Department of Natural Resources, Mines and Energy
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Queensland Minerals and Energy Review

A spatial review of the geology and coking coal potential of the Fort Cooper Coal Measures and correlatives, Bowen Basin, Queensland

Micaela Grigorescu & David Coffey

Queensland Government

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Cover photographs: *Left: Thinly bedded to thickly interlaminated interval of Fort Cooper Coal Measure strata comprising tuffaceous and partly sideritic siltstone, carbonaceous mudstone and coal, Picardy area, Bowen Basin; right: Fern leaf and arthrophyte stems in mudstone, Lenton Downs area, Bowen Basin.*

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1. Introduction

1.1 Initial beginnings

Mining has been an integral part of the development of Queensland since the earliest days of European settlement. Since 1843, coal mining, in particular, has played a vital role in helping to develop and sustain the State's economy. Initially, coal was mined for its thermal properties and used domestically for steam raising in transport (predominantly for shipping and the railway), and later for the generation of electricity and for other industrial applications, such as gasification and the manufacture of bricks, pottery and cement.

From the middle of the 19th century, the Ipswich District of southeast Queensland had been established as the State's most significant coal producing area and this remained true for much of the next 100 years. Development of coal mining in the central and northern parts of the State was driven predominantly by the progressive development of the State's rail network between 1865 and the early 1930s (Mengel *et al.,* 1990).

The first Europeans to become aware of the presence of coal in the Bowen Basin region, in central Queensland, were the members of Ludwig Leichhardt's expedition in January 1845. In his entry for the 10th January 1845, Leichhardt (1847, chapter IV) reported: *"Sandstone crops out in the gullies of the valley, in horizontal strata, some of which are hard and good for building, others like the blue clay beds of Newcastle, with the impressions of fern-leaves identical with those of that formation. At the junction of Comet Creek and the* [Mackenzie] *river, I found water-worn fragments of good coal, and large trunks of trees changed into ironstone."*

Leichhardt also mentioned a second outcrop observed about 25 kilometres further downstream on the Mackenzie River, near where it was joined by what is now known as the Burngrove Creek, in his entry for 14th January 1845. This outcrop was described as *"very high cliffs, which shewed a fine geological section of horizontal layers of sandstone and coal-slate. There were also some layers of very good coal, but the greater part of those visible were of a slaty character. Nodules of Ironstone were very frequent in the sandstone."* (Leichhardt, 1847, chapter IV).

From the location descriptions given, it would appear that the strata described in both instances were outcrops of what is now identified as parts of the Fair Hill Formation (a correlative of the lower Fort Cooper Coal Measures). The banded 'slaty' nature of the seams described in the second instance is highly consistent with such an interpretation.

The construction of the Central Railway from Rockhampton to Emerald in the late 1870s enabled access to potential markets and provided the impetus for coal exploration and mine development in the Bowen Basin.

In this context, and worthy of note, is the historical coal exploration and mining that took place near Tolmies siding on the Central Railway, approximately 15 kilometres west of Blackwater, between 1878 and 1900. These operations appear to have been within the Fair Hill Formation and are the first recorded coal mining operations in the Bowen Basin proper.

The first mention of coal at Tolmies was in an 1878 unpublished memorandum by A. C. Gregory, Geological Surveyor at the time, on coal samples obtained from a trial shaft north of the railway. Gregory (1878, page 1) described this coal as *"well adapted for steam and smith's work; but is not a first-class gas coal, though it could be used for this purpose, as it cokes well, and has little sulphur. In its general composition, it is so near the coals from Newcastle, N.S. Wales that its economic value scarcely differs".*

By the early 1890s, considerable coal prospecting and development had taken place at Tolmies in an attempt to find a local source to satisfy the requirements of the Central Railway (King, 1969). Maitland (1895) reported that a six foot-thick, banded coal seam was extensively worked from several shafts and two tunnels at Tolmies between 1892 and 1893 (Department of Mines, 1893; 1894). Maitland (1985, page 3) also reported that a 30 feet-thick seam *"with numerous shaley bands"* was intersected in a shaft north of the Railway at the 127¾ mile peg, just west of Tolmies at a depth of 120 feet. The shaley bands described would be consistent with partly weathered tuffaceous mudstones typical of the Fairhill Seam (Fair Hill Formation). The high ash content (at 26.55%) also supports such an interpretation.

