs between the Collieburn 2 and Phoenix Seams; in the Premier Sub-basin it lies between the Premier 0 and the Iona Seams (Table 6). This 'reflectance jump' coincides with the base of the *Didecitriletes ericianus* (Backhouse, 1991) Zone and is interpreted as a lacuna with a possible disconformity between the Muja and Premier Coal Measures. A possible alternative explanation for the reflectance jump involves a very selective heat pulse (Barker, 1991) although the mechanism for achieving this is unclear.

A basic cyclic process is involved where peat is buried, thermally matures (metamorphoses), and is uplifted with a synchronous erosion of the rock cover such that coal seams are elevated to shallow (mineable) depths. The thermal maturation can be accounted for by either, or a combination of, heat pulse and geothermal gradient. The vitrinite reflectance jump outlined above suggests that the process occurred at least twice in the history of the Collie Basin. The first cycle was in the mid-Permian (approximately Kungurian–Ufimian), and is marked by the *D. ericianus* Zone. If the geothermal gradient option is applied, then an uplift of approximately 5 km is indicated which may be associated with the synchronous shallow

Table 6. **Petrographically determined vitrinite reflectance for coal seams in descending stratigraphic order, Collie Basin (modified from Sappal, 1986)**

Formation	*Seam*	*Ro (rnd)*	*n*	*s*	*Range*	*Ro (max)*
		Premier Sub-basin				
Muja Coal Measures	Ate	0.41	30	0.02	0.38–0.45	0.43
	Ate Lower	0.42	30	0.02	0.37–0.46	0.43
	Bellona	0.42	30	0.02	0.40–0.45	0.43
	Ceres	0.42	30	0.02	0.36–0.48	0.43
	Diana	0.39	30	0.02	0.34–0.45	0.41
	Eos	0.43	30	0.02	0.37–0.46	0.45
	Flora	0.43	30	0.02	0.37–0.47	0.45
	Galatea	0.41	30	0.02	0.37–0.44	0.43
	Hebe	0.42	30	0.03	0.33–0.50	0.44
	Iona	0.43	30	0.02	0.37–0.47	0.45
Premier Coal Measures	Apis	0.58	30	0.03	0.53–0.63	0.61
	'seamlet' (at base of PCM)	0.57	30	0.03	0.51–0.62	0.60
Ewington Coal Measures	Ewington 1	0.56	30	0.04	0.50–0.62	0.59
		Cardiff Sub-basin				
Muja Coal Measures	Wyvern	0.45	30	0.04	0.37–0.51	0.47
	Collieburn 2	0.43	30	0.04	0.37–0.51	0.47
Premier Coal Measures	'Phoenix' (top split)	0.56	30	0.03	0.54–0.61	0.59
	Phoenix	0.57	30	0.03	0.51–0.61	0.60
	Griffin	0.58	30	0.03	0.51–0.64	0.61
	'Griffin' (base split)	0.56	30	0.02	0.53–0.61	0.59
Ewington Coal Measures	No data					

Notes: Ro (rnd) random vitrinite reflectance
Ro (max) maximum vitrinite reflectance
n number of samples
s standard deviation

marine deposition of the Byro Group and the Kennedy Group in the Carnarvon Basin (Hocking, R. M., 1991, pers. comm.) in the northwest of the State. The second cycle is marked by the unconformity between the Permian Muja Coal Measures and the Cretaceous Nakina Formation prior to Hauterivian–Barremian times (Backhouse and Wilson, 1989). Again, the depth of cover eroded (i.e. burial depth) is approximately 4 km. This material may have been the source for the Parmelia Formation (amongst others) in the Perth Basin, as this unit contains reworked palynomorphs.

If a geothermal gradient of 20°C/km is assumed for the Collie Basin, then the suggested depth of cover-rock removed is about 6500 m. The preserved stratigraphic section in the coalfield is at least 1400 m which, if combined with the 'missing' 6500 m, yields a section thickness of 8 km. This is of similar order to the sediments preserved in the southern Perth Basin (Iasky, 1990b). These data suggest that, as envisaged by Woolnough (1916), Maitland (1919) and Montgomery (1925), a substantial thickness of sedimentary strata (up to 8 km) extended eastwards from the southern Perth Basin and covered vast areas of the present-day Yilgarn Craton on which the outliers of Collie, Wilga, and Boyup are preserved. It is likely that this cover extended much farther to the east, although probably with a steadily diminishing thickness. This pattern is suggestive of Permian sediment accumulation in a large interior sag basin (Kingston et al., 1983).

Confirmation of deep burial and an extensive sedimentary cover are provided by Glover (1952). In a petrological investigation of the sedimentary rocks in the Collie Basin, he found substantial diagenetic action on the minerals of the heavy residue had occurred, 'which involved solution and partial removal of some of these minerals'. The absence of epidote and hornblende, which are common in adjacent amphibolite ridges, can be accounted for by solution (Glover, 1952; Bramlette, 1941). This diagenetic process and loss of mafic minerals is attributed to the effects of solution by high-pressure subterranean waters at considerable depth (Smithson, 1941) under conditions of unconfined circulation (Bramlette, 1941).

An economic ramification is that significant accumulations of coal could lie in structurally favourable settings on the Yilgarn Craton even farther to the east than those of the Collie Coalfield. These could be located using gravity methods over areas flanking logical projections of major fault loci.

In summary, the combined tectonic structures of the Collie Basin form patterns that can be divided into domains and interpreted in the context of right- and left-lateral shear, as depicted in Sylvester (1988, fig. 12), with predominance of dip-slip with a component of right-lateral shear. The mode of basinal formation and preservation is attributed to the formation of extensional (pull-apart) basins that formed as a consequence of wrench tectonics and strike-slip movement on ancient faults. Segments of an areally-extensive pre-existing platform of Permian strata were down-thrown and preserved in the Collie Basin as a result of movement and tilting of the basement along ancient shears in a transtensional setting. The major tectonic events started in the Permian, with substantial uplift and subsidence events occurring as early as the mid-Permian (approximately Kungurian–Ufimian) and periodically until the Cretaceous (Hauterivian–Barremian). It is considered likely that other Permian outliers such as the Wilga and Boyup Basins will reflect similar origins and histories.

Sedimentary geology

Sedimentary facies

The petrology of the sedimentary rocks in the Collie Basin was investigated by Glover (1952), who found that:

(a) Granitic and metasedimentary formations have contributed to the sediments of the Coal Measures. There is only negative evidence that greenstones did not.

(b) The quartzite pebbles, and probably much of the quartz, have been derived from Precambrian quartzites.

(c) The proportion of heavy minerals is low.

(d) The heavy minerals garnet, kyanite, and staurolite have probably been derived directly from the parent rocks in which they were formed by metamorphic processes, and

(e) No mineral or assemblage of minerals is characteristic of any one stratigraphic unit.

The sediments in this study have been subdivided into groups with similar attributes and are termed facies. The facies concept used follows that of Moore (1949) and Selley (1970).

The information on the sedimentary rocks in the Collie Basin is principally from subsurface sources and is overwhelmingly weighted towards lithological rather than palaeontological and geophysical data. The facies developed under this emphasis stress observable lithologic variations rather than the more subjective and abstract interpretations of environment. Miall (1977) proposed a coding scheme for facies nomenclature for sediments deposited in the braided-river depositional environment. This scheme was modified into a computer compatible 'Logical-letter coding system for facies nomenclature' for use in coalfield sedimentology (Le Blanc Smith, 1980a,c), and the concept is used here.

Conglomerate facies: gravel (*G*) and diamictite (*D*)

The conglomeratic facies is relatively uncommon, occurring at the base of the stratigraphic section, and sporadically elsewhere. Within this facies individual clasts lie in the conglomerate size range, and are mostly within the granule to pebble range (2–64 mm). Two variations occur; clast-supported and matrix-supported conglomerate. The majority of small pebbles are derived from Precambrian quartzite (Glover, 1952).

Facies *Dm*: diamictite, massive

Description: This facies comprises structureless diamictite found in the Shotts Formation of the Stockton Group. The diamictite has a massive, ungraded matrix that is pale grey with a bluish to greenish tinge. The matrix is predominantly sandy, silty mudstone which supports extrabasinal, polymodal, polymictic conglomerate clasts. The clasts are rounded to very angular. The unit is a few metres thick and has been observed to overlie striated basement (Low, 1958e).

At some locations Facies *Dm* is overlain by crudely stratified clast-supported conglomerate and pebbly sandstone units a few metres thick. These units generally fine upwards over a few metres into dark-grey to brownish interlaminated siltstone and mudstone units of the Moorhead Formation (Plate 3).

Interpretation: The ungraded, unstratified, polymodal matrix-supported nature of Facies *Dm* is typical of slump, debris flow, and glacial till deposits (Harmes et al., 1975). The presence of a striated pavement underlying this facies and the mixture of rounded and very angular polymictic clasts strongly suggest that these deposits are tillites representing glacial moraines deposited at the bottom and in front of the retreating Gondwana ice sheet during the Late Carboniferous to Early Permian.

Facies *Gs*: gravel, stratified

Description: The facies comprises crudely stratified, clast-supported granule to pebble conglomerate with a poorly sorted sandstone and white kaolinitic-clay matrix (Fig. 24; Plate 3). The large clast size precludes determination of detailed sedimentary structure in core samples. The clasts are extrabasinal, most frequently quartz, feldspars, and granitoid in composition, and similar to those in Facies *Dm*. Colour is generally pale grey to creamy white. Unit thickness varies from a few tens of centimetres to a maximum of about 3 m. This facies has been observed only in core but it most probably contains cross-stratification.

Interpretation: The close association of thick, areally extensive coal seams with the conglomeratic facies, together with the underlying tillite of Facies *Dm*, indicates a cold-temperate and probably glacially influenced environment which could include alluvial fan (wet), multi-channel stream, and shoreline settings.

Sandstone facies: (*S*)

Sandstone constitutes the bulk of the stratigraphic section. Included in the sandstone facies are deposits ranging in size from fine grained to granule; the coarser beds are commonly pebbly and contain scattered small pebble-size clasts. The sorting, though generally poor, is extremely variable and suggests a close proximity to the source material. The sandstones are texturally immature and compositionally subarkosic. The coarser grained sandstones are porous and have a white kaolinitic matrix. The finer grained sandstones are associated with either a pale-brown or pale-grey to dark-grey carbonaceous siltstone matrix. Mica is not common in the sandstone facies, but some beds contain heavy-mineral grains such as garnet.

Facies *Sx*: sandstone, cross-bedded

Description: This facies comprises undifferentiated cross-bedded sandstone; the difficulty in interpreting the type of cross-bedding from core warrants the recognition of this composite facies. The facies comprises sandstone that is poorly sorted, medium to very coarse grained and locally pebbly (Fig. 23; Plate 3). The coarser fractions predominate. The sandstone is poorly consolidated and primarily quartzitic, although a significant feldspar component is indicated by the presence of feldspar pseudomorphs and a kaolinitic matrix from which an original subarkosic composition is inferred. The sorting is poor and rounded-pebble lag conglomerates are commonly found at the base of scour and fill structures that frequently mark the base of sandstone units. Cross-bed sets may attain 1.5 m in amplitude, with sets commonly from 0.1 to 0.5 m; coset stacks reach 30 m in thickness. The geometry of Facies *Sx* frequently displays a tabular form with a lensoid cross section; however, exact reconstructions are difficult due to faulting. This facies includes two sub-facies types: trough cross-bedded (*Sxt*) and planar cross-bedded (*Sxp*). Trough cross-bed cosets feature relatively tangential foresets and an erosional scour at the base of each set. The basal contacts are sometimes armoured with pebble lags and rip-up clasts of dark-grey or brown siltstone, and macerated carbonaceous detritus. Planar cross-bedded sets generally have a flat basal contact and also relatively straight foresets which juxtapose at a sharp angle with underlying units or sets. Cross-bed measurements by Wilson (1990) indicate that this facies has unidirectional, mostly northwesterly, palaeocurrents.

Interpretation: Cross-bedding is attributed to migrating dune and bar bedforms (Harmes et al., 1975) in channels. The trough cross-bedding variant is attributed to deposition associated with sinuous-crested bar forms at slightly higher flow velocities, whereas the planar cross-bedding is a product of straight-crested bar forms at lower flow rates. It would appear that the two forms grade into one another. Complex cosets can be attributed to deposition from migrating sand waves under conditions of unidirectional flow. Large-scale cross-bedding has been observed in many depositional settings, although in the Collie Basin it is attributed to fluvial and deltaic processes.

Facies *Sh*: sandstone, horizontally stratified

Description: This is an uncommon facies which comprises sets of horizontal to subhorizontal laminae in sandstone that is generally off-white to pale grey and coarse grained (Fig. 25; Plate 3). The facies occurs most frequently as thin units associated with Facies *Al* and *Sr*.

Interpretation: Horizontal stratification forms with deposition on a flat bed. Harmes et al. (1975) point out that for most sand, the flat-bed configuration suggests flow velocities higher than for ripple, sand-wave, or dune formation and flow depths great enough to inhibit the development of in-phase waves. An important feature is that a lower flat-bed regime exists at low flow velocities for sand coarser than 0.6 mm (Harmes et al., 1975); thus for the coarse-grained sandstone, an interpretation as lower flat-bed deposits is appropriate and is consistent with their scarcity. If primary current lineation is observed then, as evidenced by the intercalation of Facies *Al* and rippled sandstones of Facies *Sr*, the flat-bedded variant is associated with the upper flat-bed lamination regime in a setting that is otherwise relatively quiescent.

Facies *Sm*: sandstone, massive (unstratified)

Description: This facies is relatively uncommon in the cores examined. The sandstone is devoid of stratification and is generally less than 2 m thick. The top contact of the unit is usually gradational. However, the base is invariably sharp and frequently displays erosional characteristics such as mud chips and macerated plant debris. Coalified twigs are occasionally present (Fig. 26; Plate 3).

Interpretation: The absence of stratification can be attributed either to deposition of remarkably homogeneous sand or, more likely, to grain-flow processes (Middleton and Hampton, 1973). Sandstones of this type could have lost their original structure as a result of liquefaction induced by slope instability or sudden shock (e.g. earthquakes) acting on soft, saturated sediment.

Facies *Sr*: sandstone, ripple cross-stratified

Description: Most core logs do not differentiate between the types of ripple cross-lamination, and Facies *Sr* (Fig. 27; Plate 3) thus contains several varieties: asymmetric (*Sra*), symmetric (*Srs*), climbing (*Src*) and undifferentiated cross-lamination (*Slx*), and both the trough (*Slt*) and planar (*Slp*) types. Ripple amplitude is less than 5 cm by definition, and the grain size ranges from very fine grained to coarse grained. Colour varies with grain size; the coarser units are commonly off-white, while the finer grained units are pale grey to pale brown. Facies thickness ranges from a few centimetres to several metres. Contacts with adjacent units are most frequently gradational. The most common form of ripple cross-lamination observed in core is asymmetric.

Interpretation: The presence of asymmetric ripple cross-lamination in sandstone indicates deposition by gentle traction currents (Harmes et al., 1975). Such currents can be found in a variety of low-energy shallow-water environments including fluvial, estuarine, lagoonal, and marine.

Facies *Sf*: sandstone, flaser bedded

Description: This facies comprises ripple cross-stratified sandstone in which mudstone streaks and drapes are preserved completely in the troughs and partially on the

Figure 24. Facies *Gs* crudely stratified clast-supported granule to pebble conglomerate with a poorly sorted sandstone and white kaolinitic clay matrix. Sample from WCL-P-1008 corehole

Figure 25. Facies *Sh* horizontally bedded and laminated sandstone. Sample from WCL-P-1008 corehole

Figure 26. Facies *Sm* massive or structureless sandstone. Note uncompressed coalified twig and small mud chips. Sample from WCL-P-1008 corehole

Figure 27. Facies *Sr* ripple cross-laminated sandstone. Note some of the ripple foresets are draped with a thin veneer of macerated carbonaceous detritus. Sample from WCL-P-1008 corehole

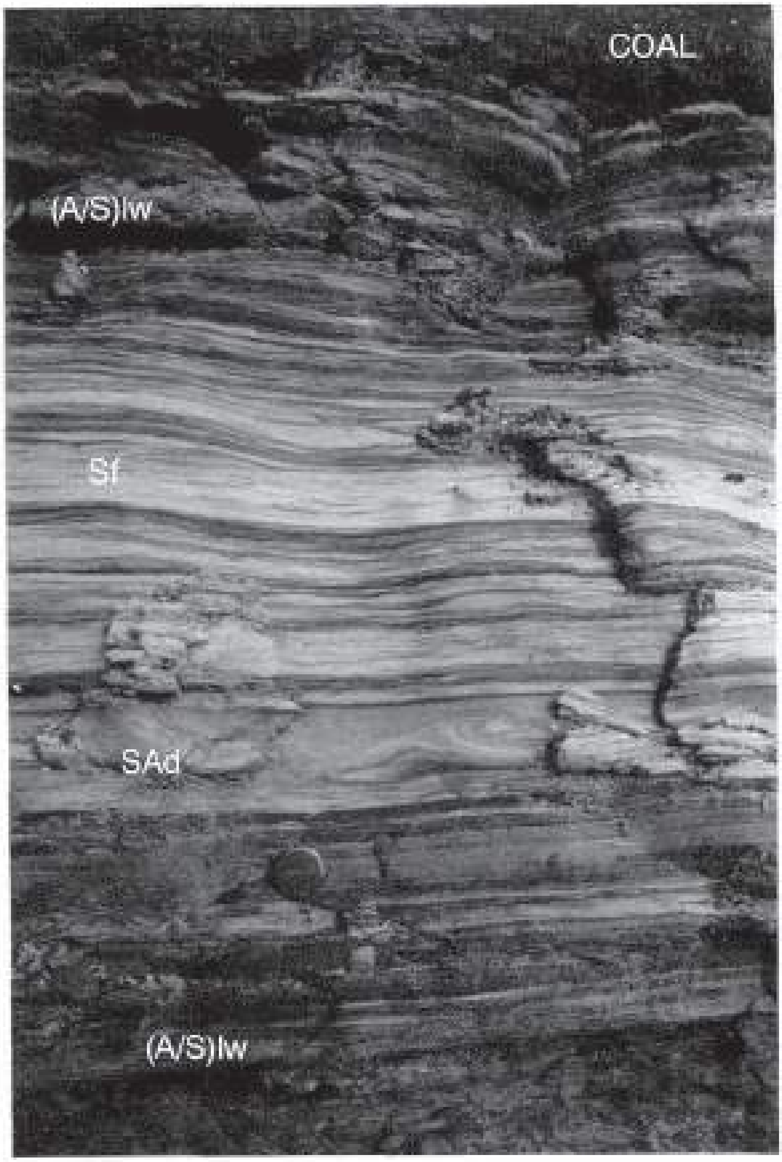


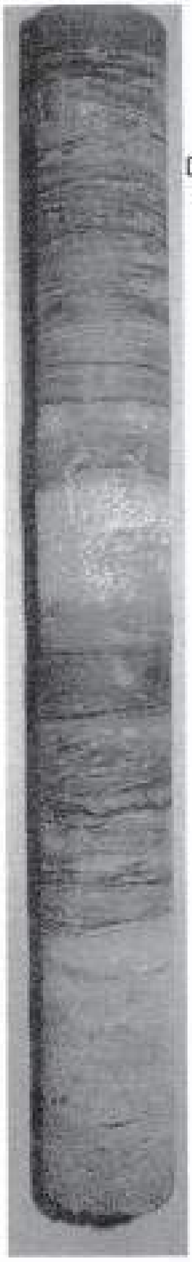
Figure 28. Overbank fines architectural element (*OF*) consisting of: Facies *Sf* flaser-bedded sandstone; Facies *(A/S)ll* lenticular-laminated sandstone in siltstone; Facies *(A/S)lw* wavy-laminated sandstone and siltstone. Note how these structures grade into one another

crests (Fig. 28; Plate 3). Sandstone is the dominant lithology with subordinate, and frequently micaceous, quantities of dark-grey to brown siltstone and mudstone. This facies attains a thickness of several metres and frequently displays gradational relationships with Facies *(A/S)ll*, *(A/S)lw* and *Sr*. Facies *Sf* is frequently associated with dewatering structures.

Interpretation: Flaser bedding implies that both sand and mud are available and that periods of current activity alternate with periods of quiescence (Reineck and Wunderlich, 1968). During periods of current activity, sand is transported and deposited as ripples while mud is held in suspension. When the current pauses, the suspended sediment is deposited in troughs and over the ripples. In the ensuing current-flow phase ripple crests are eroded and new sand is deposited in the form of ripples, burying and preserving ripple beds with mud flasers in the troughs. Associated dewatering structures are indicative of very rapid deposition.

Facies *Sd*: sandstone, deformed bedded

Description: A significant quantity of cores contain sandstones with deformation structures. A wide variety of names including load, slump, ball and pillow, convolute lamination and nodular bedding (Fig. 29) have been used to describe these types of deformation features. Facies *Sd* is proposed to include these bed forms. This structure is essentially secondary and a modification of the primary sedimentary structure and, as such, commonly overprints a variety of primary facies types. The deformation



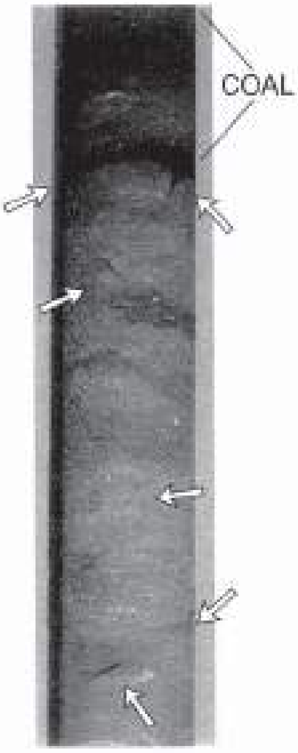


Figure 32. Facies *AS(l/br)* rootlet bioturbation carbonaceous filaments in laminated carbonaceous sandy siltstone footwall to coal seam. Sample from corehole WCL-P-1008

Figure 31. Facies *S(l/bv)* near vertical tube-burrow in wavy- to flaser-bedded sandstone. Sample from corehole WCL-P-1008

Figure 30. Facies *(S/A)(lw/bl)* lateral grazing-trail bioturbation in wavy-laminated carbonaceous sandstone–siltstone. Sample from corehole WCL-P-1008

Figure 29. Facies *Sd* deformed-bedded sandstone over-printing flaser- and wavy-bedded sandstone. Sample from WCL-P-1008 corehole

Figure 33. Facies *AGs* stratified carbonaceous matrix-supported sandy to pebbly siltstone. Sample from WCL-P-1008 corehole

Figure 34. Facies *Al* laminated dark-grey to black silty mudstone (argillite). This facies is frequently carbonaceous (*ACl*). Sample from corehole WCL-P-1008

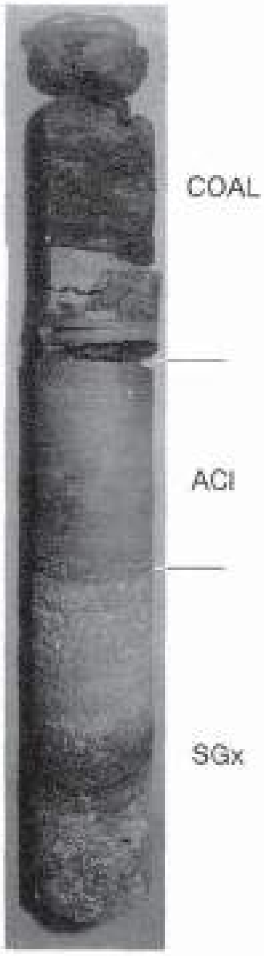


Figure 35. Facies *C* coal seam is seated on Facies *ACl* that grades sharply into the underlying pebbly sandstone of Facies *SGx*. This type of relatively abrupt coal capped, upward-fining cycle is common in the coalfield. Sample from WCL-P-1008 corehole

structures occur on a variety of scales from small sandstone flame structures that penetrate overlying siltstone laminae, to dewatering features that affect strata over several metres.

Interpretation: This kind of feature can be attributed to dewatering under differential compaction pressures from overlying strata. They are thought to be indicative of rapid sedimentation. Other causes could be slope instability and slumping, and sudden shock (by earthquakes) acting on saturated, soft sediment.

Facies *(S/A)b*: sandstone, silty, bioturbated

Description: This facies comprises sandstone and/or siltstone in various proportions and with a variety of relict primary sedimentary structures overprinted with bioturbation structures. Bioturbation structures are relatively rare in the cores. Bioturbation is a secondary sedimentary structure and can range from minor reworking of the primary sedimentary structure to a total destruction of the primary bedding. This facies is commonly characterized by minor bioturbation, and the primary structure can often be seen. Three variants have been observed in core: lateral bioturbation structures (*bl*) that are commonly associated with thin, dark carbonaceous siltstone laminae in Facies *(S/A)lw*, where they are present as thin, pale-brown to white mottled lenses (Fig. 30; Plate 3); rare vertical tube structures (*bv*), usually in Facies *Sf* (Fig. 31); and subvertical carbonaceous filaments beneath coal seams in a relatively structureless brown sandy siltstone up to a metre thick (Fig. 32). In contrast to floral (carbonaceous-filament) bioturbation which is frequently found beneath the many coal seams, faunal bioturbation appears to be uncommon.

Interpretation: Bioturbation structures are authigenic and cannot be concentrated by reworking. The preservation of the trace fossils is accomplished only through the process of deposition, whereby the sediment disturbed as a result of the activity of benthonic organisms and plants is preserved (Reineck and Singh, 1975). The variety of trace fossils found in Facies *(S/A)b* includes vertical structures (rare) indicative of suspension-feeders (*bv*), lateral structures of sediment-feeders (*bl*), and rootlets (*br*).

Argillite: fine-grained facies: (*A*)

Siltstone, mudstone and claystone constitute a relatively small percentage of the Permian succession. These lithologies are collectively termed argillite ('fines') because the standard of logging of these facies has proved to be very inconsistent.

Facies *AGs*: argillite, gravelly, stratified

Description: This facies comprises pebbly siltstone and pebbly mudstone, sometimes as stacked couplets, with thin subordinate intercalated sandstone layers and sparse, dispersed extrabasinal clasts up to cobble size. The stratification is horizontal to sub-horizontal. The facies is generally dark grey to black and may display white speckling from pebbles, sand grains, and lenses (Fig. 33; Plate 3). Two variants have been identified:

1. non-carbonaceous, found in the Moorhead Formation where it is up to 200 m thick and
2. carbonaceous, in the proximity of coal seams (usually underneath) where it is rarely over a metre thick.

Interpretation: The predominance of argillite indicates deposition from suspension (as for Facies *Al*) but with a secondary mechanism for the introduction of the coarse detritus. In the non-carbonaceous variant, the mechanism envisaged is essentially proglacial whereby ice-rafted material 'rained' down onto the floor of a lake during the summer thaw. Couplets are seasonal phenomena with the coarser material associated with summer melting. In the carbonaceous variant the mechanism envisaged is essentially vegetal rafting of detritus, whereby floods uprooted trees and the coarse detritus was dropped from material caught up in the roots.