Following up on the discoveries at Tolmies, Andrew Gibb Maitland, Government Geologist at the time, was assigned to investigate the coal resources of the region on behalf of the Central Railway in 1895. Maitland proposed the drilling of three holes to test for coal but only the one west of Tolmies was ever actually drilled in 1897. This hole was unsuccessful (King, 1969), only intersecting the marine sandstones of the Maria Formation (now known to underlie the Fair Hill Formation). Ironically, the other two proposed sites would have intersected numerous thick and clean coal seams near both Blackwater and Clermont but, following the failure of the first hole, they were never drilled.

In his comprehensive review of coal occurrences in the Mackenzie River area, Dunstan (1901) described in detail the shafts and tunnels at Tolmies, provided a geological cross section and three coal analyses. The reported values were as follows: ash = 15–28%, volatile matter = 20–24% and fixed carbon = 44–59%. He stated that *"when heated the coal cakes into a pasty mass, and when burning in a firebox care must be exercised to prevent this caking from choking the draught. The volatile hydrocarbons do not well aid the fixed carbon in forming a coke, and in consequence an inferior coke is produced. The coal, in fact, is a good caking coal, but a bad coking coal"* (Dunstan, 1901, page 19). It is important to note that the meaning of 'coke' as Dunstan (1901) referred to here is in terms of a low smoke-emitting fuel for steam engines and not with respect to its possible application as metallurgical coke for steel making.

Coal mining operations at Tolmies ceased in 1900 and the field was abandoned. Ironically, it was the strong caking properties of the coal that caused the demise of this field, as this property degraded its value and sale price as a boiler fuel.

The last known attempt to extract coal from a correlative of the Fort Cooper Coal Measures (this time from the upper Burngrove Formation sequence) was 10 km northeast of Tolmies, on the Burngrove Creek, where a water bore encountered coal at 65 feet (King, 1969). Ridgway (1944) described the exploration shaft and reported on one coal analysis. Further work was abandoned due to the high ash value of the coal and the faulting of the site.

The coals in the Fort Cooper Coal Measures correlatives were regarded as being of poor quality and unsuitable for use by the railway, which at that time sourced most of its coal from mines in the Ipswich District. Nonetheless, the sites are worthy of note since they probably represent, the only historical coal workings within these sequences in the Bowen Basin.

1.2 The coking coal industry in Queensland

In November 1947, a major step in the future development of the Queensland coal industry was taken when the State Government commissioned the UK based consultants, Powell Duffryn Technical Services Ltd (PDTS), to conduct a comprehensive survey of all aspects of the Queensland coal industry. The report took some 18 months to complete and was presented to the then Premier of Queensland, the Hon. E.M. Hanlon, in July 1949.

After comprehensively describing the state of the coal industry in Queensland at that time, the report presented a series of immediate, short-term and long-term recommendations, some relating to the need for prospecting and evaluation of the coal resources of the State.

Part of the Government's response to these recommendations was the establishment of the Queensland Coal Board and the Coal Section within the Geological Survey of Queensland (GSQ), as well as the formation of a Drilling Branch within the Department of Mines.

In the decade following the end of the Second World War, the coal industry in Queensland remained largely unmechanised, being dominated by very small-scale and predominantly underground operations. As at June 1952, for example, 73 of the 83 underground coal mines reported as operating in the State at that time, had raw coal production levels of less than 150 tons per day (Queensland Coal Board, 1952).