Facies *(A/S)lw*: argillite, sandstone, laminated wavy

Description: This facies comprises an interlamination of dark-grey siltstone/mudstone with rippled sandstone (Fig. 28; Plate 3). The facies is relatively common and displays transitional upper and lower contacts similar to those of Facies *(A/S)ll*. Thickness varies from a few tens of centimetres up to 4 metres.

Interpretation: Wavy lamination is produced when there is an alternation between weak current- or wave-action deposition of sand ripples over a muddy substratum, and slack-water deposition of a succeeding mud layer. Thus, both the sand supply and current were intermittent but relatively regular.

Facies *(A/S)ll*: argillite, sandstone, laminated lenticular

Description: Laminated dark-grey siltstone and mudstone predominate in this facies, with subordinate thin lenses of intercalated sandstone (Fig. 35). This facies is generally less than a metre thick. Most sandstone lenticles are discontinuous and appear to 'float' in the siltstone and mudstone. This facies is relatively uncommon and displays transitional upper and lower contacts. Two styles of association are evident for Facies *(A/S)ll*: an upward-coarsening association where the upper transition is usually through *(A/S)lw* into Facies *Sf* (flaser-bedded sandstone) and the lower is into Facies *Al*; an upward-fining association where the underlying unit is frequently a sandstone of Facies *Sx* or *Sr* and the upper is Facies *Al* or, more rarely, a coal seam.

Interpretation: The vertically and laterally discontinuous sandstone lenses are starved ripples on a muddy substrate. Reineck and Singh (1975) point out that lenticular bedding is produced when incomplete sand ripples are formed on a muddy substratum and preserved as a result of deposition of the next mud layer. Thus, the sand supply was meagre and conditions largely quiescent favouring deposition of suspended sediment. An alternation of weak current or wave action depositing sand, with slack-water conditions depositing mud, will produce lenticular lamination.

Facies *Al*: argillite, laminated

Description: This facies comprises dark-grey, horizontally laminated or occasionally massive (*Am*) mudstone and siltstone. The unit thickness may vary from a few centimetres up to several tens of metres (Stockton Group). Facies *Al* is frequently carbonaceous (*ACl*) and may contain fine micaceous platelets on the laminae (Fig. 34; Plate 3). The facies most frequently displays a gradational association with sandstone below and coal above. Core logs suggest a variant of the facies (at the base of the Moorhead Formation) that comprises alternating couplets of siltstone and claystone, but no core survives to confirm this.

Interpretation: The fine-grained laminated structure of facies Al points to deposition from suspension under quiescent conditions in lagoons, lakes and ponded-water bodies. The presence of carbonaceous debris in zones is indicative of proximity to swamps and marshes and can be accounted for by rafting of plant remains that became waterlogged and sank to become entombed. The alternating couplets of siltstone and claystone, with subordinate sandstone lenses, can be accounted for as a response to seasonal flooding or seasonal turbidity-flow mechanism, as outlined by Gustavson (1975) for paraglacial environments. The general lack of massive units suggests that deposition was in fresh water, and that flocculation processes indicative of mixing with marine water did not occur to any extent.

Organochemical facies

As the name suggests, this facies group contains organic accumulations and chemical precipitates.

Facies *C*: coal

Description: This facies consists of black coal in seams and lenses (Fig. 35; Plate 3). Thickness varies from a few centimetres in local lenses to over 13 m for the largest coal seam. The thicker coal seams extend throughout the basin; however, in some instances the coal seams are split by sandstone and shaly units of varying thickness. Sappal (1982, 1986) has described the petrography of the coal.

Interpretation: Coal is produced as the result of accumulation of organic material in a swamp, marsh or fen environment where plant growth and organic accumulation matches the rate of burial. This delicate balance needs to be maintained over substantial periods of time.

Facies *L*: limestone

Description: This facies comprises pale-grey silty and sandy limestone which is only sporadically developed and appears to be associated with the thickest sections of Facies *Al*, particularly in the Moorhead Formation. The thickness ranges from a few centimetres to 71 cm in Municipal Bore No. 1. Lord (1952a) reported that dwarfed foraminifera were found in this facies, although their existence is now considered doubtful.

Interpretation: The association of Facies *L* with Facies *Al* suggests deposition under quiescent conditions, probably in a glaciolacustrine environment. Should the presence of foraminifera be substantiated, a brackish-glaciomarine setting may be indicated. Water bodies were probably fjord-like with a restricted benthonic fauna (Moorhead Formation). The rarity of this facies could be attributed to a low preservation potential due to cold-water conditions which favour the solution of carbonate.

Facies associations

In some instances several primary lithofacies occur together. These 'mixed' facies types are termed facies associations. Examples include: interbedded, interlaminated and cyclic groupings that are generally on a scale too fine to be practically logged or mapped individually. The facies associations are generally composed of a regular repetition of two or more of the basic or primary facies types listed above. Facies in facies associations are denoted by parenthetic groupings of lithologies. The respective lithologies usually display different sedimentological structures.

Facies Association 1 (FA1). Facies *(Sr/Al)i*: sandstone–argillite, interbedded

Description: FA1 comprises a small-scale, upward-fining, interbedded association of Facies *Sr* and *Al*. The thickness of the couplet components ranges from 5 cm to several tens of centimetres, and the facies association may be stacked through several metres. The Muja pit above the Hebe Seam displays a typical example (Fig. 12) with a two-scale cyclicity of a relatively fine facies intercalation that is itself arranged in broader scale upward-fining cycles. The larger cycles manifest a relative upward thinning of the respective light-grey to buff sandstone units in favour of the dark argillite over a distance of up to a metre, until the whole becomes interlaminated. The argillite has in the past been termed the 'Hebe Shale' but inspection of the current pit exposure reveals the dark material to be predominantly a silty fine-grained sandstone with a high proportion of macerated carbonaceous material.

Interpretation: FA1 is interpreted as the product of an oscillation between weak traction currents that transport sand in a variety of laminated and rippled forms, and quiescent conditions that favoured suspension settling of argillaceous sediment. Episodic events, such as storms and seasonal discharge possibly associated with spring thaw, can account for this type of depositional pattern in a ponded or embayment setting. There is no clear evidence to suggest tidal influences. The pulsatory influx of macerated organic material could be accounted for by seasonal leaf-fall and purging by spring floodwaters.

Depositional systems and controls on coal distribution

The Collie Group contains a number of cyclic composite units that reflect recognizable depositional patterns as identified from variations in rock type and sedimentary structure. Patterns such as these can result from depositional pulses in response to various processes including tectonics, avulsion, and water-level shifts caused by weather changes such as those described by Milankovitch cycles (Berger, 1988). A depositional cycle generally comprises an association of one or more discrete but genetically related sedimentary rock types that are bounded by an event-surface such as a coal seam or unconformity. This association can be interpreted in terms of a set of depositional processes which, when operating jointly, constitute a depositional system that can produce a recognizable sedimentary 'fingerprint' in the rock record. Understanding depositional system processes provides a basis for predictive interpretation of coal-seam geometry (correlation), mining conditions and coal quality.

Correlation based predominantly on the attributes of coal seams alone has long been used in the basin to provide a practical method of subdividing coal-bearing successions. However, this approach is inadequate for efficient coal exploitation in the Collie Basin, where coal resources lie in *moderate* and *complex geology type* (Hughes et al., 1989) categories. Although the coal measures persist over substantial areas, faulting, folding, seam-splitting, pinch-outs, shale-outs, and erosional cut-outs occur in several different areas both within and between seams, and it is in these areas that the problems of correlation and mining are compounded. The existing lithostratigraphic and biostratigraphic approaches to stratigraphy, although useful, are not sufficient to resolve the problems. A genetic approach to stratigraphy (Busch, 1971) and correlation, with its emphasis on recognition of patterns of association in sedimentary rocks linked to depositional processes, provides a very practical means of subdividing the coal-bearing sections in a way that facilitates exploration and mining (Busch, 1971; Le Blanc Smith, 1980a,b; Winter et al., 1987).

The concept (Busch, 1971) of the Genetic Increment of Strata (GIS) and the Genetic Sequence of Strata (GSS) facilitates picking marker-defined vertical aggregations of rock units for the dissection and mapping of the coal measures. The technique of genetically grouping strata has been used to good effect in coal exploration (Wanless et al., 1970; Le Blanc Smith, 1980a,b; Winter et al., 1987) and for oil (Wermund and Jenkins, 1970; Busch, 1974).

A pragmatic genetic stratigraphy for the coal-bearing strata is presently being developed for the Collie Basin. Three genetic sequences are identified in this study and further genetic subdivision should provide an improved framework for mapping significant seam-splits, partings, washouts and similar features, and facilitate correlations between faulted resource blocks.

Sequence P1: synthesis

Sequence P1 has been identified as the primary Permian genetic sequence of strata. It starts at the basement unconformity and incorporates the Shotts Formation, Moorhead Formation, Westralia Sandstone, and Ewington Coal Measures (Plate 4). Sequence P1 represents the first major Permo-Carboniferous depositional pulse that accompanied climatic amelioration and ablation of the Gondwana ice sheet. Sequence P1 has also been identified in southern Africa (Witbank GSS of Le Blanc Smith, 1980a,b) where it has regional extent through all the major Permo-Carboniferous coal-bearing areas (Falcon et al., 1984; Falcon, 1989). Sequence P1 would appear to have Gondwana-wide significance and forms an excellent basis for regional and intercontinental correlation.

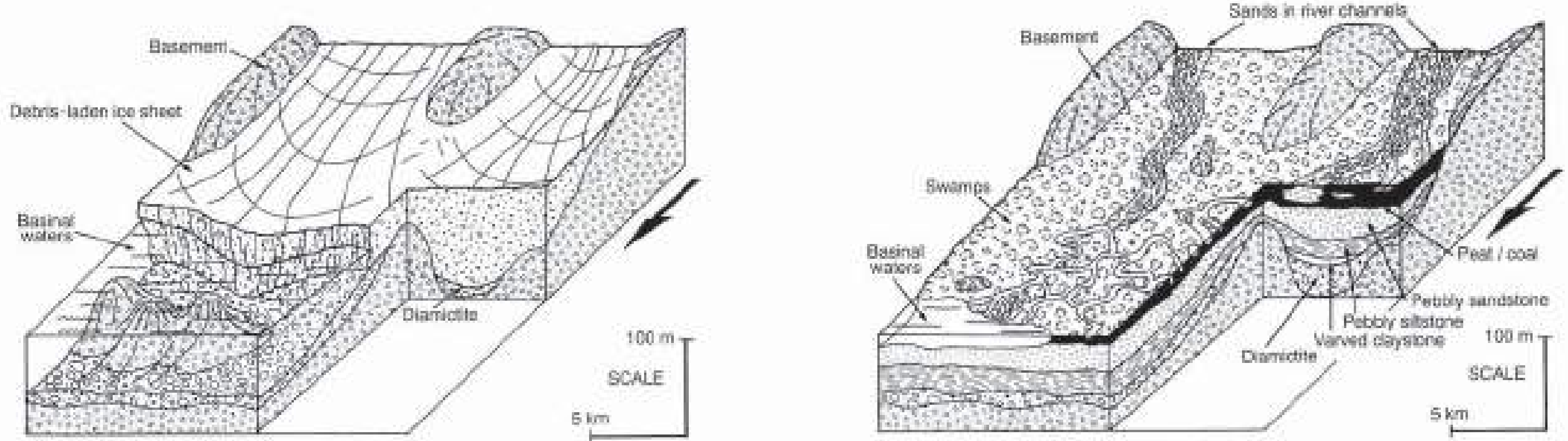
The sediments constitute a broadly upward-coarsening sequence (Plate 3) that is capped by a number of thick, areally extensive coal seams. The base of the Permian succession is marked by diamictite (*Dm*) of the Shotts Formation that overlies striated basement (Low, 1958e). Overlying this is a succession up to 200 m thick of fine-grained rocks (*AGs*, *Al* and *(Sr/Al)i*) of the Moorhead Formation. These grade upwards into sandstones (*Sr*, *Sd*, and *Sx*) of the Westralia Sandstone that are up to 75 m thick. The sequence is capped by up to 80 m of coal-bearing sandstones of the Ewington Coal Measures. Coal seams attain a thickness of up to 5 m and the cumulative coal thickness is approximately 12 metres.

The predominantly upward-coarsening succession that overlies a basal tillite suggests that the essential components of a glaciolacustrine delta are present. These components can be incorporated into a depositional model for the Early Permian coals of southwestern Australia. Interpretation is based substantially upon old core descriptions. The essential deposition features of the Sequence P1 model are outlined in Figure 36.

The proposed glaciolacustrine and glaciofluvial model involves sediments that accumulated from the process of ablation, with deposition by glacial meltwaters during the southward retreat of the Gondwana ice sheet during a major climatic amelioration. Deposition occurred in and along the embayed margins of a large standing waterbody created as a consequence of continental ice-sheet retreat. The waterbody was probably brackish with a marine connection to the north (Fig. 36a).

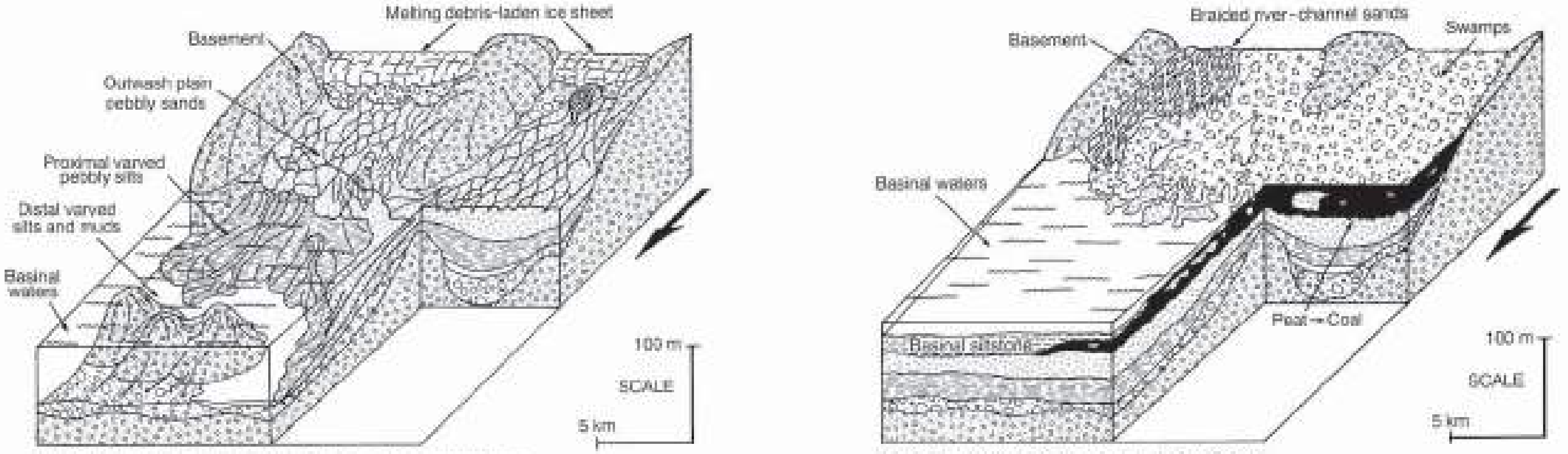
The envisaged process entails northward sluicing of outwash debris derived initially from subglacial till, and subsequently from subaerially exposed till at the toe of the retreating ice sheet. Consequent outwash sediment accumulated as proglacial lake-fill fan-delta deposits. These wet outwash-fan (Boothroyd and Nummedal, 1978) deposits rapidly built out into a standing waterbody. Outwash or glaciolacustrine fan deltas are characterized by hyperpycnal processes (Bates, 1953) where cold inflowing river waters with a high suspended load are more dense than relatively fresh lake waters. A density underflow results (Jopling and Walker, 1968) and subaqueous gravity-flow mechanisms operate (Middleton and Hampton, 1973); these are dominated by turbidity currents (Banerjee, 1966; Gustavson, 1975).

Jopling and Walker (1968) define the essential components of a glaciolacustrine delta as bottomsets, foresets, and topsets.



(a) Stage 1 Retreat of subaqueously based ice sheet

(c) Stage 3 Stabilisation of outwash plain by prolific plant growth and accumulation of thick peats laced with bank-stablized channels



(b) Stage 2 Basin infilling by prograding fan-deltas sourced from subaerially exposed glacial debris

(d) Stage 4 Transgression and inundation of peats

Figure 36. (a) Stage 1: Climatic amelioration and southward retreat of ice sheet with formation of a sea filled with fresh to brackish meltwater. Diamictite and subaqueous outwash deposits blanket the basin floor, (b) Stage 2: Basin infilling by prograding fan-deltas sourced from subaerially exposed glacial debris released from retreating icesheet, (c) Stage 3: Periods of abandonment (glacial readvance), prolific plant growth, stabilization of outwash plain channels and accumulation of thick peat, (d) Stage 4: Episodic pulses of siliclastic influx and associated channel switching to gradients of advantage (tectonics and glacial retreat). Burial and preservation of peats beneath channel units with localized organic accumulations in adjacent backswamps and abandoned channel reaches

The proximal bottomset sediments of the Collie Basin consist of upward-fining massive, deformed-bedded, plane-bedded and rippled sandstones and siltstones (*Sm*, *Sd*, *Sr*; drillholes GOV-GF39, GOV-DD-B) that were deposited from waning turbidity currents. These units in the Premier Sub-basin generally overlie basement (drillholes GOV-GF35, GOV-GF39, GOV-GF40); however, in the Cardiff Sub-basin they overlie (and grade downwards into) progressively finer and more distal lake-floor deposits comprising pebbly mudstones, intercalated thin sandstones (*AGs*) and distal sandstones, siltstones and shales that are rhythmically bedded (drillholes GOV-DD-A, GOV-DD-B, GOV-DD-J, GOV-GF28). This cyclicity could be interpreted as evidence of summer thawing and winter freezing of lake waters. The presence of carbonate Facies *L*, associated with the argillite facies of the Moorhead Formation, suggests a marine connection. Lithostratigraphic and genetic correlation of Facies *L* to the fossiliferous shales and limestones of the Holmwood Shale and Fossil Cliff Member (Playford et al., 1975) of the northern Perth Basin indicates the sea lay to the north.

Topset deposits consist predominantly of outwash-fan conglomerate and sandstone with subordinate argillite (*Gx*, *Sx* and *Al*; logs GOV-F05, GOV-F14, GOV-F17). The conglomerates and sandstone units are stratified and erosively-based. Scour features are prevalent and the basal contact zone commonly has a dark-grey matrix and contains intra-formational rip-up clasts derived from the removal of underlying argillite units (*Al*). The depositional motif comprises stacked, broadly upward-fining cycles, many of which are incomplete as they have been scoured away prior to deposition of the successive cycle. Cross-bedding (*Sx*) is abundant and would appear to be mostly trough-type with associated scour and fill. Individual cycles fine-upward relatively abruptly and may be capped by argillite (*Sr* and *Al*). Cycles are generally about 6 m thick (ranging up to 12 m) in stacks up to 35 m thick. These cycles are attributed to scour followed by dune and bar migration down wide channels. Deposition was dominated by bed-load processes with breaks in flow marked by the deposition of argillite from suspension. There is an upward increase in carbonaceous detritus and coaly spar, which points to subaerial exposure, and a proliferation of plant growth on the outwash platform. These processes represent the second phase of development (Fig. 36b).

The coal seams in the Ewington Coal Measures confirm subaerial exposure, plant growth and peat accumulation. Rootlet horizons (*ASbr*) are relatively common, indicating the peats accumulated in situ. In this setting there was a delicate balance where subsidence matched the peat accumulation rate over substantial periods of time. With the abandonment of the outwash plain, extensive peat bogs developed in close proximity to glacial lakes. Periods of clastic influx punctuated this interval, probably in response to warmer interglacial conditions (cyclic) with associated high-clastic influx.

Organic accumulation rates of between 0.5 and 1 mm per annum are considered normal in cool-temperate settings (Stach et al., 1982). The net period over which these early peats (coals) accumulated can be estimated from the 12 m cumulative thickness of coal and an accumulation rate of approximately 6000–9000 years per metre of black coal. Thus the net peat-forming interval spanned at least 70 000 years, but the gross interval was probably substantially greater than 110 000 years (Fig. 36c).

This model is similar to that of the Permo-Carboniferous coals of the northeastern Karoo Basin in South Africa (Le Blanc Smith and Eriksson, 1979; Le Blanc Smith, 1980a).

Glacial and proglacial deposition was predominant in the Early Permian (Sakmarian 280 Ma) as the Collie Basin was in a cold-temperate setting at high latitude of approximately 70° south (Fig. 37). This setting was at a similar latitude to the southern African Karoo coalfields and the Indian Gondwana coalfields. It is interesting to speculate that the sea may have had a common shoreline with these other coal-bearing areas and that a number of similarities could therefore be expected in the coal types and depositional settings.

A comparison of the palynology from Collie (Backhouse 1990, 1991) and from southern Africa (Falcon, 1989) shows that Sequence P1 was broadly contemporaneous in the two locations. However, the onset of peat accumulation in southern Africa appears earlier than that in Western Australia. The coals of the 1 and 2 Seams in the Transvaal (Witbank) Coalfield lie in the *Pseudoreticulatispora pseudoreticulata* Zone which is equivalent to the construction phase of the fluvioglacial platform in Western Australia (Westralia Sandstone — Stage 2 of the model). In the Collie Basin, the base of the *Striatopodocarpites fusus* Zone marks the onset of significant peat accumulation in the Ewington Coal Measures (Stage 3 of the model); this zone correlates with palynomorphs of the 3 Seam of the Witbank Coalfield (Karoo Basin). Further, the top of the Ewington Coal Measures is marked by the *Praecolpatites sinuosus* Zone base, which correlates with palynomorphs of the 5 Seam of the Witbank Coalfield. The Westralia Sandstone and Ewington Coal Measures are litho-stratigraphic equivalents of the coal-bearing Vryheid Formation of South Africa. Similarly, the Western Australian Moorhead and Shotts Formations correlate with the Pietermaritzburg ('Lower Ecca') and Dwyka Formations. The effects of the global climatic amelioration appear to have commenced in the west of Gondwana (southern Africa) and progressed eastwards, through the Indian sub-continent to western Australia and on to eastern Australia.

Sequence P2: synthesis

Sequence P2 broadly incorporates the lithofacies of the Allanson Sandstone (up to 150 m thick) and the overlying Premier Coal Measures, which is up to 300 m thick (Plates 4 and 5). The upper contact is defined by suspected disconformity and lacuna that appears coincident with the base of the *Didecitriletes ericianus* Zone. Sequence P2 represents a second major Permo-Carboniferous depositional phase. The lower section is dominated by sandstone (Allanson Sandstone) and

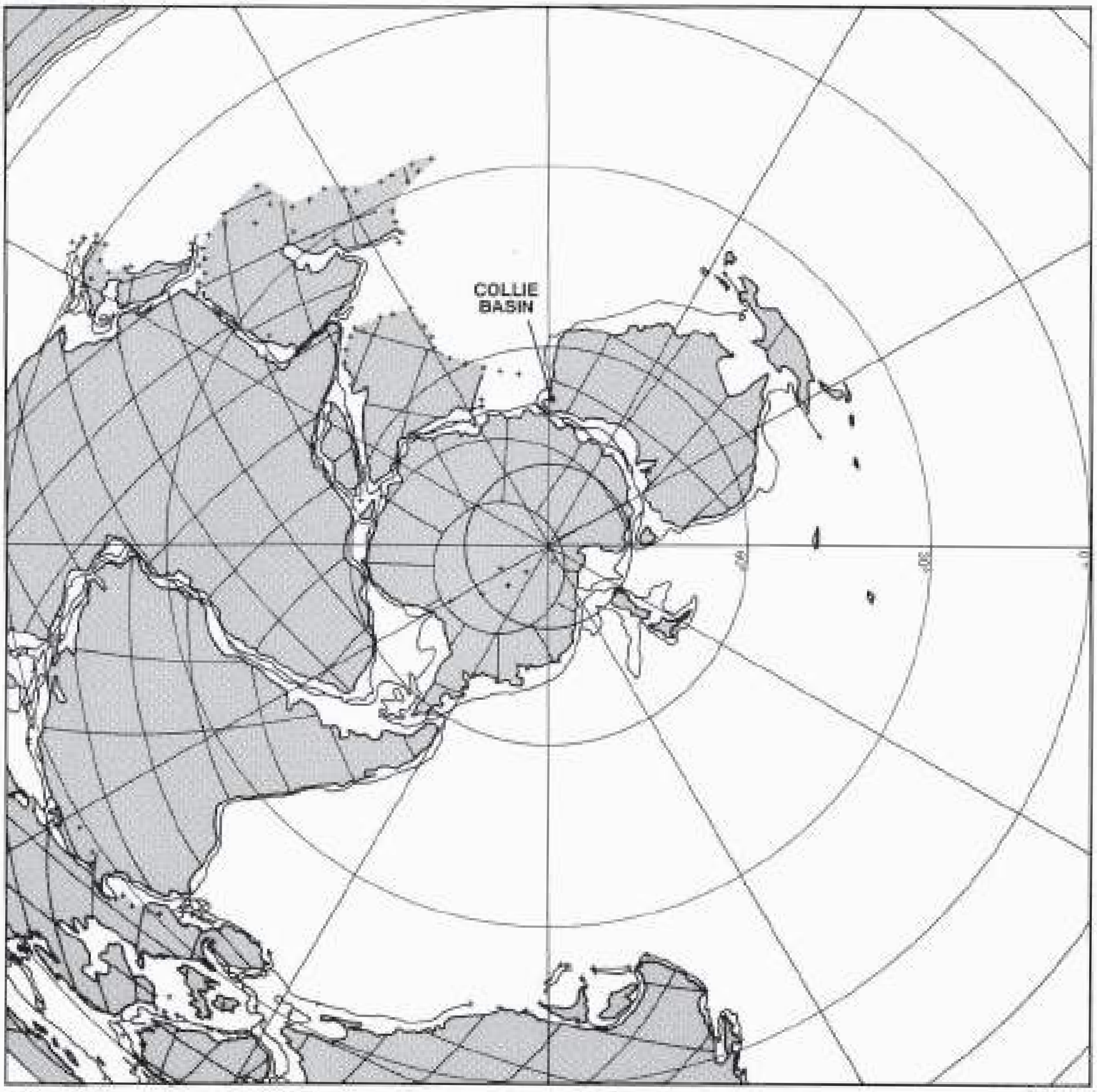


Figure 37. Location of the Collie Basin on an Early Permian (Sakmarian 280 Ma) palaeogeographic reconstruction of Gondwana, (modified from Smith et al., 1981)

displays stacked upward-fining sandstone cycles that are sometimes capped by thin, uneconomic coal seams. The depositional setting envisaged is a wet alluvial fan (Boothroyd and Nummedal, 1978) slightly proximal to the areas of main peat development in the lower fan. The depositional character progressively changes upwards with an increase in the amount of argillite and coal at the expense of sandstone (Premier Coal Measures) (Plate 6(a)). This is attributed to relative transgression and deposition in more distal alluvial fan-delta settings along the margin of a large interior sag basin (terminology of Kingston et al., 1983).

In the lower section, medium to coarse pebbly sandstone and occasional small-pebble conglomerate facies predominate (*G*, *GS*, *SG*, *S*) and contain a variety of sedimentary structures that include massive (*m*), cross-bedded (*x*), trough cross-laminated (*lt*), rippled (*r*) and deformed bedding (*d*) and, moreover, commonly feature erosive basal contacts. Sporadic occurrences of finer grained and organic facies (*AS*, *A*, and *C*) are preserved and feature low-energy sedimentary structures such as wavy lamination (*lw*), interbedding (*i*), lamination (*l*) and rootlet bioturbation (*br*). Many of the stacked broadly upward-fining depositional cycles are incomplete as the upper portions have been scoured away prior to deposition of the successive cycle. Cross-bedding (*Sx*) is abundant and would appear to be mostly trough-type with associated scour and fill. Individual cycles fine upward relatively abruptly and may be capped by argillite (*Sr*, *Al*, and (*Sr/Al*)*i*). Cycles are generally about 6 m thick, but can range up to 12 m, in stacks up to 35 m thick. These cycles are attributed to strong ephemeral alluvial discharges with initial scouring of the substrate followed by dune and bar migration down wide channels. Deposition, particularly in the lower (earlier) sediments, was dominated by bed-load depositional processes (*Sx*, *Sr*, and *Sd*) with relatively few occurrences of suspension deposits (*Al*) and coal. The paucity of preserved breaks in flow, marked by argillite deposition, is interpreted as reflecting a period with relatively slow subsidence rates and sustained sediment supply. The trend within Sequence P2 reflects an upward increase in the amount of carbonaceous detritus, argillite, and coal seams, although the sandstone units are still present. This points to episodically increased rates of subsidence and reduced sediment supply more favourable to the preservation of organic material and the formation of coal seams. Individual coal seams attain widths of up to 5 m and a cumulative coal thickness may reach 32 metres.

Sequence P2 is terminated by a suspected disconformity that appears coincident with the palynomorph zone boundary (*D. ericianus*) at the top of the Premier Coal Measures. Further investigation is required to refine the nature and extent of this boundary.

Sequence P3: synthesis

Sequence P3 attains thicknesses up to 450 metres. It overlies Sequence P2, is bounded at the top by an unconformity with Cretaceous sediments (Nakina Formation), and incorporates lithofacies as described for the Muja Coal Measures (Plates 4 and 5). Sequence P3 represents a third major Permo-Carboniferous depositional phase dominated by stacked, predominantly upward-fining increments of strata (and subordinate upward-coarsening increments) which are frequently capped by thick coal (Plate 6(b)).

The depositional motif and setting is similar to that of Sequence P2, with the exception of the sandstone units and the coal seams which, in P3, are thicker on average. This is particularly true in the east of the basin where, for example, a number of seams coalesce to form the Hebe Seam which thus attains a thickness of up to 13 metres. The succession comprises stacked, abruptly upward-fining cycles. Each cycle is generally about 6 m thick (but up to 12 metres) with stacks ranging in thickness up to 35 metres. These cycles are attributed to strong ephemeral discharges with initial scouring of the substrate, followed by dune and bar migration down wide channels. The abundance of macerated plant material and coaly spar in the sandstones indicates abundant plant growth on channel banks and bars. Deposition style features periodic pulses of vigorous deposition punctuated by periods of quiescence, with abundant plant growth and peat accumulation (and preservation) on a gently subsiding platform that remained in equilibrium with the watertable.

Park (1982) provided the first sedimentological facies analysis from the coalfield with a study of the Muja Formation (Sequence P3) in the southeast of the basin in the vicinity of the Muja Mine. He described two facies associations: 'braided river facies' and 'floodplain and lacustrine facies', which essentially reflect the coarser grained and finer grained components of the stratigraphic column. The braided association was postulated to reflect deposition by longitudinal and transverse bars that coalesced as the numerous stream channels migrated over the width of the river system. In this way the sandstone accumulated (*Sx*) through the processes of lateral accretion. Local argillaceous accretion beds were formed as island and channel-bank deposits.

The floodplain and lacustrine association was proposed in the context of the definition by Reineck and Singh (1975) for fluvial systems in which active lateral migration occurs. The main facies include sandstones up to several metres thick that are generally fine to medium grained with a relatively minor coarse fraction. Interbedded sandstone/argillaceous units (FA1: *(Sr/Al)i*, of this study) ranging from millimetre to decimetre scale are common and are often predominant. Small-scale cross-bedding (*Sx*), convolute bedding (*Sd*) and upward fining are commonly observed features. Argillaceous beds range from less than one to several metres thick, and represent the most common lithology in the facies association. These units are dark-grey horizontally-bedded silty-shales (*Al*) and locally contain leaf fossils. Park (1982) interpreted the depositional setting as being a flood basin with prolonged wet humid conditions under which deposition took place within large shallow lakes. This setting favoured thick vegetation growth and development of backswamps.

Periodic sediment incursions into the lakes and ponds produced upward-coarsening increments with transitions from lacustrine to floodplain deposition. An example can be seen in the increment of strata between the underlying Hebe Seam and the Galatea Seam, Muja Mine northern highwall (Fig. 12). This increment is interpreted as crevasse-delta deposit infilling a lake or embayment. The infill comprises basal carbonaceous sandy siltstone (*ASCl*), deposited under quiescent conditions, overlain by Facies Association 1 indicating onset of overbank deposition, crevassing, and avulsion. The argillite diminishes upwards and the sandstone content, grainsize, and set width increases (*Sr/Sx*) indicating significant crevasse development. The cycle culminates with deposition of over ten metres of coarse-grained cross-bedded sandstone (*Sx*) attributed to the development of a major channel.

Cross-stratification is attributed to migrating dune and bar-bed forms (Harmes et al., 1975). A braided fluvial depositional setting is envisaged, possibly similar to the Alaskan 'humid alluvial fan' model erected by Boothroyd and Nummedal (1978). The morphological elements of these rivers were complex, comprising individual sandy bedforms and bar complexes which matured into vegetation-stablilized islands (Smith, 1976). A complex of river channels flowed over and between these barforms, constantly dividing and rejoining. The clays, silts and finer sediments were largely flushed through the system.

Hydrogeology

Consultants for the State Energy Commission of Western Australia (SECWA) and mining companies have prepared numerous unpublished hydrogeological reports including, since 1986, biennial reviews of the groundwater-level monitoring that is undertaken in the basin for SECWA. Descriptions of the hydrogeology and groundwater resources of the basin have been prepared by Hirschberg (1976), Moncrieff (1985), and Allen (1991). Groundwater-control schemes at some of the mines are described by Vogwill and Brunner (1985), Jones (1986), Humphries and Hebblewhite (1988), Hammond and Boyd (1988), and Dundon et al. (1988).

Moncrieff (1993) investigated the hydrogeology of the Collie Basin and determined that its complexity is due to both the complicated geology and the widespread effects of pumping in the basin. The Collie Group contains a regional groundwater flow system in which groundwater is unconfined in the upper part and confined at depth. There are about 5600×10^6 m^3 in storage. Recharge is estimated to be 31×10^6 m^3/year and comprises two main components; rainfall recharge of about 26×10^6 m^3/year (13% of average annual rainfall) and recharge of some 5×10^6 m^3/year from small streams which dissipate onto the basin. There is also some leakage from the Collie River South Branch in the southern Cardiff Sub-basin. The watertable is highest around the basin margins and in the northern Premier Sub-basin and flow is towards the Collie River and its tributaries, where discharge occurs. Groundwater moves to the deeper parts of the flow system under downward hydraulic-head gradients, particularly in areas where the watertable is high. Owing to groundwater abstraction at opencut and underground mines, and from production borefields, the watertable is depressed over about 100 km^2 of the basin. Drawdowns are not evenly spread around the abstraction zones but may occur in the vicinity of the pumping, or where depressurized aquifers intersect the watertable and probably extend to the basin boundary. Groundwater flow directions at depth are uncertain and have been modified by groundwater abstraction.

The salinity of groundwater in the Collie Basin is mainly below 1000 mg/L (total dissolved solids) and much is lower than 500 mg/L. The groundwater is mainly of sodium chloride type. It is acidic, due to its contact with sulfide-bearing sedimentary rocks, and corrosive due to its acidity, carbon dioxide, hydrogen sulfide and chloride content.

Coal resources

The variable amounts of different components in Collie coal give it a range of properties. The character of the coal is related mainly to its petrography (Sappal, 1982, 1986) determined by the original types of peat-forming vegetal debris, environments of accumulation (Park, 1982), degree of organic maturation (rank), and mineralization. In general, Collie coal is clean, high in moisture (20–30%), high in volatiles (24–37%), very low in sulfur (below 0.5%), and low in ash content (3–9%). Consequently, silicate components and trace elements are also at low levels (Davy and Wilson, 1989, 1990). The coal type is humic (vitric to fusic) and the rank is low (metalignite *cf* Alpern et al., 1989) with specific energy less than 24 MJ/kg (moist, ash-free). Vitrinite reflectance values range from 0.41 at the top of the succession, to 0.61 at the base (Sappal, 1986). The specific energy varies between 19.5 and 21.5 MJ/kg (as received), fixed carbon usually lies between 41 and 45%, and hydrogen content ranges from 2.9 to 3.2% (Mandyczewsky and Weir, 1984).

Coal resource reporting terminology

Coal is common in the Collie Basin. However, to be considered a resource the coal must have economic potential. Estimates of the basin's coal resources must therefore be constrained by the volumetric extent (geometry) and commercial potential of the coal. Coal seams less than 50 cm thick and beds deeper than 350 m are presently not classified as coal resources. The process of determining the coal resources and reserves is a dynamic one that proceeds on the basis of an iterative assessment of coal attributes against evolving exploration, supply, and demand.

Historically there has been confusion in terminology used for reporting Collie coal 'resources' and 'reserves' as there were no national standards. Earlier assessments (Jack, 1905; Maitland and Montgomery, 1912; Kent, 1939; Wilson, 1944; Low, 1958e; Ashton, 1988) of the resource quantities were made on the basis of spatial distribution of available data, and it was assumed that resources defined near observation points had a higher degree of assurance than those more remote. However, the limits used have remained largely undefined. It is possible to use geostatistical methods for objectively quantifying the limits (Whitchurch et al., 1990), although these techniques have not been incorporated into reporting standards and have not been used at Collie.

The problem of inconsistencies in reported figures to differing levels of assurance was substantially resolved by the introduction in 1986 of the *Australian Code for Reporting of Identified Coal Resources and Reserves* (Galligan and Mengel, 1986). This code is adopted in this report (Appendix 1) and the term *coal resource* refers to coal deposits that occur within specified limits of thickness and depth from the surface. These thickness and depth limits are intended to reflect limits of economic and/or technological feasibility for exploiting the Collie coals. Also used here are the maximum distances between points of observation for *inferred*, *indicated*, and *measured resources* recommended in the code (Fig. 38). However, the structural and sedimentological complexities in the Collie Basin will require that a closer spacing of points of observation be adopted in the future, as provided for in the 'Introduction' to the Code. *Reserves* are a subset of *indicated* and *measured resources* for which sufficient information is available to allow detailed or conceptual mine planning, and for which planning has been undertaken.

Resources could be apportioned more accurately using revised radii of influence around points of observation. These radii are determined as a function of *geology type* (Hughes et al., 1989). Collie resources lie in *moderate* and *complex type* categories when consideration is given to structural influences (folds and faults) and sedimentological features (splits, shale-outs and erosional

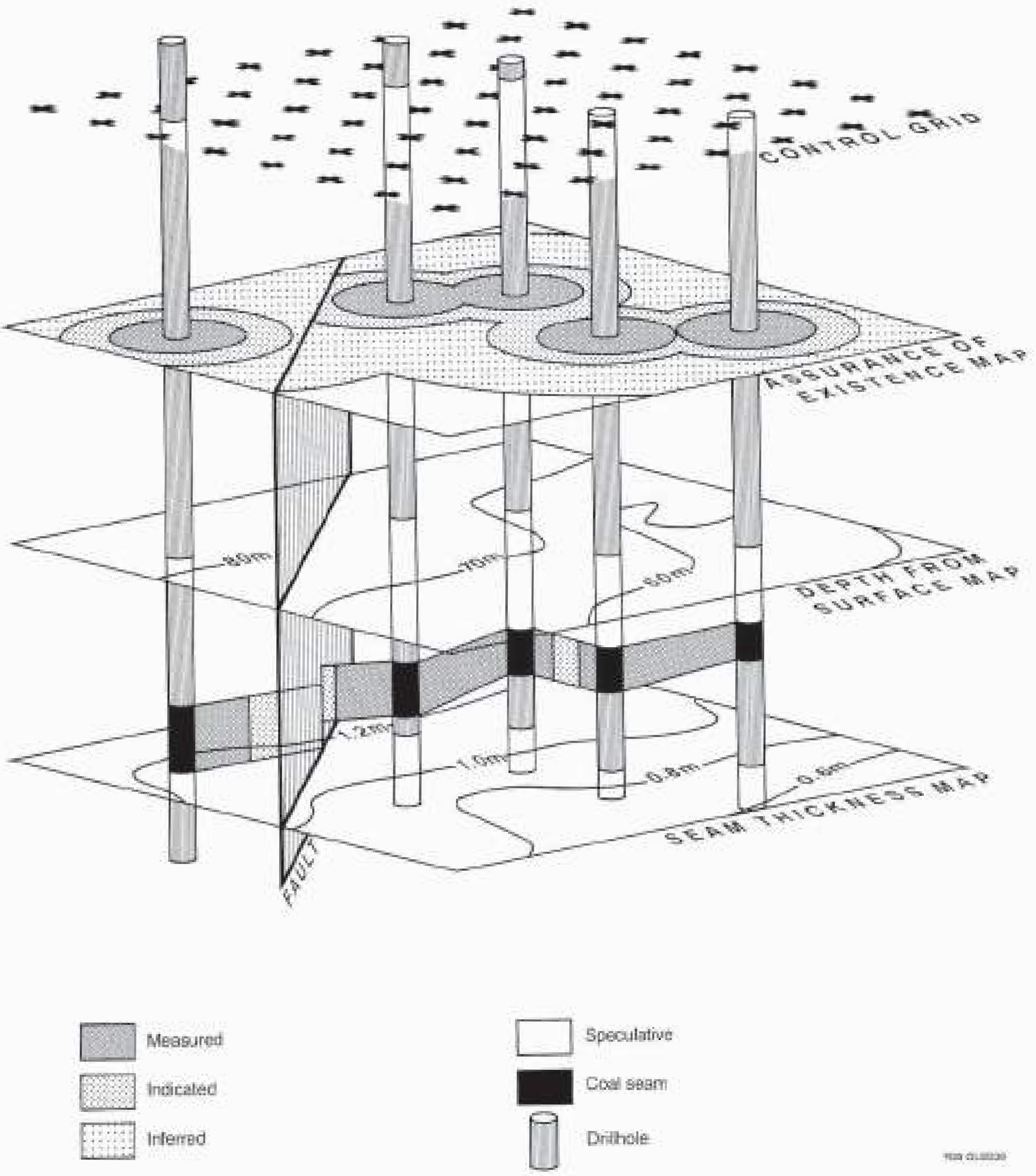


Figure 38. Resources reporting categories (adapted from Hughes et al., 1989)

Table 7. Collie Coalfield resources (February 1991)

Style of mining	*Demonstrated* *Measured* *(Mt)*	*Indicated* *(Mt)*	*Inferred* *(Mt)*	*Total* *(Mt)*
Opencut	620	210	50	880
Underground	320	280	920	1520
Totals	**940**	**490**	**970**	**2400**

Notes:
1. For underground categories, seams ≥1.50 m
2. For opencut categories, seams ≥0.30 m. Maximum stripping ratio of 10:1 bcm/tonne
3. Estimates made using maximum radii of circular influence permissible under the Code. Structural and sedimentological features of coal seams have been ignored

cut-outs). The strong northwesterly trends observed in the structural features suggest that assurance levels would be improved if orientated elliptical areas of influence around points of observation were to be used in future computations.

Resource estimates

Unstandardized resource and reserve estimates have been made over time from an ever-increasing drillhole database, which now contains in excess of 10 000 holes of assorted types and depths. The current estimates for the respective resource categories in the Collie Basin are given in Table 7.

The earliest detailed investigation into all aspects of the Collie coal industry was undertaken by the 1904 Royal Commission on the Collie Coalfield (Jack, 1905). An estimate of the total amount of coal in the field was put at 310 680 576 tons (315.65 Mt) for the Wallsend and various Cardiff and Collieburn seams.

In 1912, the Geological Survey published updated information on the Collie Coalfield. Simpson (1912) outlined the composition and properties of Collie coal, data for which were based on face-sampling of the workings. Maitland and Montgomery (1912) reviewed the geology and mineral industry of Western Australia and confirmed Jack's (1905) estimate for six seams in a field bounded, 'with one exception', by faults.

Woolnough (1916) presented a report on the Royal Commission into the Collie Coal Industry, in which the coal 'reserves' (*resources*) were estimated at 3000 Mt.

Kent (1939) published an extensive summary of the constitution of the Collie coals, including petrographic and chemical analyses, and an estimate of 3500 million tons (3556 Mt) for the known coal to a depth of 2000 feet (610 m).

In 1940, a Royal Commission was appointed to investigate creep at the Proprietary Colliery and to study available coal supplies and future development. The Commission estimated the coalfield to extend over 129.5 km^2 and to contain over 600 m of coal-bearing sediments with an aggregate thickness of 38.71 metres. The reserve total was estimated at 240 million tons (244 Mt).

Wilson (1944) gave a figure of 1521 million tons (1545 Mt) of coal reserves (*resources*) in the well-prospected areas of the basin. This was a qualified figure and included only seams thicker than 1.5 metres. This halved the previous estimates made by Woolnough (1916).

Low (1958e) published the results of the Government Drilling Programs and summarized basinal geology. From some 1700 boreholes he determined reserves (*resources*) at 1907 Mt, with 85% in the 'inferred' category and an estimated 113 Mt extractable. Coalfield resources were comprehensively estimated for the first time and included quality appraisals.

By mid-1980, geological reserve (*resources*) calculations for WCL leases were revised to 233 Mt measured, 224 Mt indicated and 630 Mt inferred, totalling 1087 Mt (Ashton, 1988). The extractable *reserves* were placed at 82.8 Mt for underground mining and 65.8 Mt for opencut.

Revised 'measured and indicated extractable reserves' of 482 Mt were stated in Kristensen and Wilson (1986) and are equated with *recoverable reserves* in general compliance with the *Australian Code for Reporting of Identified Coal Resources and Reserves*.

The estimate of coal *resources* determined in the course of this study is 2400 Mt (Table 7).

For the purposes of comparison with other coalfields, Collie coal resources may be specified as 1720 Mtce. The *tonnes coal equivalent* (tce) is determined by factoring coal tonnage in proportion to the unit heat value of the basin's coal against a standard 29.3 MJ/kg (Smith, 1989, p. 11; Appendix 2).

The coal seams range in thickness up to 13 m for the Hebe Seam. The majority of seams are less than 4 m thick (Figs 39–41; Appendix 3).

Coal quality and characterization

An extensive summary of the constitution of the Collie coals, including petrographic and chemical analyses, was published by Kent (1939) and additional contributions have been made by Lord (1952a), Low (1958e), and Sappal (1982, 1986). The mining companies operating in the basin have substantial coal-quality databases, some of which have been submitted to Government under the requirements of the mining legislation.

Prior to 1971, most of the coal testing was conducted by the Government Chemical Laboratories (now Chemistry Centre (WA)) in Perth. Subsequently some testing was performed by mining groups at Collie using X-ray methods to select coal plies for sampling, composite analysis, and washability tests. Since June 1988, GCM has contracted out all analytical work through Australian Coal Industries Research Laboratories

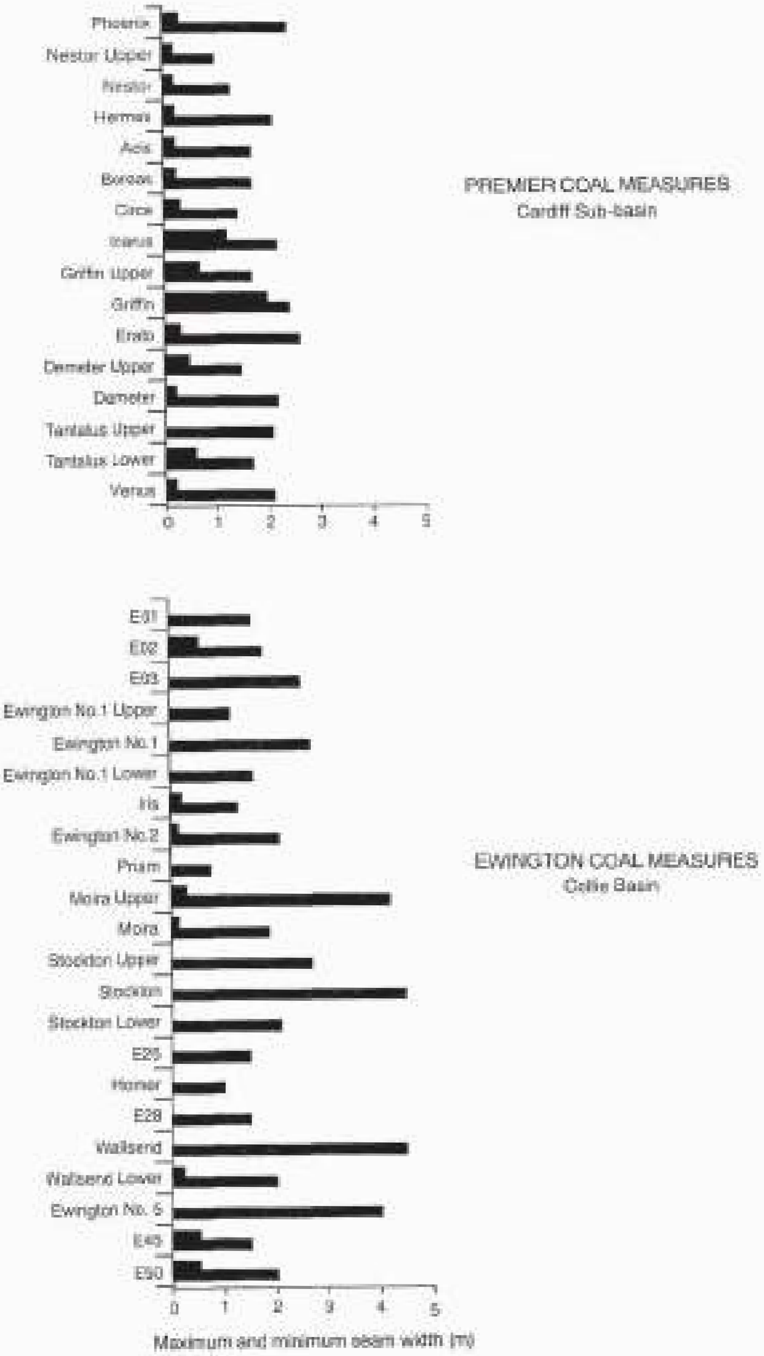


Figure 39. **Seam-width ranges: Ewington Coal Measures and Premier Coal Measures of the Cardiff Sub-basin. Coal seams are listed by stratigraphic depth**

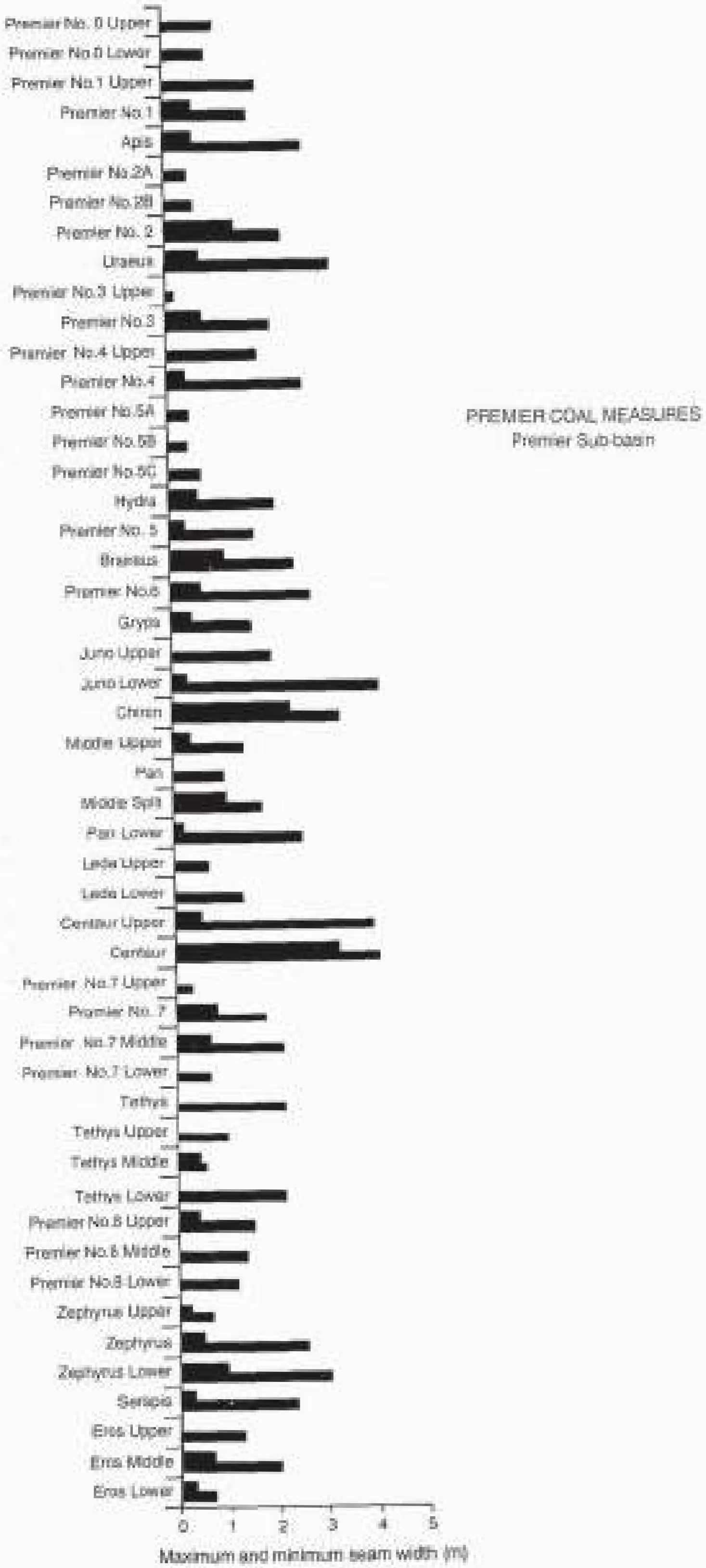


Figure 40. Seam-width ranges: Premier Coal Measures of the Premier Sub-basin. Coal seams are listed by stratigraphic depth