By far, the greatest consumption of the coal produced in Queensland at this time (>70%) was used for domestic consumption to supply public utilities which comprised the railways, electricity generators, gas producers and hospitals (Queensland Coal Board, 1952).

The industry remained hampered by low prices and the cost of transportation, which tended to restrict markets to those nearby (Norrie, 1965). Sales of coal either to other States within Australia or to overseas destinations were almost negligible at that time (Queensland Coal Board, 1952).

In the late 1950s and early 1960s, however, Japan's need for the raw materials to be used in its expanding steel industry started to drive exploration for iron ore in the Pilbara region of Western Australia and for coking coal in the Bowen Basin in Queensland.

Arising out of this demand, the Queensland coal industry commenced a period of major growth in the late 1950s, with the progressive establishment of new export mines in the Bowen Basin. The first of these mines was developed by Thiess Bros Pty Ltd, (later restructured into the Thiess Peabody Mitsui Joint Venture (TPM)), initially at Kianga and later at Moura (locations in Figure 1). The first significant shipments (about 287,000 tonnes) of coking coal from these operations to Japan began in 1961–62, when the entire State's coal production totalled just a little over 2.8 million tonnes (Queensland Coal Board, 1962).

During the 1964–65 financial year, production from the combined open-cut and underground mines at Moura was a little over 1.2 million tonnes and Queensland coal exports to markets overseas (as distinct from other states in Australia) exceeded 1 million tonnes per annum for the first time (Queensland Coal Board, 1965).

Elsewhere in the Bowen Basin, regional exploration by US-based Utah Development Company (UDC) during the mid-1960s also led to the discovery of large tonnages of shallow, high quality coking coal, in the central and northern sectors of the basin, culminating in the commencement of open-cut mining operations at Blackwater Mine in 1967. King (1969) provides a comprehensive summary of the UDC's exploration efforts in the Bowen Basin during this period, leading up to the development of the Blackwater open-cut. In the decade that followed, UDC and its partners, comprising the Central Queensland Coal Associates (CQCA), progressively developed other new open-cut mines further north at Goonyella (1971), Peak Downs (1972), Saraji (1975) and Norwich Park (1979). These mine locations are shown in Figure 1. As with the previous mine developments at Kianga and Moura, all of these new CQCA Joint Venture mines produced coking coal for export, initially to service the Japanese steel industry.