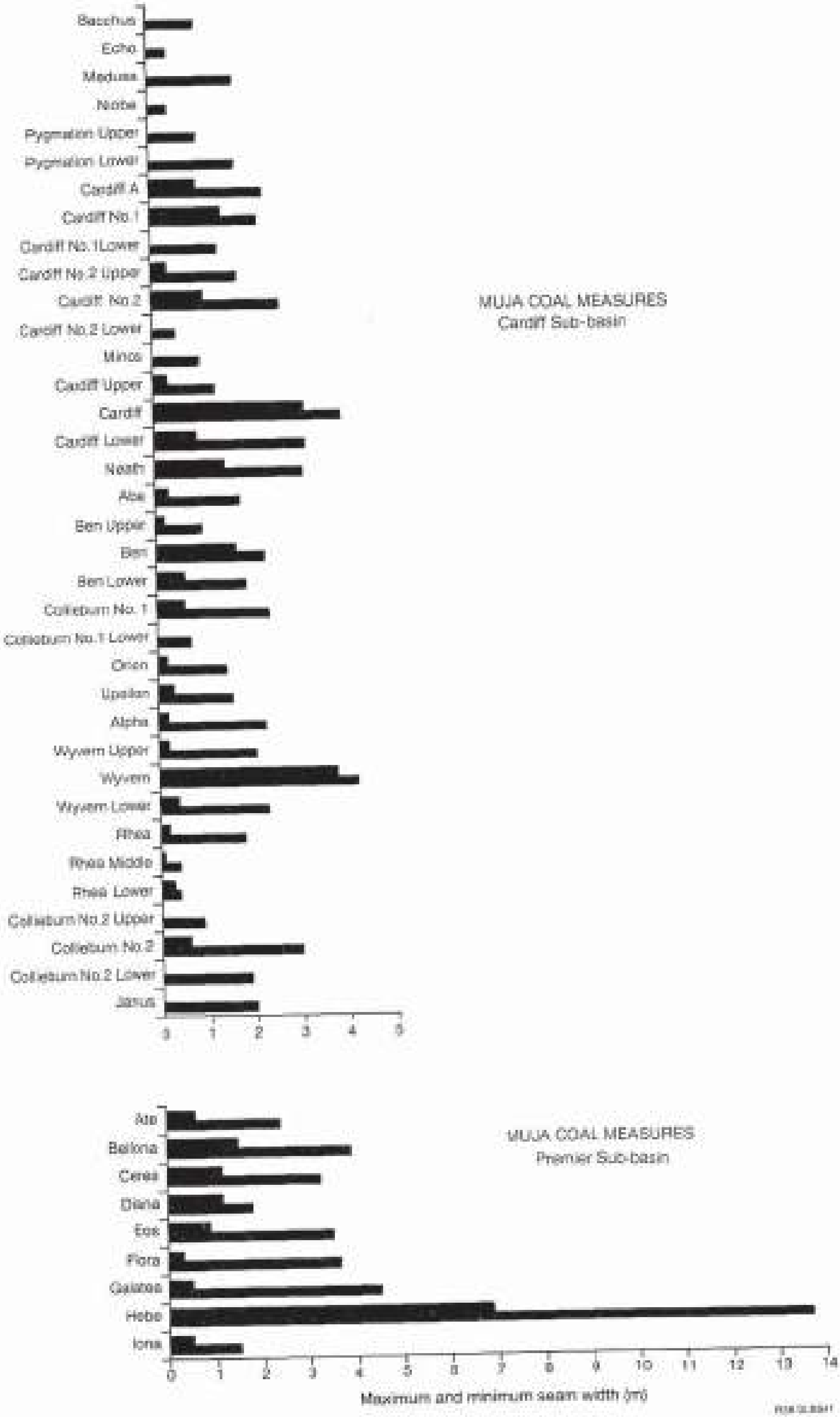


Figure 41. **Seam-width ranges: Muja Coal Measures of the Premier Sub-basin and the Cardiff Sub-basin. Coal seams are listed by stratigraphic depth**

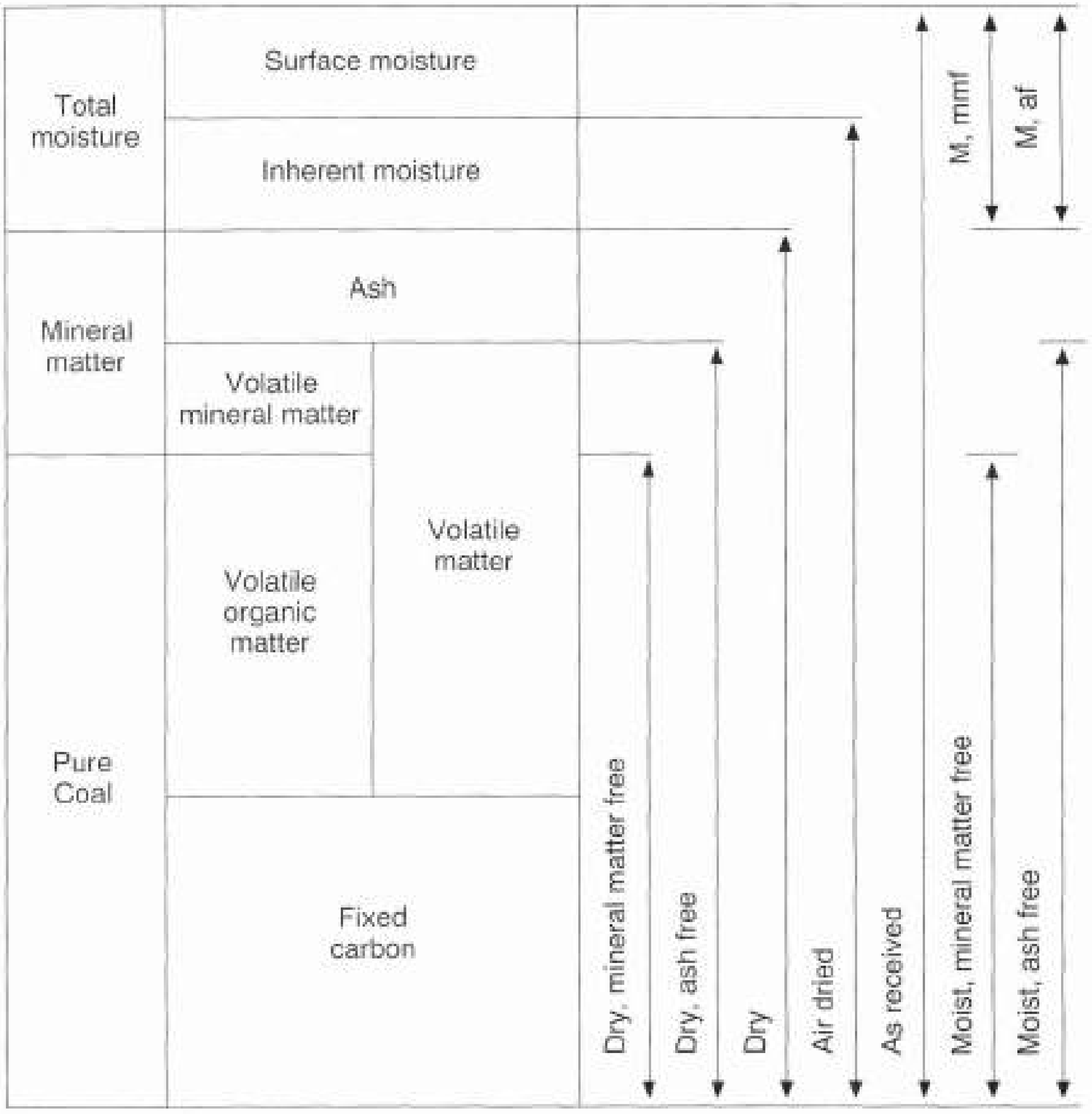


Figure 42. Components of coal included when reporting analyses to different bases

(ACIRL). Analyses prior to this were undertaken by ACIRL, SGS Australia Pty Ltd, Pilbara Laboratories Pty Ltd, and MinLab. In 1984 most coal-quality testing was contracted out by WCL. However, a blend of in-house and contract testing resumed in 1989 when WCL recommenced testing for proximate, specific energy and relative density values. Complete composite analyses (proximate, sulfur, forms of sulfur, chlorine, ash fusion temperature (AFT), relative density (RD), ultimate analysis, maceral analysis, Hardgrove grindability index (HGI), abrasion index (AI), moisture holding capacity, and ash analysis) are contracted out.

Most chemical analyses of coals are carried out on air-dried samples. Collie coals have a high moisture content, between 20 and 30%, and the coals dry steadily when exposed. Analytical values vary according to the sample exposure time before laboratory analysis. This has introduced irregular bias in much of the early analytical work. Precautions are now taken to reduce moisture loss prior to analysis by wrapping core in plastic and placing it in sealed containers, but moisture loss nonetheless remains a problem.

Comparison and classification of coals are based essentially on the nature of the organic fraction. In order to make use of such classifications it is necessary to allow for the effects on chemical composition brought about by mineral impurities. Thus the percentages may need to be re-expressed in terms of 'pure coal' rather than moist mineral-bearing material. The analytical results can be modified by appropriate corrections that allow expressions on a different basis (Ward, 1984). The most common bases are indicated in Figure 42. Conversion of analytical

Table 8. Examples

Formation	Seam	Proximate analyses (%)				Sulfur	SE (ar) MJ/kg	SG (RD)	HGI	Moisture holding (%)	Ash fusion temperature (°C)			
		Moisture	Ash	Volatiles	Fixed Carbon						Deformation	Sphericity	Hemisphere	Flow
													CARDIFF	
MCM	Cardiff A*	25.0	3.9	28.9	42.2	0.3	20.33	1.33	43	25.0	1 290	1 445	1 485	1 495
	Cardiff1*	25.0	5.3	26.5	43.3	0.9	20.04	1.35	44	21.4	1 170	1 300	1 340	1 385
	Cardiff 2 Upr	-	-	-	-	-	-	-	-	-	1 190	1 460	1 510	1 550
	Cardiff 2*	25.0	6.3	26.6	42.1	0.7	19.68	1.36	47	21.5	1 165	1 320	1 355	1 395
	Cardiff*	25.0	6.9	27.0	41.1	0.4	19.4	1.36	45	21.0	1 140	1 285	1 320	1 355
	Neath*	25.0	4.3	28.1	42.6	0.4	20.17	1.34	36	21.9	1 085	1 110	1 125	1 230
	Upsilon*	25.0	2.7	29.3	43.0	0.8	20.85	1.35	48	24.9	1 250	1 335	1 350	1 385
	Alpha*	25.0	3.7	28.6	42.7	0.7	20.5	1.34	41	20.0	1 270	1 300	1 330	1 370
	Wyvern	21.1	4.6	29.4	44.9	0.6	21.81	1.37	44	19.4	1 190	1 258	1 273	1 310
	Wyvern Lwr	21.3	4.6	31.2	43.0	0.5	21.69	1.37	46	20.2	1 190	1 260	1 300	1 440
	Rhea*	25.0	4.0	34.9	36.1	0.8	20.85	1.31	35	21.9	1 195	1 325	1 330	1 390
	Collieburn 2 Upr	16.3	7.0	3.8	44.9	0.6	22.18	1.40	-	21.0	1 190	1 460	1 510	1 550
	Collieburn 2 Lwr	19.7	6.2	31.4	42.6	0.6	21.68	1.38	46	20.4	1 246	1 447	1 464	1 497
PCM	Icarus*	25.0	3.9	29.0	42.1	0.8	21.35	1.33	39	18.2	1 205	1 355	1 375	1 400
	Griffin Upr*	25.0	6.7	28.2	40.1	0.6	19.35	1.28	-	-	-	-	-	-
	Griffin*	25.0	3.1	30.0	41.9	0.8	21.75	1.32	38	20.9	1 080	1 095	1 115	1 145
AS	Hymen	20.8	8.6	25.3	46.2	0.6	21.5	-	-	-	-	-	-	-
ECM	Ewington 1	18.8	5.8	25.6	49.8	0.8	22.74	1.39	69	21.5	1 190	1 400	1 420	1 450
	Ewington 2	19.9	10.2	22.9	49.0	0.5	21.1	1.41	76	22.0	1 200	1 450	1 490	1 550
	Moira	19.7	6.5	24.0	49.8	0.7	22.07	1.41	72	18.5	1 256	1 514	1 547	1 583
	Stockton	14.6	10.1	22.4	52.9	0.4	22.64	1.46	56	17.5	1 300	1 540	1 550	1 570
	Wallsend	17.4	4.3	26.3	50.4	0.8	23.21	1.38	60	19.9	1 187	1 293	1 348	1 405
													PREMIER	
MCM	Floater Upr	28.0	8.2	28.1	35.7	0.3	19.01	1.34	55 ± 5	-	-	-	-	-
	Floater Mid	28.0	4.9	29.5	37.6	0.3	20.13	1.31	55 ± 5	-	-	-	-	-
	Floater Lwr	28.0	5.3	29.4	37.3	0.3	20.00	1.31	55 ± 5	-	-	-	-	-
	Ate	28.0	7.0	27.3	37.7	0.5	19.42	1.33	55 ± 5	-	1 360	1 510	1 540	1 600
	Bellona	28.0	6.6	27.5	37.9	0.5	19.55	1.33	55 ± 5	-	1 450	1 600	1 600	1 600
	Ceres	28.0	3.9	28.6	39.5	0.5	20.48	1.30	55 ± 5	-	1 450	1 550	1 600	1 600
	Diana	28.0	8.9	25.2	37.9	0.5	18.77	1.35	55 ± 5	-	1 350	1 500	1 520	1 550
	Eos	28.0	4.3	27.1	40.6	0.5	20.34	1.30	55 ± 5	-	1 380	1 520	1 540	1 560
	Flora	28.0	4.8	26.9	40.3	0.5	20.17	1.31	55 ± 5	-	1 400	1 500	1 530	1 560
	Galatea	28.0	5.1	26.1	40.8	0.5	20.07	1.31	55 ± 5	-	1 380	1 500	1 520	1 540
	Hebe	28.0	3.9	25.6	41.5	0.5	20.48	1.30	55 ± 5	-	1 250	1 400	1 430	1 450
	Iona	28.0	4.2	26.4	41.4	0.6	20.37	1.30	55 ± 5	-	1 280	1 380	1 400	1 440
PCM	Premier 1	20.7	8.9	30.8	39.6	0.9	20.84		52		1 430	1 601	1 601	1 601
	Premier 2	19.9	3.6	31.4	44.6	0.8	22.55	1.35	46	22.9	1 130	1 209	1 234	1 315
	Premier 3	21.2	4.3	31.3	43.1	0.7	22.04	1.37	42	23.2	1 166	1 365	1 384	1 414
	Premier 4	21.6	4.7	30.8	41.6	0.6	21.59	1.38	46	23.2	1 160	1 343	1 250	1 301
	Premier 5a	21.7	5.4	33.3	41.9	0.7	21.26	1.36	39	21.3	1 045	1 085	1 100	1 120
	Premier 5b	21.8	7.6	31.1	39.6	1.2	20.88	1.36	29	22.7	1 378	1 601	1 601	1 601
	Premier 5	20.6	4.6	29.7	45.2	0.6	22.05	1.41	42	21.9	1 091	1 290	1 305	1 331
	Premier 6	21.5	3.5	34.6	40.5	0.6	22.07	1.36	32	23.9	1 245	1 315	1 343	1 387
	Juno Upr	19.9	10.2	27.5	42.6	0.4	20.64	1.44	34	20.9	1 233	1 465	1 485	1 511
	Juno Lwr	20.1	9.7	28.6	41.6	0.6	20.50	1.42	47	21.7	1 233	1 465	1 485	1 511
	Chiron*	27.0	4.0	27.6	41.4	0.5	20.40	1.33	60	24.5	1 250	1 410	1 450	1 500
	Pan Upr	21.7	5.2	27.7	45.5	0.4	21.32	1.38	61	24.9	1 601	1 601	1 601	1 601
	Pan Lwr	19.8	13.1	26.4	44.5	0.8	19.38	1.42	55	20.1	1 379	1 567	1 569	1 587
	Leda Upr	21.6	7.7	30.2	40.5	0.5	20.76	1.37	36	23.1	1 442	1 601	1 601	1 601
	Leda Lwr	21.3	7.6	29.9	41.2	0.5	20.85	1.38	39	23.0	1 385	1 593	1 596	1 601
	Premier 7	20.0	6.7	28.4	45.0	0.6	21.49	1.39	47	-	1 469	1 541	1 547	1 552
	Centaur*	27.0	3.5	27.1	42.4	0.5	20.60	1.33	50	22.4	1 340	1 430	1 470	1 530
	Tethys Lwr	19.9	10.2	26.6	43.5	0.4	20.31	1.45	60	29.0	1 130	1 600	1 600	1 600
	Premier 8 Upr	20.0	8.6	27.5	43.9	0.7	21.10	1.40	47	19.8	1 239	1 499	1 514	1 523
	Premier 8 Lwr	19.2	8.8	28.2	43.9	0.7	21.14	1.39	43	18.2	1 373	1 571	1 581	1 591
	Zephyrus	20.9	6.7	26.9	45.6	0.4	21.6	1.33	43	18.4	1 192	1 444	1 459	1 496
	Serapis	20.0	9.6	27.3	44.0	0.3	20.56	1.40	55	22.4	1 418	1 601	1 601	1 601
	Eros Upr*	25.0	9.7	25.3	40.0	0.3	19.3	1.40	40	16.1	1 501	1 501	1 501	1 501
	Eros Lwr*	25.0	11.5	24.4	39.1	0.7	19.3	1.40	46	17.8	1 460	1 490	1 501	1 501

Notes: * Proximate analyses normalised to a specific moisture percentage; **MCM** = Muja Coal Measures; **PCM** = Premier Coal Measures; **AS** = Allanson Sandstone; **ECM** = Ewington Coal of seam analyses

Ultimate analyses (%)					Ash analyses (%)												Maceral analyses (%)			
C	*H*	*N*	*S*	*O* (+*err*)	SiO_2	Al_2O_3	Fe_2O_3	*CaO*	*MgO*	TiO_2	Na_2O	K_2O	P_2O_5	Mn_3O_4	SO_3	*RoV max (calc)*	*Vitrinite*	*Mineral matter*	*All reactives*	*All inerts*
SUB-BASIN																				
62.02	3.76	1.07	0.16	19.51	44.40	33.20	9.49	3.46	3.76	1.44	0.49	0.11	0.05	0.05	2.23	-	-	-	-	-
73.76	4.15	1.42	1.25	20.25	51.10	20.00	19.20	1.37	2.25	1.48	0.57	0.27	0.05	0.14	1.59	-	43.5	3.0	69.5	27.5
74.05	4.61	1.37	0.75	19.22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
74.04	4.24	1.33	1.05	19.89	56.4	21.7	12.7	1.34	2.10	1.44	0.64	0.21	0.03	0.11	1.73	-	53.56	2.7	81.5	15.8
73.40	4.23	1.25	0.51	20.87	53.0	22.3	15.2	1.96	1.86	1.57	0.45	0.44	0.93	0.23	1.63	-	59.7	2.9	82.6	14.5
72.99	4.28	1.38	0.59	21.06	40.50	22.50	22.70	3.24	2.34	1.60	0.55	0.38	3.37	0.28	1.37	-	60.7	3.4	82.0	14.6
70.06	4.20	1.12	0.67	19.97	25.40	34.70	24.00	2.77	1.57	1.56	0.79	0.11	4.67	0.01	0.24	-	-	-	-	-
73.19	4.09	1.26	0.92	21.32	21.20	16.80	46.60	4.56	1.77	1.02	0.34	0.45	1.08	0.37	3.83	-	67.7	2.0	76.4	21.6
74.59	4.31	1.31	0.36	19.44	24.35	20.85	36.25	4.93	2.46	1.20	0.25	0.52	1.19	0.43	4.35	0.43	62.00	2.45	85.10	12.45
74.06	4.28	1.35	0.17	20.14	24.35	20.85	36.25	4.93	2.46	1.20	0.25	0.52	1.19	0.43	4.35	0.41	56.70	3.00	79.90	17.20
68.79	4.26	0.94	0.52	18.54	29.50	35.70	20.80	2.13	0.81	1.05	0.34	0.12	3.98	0.02	0.94	-	-	-	-	-
74.05	4.61	1.37	0.75	19.22	55.0	25.1	10.3	1.17	1.50	1.95	0.40	0.60	0.61	0.10	0.48	-	66.66	5.2	88.46	6.40
73.88	4.75	1.20	0.40	19.77	47.81	29.09	11.88	2.23	0.97	1.87	0.34	0.46	3.18	0.13	1.07	0.54	69.19	4.74	85.14	9.53
67.83	4.23	1.02	0.59	16.21	43.90	24.90	22.60	1.77	0.87	1.43	0.21	0.24	0.07	0.07	0.84	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
67.67	4.33	1.11	0.62	16.96	25.80	16.50	40.00	5.96	2.12	1.05	0.39	0.38	0.03	0.23	6.13	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
78.13	4.03	1.46	1.00	15.38	53.3	25.0	15.7	0.85	1.04	1.00	0.45	0.22	0.02	0.07	0.25	-	22.10	3.30	73.70	22.90
78.04	3.86	1.38	0.83	15.89	53.2	28.0	12.6	0.94	1.91	2.50	0.40	0.11	0.06	0.07	0.46	-	17.50	4.90	72.80	22.30
77.78	3.96	1.24	0.21	16.81	53.00	30.47	11.55	0.53	0.43	2.28	0.30	0.09	0.36	0.06	0.29	0.58	21.75	4.80	60.65	34.55
79.5	3.9	1.5	0.5	14.6	60.1	25.6	4.6	3.4	2.6	2.1	0.1	0.2	0.09	0.02	1.7	0.56	26.40	3.25	67.65	29.10
77.65	4.22	1.43	0.37	16.33	44.90	25.40	22.70	1.72	2.02	1.64	0.33	0.16	0.22	0.16	0.55	0.56	23.05	2.60	68.25	29.15
SUB-BASIN																				
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
72.8	5.00	1.52	1.00	19.7	52.42	32.36	8.95	0.99	0.50	1.78	0.35	0.27	1.49	0.09	0.38	-	-	-	-	-
74.0	4.98	1.38	0.43	19.2	56.72	29.60	7.73	0.89	0.47	1.91	0.25	0.30	1.31	0.08	0.05	-	-	-	-	-
73.2	4.93	1.35	0.33	20.2	59.02	28.82	8.38	0.55	0.52	1.76	0.29	0.22	0.06	0.09	0.03	-	-	-	-	-
74.8	4.76	1.96	0.88	18.1	55.64	29.27	8.76	0.95	0.68	2.42	0.27	0.44	0.94	0.05	0.23	-	-	-	-	-
75.0	4.90	1.90	0.81	17.9	47.88	34.18	9.29	1.34	0.68	2.27	0.37	0.35	2.08	0.06	0.34	-	-	-	-	-
76.0	4.49	1.47	0.30	17.7	45.78	33.76	11.44	1.48	0.80	2.27	0.36	0.30	2.44	0.08	0.60	-	-	-	-	-
75.8	4.38	1.39	0.70	17.7	46.45	32.85	11.47	1.55	0.79	2.22	0.34	0.19	2.46	0.07	0.24	-	-	-	-	-
75.3	4.64	1.38	0.54	18.1	39.83	29.64	15.86	3.39	1.95	2.02	0.45	0.28	2.76	0.13	2.11	-	-	-	-	-
-	-	-	-	-	51.07	25.57	12.75	2.24	1.25	1.58	0.44	0.33	2.92	0.10	0.77	-	-	-	-	-
74.80	4.89	1.77	1.23	17.30	53.00	32.40	5.53	1.22	0.77	1.69	0.36	0.98	1.16	0.08	1.21	0.99				
74.97	4.72	1.42	0.81	17.37	37.28	23.22	23.67	3.19	2.13	1.54	0.66	0.33	3.93	0.22	2.24	0.54	64.62	4.30	81.54	14.12
74.28	4.70	1.40	0.70	18.44	47.04	26.69	14.80	2.40	1.47	1.86	0.60	0.70	2.75	0.13	0.71	0.53	69.85	4.08	85.79	10.17
74.39	4.59	1.39	0.60	18.45	42.09	22.09	20.66	3.11	2.01	1.44	0.62	0.30	3.24	0.20	2.51	0.50	64.01	4.69	81.59	13.70
72.91	4.37	1.34	0.71	20.79	54.20	17.30	19.40	1.96	1.62	1.23	0.29	0.27	1.14	0.28	0.30	0.40	59.60	5.00	79.40	15.60
74.10	4.72	1.45	1.62	18.70	48.20	34.65	10.65	0.84	0.45	1.85	0.20	0.53	1.64	0.11	0.19	0.54	52.70	9.50	77.60	13.00
74.88	4.38	1.38	0.50	19.13	57.05	17.60	17.18	1.34	1.55	1.52	0.36	0.29	0.14	0.19	1.18	0.46	56.70	5.43	82.15	12.43
74.00	4.71	1.30	0.70	19.91	42.18	28.20	30.87	1.78	1.53	1.57	0.36	0.22	0.06	0.22	1.53	0.53	73.36	4.22	87.28	8.50
74.65	4.47	1.40	0.65	19.20	70.80	15.10	8.29	0.73	0.97	1.29	0.16	0.19	0.03	0.12	0.41	0.47	-	-	-	-
74.65	4.47	1.40	0.65	19.20	53.66	28.08	12.32	0.77	0.98	1.88	0.23	0.46	0.30	0.14	0.40	0.47	47.53	11.63	73.63	14.75
75.4	4.15	1.35	0.80	18.32	44.56	31.19	18.04	1.16	0.77	1.16	0.14	1.39	0.09	0.39	0.44	-	-	-	-	-
75.38	4.23	1.44	0.51	18.53	51.38	34.93	6.85	0.83	0.66	2.10	0.25	0.40	1.67	0.09	0.20	0.45	41.40	4.10	76.00	20.00
74.86	4.39	1.40	0.75	19.11	51.38	34.93	6.85	0.83	0.66	2.10	0.25	0.40	1.67	0.09	0.20	0.50	49.30	5.66	77.90	16.48
74.39	4.75	1.27	0.45	19.17	52.93	39.70	3.95	0.44	0.33	2.03	0.14	0.53	0.65	0.07	0.14	0.54	54.80	7.80	78.53	13.73
74.47	4.70	1.29	0.57	19.04	51.35	36.18	6.18	0.71	0.52	2.22	0.24	0.52	1.07	0.08	0.06	0.54	62.35	8.43	80.25	11.25
75.08	4.49	1.45	-	18.54	45.77	38.20	9.87	1.16	0.94	2.40	0.32	0.41	1.73	0.10	0.10	0.48	44.80	8.53	76.93	14.50
75.2	4.26	1.34	0.67	18.5	37.82	36.90	15.73	1.43	1.55	1.26	0.55	2.29	0.32	0.32	0.82	-	-	-	-	-
75.36	4.16	1.39	0.51	18.83	53.00	35.70	3.12	1.74	0.84	2.54	0.32	0.28	2.21	0.07	0.03	0.43	34.70	5.70	71.50	22.70
75.93	4.49	1.49	1.20	17.56	53.14	29.12	10.06	1.05	0.70	2.35	0.23	0.26	1.31	0.12	0.19	0.51	42.73	5.45	75.55	18.98
75.01	4.61	1.37	1.45	18.39	56.80	30.60	7.04	0.90	0.95	2.14	0.26	0.29	0.09	0.13	0.30	0.51	41.30	10.60	73.40	16.00
75.72	4.46	1.44	1.37	17.59	56.20	30.80	5.30	1.00	0.88	3.00	0.30	0.16	0.46	0.04	0.49	-	-	-	-	-
75.44	4.43	1.52	0.46	18.24	58.70	33.83	2.84	0.69	0.94	2.48	0.25	0.31	0.07	0.09	0.02	0.48	41.25	6.50	73.95	19.55
62.97	3.80	1.19	0.31	15.24	52.70	30.20	10.00	1.10	0.90	2.10	0.30	0.34	0.06	0.08	0.62	-	-	-	-	-
63.98	3.72	1.30	0.35	14.30	54.50	21.70	13.20	1.90	1.70	3.30	0.46	0.29	0.08	0.12	1.30	-	-	-	-	-

Measures: *HGI* = Hardgrove grindability index; *SG(RD)* = specific gravity(relative density); *SE(ar)* = specific energy (as received); *RoV* = vitrinite reflectance

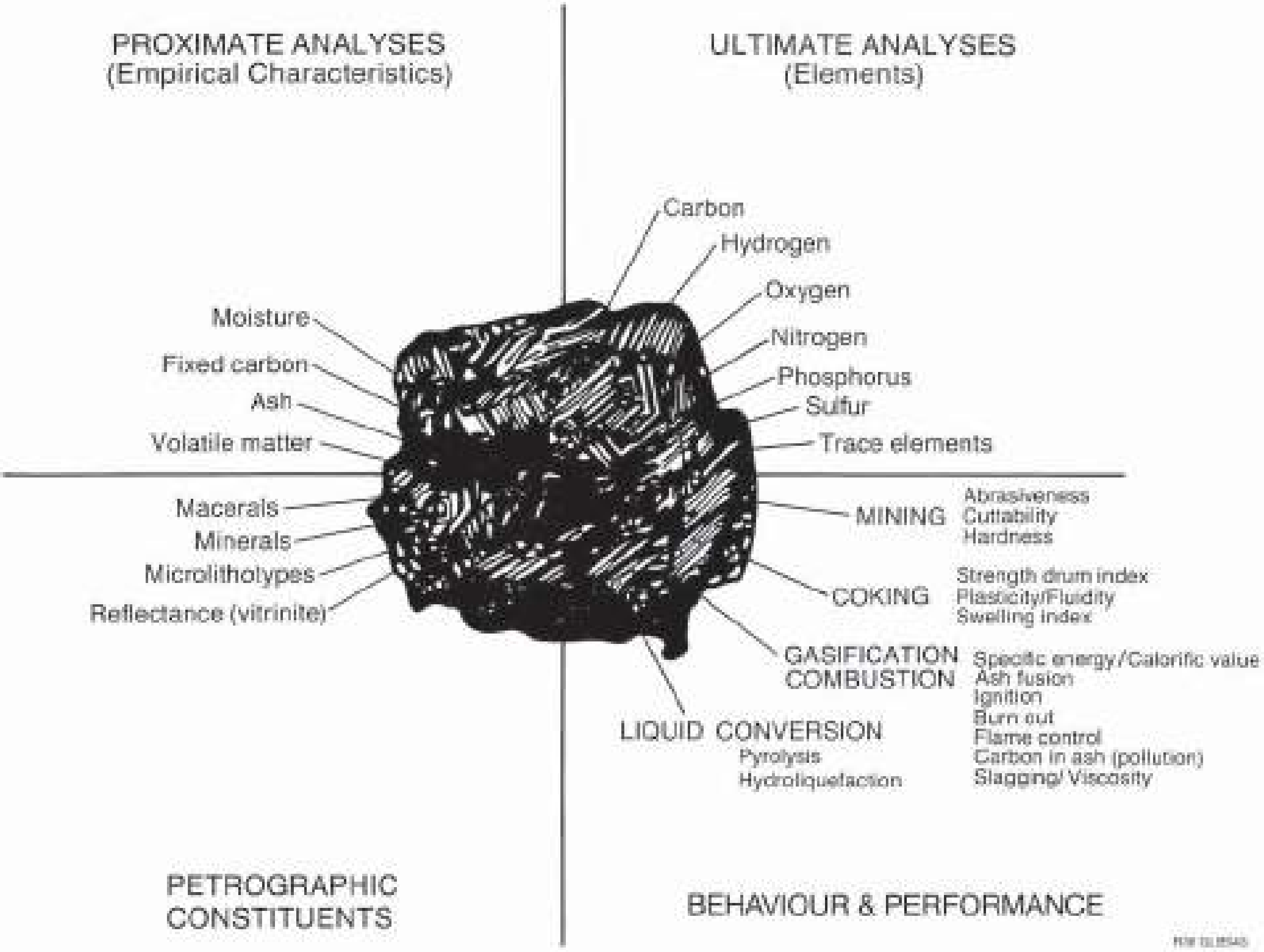


Figure 43. Principal analytical determinations used to quantify coal character and type (modified from Falcon, 1986b)

data to any other basis may be achieved by employing standard formulae developed for this purpose (Australian Standard 1038, Part 16, 1971).

The Collie coal analyses comply with various national and international standards (Le Blanc Smith and Barrow, in prep.) and are thus comparable on a quantitative basis with other coals. Collie coal is a readily combustible rock containing more than 50% by weight (>70% by volume) of carbonaceous material, including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. Differences in the kinds of plant materials (type), in degrees of metamorphism (rank), and in the range of impurity (grade) are characteristic of the coal and are used in its classification. The physical, chemical and technological properties of coal for specific purposes (e.g. gasification, liquefaction, carbonization/coke manufacture) may be evaluated by over sixty analyses (Falcon and Ham, 1988). The vast number of possible uses and multiplicity of coal types demands a detailed characterization, classification and evaluation. The characterization of Collie coal is performed at two levels: *empirical tests* for physical and chemical properties, and *petrographic analyses* by quantified observation using a petrographic microscope (Fig. 43). The most common analytical tests of Collie coal quality are discussed briefly below. The results are summarized in Table 8.

Proximate analyses

The proximate analyses of the principal Collie coal seams are set out in Table 8. They comprise a suite of tests (Australian Standard 1038, Part 3, 1979) to determine inherent moisture, ash content, volatiles and fixed carbon, expressed as percentages.

Inherent moisture is the water that is retained within the pores and fissures of coal after all the surface moisture has been removed. The moisture content of the principal Collie coal seams is high. Raw coal moisture content (as received) ranges between 16 and 25%. The coals desiccate quickly and accurate moisture determination is difficult without special precautions; this may account for the lower values. A significant portion of the reported proximate data has been normalized to a constant moisture content of 25% with appropriate adjustment of the other proximate analyses. As revealed by the increasing vitrinite reflectance, this practice does not fully take into account the differing maturity of the coal seams with depth. Analyses of the deeper coals could thus be skewed by such practices, and their true potential may be less correctly assessed. The distinction between inherent and surface moisture is practically meaningless for low-rank coal (Patterson, C., 1991, pers. comm.)

Ash value is the residue that remains after the complete combustion of the coal. The ash content of the principal Collie coal seams is very low, and raw ash value (as received) is generally between 3 and 10%. Ash analysis shows that the ash is made up principally of oxides of iron, aluminium, titanium, magnesium, calcium, and silica (Table 8). The relative proportions of these various constituents determine the ash-fusion temperature, which is the temperature at which the ash begins to soften and then melt. These temperatures are important to consumers who burn the coal in process vessels, such as power-station furnaces, which require relatively high temperatures. Molten or semi-molten ash can cause considerable difficulties inside process vessels.

Volatile matter is derived from two sources; organic matter and mineral matter. The volatile content of the principal Collie coal seams is high. Raw volatile content (as received) is generally between 22 and 37%. The organic volatile matter produces tars, oils, hydrocarbon gases, hydrogen, and oxides of carbon, which are driven off from coal as the temperature is increased. This has a very significant bearing on its ignition and combustion characteristics. The inorganic matter produces incombustible volatiles such as carbon dioxide from carbonate minerals, sulfur oxides from pyrite minerals, and water (of hydration) from some clay minerals. These components are driven off with the volatile matter; however, they are present in small quantities and do not significantly affect the performance of the coal.

Fixed carbon is that part of the organic content of coal which remains as solid carbon after the volatile matter, ash, and moisture have been removed. The fixed carbon content (as received) of the many Collie coal seams is between 37 and 50% (54–61% daf). The forms of carbon remaining after devolatilization may vary considerably in structure (porosity), texture (nature of matrix), and rates of reactivity.

Ultimate analysis

Ultimate analysis is routinely performed on the Collie coals and, as the name implies, divides the coal into its ultimate chemical components — the elements carbon, hydrogen, oxygen, nitrogen, and sulfur (Australian Standard 1038, Part 6, 1971). The ultimate elemental components of the principal seams are given in Table 8.

Ultimate analysis forms the basis for the Seyler coal classification. Snyman et al. (1983) have derived a set of empirical relationships based on ultimate analysis whereby specific energy, volatile matter, vitrinite reflectance (max), type, and oxygen may be calculated from the carbon and hydrogen content of a coal (Fig. 44). The formulae below appear generally applicable to coals from the Collie Basin, and are particularly useful in determining vitrinite reflectance (rank) for which there is a paucity of data.

$$\begin{aligned}\text{Specific energy (MJ/kg)} &= 21.1090851 - (0.6721646 \times C) + (7.0206718 \times H) + (0.0080259 \times C^2) - (0.0423184 \times C \times H) - (0.1809127 \times H^2)\end{aligned}$$

$$\begin{aligned}\text{Volatiles } (> 15\ \%) &= 195.266891 - (4.5948496 \times C) + (26.389751 \times H) + (0.0254121 \times C^2) - (0.2403579 \times C \times H) + (0.4694757 \times H^2)\end{aligned}$$

$$\begin{aligned}\text{RoV (max \%)} &= 0.9177287 - (0.26656 \times C) + (3.6055708 \times H) + (0.0037036 \times C^2) - (0.0587235 \times C \times H) + (0.1145169 \times H^2)\end{aligned}$$

$$\begin{aligned}\text{Oxygen (\%)} &= 64.4465637 - (1.0789852 \times C) + (15.454361 \times H) + (0.0032782 \times C^2) - (0.1118453 \times C \times H) + (0.7556731 \times H^2)\end{aligned}$$

where

C = carbon % (daf) from ultimate analysis
H = hydrogen % (daf) from ultimate analysis

Possibly the most significant of over sixty additional empirical coal characteristics are the measures of sulfur and energy content.

Specific energy

Specific energy is a measure of the 'heat' content or 'energy' value of a coal (Australian Standard 1038, Part 5, 1979). The specific energy of the Collie coal seams is low and lies between 18.0 and 22.0 MJ/kg (as received), and 29.0 and 31.9 MJ/kg (daf). This is one of the most important commercial parameters for the coal. The specific energy analyses of the principal Collie coal seams are listed in Table 8.

Sulfur

The coals in the Collie Basin are generally low in *sulfur* (i.e. <0.55% daf; Hunt, 1985). The total sulfur content for the coal seams being mined at the Muja opencut varies between 0.29 and 0.49% (daf) based on analyses from SECWA (Sappal, 1986, fig. 5.5) although WCL report values as high as 1%.

Major elements in ash

The *major elements in ash* (AS1038.14) provide important information used in determining the potential behaviour of ash in combustion vessels. Various formulae yield slagging and fouling indices, which are dependent principally on the relationship between the alkali and iron oxides in the ash. Table 9 shows a comparison between the ranges of major elements in ash for Collie coals in general, and for blended coal supplied to SECWA (Mandyczewsky and Weir, 1984).

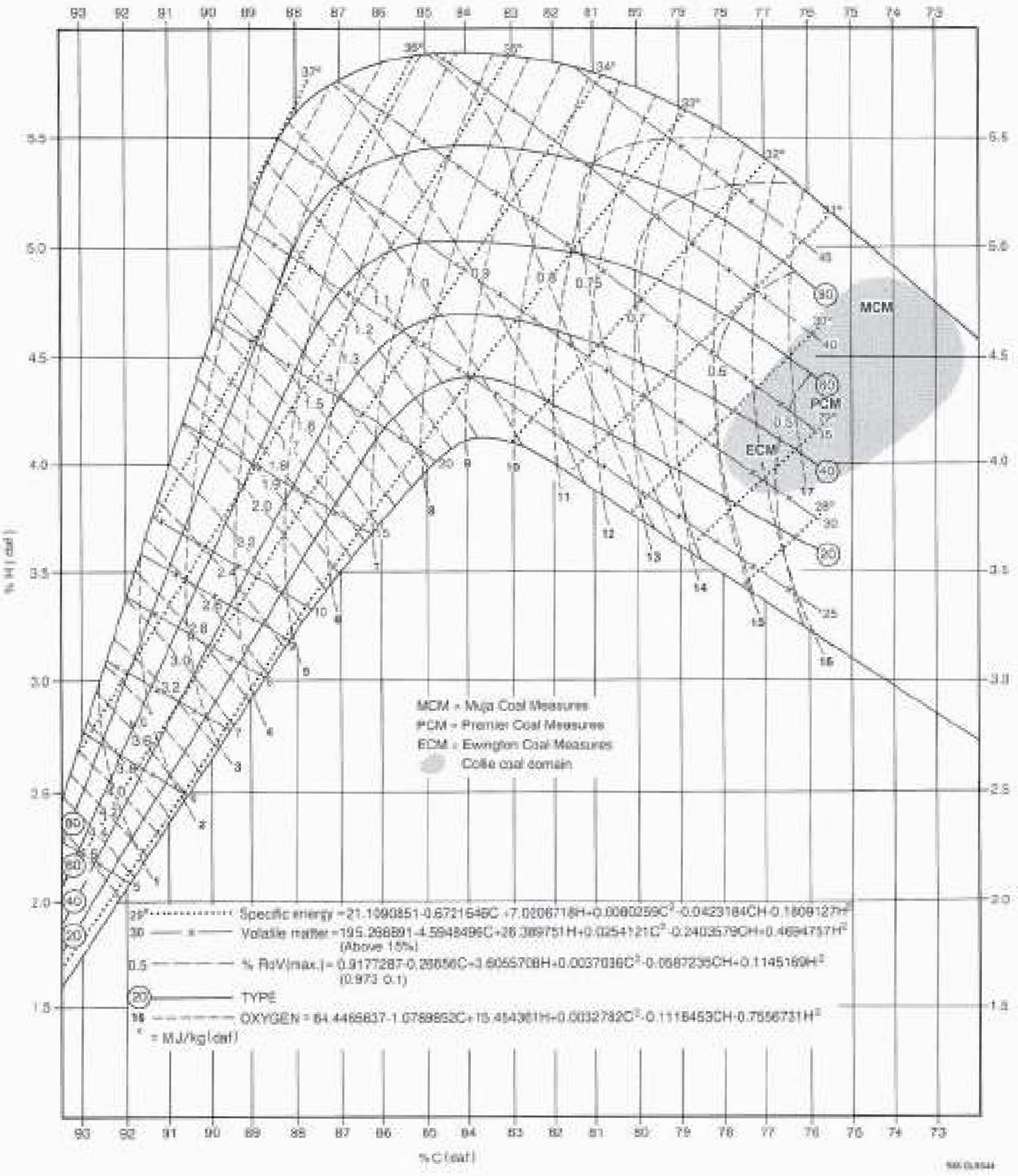


Figure 44. The domain of Collie coal mapped onto a modified Seyler classification which shows the relationship between the chemical properties of coal and its type (vitrinite content, mineral-free) and rank (RoV max) (modified from Snyman et al., 1983)

Trace elements and geochemistry

Three hundred and thirty-four samples from 26 major seams and a number of minor seams have been analysed for their ash content and for up to 34 inorganic elements (Davy and Wilson, 1989, 1990; ASTM D3683-78). In general, the Collie coals are low in ash content and, in consequence, silicate components are low. Most of the coals have a low trace-element content although individual seams may have substantially higher values. In particular, Pb levels in the upper seams of the Muja Coal Measures in the Cardiff Sub-basin are high—up to 480 ppm in the coal (1% in the coal ash)—and the maximum individual value of Pb in adjacent strata reaches 595 ppm. The

Table 9. Collie coal — major elements in ash

Elements	*SECWA coal* (%)	*Seam coals* (%)
SiO_2	40 – 60	9 – 75
Al_2O_3	20 – 40	13 – 46
Fe_2O_3	5 – 20	0.5 – 50
CaO	0.1 – 2	0.1 – 13
MgO	0.1 – 2	0.2 – 5.5
Na_2O	0.1 – 1	0.01 – 2.7
K_2O	0.1 – 1	0.04 – 1.5
TiO_2	0.5 – 2	0.1 – 4
P_2O_5	0.5 – 4	0 – 13

Al_2O_3/SiO_2 ratio of many coals is high (exceeding unity) and there is more Al_2O_3 present than can be absorbed in kaolinite, the only common clay mineral. The excess Al_2O_3 is present either as amorphous oxide/hydroxide or as crystalline gibbsite, and may represent incipient bauxitization. The amount of rare-earth elements (Ce, La, and Y) in some Collie coals is much higher than in coals from other parts of the world.

No seam has a chemical signature sufficiently distinctive to permit either the positive identification of a sample of unknown origin, or the correlation of seams across the basin. Nevertheless there are secular composition trends, particularly in the Cardiff Sub-basin where rare-earth elements (Ce, La, and Y) increase and alkaline-earth elements (especially Ba and Sr) and P decrease in successively younger seams. On the basis of these trends, the Ben Seam is probably a split of either Cardiff No. 1 or No. 2 Seams.

The minerals present indicate mixed origins related variously to detrital input, chemical precipitation, and authigenic growth. Detrital source material is dominantly felsic in origin and includes minerals derived from metasediments. Elements which seem to relate principally to detrital fractions include Al, Si, K, Cr, Cu, Li, Nb, Th, V, and Zr and, to a lesser extent, Ce, La, Pb, and Y. Other elements, B in particular, can be related to the organic fraction of coal. Some elements (e.g. Mg, Na) appear to be partitioned between minerals of different origins, and Ba and Sr (present as barytocelestite) have a mixed chemical-detrital origin.

High levels of U occur locally in a shale below the Diana seam (Muja Coal Measures, Premier Sub-basin). The distribution of this element, and of Pb in other parts of the basin, may have potential economic significance in that they point to the possibility of mineralized source rocks in an area to the south and east of the basin (Davy and Wilson, 1989).

Abrasiveness

Abrasiveness is essentially a measure of the potential for the mineral contents in the coal to cause wear in mechanical components, such as crushers and grinding mills (Australian Standard 1038, Part 19, 1981). Mandyczewsky and Weir (1984) have investigated the relationship between abrasiveness and mineral content for Collie coal. A moisture-independent form of the Yancey Geer and Price technique, the *inherent abrasive index*, ranges from 10 to 50 mg Fe/kg for coal in situ. The *gross abrasive index* is dependent on coal moisture levels and attains values as high as 210 mg Fe/kg.

Hardgrove grindability index

The *Hardgrove grindability index* (*HGI*) is essentially a measure of the rate at which fine coal can be produced by mechanical milling (Australian Standard 1038, Part 20, 1981). Mandyczewsky and Weir (1984) report values of 40–70 as being typical of Collie coal (Table 8).

Petrographic analyses

Collie coal consists of various organic and inorganic constituents and the heterogeneous nature of coal is visible to the naked eye by virtue of bright and dull bands (Sappal, 1986). Thus the coal can be characterized in terms of its observable organic and inorganic constituents (Falcon and Ham, 1988) as seen under the petrographic microscope. The coal composition can be assessed with respect to three categories: organic matter, mineral matter, and degree of maturity (Crelling and Dutcher, 1980).

Organic matter content (type)

The nature and proportions of the organic-matter content determines the type of the coal. The organic matter in Collie coal includes the fragmented and partially decomposed organic remains of the original vegetable matter. Such microscopically recognizable units of organic matter are termed *macerals* (Stopes, 1935). Historically, little emphasis was placed on determining maceral content of the Collie coals; however, this has changed and coal core is now petrographically analysed. The various maceral forms are combined into three groups: vitrinite, exinite (or liptinite), and inertinite (Sappal, 1986; ICCP, 1963) on the basis of their common chemical, physical, genetic, and technological properties. The maceral analyses of the principal Collie coal seams are given in Table 8.

For the purpose of combustion assessment, the macerals are conventionally separated into 'reactive' and 'unreactive' types. The reactive types are those which on being heated will devolatilize, change in structure, texture and form, and ultimately ignite and combust rapidly in the presence of oxygen. Unreactive types, however, are slow to change. They require more heat and oxygen in order to ignite and a longer time to burn out. The terms *reactive* and *unreactive* are relative and not absolute descriptions and refer mostly to the medium to low ranks of coal such as are found at Collie. Total reactive macerals include vitrinite, exinite, and part of the inertinite group. The ratio of reactive to unreactive macerals in Collie coals is variable. In general, the coals near the base of the succession (Ewington Coal Measures) are characterized by a much higher inertinite content, some of which is semireactive, and a vitrinite content as low as 10%. The vitrinite content increases significantly at higher levels in the succession (Premier and Muja Coal Measures) to a maximum of 80% (Table 8). The hydrogen-rich exinite proportions are low, ranging from 2 to 5% in Collie coal.

The organic-matter content can also be described in terms of associations of macerals in layers or bands thicker than 50 cm. Such associations are termed lithotypes (Seyler, 1954) and microlithotypes (Falcon, 1986b) following the European or Stopes–Heerlen system, whereas the Thiessen–U.S. Bureau of Mines system is related to the amount of banding (Fieldner et al., 1931; Parks and O'Donnell, 1956). Diessel (1965) adopted the banded concept for east Australian coals and Sappal (1986) applied this to Collie coals under the term 'lithotypes' (Plate 7). The microlithotypes may consist of pure macerals, a mixture of two, or all three maceral groups. The chemical and physical properties of the constituents give a band its basic properties. Where microlithotypes are contaminated with more than 20% mineral matter (or 5% pyrite) in an intimate mixture of maceral and mineral inclusions, they are referred to as *carbominerites* (Falcon and Ham, 1988) irrespective of the macerals present. The Flora Seam (Muja Coal Measures) contains significant carbominerite; however, the low ash and sulfur content in most coal seams precludes carbominerite development.

Microlithotypes (the types of maceral associations) can play extremely important roles in terms of the strength, density, and combustion (liberation, gasification, and coking) behaviour of coal (Falcon and Ham, 1988). For example, two coals may contain the same amounts of volatile matter, fixed carbon and ash, and indeed maceral content, but the macerals may be associated in well-banded discrete homogeneous layers, or in mixed heterogeneous layers. In the latter case, too many contaminants in a band will prevent the formation of large pores and will seriously affect the structure and combustion. The distribution and proportions of such bands are now becoming important in the technological evaluation of coal (Shibaoka and Ramsden, 1978). However, the effect of microlithotype on combustion at Collie has not been investigated in any detail and there is no information on performance differences (e.g. burn-time) between the coals supplied to SECWA from the Muja and Ewington Coal Measures (Mandyczewsky, R., 1992, pers. comm.).

Mineral matter content (grade)

The total constituents of the mineral matter determine the *grade* of a coal; the size, shape, form, type, and degree of intergrowth of the minerals in the organic matrix provide useful information concerning the hardness and abrasiveness index, the pollution potential, and the possibility of liberating such minerals in the beneficiation of coals rich in these minerals. The relationship between mineral content and abrasiveness of Collie coal was investigated by Mandyczewsky and Weir (1984).

Degree of maturity (rank)

Rank refers to the degree of maturity or metamorphism (coalification) achieved by a coal through the agencies of time, temperature and pressure as a result of burial (and consequently heating) following peat accumulation (Stach et al., 1982). The progressive change into coal passes through a number of stages:

> *plants — peat — lignite (brown coal) — sub-bituminous (black coal) — bituminous (black coal) — anthracite (black coal) — graphite.*

The position reached in this coalification series determines the rank of a coal.

With increasing rank, significant and progressive changes in the physical, chemical and technological properties of the macerals take place, particularly in the vitrinite and exinite maceral groups. The inertinite group, however, being a carbon-rich, dense and relatively inert product as a result of oxidation prior to or during swamp accumulation, maintains its original structure, form and chemistry and undergoes very little change throughout the coalification series (van Krevelen, 1981). The use of volatile matter as a measure of rank is increasingly unreliable in coals as mineral matter increases. For example, in high-ash coals, up to 60% of volatile matter is contributed by the thermal dissociation of minerals (Snyman et al., 1984; Kautz, 1982).

Vitrinite reflectance is a standardized and widely used method of rank determination. This method has been chosen because the optical reflectance of vitrinite, determined using a photomultiplier attached to the reflected-light microscope (McCartney and Teichmuller, 1972), increases regularly and progressively with increasing rank irrespective of the proportion of macerals and minerals present. This increase in reflectivity is consistent with the increase in carbon content and aromaticity with rank.

The origin, nature, constitution, and maturity of Collie coal vary markedly between different seams, and Figure 45 shows this range in comparison with that of other coals in Australia and overseas.

Coal classification

Falcon (1986b) succinctly describes coal classification as 'primarily a means of standardized communication between coal producers and users alike'. It is a system of categorization based upon a limited number of parameters that provides a framework into which coals may be placed, their behaviour predicted, and properties compared. Specifications, on the other hand, are parameters not necessarily included in a classification system; however, they are either applicable to a specific aspect, or a requirement for a particular use.

The purposes for which classification systems were devised may be divided into two broad categories:

1. ***Geological–scientific*** systems including:

   genetic classifications based on composition and origin, and

   rank classifications, based on degree of maturity or metamorphism.