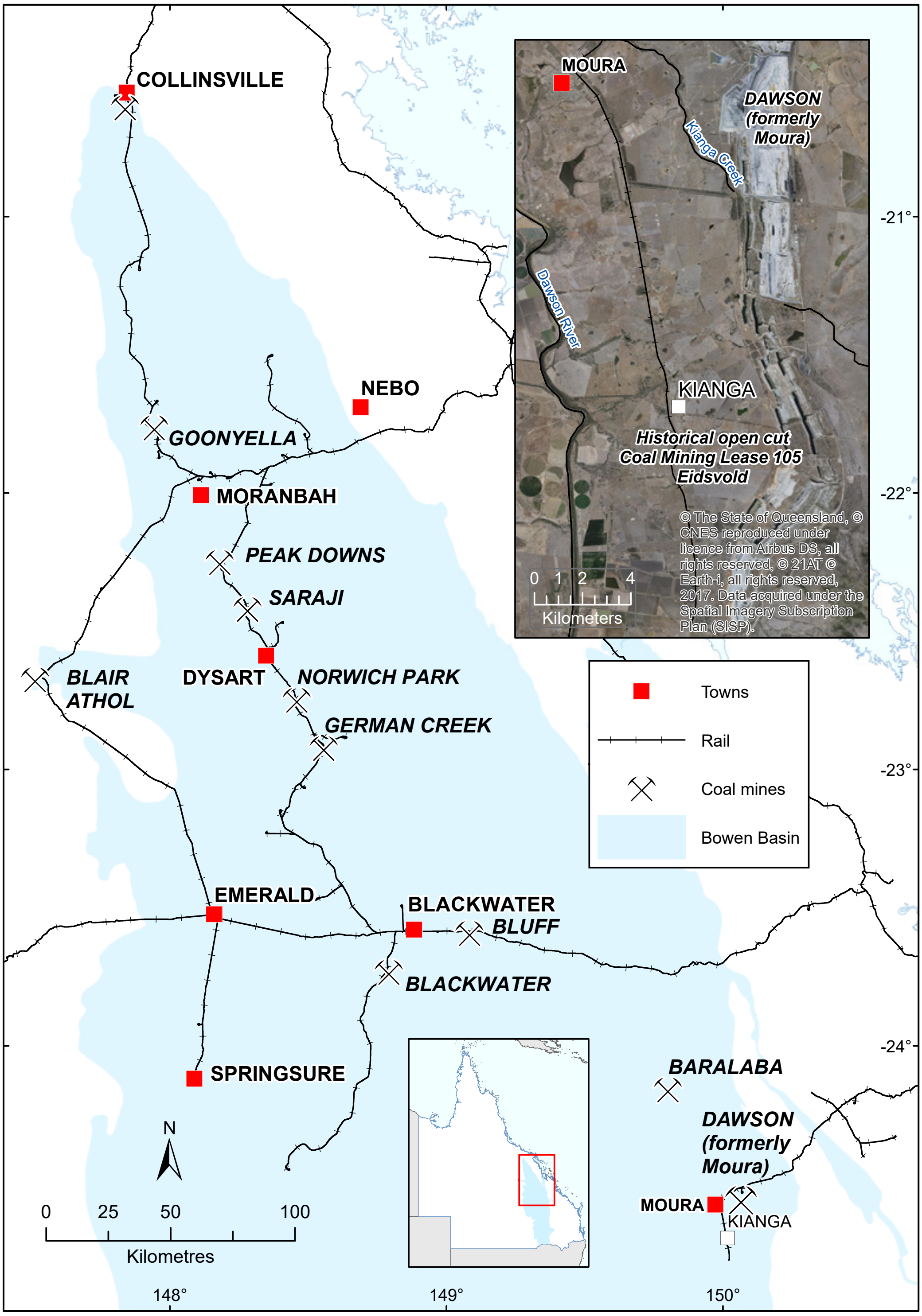

Figure 1. Initial (1950 – late 1970s) open-cut mining developments, central Queensland.

With these new mine developments, the nature of the Queensland coal industry began to change in three fundamental ways:

- Firstly, it marked the beginning of open-cut mining on a very large-scale.
- The second modification was to the market base for the coal being produced—moving from being almost entirely used for small-scale domestic consumption to one mainly servicing large-scale export markets.

- The third change was in the type of saleable coal being produced in Queensland—progressively moving away from producing coal used almost exclusively as thermal coal for domestic consumption, to one heavily biased towards producing coking coal for steel making overseas.

Following these initial mine developments by TPM and the CQCA Joint Venture, coal exports, which initially consisted almost entirely of coking coal, increased markedly during the 1970s, surpassing 10 million tonnes per annum (Mtpa) in 1972–73 (Queensland Coal Board, 1973, table V) and 20 Mtpa in 1977–78 (Queensland Coal Board, 1978, page 24). In the decades that followed, coal exports from Queensland subsequently reached other milestones of 50 Mtpa in 1985–86 (The Queensland Coal Board, 1986, page 2), 100 Mtpa in 1999–2000 (Department of Mines and Energy, 2000, page 2) and in 2006–07, when exports surpassed 150 Mtpa for the first time (Smith, 2008, page 34; figure 3).

As the Queensland coal export industry developed, coking coal (later more generally referred to as 'metallurgical coal', to include coals suited to pulverised coal injection—PCI), remained the dominant proportion of exports, although the percentage of thermal coal exports gradually increased over time. From about the mid-1980s onwards, coking coal has generally comprised about 70% of exports.