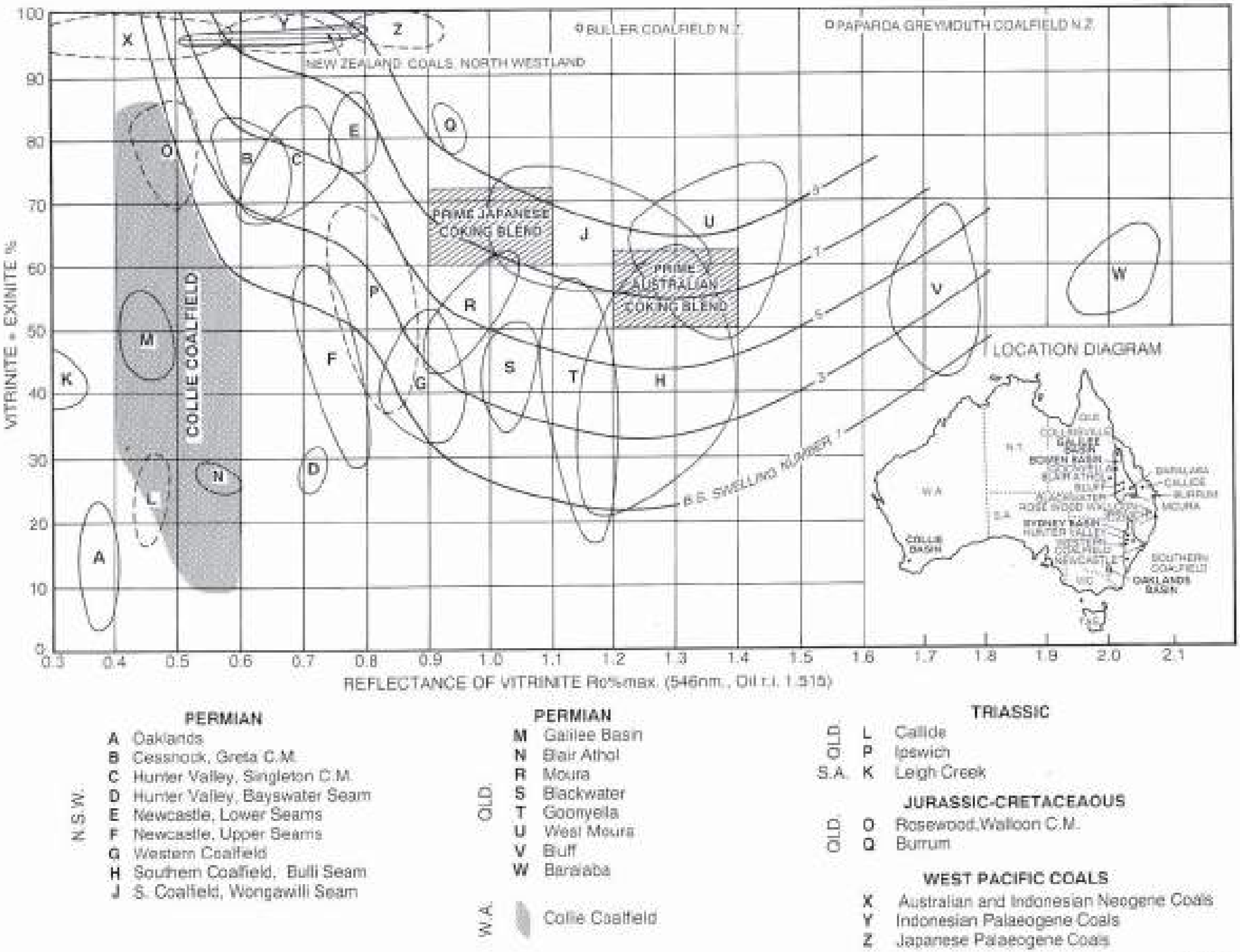


Figure 45. Comparison of characteristic values of coal type and rank for selected seams in Australasia (adapted from Strauss et al., 1976)

Table 10. Coded Commercial Coal Classification System

Mean random reflectance 1:2	%	Swelling index 3		Volatile matter content 4:5	Weight % (Daf)	Reflectogram 6	St. dev.	Gaps	Inertinite content 7	Vol. %	Gross calorific value 8	MJ/kg (Daf)
02	0.20 – 0.39	0	0 – ½	44	≥44	0	<0.1	0	0	0 – 9	0	<22
04	0.40 – 0.59	1	1 – 1½	42	42 – <44	1	0.1 – 0.2	0	1	10 – 19	1	22 – <24
06	0.60 – 0.79	2	2 – 2½	40	40 – <42	2	>0.2	0	2	20 – 29	2	24 – <26
08	0.80 – 0.99	3	3 – 3½	38	38 – <40	3	>0.2	1	3	30 – 39	3	26 – <28
10	1.00 – 1.19	4	4 – 4½	36	36 – <38	4	>0.2	2	4	40 – 49	4	28 – <30
12	1.20 – 1.39	5	5 – 5½	34	34 – <36	5	>0.2	>2	5	50 – 59	5	30 – <32
14	1.40 – 1.59	6	6 – 6½	32	32 – <34				6	60 – 69	6	32 – <34
16	1.60 – 1.79	7	7 – 7½	30	30 – <32				7	>69	7	34 – <36
18	1.80 – 1.99	8	8 – 8½	28	28 – <30						8	36 – <38
20	2.00 – 2.19	9	9	26	26 – <28						9	≥38
22	2.20 – 2.39			24	24 – <26							
24	2.40 – 2.59			22	22 – <24							
26	2.60 – 2.79			20	20 – <22							
28	2.80 – 2.99			18	18 – <20							
30	3.00 – 3.19			16	16 – <18							
32	3.20 – 3.39			14	14 – <16							
34	3.40 – 3.59			12	12 – <14							
36	3.60 – 3.79			10	10 – <12							
38	3.80 – 3.99			9	9 – <10							
40	4.00 – 4.19			8	8 – <9							
42	4.20 – 4.39			7	7 – <8							
44	4.40 – 4.59				etc							
46	4.60 – 4.79											

Example: Good coking coal	:					CODE
Mean random reflectance %	: 1.23					12
Free swelling index	: 8					8
Volatile matter content wt % (Daf)	: 27					26
Reflectogram characteristics	: s = 0.16: no gap					1
Inertinite content Vol. %	: 16					1
Gross calorific value MJ/kg (Daf)	: 36.2					8
CODED NUMBER	: 12	8	26	1	1	8

Source: UNECE Committee for Coal Classification (1985). Shaded area depicts domain of Collie coal.

2. *Commercial–technological* systems including:

   commercial classifications based upon legally defined parameters such as size, ash, specific energy, and

   technological classifications based upon behavioural/performance characteristics relative to various specialized fields of use. The parameters used in the scientific systems often provide the basis for the commercial and technological systems.

As summarized by Kruszewska (1984), most existing classifications are based upon the results of proximate and ultimate analyses and some technological properties. More recently, petrographic parameters have been introduced. The most common parameters in each of these four groups are illustrated in Figure 43.

Classification of Collie coal has traditionally been focused principally on combustion for steam-raising; initially for rail, and subsequently for electricity generation.

Combined scientific and technological classification

Kent (1939) categorized Collie coal in Seyler's (1934) coal classification and showed that coal from the Ewington Coal Measures (current stratigraphic terminology) lies in the sub-ortholignitous section, that from the Premier Coal Measures lies on the boundary with lignite, and coal from the Muja Coal Measures lies in the lignite section. However, Snyman et al. (1983) have devised a most promising classification which combines technological and scientific attributes linked through formulae based on the ultimate analyses (C and H % daf) of the Seyler system. The Collie coal domain is mapped on this revised version of the Seyler classification scheme which illustrates the relationships between chemical properties of coal, its type, and rank (Fig. 44).

The determination of proximate analyses of Collie coal is simpler and faster than that of ultimate analyses. Thus, considering also the relationship between ultimate and proximate analyses and specific energy, the American Society of Testing and Materials classification of coals by rank has been favoured (ASTM D388-7). This is the system most commonly used in discussions between the Collie coal-mining companies and SECWA. Collie coal is generally ascribed to the sub-bituminous class. However, it has unusual physical and chemical properties. For example, it is non-agglomerating coal with specific energy of 29.0–31.9 MJ/kg daf (dmmf will increase these values). This range falls within the limits of heating value of the 'high-volatile C bituminous coal' rank (hvCb) in the ASTM classification, and a few seams rank as hvBb coals. Thus, Collie coal does not fit the ASTM classification system.

The classification system for Australian hard coals (Australian Standard 2096, 1977) is rarely, if ever, used for Collie coal (Mandyczewsky, R., 1992, pers. comm.). Furthermore, the International Classification of Hard Coals proposed by the United Nations Economic Commission

Table 11. Comparative Collie Coal parameters on the Coded Commercial Classification System (UNECECCC, 1983)

Code Digits	*Parameter (Raw)*	*Code*
1 and 2	Mean random reflectance %	04
3	Free swelling index	0
4 and 5	Volatile matter (daf) wt %	30–48
6	Reflectogram characteristics	0
7	Inertinite content vol. %	7–2
8	Gross calorific value (daf) MJ/kg	4

for Europe Coal Committee (1983) is not considered the most suitable because it has the following significant weaknesses (Alpern, 1981):

- it does not cover all ranks of coal
- it does not distinguish clearly between hard coal and lignite
- volatile matter content is not acceptable as a parameter of rank
- it is mute on the variation of maceral matter and its influence on volatile content
- it is a numeric code which lacks logical linkage to the parameters
- it does not address all parameters related to carbonization
- it does not function for coal with an ash content higher than 10%.

The Coded Commercial Classification System (CCCS) for medium- to high-rank coals (United Nations Economic Commission for Europe Coal Committee, 1983; Uribe and Perez, 1985), which is based upon six parameters involving eight digits, can be applied to most Collie coal seams because the raw ash content is so low (3–9%) (Tables 10 and 11). The CCCS code number for a typical Collie coal is 04 0 38 0 2 4. This system has similarities to the Australian classification for hard coals.

Alpern universal coal classification

The system devised by Alpern (1981) and subsequently modified (Falcon, 1986b; Alpern et al., 1989) is a genetic geological classification which has major advantages as it incorporates all coals from raw to processed products and is based on fundamental inherent properties of coal:

- *rank*, using reflectance of vitrinite;
- *type*, using maceral composition; and
- *grade* or facies, using ash content.

With Alpern's system most of the seams from the Collie Basin can be plotted using vitrinite reflectance determinations and maceral composition (Fig. 46). Maceral analysis has been performed routinely on Collie coal core for a number of years. Vitrinite reflectance values are derived from two sources: determinations from direct observation (Sappal, 1986), and derivations from ultimate analyses using the formula of Snyman et al. (1983) for those seams without petrographic reflectance data. Checks show a correlation between the vitrinite reflectance values derived from ultimate analyses, and those from direct observation of the same seam.

Table 12. Collie Coalfield coal production (Mt)

Year	*Opencut*	*Underground*	*Total (Mt)*
1899			0.004
1900			0.120
1905			0.129
1910			0.266
1915	Production figures not presented		0.291
1920			0.469
1925			0.444
1930			0.509
1935			0.546
1940			0.548
1945			0.552
1950			0.827
1955			0.918
1960			0.937
1965			1.010
1970			1.216
1975			1.167
1979	2.143	0.592	2.735
1980	2.521	0.631	3.152
1981	2.578	0.677	3.255
1982	2.962	0.741	3.703
1983	3.154	0.799	3.953
1984	2.904	0.788	3.692
1985	2.923	0.863	3.786
1986	2.945	0.881	3.826
1987	2.836	0.874	3.710
1988	2.808	0.894	3.702
1989	2.929	0.902	3.831
1990	3.806	1.020	4.826
1991	4.195	0.913	5.108

The average qualities of the Collie coals in terms of rank, type, and grade are shown on Figure 46. Note that the junction between bituminous and sub-bituminous is placed at 0.5% (Falcon, 1986b) and vitrinite reflectance is plotted on a logarithmic axis to conveniently display the lower rank coals typical of the Collie Basin. The *rank* axis is marked by the values for the vitrinite reflectance code digits 1 and 2 as defined by the International Committee for Coal Petrology (ICCP) for the Commercial ECECC system of classification (Table 11); similarly, the modified code digit 7 for inertinite is placed along the *type* axis. The inertinite coding is based on the formula

> *100 – Total reactive macerals* (i.e. vitrinite + exinite + reactive inertinite macerals)

which takes into account the transitional reactive macerals in the inertinite category, a significant component of Collie coal.

Using the modified Universal Classification for solid fuel, Collie coal may be categorized thus:

Type: humic with a range between code 2 (vitric) and code 7 (inertic), and reactives up to 80%

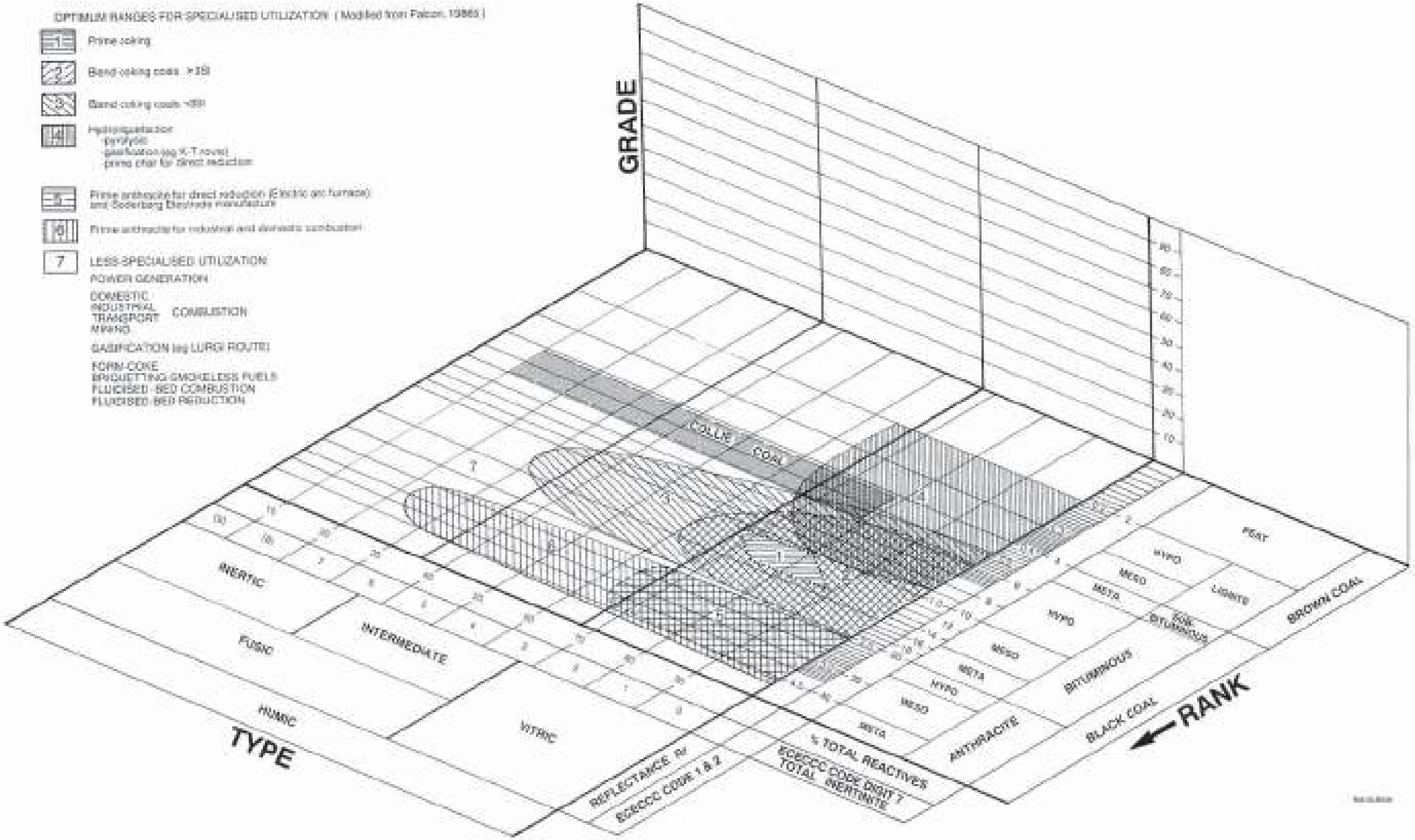


Figure 46. Integrated graphic coal classification showing Collie coal-classification domain compared to coal-utilization domains

Rank: (hypo) bituminous in the Ewington and Premier Coal Measures and (meta) sub-bituminous in the Muja Coal Measures; crosses the boundary (0.5%).

Production and utilization

Collie is the only producing coalfield in the State at present. There are two companies mining coal; The Griffin Coal Mining Company Proprietary Limited and Western Collieries Limited. The locations and operating dates for all mines in the Collie Basin are given in Figure 5. Underground mining commenced in 1898 at the Government Mine (later renamed the Wallsend Colliery). Opencut mining first commenced at the Stockton Colliery in 1943 and was followed by Wallsend Opencut in 1946 and Black Diamond in 1948. There are currently seven mines; four opencut (Muja, Chicken Creek, Western Opencuts 3 and 5) and three underground (Western Deep 2, 6, and 7). Production figures are given in Table 12.

About 79% of Collie coal is purchased by the State Energy Commission for its power stations at Muja, Kwinana, and Bunbury. The balance of the production is sold for use in private power generation, cement manufacture, brick making, mineral sands production and refining, and other industrial applications. There are currently no coal exports from Western Australia. There is potential for the development of alternative coal-utilization technology (Fig. 46), including hydroliquefaction for synfuels and reduction of metal ores (Roberts, 1988; Shields, 1990), and investigation into carbonizing properties and form-coke production from char (Goodheart and Brennan, 1980). Van den Berg and Dippenaar (1989) demonstrated the superiority of Collie coal over a range of South African coals in a study of fluidized-bed reduction of fine iron ore by the on-site combustion of coal.

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Appendix 1

Australian code for reporting identified coal resources and reserves (February 1986)*

Introduction

This code outlines general concepts for reporting identified Coal Resources and Reserves. It is broad in nature to accommodate the wide range of coal deposits, in terms of rank, quality, and geological environment, that are present in Australia.

In this Code, the term Resources is used to refer to all of the coal in situ which may have potential for use, and the various categories indicate the level of confidence of the assessment. Reserves are those resources which are planned to be mined and for which such planning has been undertaken. The Code sets only minimum guidelines for evaluating Resources and Reserves and the estimator is required to state clearly the criteria used in any assessment.

Additional guidelines and parameters may be required for reporting coal Resources and Reserves from specific basins or regions.

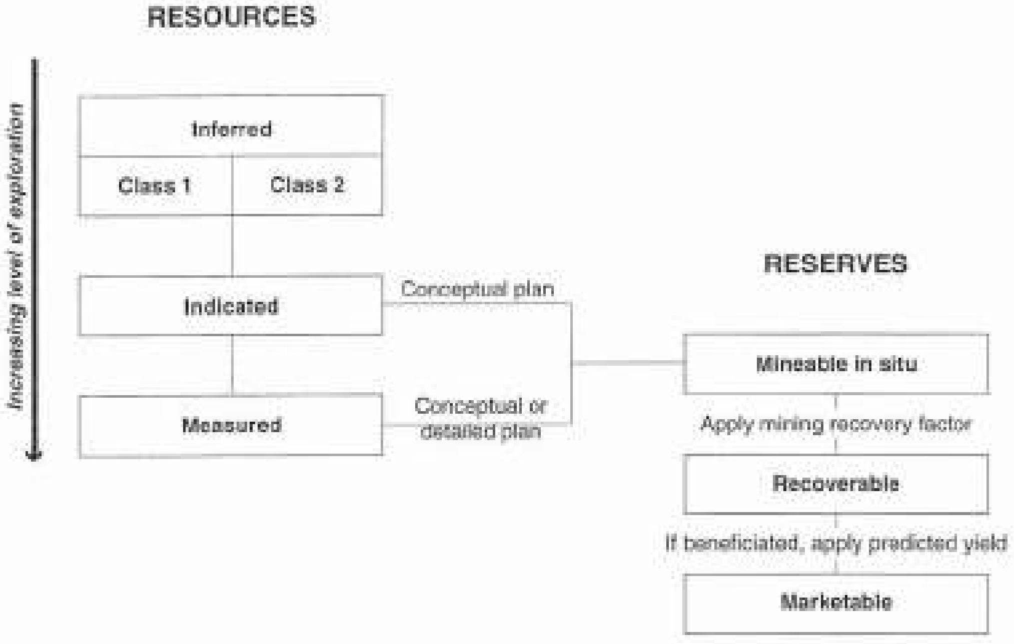
Definitions

Coal Resources

Coal Resources are all of the potentially usable coal in a defined area, and are based on points of observation and extrapolations from those points. Potentially usable coal is defined as coal which has, or could be beneficiated to give, a quality acceptable for commercial usage in the forseeable future, and excludes minor coal occurrences. The estimator should state both the quality and thickness limits to define potentially usable coal in any resource evaluation.

Coal Reserves

Coal Reserves are those parts of the Coal Resources for which sufficient information is available to enable



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* Source: Galligan and Mengel (1986)

detailed or conceptual mine planning and for which such planning has been undertaken.

Points of Observation

A Point of Observation is an intersection, at a known location, of coal-bearing strata, which provides information about the strata by one or more of the following methods:

- Observation, measurement and testing of surface or underground exposures
- Observation, measurement and testing of bore core
- Observation and testing of cuttings, and use of down-hole geophysical logs of non-cored boreholes

A point of observation for coal quantity may not be used necessarily for coal quality. The most reliable quality information is provided by testing of surface or underground exposures or by testing of bore core.

Geophysical techniques such as seismic surveys are not direct points of observation but may increase confidence in the continuity of seams between points of observation, especially in the broader Resource categories.

The distances between points of observation and extrapolations from points of observation quoted for each Resource category are normally the maximum under favourable geological conditions. More closely spaced points of observation will be required in areas where faulting, intrusion, seam splitting and other breaks in seam continuity are known to occur, or where the seam is subject to significant variation in thickness or quality.

Categories of Resources

Measured Resources are those for which the density and quality of points of observation are sufficient to allow a reliable estimate of the coal thickness, quality, depth and in situ tonnage.

Points of observation should provide a level of confidence sufficient to allow detailed planning, costing of extraction and specification of a marketable product.

The points of observation generally should be not more than 1 km apart. Where geological conditions are favourable it may be possible to extrapolate known trends a maximum distance of 0.5 km from points of observation.

Indicated Resources are those for which the density and quality of points of observation are sufficient to allow a realistic estimate of the coal thickness, quality, depth and in situ tonnage and for which there is reasonable expectation that the estimate of resources will not vary significantly with more detailed exploration.

Points of observation generally should be not more than 2 km apart. Where geological conditions are favourable, it may be possible to extrapolate known trends a maximum distance of 0.5 km from points of observation.

Inferred Resources are those for which the points of observation are widely spaced and as a result, assessment of this type of resource may be unreliable.

Points of observation should allow the presence of coal to be unambiguously determined.

Inferred Resources Class 1 are those resources for which the points of observation allow an estimate of the coal thickness and general coal quality to be made, and the geological conditions indicate continuity of seams between the points of observation.

Points of observation generally should not be more than 4 km apart. Extrapolations of trends should not extend more than 2 km from the points of observation.

Inferred Resources Class 2 are those for which there is limited information and as a result the assessment of this type may be unreliable.

Provided the coal thickness can be determined, the order to magnitude of Inferred Resources Class 2 may be expressed within the following ranges:

1–10 million tonnes
10–100 million tonnes
100–500 million tonnes
500–1000 million tonnes
>1000 million tonnes

If a more specific quantitative estimate is made to determine exploration priorities etc., it should not be quoted in public reports or in any prospectus.

Type of Reserves

Mineable In situ Reserves are the tonnages of in situ coal contained in seams or sections of seams for which sufficient information is available to enable detailed or conceptual mine planning and for which such planning has been undertaken.

Mineable In situ Reserves may be calculated only from Measured and Indicated Resources. Measured Resources are required for detailed mine planning, and are the preferred basis for Mineable In situ Reserves. Indicated Resources may be used for conceptual mine planning. In general, further exploration will be required prior to commencement of mining operations.

Mineable In situ Reserves should be quoted separately for surface and underground mines and an outline of the proposed mining methods(s) should be provided.

Recoverable Reserves are the tonnages of Mineable In situ Reserves that are expected to be recovered, i.e. that proportion of the seam(s) which will be extracted. If dilution is added to the Recoverable Reserves tonnage, the total equates to the 'run-of-mine' tonnage. If allowance is made for dilution it should be stated.

In calculating Recoverable Reserves a Mining Recovery Factor must be applied to the Mineable In situ

Reserves. This factor will depend on the mining method to be used. Unless a specific factor has been determined for conceptual studies, the historically proven Mining Recovery Factor should be used. If such information is not available, a Mining Recovery Factor of 50% for underground reserves and 90% for surface reserves may be applied. An outline of the proposed mining method should accompany any statement of Recoverable Reserves.

Marketable Reserves are the tonnages of coal that will be available for sale.

If the coal is to be marketed raw, the Marketable Reserves will be the same as the Recoverable Reserves plus dilution, i.e. the 'run-of-mine' tonnage. If the coal is to be beneficiated, Marketable Reserves are calculated by applying the predicted yield to the Recoverable Reserves. The basis of the predicted yield should be stated, e.g. 200 mm cores, slim cores, pretreated cores.

Reporting of Resources and Reserves

All factors used to limit Resources and Reserves and necessary to verify the calculations (including the types of observations, e.g. core hole, outcrop) must be stated explicitly. The relative density value adopted in calculating the coal tonnage should be noted, together with the evidence on which it is based. Tonnage estimates always should be rounded, commensurate with the accuracy of estimation.

Resources and Reserves should be stated:

- for each seam
- on a depth basis, in regular depth increments if sufficient information is available
- on a seam thickness basis, the minimum thickness used should be stated and separate tonnages should be quoted for seams less than 1.5 m thick and seams equal to or greater than 1.5 m (this limit may be greater for brown coal e.g. 3 m). The maximum thickness of any included non-coal bands should be stated. Normally where a seam contains non-coal bands thicker than 0.3 m the two coal splits should be considered as separate seams and tonnages should be reported for each (the limit for non-coal bands may be greater for brown coal sequences, e.g. 1 m)
- on a quality basis, maximum raw coal ash should be stated and only that coal which can be used or beneficiated at an acceptable yield (to be stated) should be included in the estimate. Other raw coal quality parameters, particulary those which affect utilization behaviour, should be stated and further subdivision of the resources made if significant variations occur, e.g. heat affected coal, oxidized coal.

In addition, for reporting of Reserves the following information is required, as a minimum.

- an outline of the proposed mining method
- physical criteria limiting mining such as maximum and minimum working section, thickness, minimum separation of seams, maximum dip, geological structure, areas of prohibition
- for Recoverable Reserves, the Mining Recovery Factor used
- for Marketable Reserves, the predicted yield if the coal is to be beneficiated and the quality specification of the product coal.
- the overburden ratio expressed as bank cubic metres of overburden to tonnes of coal in situ for reserves amenable to surface mining
- the depth of planned mining
- the percentage of the Resources which are the Mineable In situ Reserves within the area(s) proposed to be mined.

Maps

Any report of Resources and/or Reserves must be substantiated, to the relevant Government authority, by maps at scales appropriate to the accuracy claimed for the Resources and/or Reserves, showing all relevant data including the areas considered for each category of Resources and/or Reserves, the limits imposed (e.g. cover lines, seam isopachs, isoashes), the areas of prohibition, and seam thickness at points of observation.

A Public Statement

A Public Statement of Resources and/or Reserves claiming the authority of this Code should be in the format described in the section 'Reporting of Resources and Reserves'. The qualifications of the person(s) responsible for this 'Reporting' should be stated.

Reference

For guidance in determining coal quality from bore cores, reference should be made to Australian Standard 2519–1982: Guide to the evaluation of hard coal deposits using borehole techniques.

Appendix 2

Coal units conversion factors

Required units	=	*Existing units*	x	*Conversion factor*
Tonnes	=	Long tons	x	1.016
Tonnes	=	Short tons	x	0.907
Long tons	=	Short tons	x	0.893
Btu	=	kJ	x	0.948
Therms	=	MJ	x	0.948×10^{-2}
Btu/lb	=	kcal/kg	x	1.8
Btu/lb	=	MJ/kg	x	4.3×10^{2}
kcal/kg	=	MJ/kg	x	2.39×10^{2}
Therms/tonne	=	Btu/lb	x	2.21×10^{-2}
SE (a.r.)	=	$\frac{\text{SE (a.d)} \times (100-\%\text{TM})}{100-\%\text{IM}}$		

Notes: a.r. = as received; a.d. = air dried; IM = inherent moisture; TM = total moisture; SE (specific energy) = CV (calorific value)

Appendix 3

Collie coal seam names

Codes (a)			Width (m)			
WCL	*GCM*	*Seam names*	*Average*	*Min*	*Max*	*Host formation*
ABE		Abe Seam	1.0	0.3	1.8	Muja Coal Measures
ABU		Abe Seam Upper Split				
	E10	Achilles Seam	3.8	1.6	3.8	Ewington Coal Measures
		Achilles Lower Seam	0.4			Ewington Coal Measures
		Acis Seam				Premier Coal Measures
	E20	Ajax Seam (Moira)	1.9	0.3	2.2	Ewington Coal Measures
	E25	Ajax Lower Seam (Moira Lower)	0.4			Ewington Coal Measures
AS		Alpha Seam	1.3	0.2	2.3	Muja Coal Measures
APS	P10	Apis Seam (Premier No.1)	1.1	0.6	2.0	Premier Coal Measures
	E30	Ares Seam (Wallsend)	2.6	1.8	2.9	Ewington Coal Measures
ATE	M10	Ate Seam	0.7	0.6	2.4	Muja Coal Measures
ATL	M12	Ate Seam Lower Split				
ATU	M08	Ate Seam Upper Split				
BS		Bacchus Seam	1.0			Muja Coal Measures
BLS	M20	Bellona Seam	1.5	1.5	3.9	Muja Coal Measures
BEN		Ben Seam	2.1	1.7	2.3	Muja Coal Measures
BEU		Ben Seam Upper Split	0.6	0.2	1.0	
BEL		Ben Seam Lower Split	1.4	0.6	1.9	
BOS		Boreas Seam	0.8	0.2	1.7	Premier Coal Measures
	P60	Briareus Seam (Premier No. 6)	2.2	1.1	2.5	Premier Coal Measures
CS		Cardiff Seam	3.9	3.3	4.0	Muja Coal Measures
CSU		Cardiff Seam Upper Split	0.5	0.3	1.3	
CSL		Cardiff Seam Lower Split	2.8	0.9	3.3	
C1S		Cardiff No. 1 Seam	0.9	1.5	2.3	Muja Coal Measures
C1L		Cardiff No. 1 Seam Lower Split	1.4			
C2S		Cardiff No. 2 Seam	1.8	1.1	2.7	Muja Coal Measures
C2U		Cardiff No. 2 Seam Upper Split	0.8	0.2	1.8	
C2L		Cardiff No. 2 Seam Lower Split	0.3	0.0	0.5	
CAS		Cardiff A Seam	1.9	1.0	2.4	Muja Coal Measures
CES	P90	Centaur Seam (Premier No. 8)	3.63	3.32	4.12	Premier Coal Measures
CEU	P89	Centaur Rider Seam	2.57	0.52	4.04	
CEM	P90U	Centaur Seam Middle Split				
CEL	P90L	Centaur Seam Lower Split				
CRS	M30	Ceres Seam	2.3	1.8	3.3	Muja Coal Measures
CHS	P80	Chiron Seam (Premier No.7)	2.63	2.40	2.82	Premier Coal Measures
CHU	P84	Chiron Middle Upper Seam	0.73	0.36	0.98	
CHM	P85	Chiron Middle Split Seam	1.45	1.06	1.78	
CCS		Circe Seam	0.7	0.3	1.4	Premier Coal Measures
K1S		Collieburn No. 1 Seam	0.9	0.6	2.4	Muja Coal Measures
K1U		Collieburn No. 1 Seam Upper Split				
K1L		Collieburn No. 1 Seam Lower Split	0.7			

Appendix 3 (*continued*)

Codes (a)			*Width (m)*			
WCL	*GCM*	*Seam names*	*Average*	*Min*	*Max*	*Host formation*
K2S		Collieburn No. 2 Seam	1.7	0.6	3.0	Muja Coal Measures
K2L		Collieburn No. 2 Seam Lower Split	0.9			
M38		Delta Seam	0.5			Muja Coal Measures
		Demeter Seam				Premier Coal Measures
DS	M40	Diana Seam	1.5	0.6	1.5	Muja Coal Measures
DSU		Diana Seam Upper Split				
E01		E01				Allanson Sandstone
E02		E02				Allanson Sandstone
E03		E03				Allanson Sandstone
E04		E04				Allanson Sandstone
E05		E05				Allanson Sandstone
E06		E06 (Ewington No. 1)				Ewington Coal Measures
E07		E07				Ewington Coal Measures
E08		E08				Ewington Coal Measures
E09		E09				Ewington Coal Measures
E10		E10 (Moira) (Achilles)				Ewington Coal Measures
E20		E20 (Stockton) (Ajax)				Ewington Coal Measures
E25		E25				Ewington Coal Measures
E30		E30 (Wallsend) (Ares)				Ewington Coal Measures
E32		E32				Ewington Coal Measures
E40		E40 (Ewington No. 5)				Ewington Coal Measures
E45		E45				Ewington Coal Measures
E50		E50				Ewington Coal Measures
ES		Echo Seam	0.4			Muja Coal Measures
EOS	M50	Eos Seam	3.3	0.9	3.5	Muja Coal Measures
ES		Erato Seam	1.3	0.3	2.6	Premier Coal Measures
ERS		Eros Seam				Premier Coal Measures
ERU		Eros Seam Upper Split	0.8	0.0	1.3	
ERM		Eros Seam Middle Split	0.7	0.7	2.0	
ERL		Eros Seam Lower Split	0.5	0.3	0.7	
E1S	E06 ?	Ewington No. 1 Seam	0.7	0.6	1.0	Ewington Coal Measures
E1U	E05 ?	Ewington No. 1 Seam Upper Split	0.5			
E1L	E07 ?	Ewington No. 1 Seam Lower Split	1.0			
		Ewington No. 1A Seam				
E2S	E08 ?	Ewington No. 2 Seam	0.3	0.0	1.6	Ewington Coal Measures
E2L	E09 ?	Ewington No. 2 Seam Lower Split				
E5S	E40	Ewington No. 5 Seam	0.6	0.1	1.3	Ewington Coal Measures

Appendix 3 (*continued*)

Codes (a)			*Width (m)*			
WCL	*GCM*	*Seam names*	*Average*	*Min*	*Max*	*Host formation*
	M02	Floater Seam Upper				Muja Coal Measures
	M04	Floater Seam Middle				
	M06	Floater Seam Lower				
FS	M60	Flora Seam	1.8	1.5	3.3	Muja Coal Measures
GAS	M70	Galatea Seam	3.3	1.5	4.5	Muja Coal Measures
GAL	M72	Galatea Seam Lower Split				
GS		Griffin Seam	2.3	2.0	2.4	Premier Coal Measures
GSU		Griffin Seam Upper Split				
GYS	P70	Gryps Seam	0.5	0.4	1.6	Premier Coal Measures
HS	M80	Hebe Seam	13.5	7.9	13.7	Muja Coal Measures
HES		Hermes Seam	0.9	0.2	2.1	Premier Coal Measures
HOS		Homer Seam	0.7	0.1	1.0	Ewington Coal Measures
	P50	Hydra Seam (Premier No.5)	1.3	0.6	2.1	Premier Coal Measures
HYS		Hymen Seam	0.7	0.3	1.8	Allanson Sandstone
IS		Icarus Seam	1.9	1.2	2.2	Premier Coal Measures
	M90	Iona Seam	1.5	0.6	1.5	Muja Coal Measures
		Iris Seam	0.4	0.3	1.3	Ewington Coal Measures
	P03	'J' Seam				Muja Coal Measures
JS		Janus Seam	1.3	0.0	2.0	?Muja Coal Measures
JUS		Juno Seam				Premier Coal Measures
JUU		Juno Seam Upper Split	0.8	0.0	2.0	
JUL		Juno Seam Lower Split	2.2	0.3	4.2	
LS		Leda Seam (Nyx)				Premier Coal Measures
LSU		Leda Seam Upper Split	0.4	0.0	0.6	
LSL		Leda Seam Lower Split	0.6	0.0	1.4	
MDS		Medusa				Muja Coal Measures
MIM		Minos Seam	0.4	0.0	1.0	Muja Coal Measures
MS	E10	Moira Seam	3.9	0.3	4.2	Ewington Coal Measures
MSU		Moira Seam Upper Split	4.0			
MSL		Moira Seam Lower Split	1.2			
NS		Neath Seam	2.4	1.5	3.2	Muja Coal Measures
NES		Nestor Seam	0.9	0.2	1.3	Premier Coal Measures
NIS		Niobe Seam	0.4			Muja Coal Measures
ORS		Orion Seam	0.9	0.2	1.5	Muja Coal Measures
PAN		Pan Seam				Premier Coal Measures
PAU		Pan Seam Upper Split	0.6	0.0	1.0	
PAL		Pan Seam Lower Split	1.4	0.2	2.2	
	P40	Pegasus Seam (Premier No.4)	1.3	0.3	2.1	Premier Coal Measures
PHS		Phoenix Seam	1.6	0.3	2.4	Premier Coal Measures

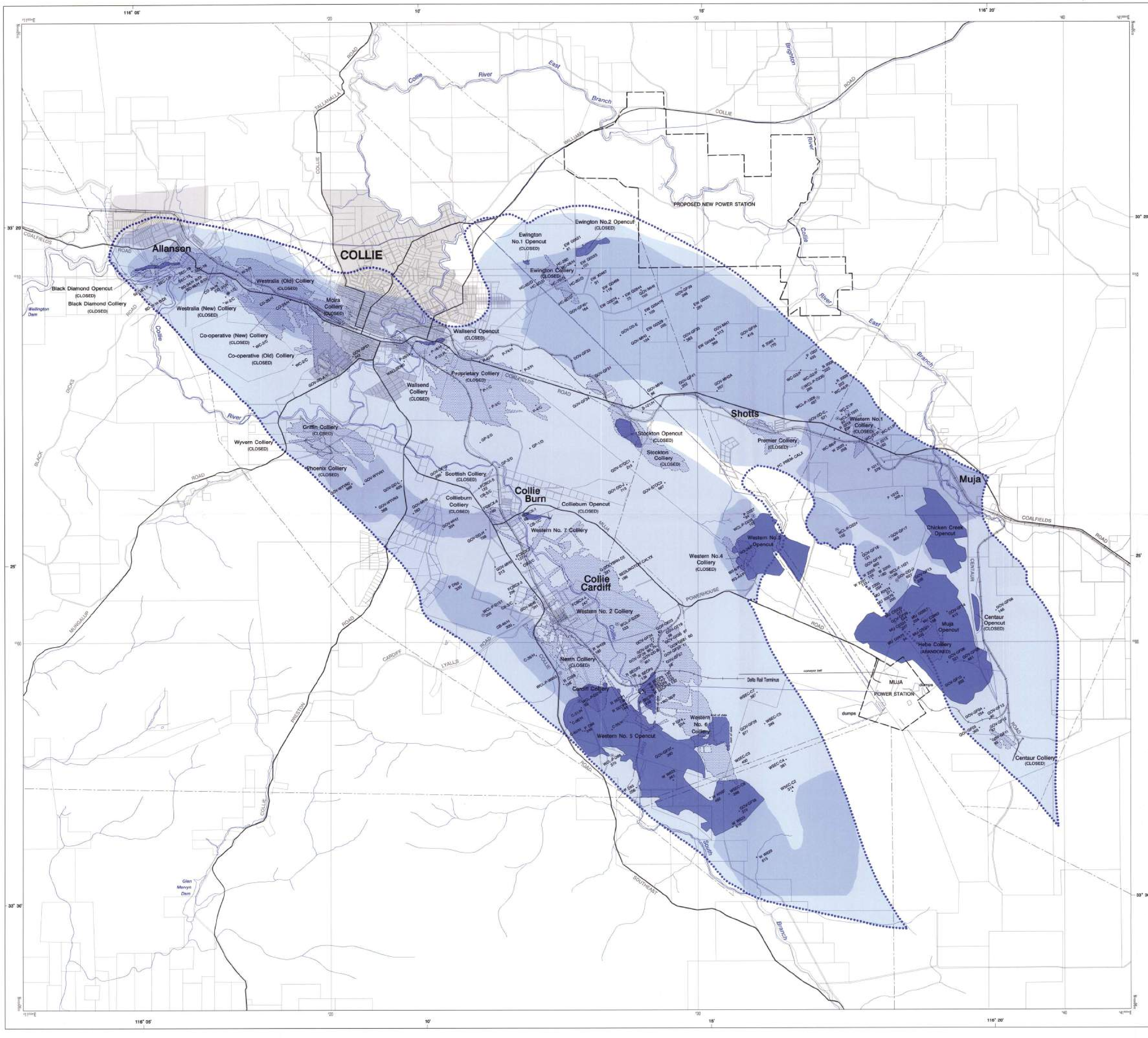
Appendix 3 (*continued*)

Codes (a)			*Width (m)*			
WCL	*GCM*	*Seam names*	*Average*	*Min*	*Max*	*Host formation*
P0A		Premier No. 0 Seam Split A				Premier Coal Measures
P0B		Premier No. 0 Seam Split B				
P0C		Premier No. 0 Seam Split C				
P1S		Premier No. 1 Seam (Apis)	0.9	0.7	1.7	Premier Coal Measures
P1U		Premier No. 1 Seam Upper Split				
		Premier No. 1A Seam				
P2S		Premier No. 2 Seam (Uraeus)	2.0	1.4	2.3	Premier Coal Measures
		Premier No. 2C Seam				
PS3		Premier No. 3 Seam (Unicorn)	1.8	1.2	2.1	Premier Coal Measures
P4S		Premier No. 4 Seam (Pegasus)	2.1	1.8	2.2	Premier Coal Measures
P4U		Premier No. 4 Seam Upper Split				
P4L		Premier No. 4 Seam Lower Split				
P5S		Premier No. 5 Seam (Hydra)	1.1	0.3	1.7	Premier Coal Measures
		Premier No. 5B Seam				
P6S		Premier No. 6 Seam (Bmireus)	1.2	0.9	2.2	Premier Coal Measures
P7S		Premier No. 7 Seam (Centaur)				Premier Coal Measures
P7U		Premier No. 7 Seam Upper Split	0.2	0.0	0.3	
P7M		Premier No. 7 Seam Middle Split	1.9	0.7	2.0	
P7L		Premier No. 7 Seam Lower Split	0.3	0.0	0.7	
P8S		Premier No. 8 Seam				Premier Coal Measures
P8U		Premier No. 8 Seam Upper Split	1.3	0.4	4.2	
P8M		Premier No. 8 Seam Middle Split	0.7	0.0	1.4	
P8L		Premier No. 8 Seam Lower Split	0.6	0.0	1.2	
PRS		Priam Seam	0.3	0.0	07	Ewington Coal Measures
PYS		Pygmalion Seam				Muja Coal Measures
PYU		Pygmalion Seam Upper Split	1.0			
PYL		Pygmalion Seam Lower Split	1.8			
RS		Rhea Seam	1.3	0.2	1.8	Muja Coal Measures
SES		Serapis Seam	0.8	0.3	2.4	Premier Coal Measures
SS	E20	Stockton Seam				Ewington Coal Measures
SSU		Stockton Seam Upper Split	2.6	1.0	4.3	
SSL		Stockton Seam Lower Split	1.0	0.4	2.1	
TAS		Tantalus Seam				Premier Coal Measures
TAU		Tantalus Seam Upper Split	1.2	0.0	2.1	
TAL		Tantalus Seam Lower Split	1.4	0.6	1.7	
TS		Tethys Seam				Premier Coal Measures
TSU		Tethys Seam Upper Split	0.4	0.0	1.0	
TSL		Tethys Seam Lower Split	0.7	0.0	2.2	
P3S	P30	Unicorn Seam (Premier No.3)	1.5	0.7	2.1	Premier Coal Measures
UPS		Upsilon Seam	1.3	0.3	1.6	Muja Coal Measures
P2S	P20	Uraeus Seam (Premier No.2)	2.3	0.7	2.4	Premier Coal Measures
VS		Venus Seam	0.9	0.2	2.1	Premier Coal Measures
WLS	E30	Wallsend Seam	2.8	1.7	3.1	Ewington Coal Measures
WLU		Wallsend Seam Upper Split				

Appendix 3 (*continued*)

Codes (a)			*Width (m)*			
WCL	*GCM*	*Seam names*	*Average*	*Min*	*Max*	*Host formation*
WS		Wyvern Seam				Muja Coal Measures
WSU		Wyvern Seam Upper Split	1.4	0.2	2.1	
WSM		Wyvern Seam Middle Split	3.9	3.8	4.2	
WSL		Wyvern Seam Lower Split	1.3	0.4	2.3	
ZS		Zephyrus Seam	1.8	0.5	2.6	Premier Coal Measures
ZSU		Zephyrus Seam Upper Split				
ZSL		Zephyrus Seam Lower Split				
		Zeus Seam.				Muja Coal Measures

Note: (a) WCL: Western Collieries Limited
GCM: Griffin Coal Mining Company Proprietary Limited



Coal basin boundary .... ••••••••••

Opencut mining area .... ▆

Underground mining area .... ▨

Potential opencut mining .... ▆

Coal resources area .... ▭

Drillhole, depth in metres .... • GOV-GF21 60

Reference drillhole, depth in metres .... ⊙ WCL-P-D224 132

Residential .... ▭

Major roads .... ━

Railway .... ┼

Transmission line .... — · —

Pipeline .... ─

Main watercourse .... ∽

LOCATION DIAGRAM

INDEX TO 1 : 50 000 SHEETS

HARVEY 2031 I	TALLANALLA 2131 IV	NALYERIN 2131 I
BUREKUP 2031 II	COLLIE 2131 III	MUJA 2131 II
DONNYBROOK 2030 I	WILGA 2130 IV	EVANS 2130 I

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OF WESTERN AUSTRALIA

REPORT 38 PLATE 1

COAL RESOURCES OF THE COLLIE BASIN

SCALE 1: 50 000

1000 0 1 2 3 4 5
Metres Kilometres

TRANSVERSE MERCATOR PROJECTION
Grid indicates 10 000 metre interval of the Australian Map Grid Zone 50

Compiled by G. Le Blanc Smith, 1988-91.
Additional information from Griffin Coal Mining Co. Pty Ltd and Western Collieries Ltd.
Cartography by the Cartographic Services Branch, Surveys and Mapping Division, Department of Minerals and Energy, Western Australia.
Digital cadastral data supplied by the Department of Land Administration, Perth, Western Australia, 1991.
Published by and available from the Geological Survey of Western Australia, Department of Minerals and Energy, 100 Plain Street, East Perth, 6004
Printed by the State Print, Department of State Services, Western Australia

REFERENCE

PERMIAN	COLLIE GROUP	🟨	Muja Coal Measures
		🟨	Premier Coal Measures
		🟧	Allanson Sandstone
		🟧	Ewington Coal Measures
		🟩	Westralia Sandstone
	STOCKTON GROUP	🟩	Moorhead Formation
		🟦	Shotts Formation
ARCHAEAN		▨	Basement

SYMBOLS

- Dip of strata
- Fault with throw
- Coal seam subcrop line
- Fold showing plunge
- Section line
- Drillhole, depth in metres
- Reference drillhole, depth in metres

LOCATION DIAGRAM

INDEX TO 1:50000 SHEETS

HARVEY 2031 I	TALLANALLA 2131 IV	NALYERIN 2131 I
BUREKUP 2031 II	COLLIE 2131 III	MUJA 2131 II
DONNYBROOK 2030 I	WILGA 2130 IV	EVANS 2130 I

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REPORT 38 PLATE 2

STRATIGRAPHY AND STRUCTURE OF THE COLLIE BASIN

SCALE 1:25 000

1000 Metres 0 1 2 Kilometres

TRANSVERSE MERCATOR PROJECTION
Grid indicates 1000 metre interval of the Australian Map Grid Zone 50

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Additional information from Griffin Coal Mining Co. Pty Ltd and Western Collieries Ltd

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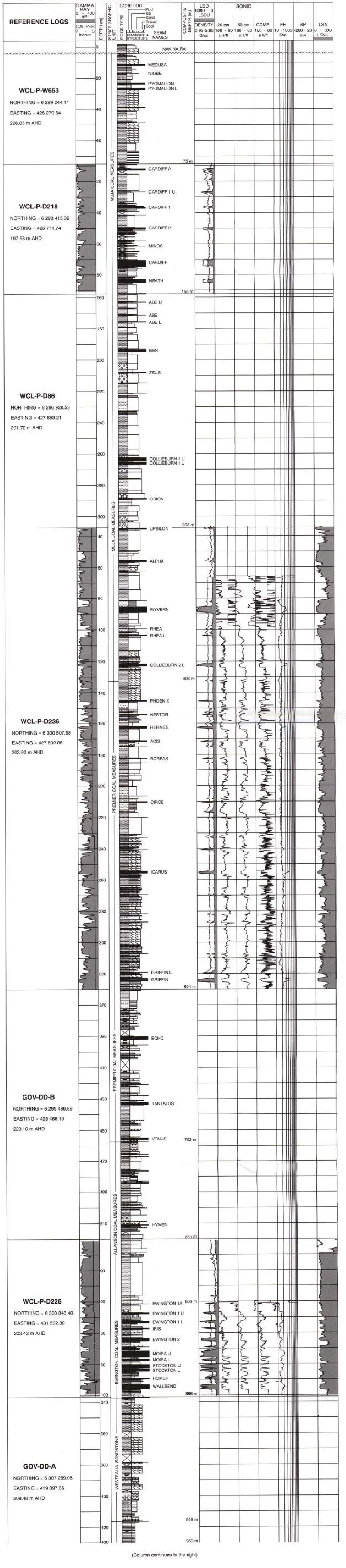
COLLIE COAL SEAM CODES AND NAMES

ABE	Abe Seam	IRS	Iris Seam
APS	Apis Seam (Premier No. 1)	IS	Icarus Seam
AS	Alpha Seam	JS	Janus Seam
ATE	Ate Seam	K1S	Collieburn No. 1 Seam
BEN	Ben Seam	K1L	Collieburn No. 1 Seam Lower Split
BLS	Bellona Seam	K1U	Collieburn No. 1 Seam Upper Split
BRS	Braireus Seam (Premier No. 6)	K2S	Collieburn No. 2 Seam
C1S	Cardiff No. 1 Seam	MDS	Medusa Seam
C2S	Cardiff No. 2 Seam	MS	Moira Seam
CAS	Cardiff A Seam	MSU	Moira Seam Upper Limit
CES	Centaur Seam (Premier No. 8)	NIS	Niobe Seam
CHS	Chiron Seam (Premier No. 7)	NS	Neath Seam
CRS	Ceres Seam	P1S	Premier No. 1 Seam (Apis Seam)
CS	Cardiff Seam	P2S	Premier No. 2 Seam (Uraeus Seam)
CSL	Cardiff Seam Lower Split	P3S	Premier No. 3 Seam (Unicorn Seam)
CSU	Cardiff Seam Upper Split	P4S	Premier No. 4 Seam (Pegasus Seam)
DS	Diana Seam	P5S	Premier No. 5 Seam (Hydra Seam)
E1S	Ewington No. 1 Seam	P6S	Premier No. 6 Seam (Braireus Seam)
E1L	Ewington No. 1 Seam Lower Split	PAN	Pan Seam
E1U	Ewington No. 1 Seam Upper Split	PHS	Phoenix Seam
E2S	Ewington No. 2 Seam	PYS	Pygmalion Seam
E5S	Ewington No. 5 Seam	RS	Rhea Seam
EOS	Eos Seam	SS	Stockton Seam
FS	Flora Seam	SSU	Stockton Seam Upper Split
GAS	Galatea Seam	TAS	Tantalus Seam
GS	Griffin Seam	UNS	Unicorn Seam (Premier No. 3)
GYS	Gryps Seam	UPS	Upsilon Seam
HDS	Hydra Seam (Premier No. 5)	URS	Uraeus Seam (Premier No. 2)
HOS	Homer Seam	WLS	Wallsend Seam
HS	Hebe Seam	WS	Wyvern Seam
HYS	Hymen Seam	WSL	Wyvern Seam Lower Split
ION	Iona Seam	WSU	Wyvern Seam Upper Split

CARDIFF SUB-BASIN COMPOSITE STRATIGRAPHIC COLUMN



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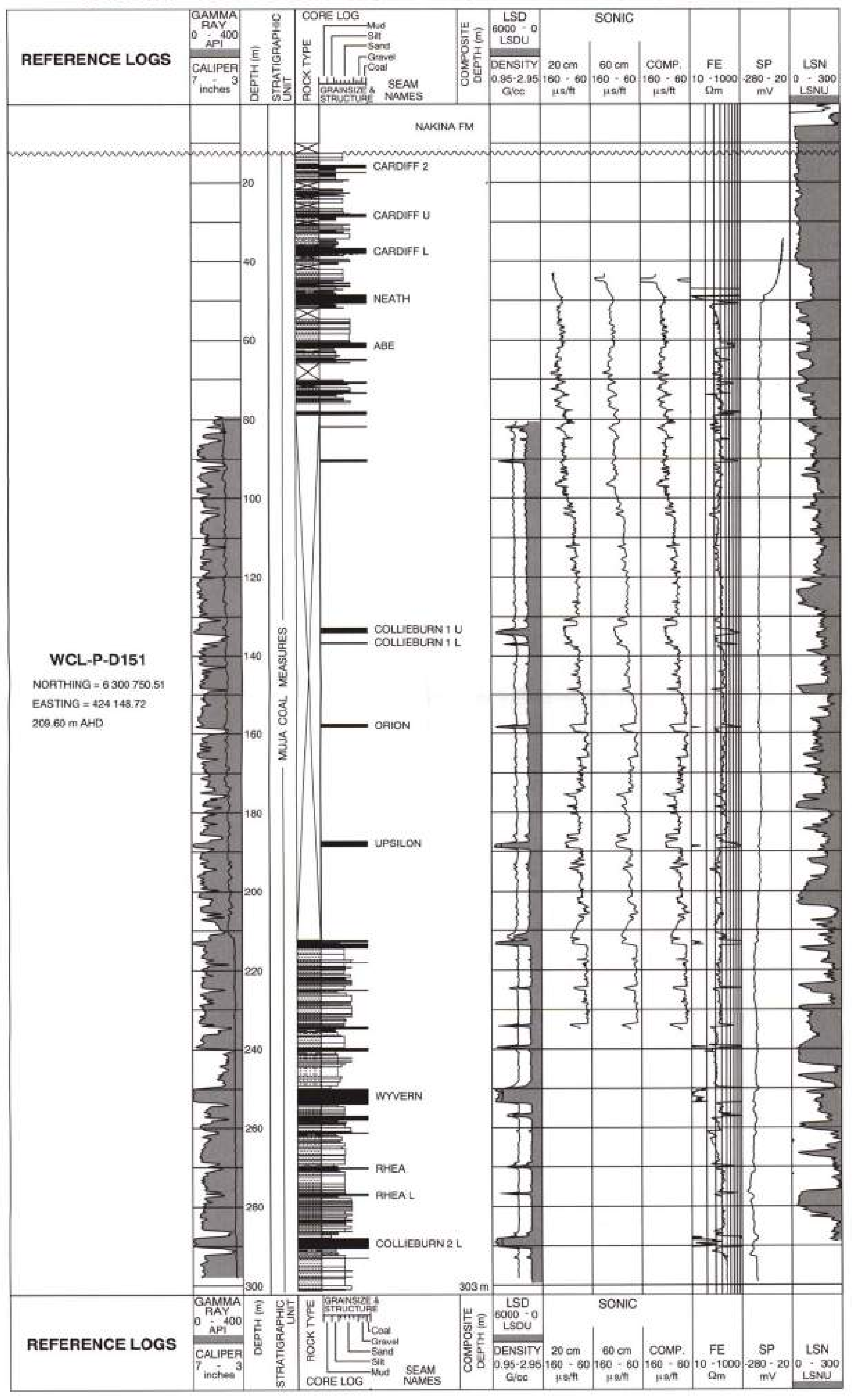
CARDIFF SUB-BASIN WCL-P-D151 REFERENCE SECTION