The development of the State's coking coal industry was based initially on mines developed on coal seams within the Rangal Coal Measures (Moura and Blackwater). This was closely followed by staged development of other large-scaled open-cut mines along the western margin of the Bowen Basin, firstly extracting coal from seams within the Moranbah Coal Measures (Goonyella, Peak Downs and Saraji) and later, the German Creek Formation (Norwich Park and German Creek; locations in Figure 1).

During the course of the regional exploration undertaken in the northern and central parts of the Bowen Basin by UDC, which ultimately led to the development of its open-cut strip mines, it seemed that serious consideration was never given to the possibility that the banded seams in the Burngrove and Fair Hill formations might have some coking potential. The tuffaceous nature of these coals was used as a stratigraphic 'marker' to guide the placement of drill sites, which targeted the seams in the underlying Moranbah Coal Measures and German Creek Formation along the Collinsville Shelf and the overlying Rangal Coal Measures around Blackwater, as well as Rangal seams in structurally complex areas (locations and details in subsequent sections).

1.3 Departmental drilling and Queensland's coal resource inventory

One of the initial roles of the GSQ Coal Section was to plan and supervise systematic diamond drilling programs to investigate the State's coal resources.

Until the mid to late 1960s, these departmental drilling programs were aimed primarily at evaluating non-coking coal deposits in areas where coal mines were already established, particularly in southern Queensland. These programs were aimed at proving up reserves of coal to ensure that the State had a sufficient supply of thermal coal for its own use in existing and future coal-fired power stations. Most of this work was undertaken in association with the Queensland Coal Board (QCB) and the State Electricity Commission.

From the mid-1960s onwards, the government's policy of proving up reserves of coal to meet targets for future power requirements of Queensland was expended outside the southeast, with the commencement of coal drilling programs in the southern Bowen Basin around the Moura, Theodore and Blackwater areas.

From the Queensland Coal Board establishment in 1950, tabulations of 'coal reserves' were presented in some of its early publications (*e.g.,* Norman, 1960, table 1; Queensland Coal Board, 1961, table XIX). These estimates were presented by coalfield or Mining District. At that time, the coalfields operating within the Bowen Basin were at Collinsville, Kianga, Bluff, Baralaba and Blair Athol (Figure 1).

At a time when the coal industry in Queensland was beginning its transition from domestic to large-scale export production, the Department of Mines published its parameters for the calculation and reporting of 'coal reserves' in the Queensland Government Mining Journal (The Department of Mines, 1968). The term '(coal) reserves' was used for estimates of raw coal *in situ*, based on 'points of observations' (boreholes, outcrops, mine workings, etc.). The publication, titled 'Parameters for the Calculation and Reporting of Coal Reserves' also included an appendix outlining the departmental 'Criteria for Recognition of Coking Coal'.

From the early 1970s, the GSQ Coal Section began to align categories used for compiling the State's coal inventory with the changes that were occurring in the industry, as open-cut mining and the production of coking coal gained prominence (Figure 2).