ROCK TYPES

- ☒ Unknown (core loss)
- ▨ Gravel, clast-supported conglomerate
- ▨ Gravel, sandy
- ▨ Diamictite, matrix-supported conglomerate
- ▨ Sandstone, pebbly
- ▨ Sandstones
- ▨ Sandstone, silty
- ▨ Siltstone ("fines")
- ▨ Siltstone, carbonaceous
- ▨ Mudstone
- ▨ Mudstone, carbonaceous
- ■ Coal (unspecified type)
- ▨ Coal, shaly
- ▨ Archaean basement (undifferentiated)

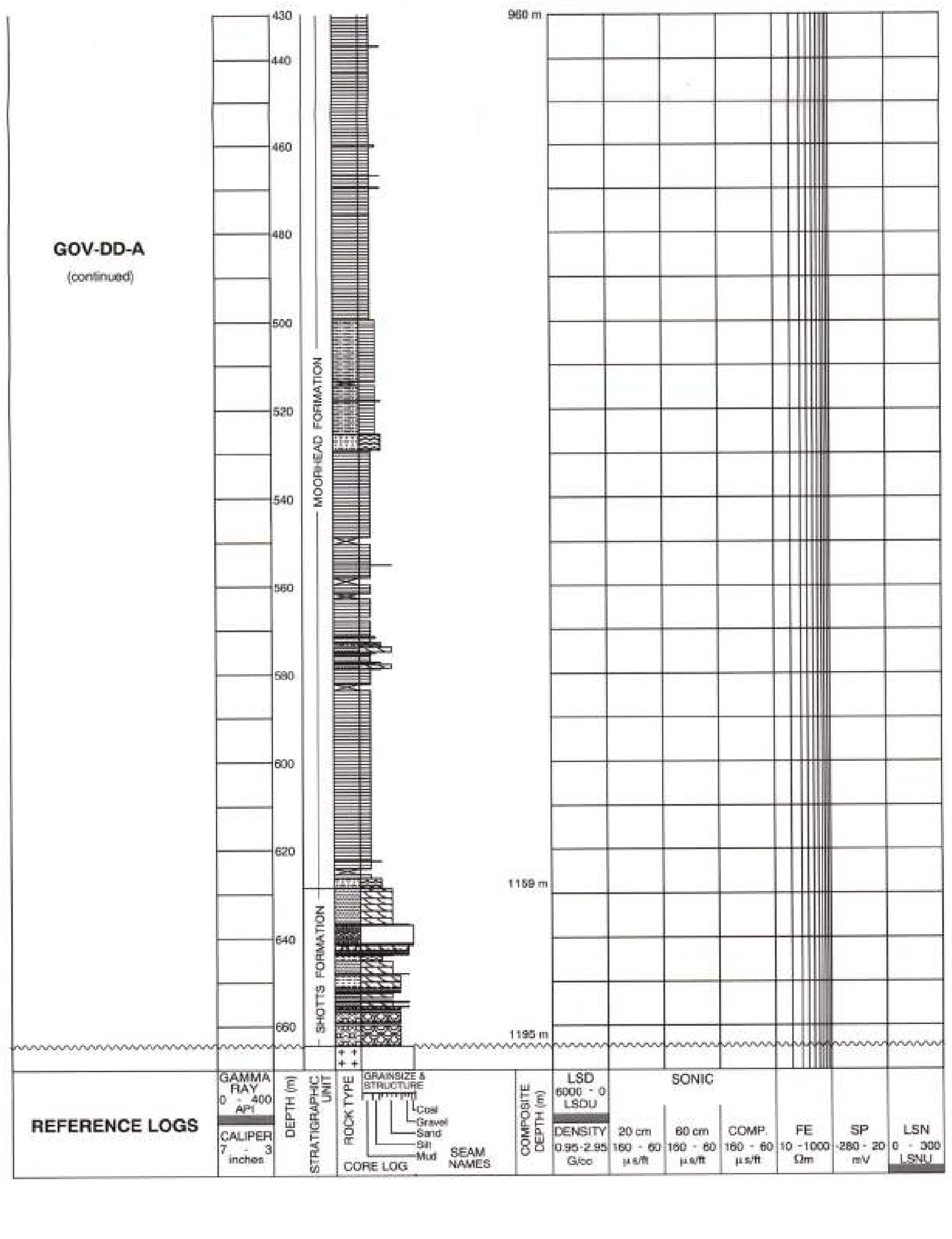
STRUCTURES

- ▨ Trough cross-bedded
- ▨ Planar cross-bedded
- ▨ Trough cross-laminated
- ▨ Rippled (undifferentiated)
- ▨ Flaser laminated
- ▨ Wavy laminated
- ▨ Laminated (undifferentiated)
- ▨ Deformation structures (undifferentiated)
- ▨ Interbedded
- □ Massive (structureless or no description)

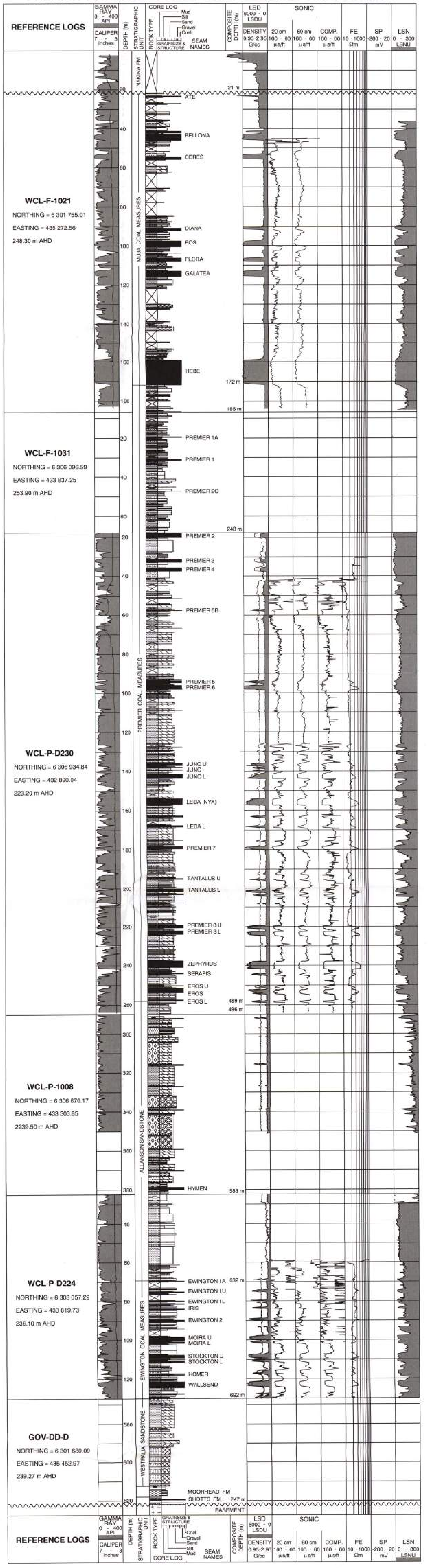
CONTACTS

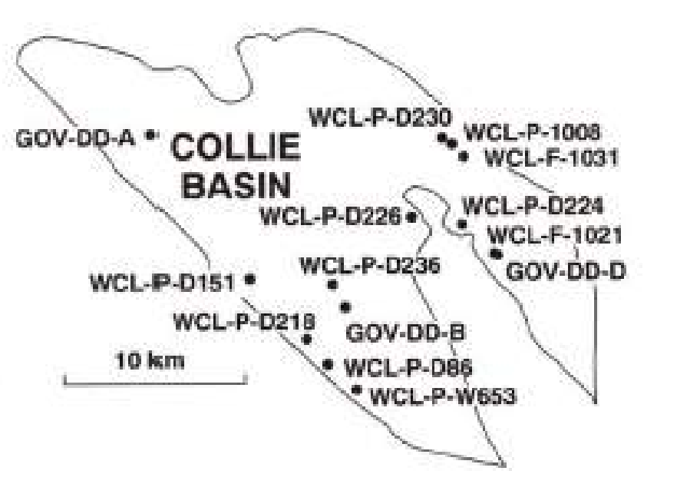
- ------ Erosional
- ∿∿∿ Unconformable

CARDIFF SUB-BASIN COMPOSITE STRATIGRAPHIC COLUMN (CONTINUED)



PREMIER SUB-BASIN COMPOSITE STRATIGRAPHIC COLUMN





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OF WESTERN AUSTRALIA

REPORT 38 PLATE 3

STRATIGRAPHIC REFERENCE LOGS

COLLIE BASIN

VERTICAL SCALE 1:1 000

Compiled by G. Le Blanc Smith 1989-1992
Additional information from Griffin Coal Mining Co. Pty Ltd and Western Collieries Ltd

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REPORT 38 PLATE 4

STRATIGRAPHIC SECTION CARDIFF SUB-BASIN
COLLIE BASIN

HORIZONTAL SCALE 1:30 000
VERTICAL SCALE 1:2 000

REFERENCE

▨	Sandstone
■	Coal seam
⊞	Archaean basement
╷	Biostratigraphic sample site with range to next site

Compiled by G. Le Blanc Smith 1988-1992
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REPORT 38 PLATE 5

STRATIGRAPHIC SECTION
PREMIER SUB-BASIN
COLLIE BASIN

HORIZONTAL SCALE 1:30 000
VERTICAL SCALE 1:2 000

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REFERENCE

▨	Sandstone
▤	Mudstone, carbonaceous
▤	Mudstone
■	Coal seam
▤	Siltstone
▨	Conglomerate
⊡	Archaean basement
▪	Biostratigraphic sample site with range to next site

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REPORT 38 PLATE 6A

SEQUENCE 2 - COAL SEAM CORRELATION AND LITHOLOGY LOGS

COLLIE BASIN

VERTICAL SCALE 1:800

Compiled by G. Le Blanc Smith 1988-1992
Additional information from Griffin Coal Mining Co. Pty Ltd and Western Collieries Ltd
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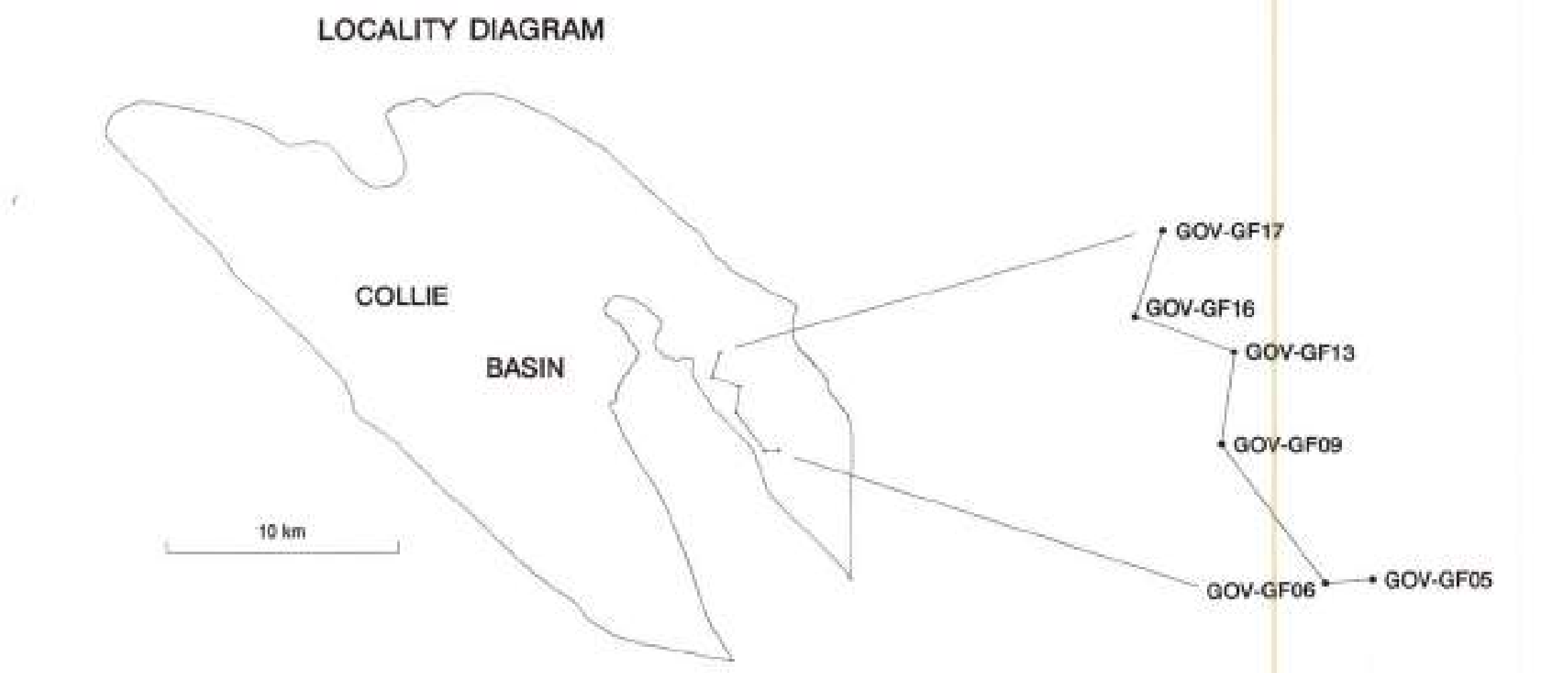
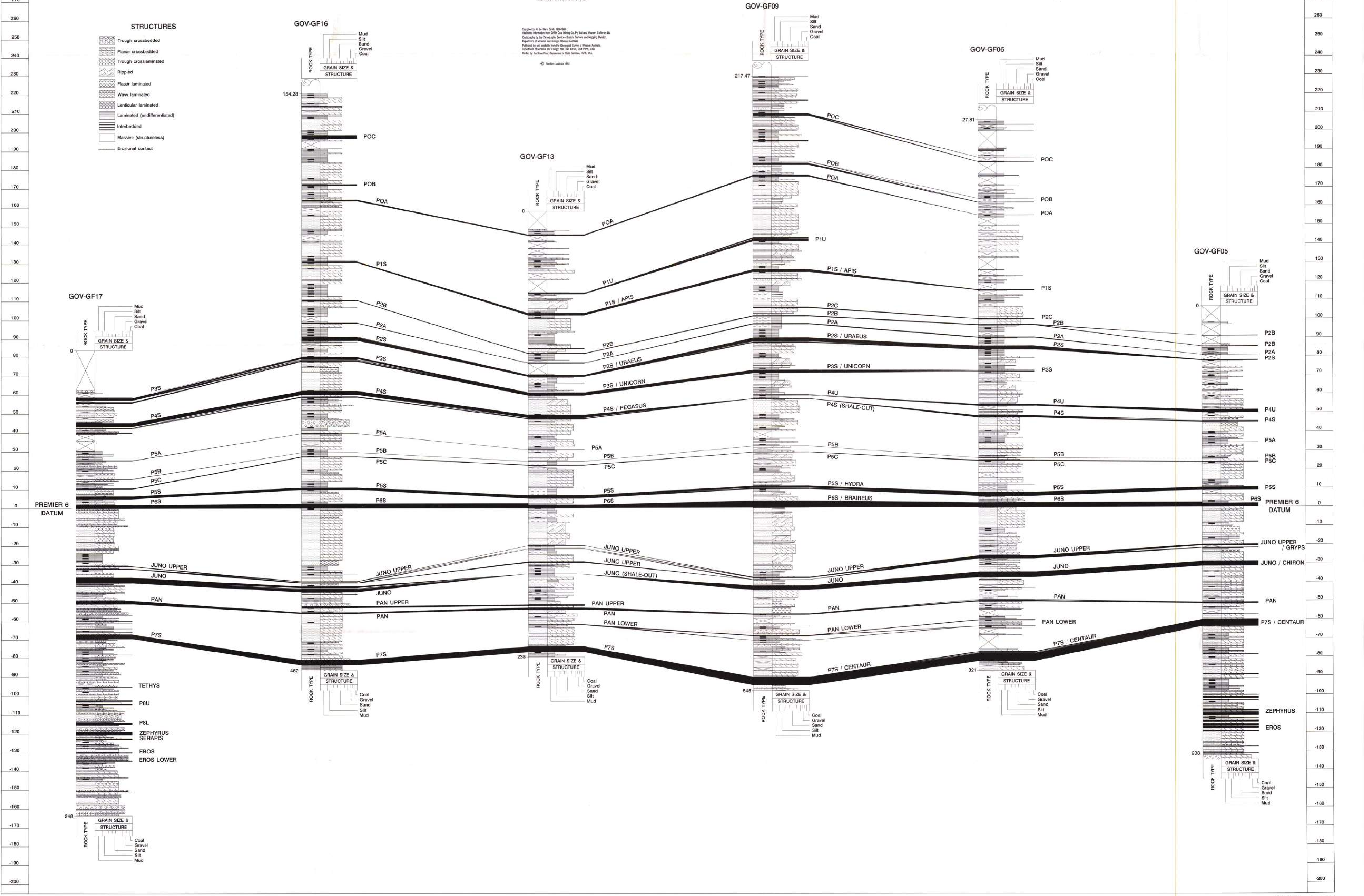
ROCK TYPES

- ☒ Unknown (core loss)
- Weathered
- Gravel, clast-supported conglomerate
- Gravel, sandy
- Sandstone
- Sandstone, silty
- Siltstone, sandy
- Siltstone (fines)
- Siltstone, carbonaceous
- Mudstone
- Mudstone, carbonaceous
- ■ Coal (unspecified type)
- Coal, shaly

STRUCTURES

- Trough crossbedded
- Planar crossbedded
- Trough crosslaminated
- Rippled
- Flaser laminated
- Wavy laminated
- Lenticular laminated
- Laminated (undifferentiated)
- Interbedded
- ☐ Massive (structureless)
- Erosional contact


LOCALITY DIAGRAM



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OF WESTERN AUSTRALIA

REPORT 38 PLATE 6B

SEQUENCE 3 - COAL SEAM CORRELATION AND LITHOLOGY LOGS

COLLIE BASIN

VERTICAL SCALE 1:800

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Additional information from Griffin Coal Mining Co. Pty Ltd and Western Collieries Ltd
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Printed by the State Print, Department of State Services, Perth, W.A.

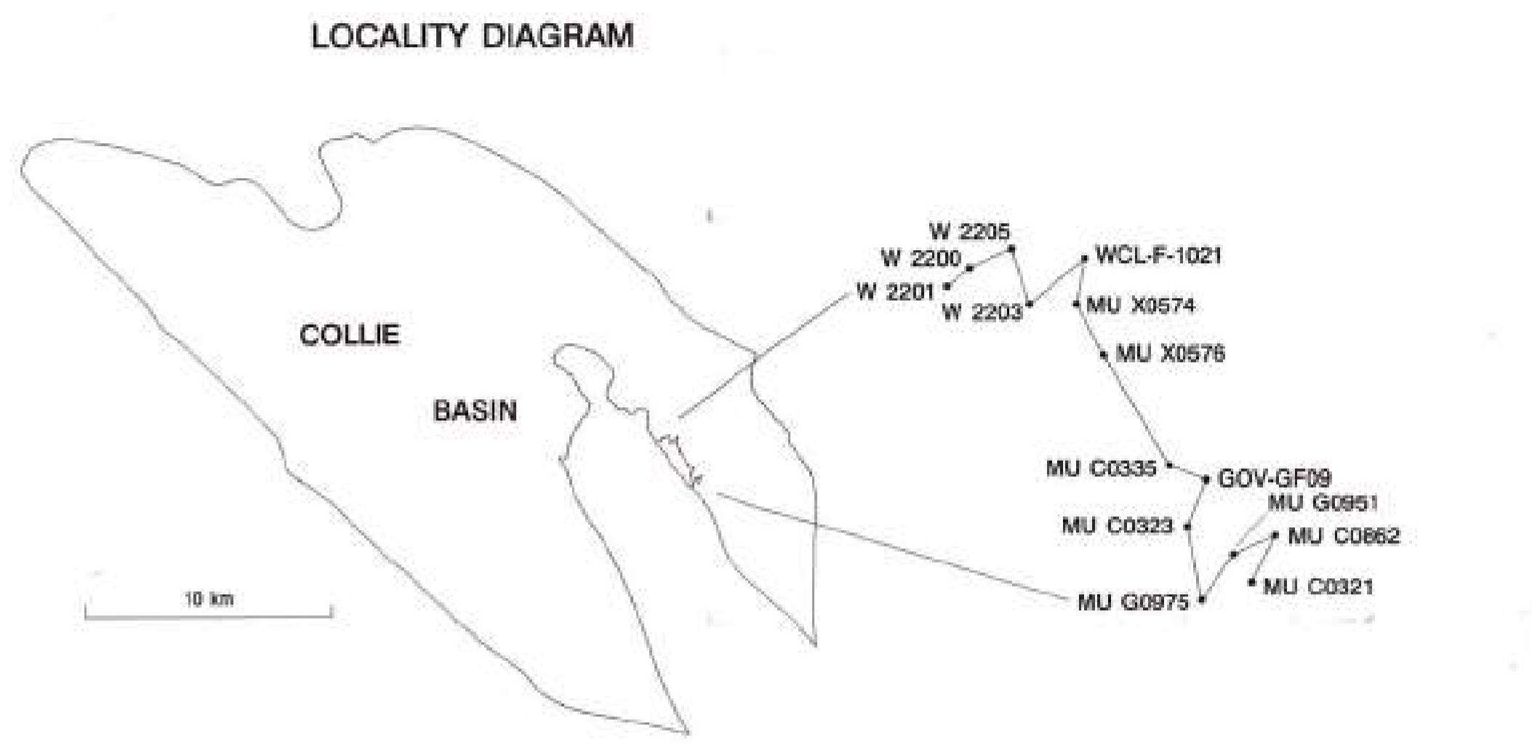
ROCK TYPES

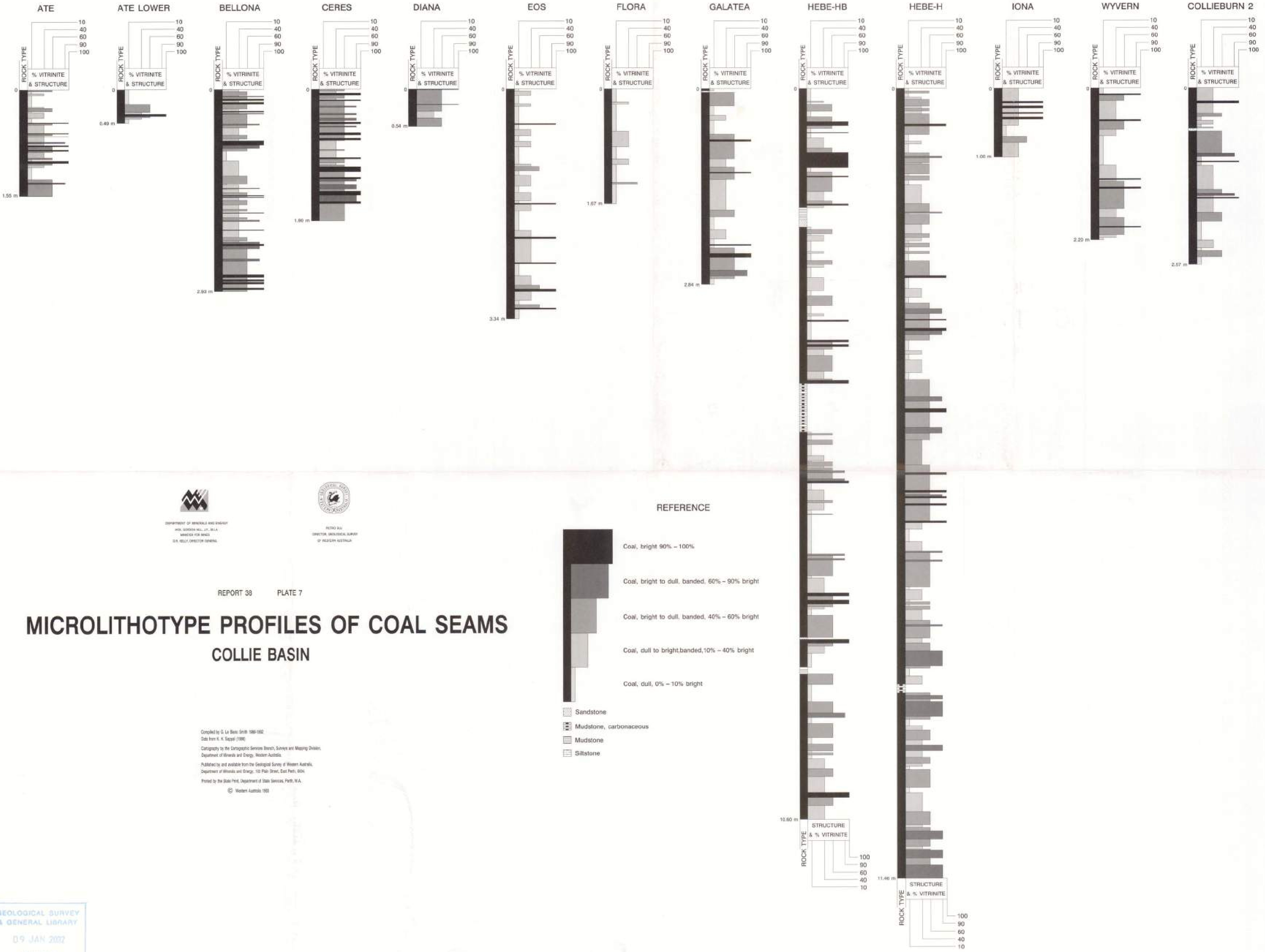
☒	Unknown (core loss)
▥	Weathered
▩	Gravel, clast-supported conglomerate
○	Gravel, sandy
◿	Sandstone
▤	Sandstone, silty
⁙	Siltstone, sandy
┄	Siltstone (fines)
▦	Siltstone, carbonaceous
☰	Mudstone
▤	Mudstone, carbonaceous
■	Coal (unspecified type)
▬	Coal, shaly

STRUCTURES

▩	Trough crossbedded
▨	Planar crossbedded
▩	Trough crosslaminated
◬	Rippled
⁘	Flaser laminated
≈	Wavy laminated
▦	Lenticular laminated
☰	Laminated (undifferentiated)
☰	Interbedded
□	Massive (structureless)

LOCALITY DIAGRAM





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OF WESTERN AUSTRALIA

REPORT 38 PLATE 7

MICROLITHOTYPE PROFILES OF COAL SEAMS

COLLIE BASIN

Compiled by G. Le Blanc Smith 1989-1992
Data from K. K. Sappal (1986)
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REFERENCE

- Coal, bright 90% – 100%
- Coal, bright to dull, banded, 60% – 90% bright
- Coal, bright to dull, banded, 40% – 60% bright
- Coal, dull to bright,banded,10% – 40% bright
- Coal, dull, 0% – 10% bright
- ▨ Sandstone
- ▨ Mudstone, carbonaceous
- ▨ Mudstone
- ▨ Siltstone