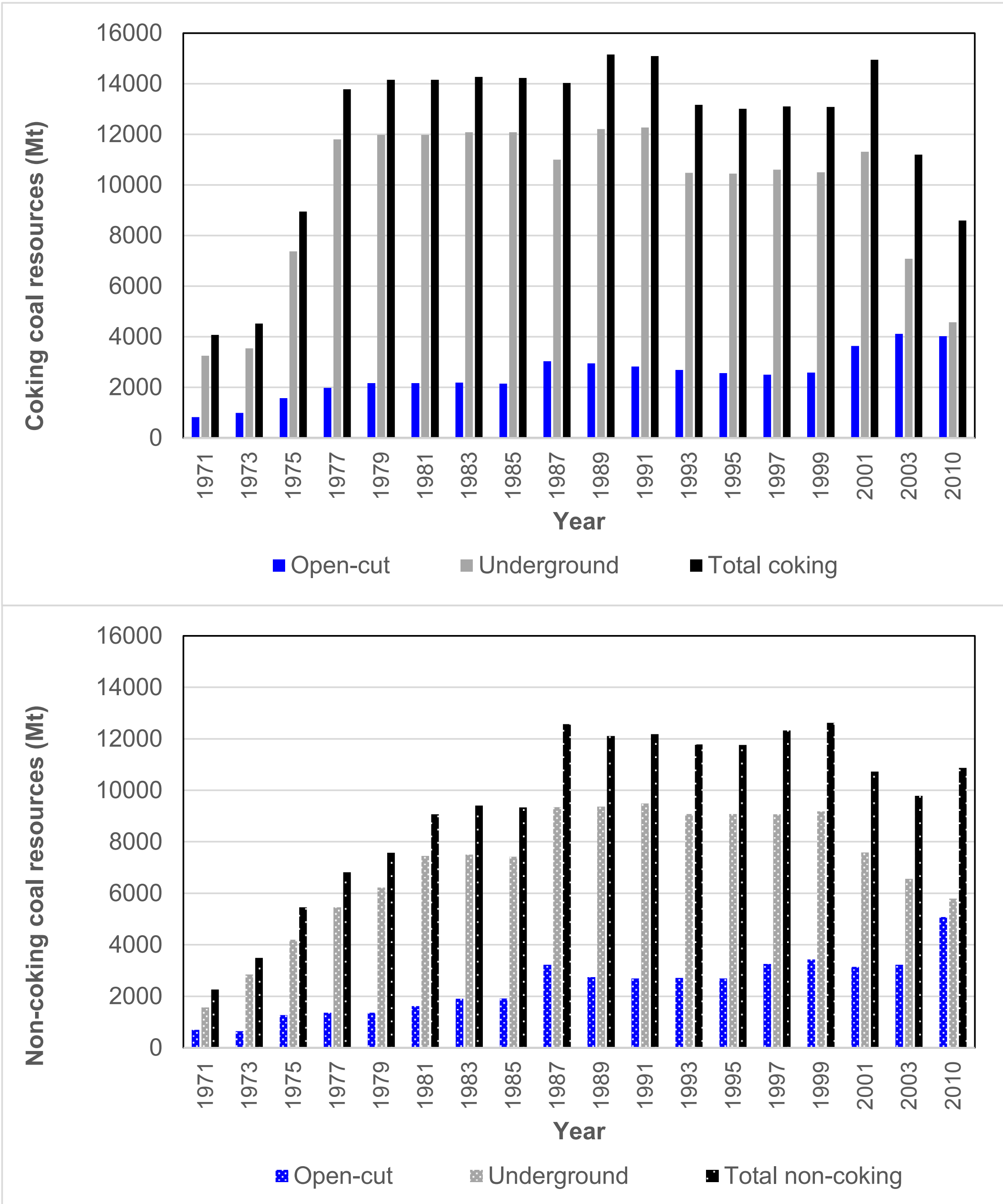

Figure 2. Coal resources over four decades. Sources: 1971–1978 data after Staines & Koppe (1980); 1979–2003 after the respective Coal Board reports (see references in section 'Queensland Coal Board publications'); 2010 data based on an unpublished inventory by C. Lamont cited by Smith (2013).

The State-funded coal exploration programs carried out by the Coal Section during the 1970s and 1980s played a key role in providing much needed information about the geology and quality of coals in Queensland, particularly in the Bowen Basin where interest was focussed and many of the new mine developments were occurring.

In 1977, D.C. Mengel, who was the Section head at the time, outlined the rationale behind, and provided a historical overview of, the Section's drilling activities up to that time. He also noted that one of the main objectives of the departmental reconnaissance drilling programs in the northern and central parts of the Bowen Basin was to obtain stratigraphic information that enabled *"a review of the stratigraphic relationships of rock units in the upper part of the Permian sequence, and changes to the nomenclature"* (Mengel, 1977, page 30)—a reference to the significant stratigraphic review subsequently published by Koppe (1978), in which he defined and introduced the name Moranbah Coal Measures for the first time.

Mengel (1977) also presented a metricated version of the Departmental 'coal reserve' estimation parameters (incorporating definitions, procedures and assumptions), first published by the Department of Mines in 1968. This revised code was used by the department and industry until it was replaced in turn by 'The Australian Code for Reporting Identified Coal Resources and Reserves', which was ratified as the national coal code in 1986 (Commonwealth of Australia, 1987 based on Galligan & Mengel, 1986). The 'Galligan and Mengel Code', as it was sometimes referred to, was ultimately replaced by the resource/reserve codes prepared under the mantle of the Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy. In the Galligan and Mengel code, the term '(coal) resources' had a similar meaning to the term 'reserves' used in the departmental code; the term 'reserves' used by Galligan & Mengel (1986) applied to estimates of that portion of the 'resources' regarded as being either, potentially mineable, recoverable or marketable.

The Coal Section continued in this role until the GSQ's Drilling Branch was disbanded and its assets sold in 1991. Further details of, and rationale behind, the coal reconnaissance drilling programs undertaken by Department of Mines between 1950 and the mid-1980s are provided by Hawthorne (2011). Over a period of more than 40 years, the exploration programs undertaken by the Coal Section resulted in the drilling of more than 7800 boreholes for an aggregate total of more than one million metres of drilling, of which almost half (~484,000 metres) was cored (Figure 3; Department of Resource Industries, 1991).

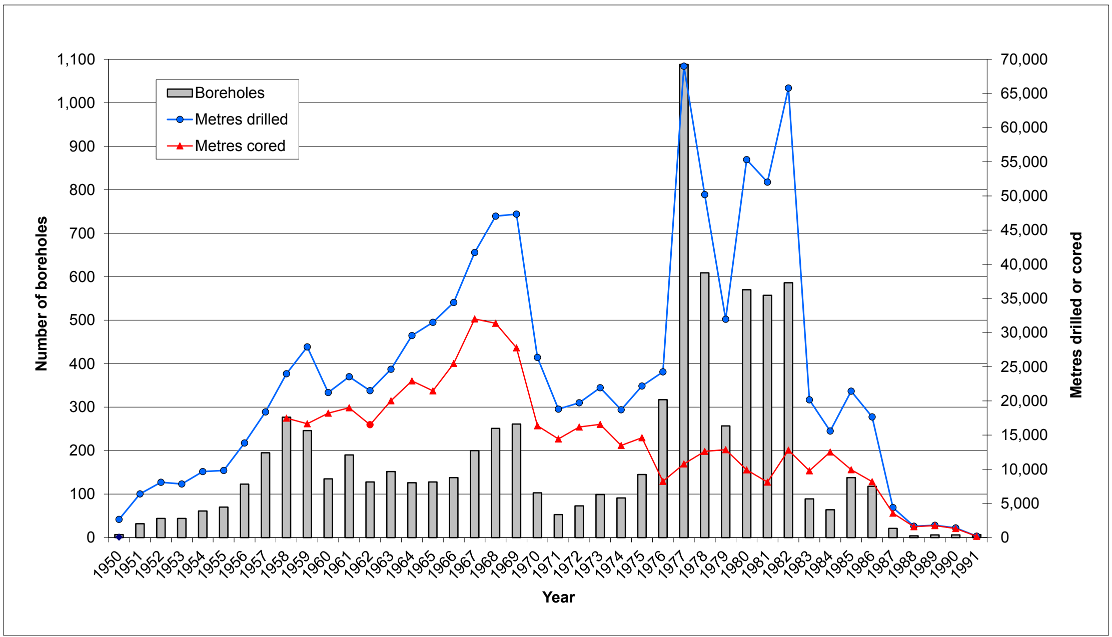

Figure 3. GSQ coal exploration drilling. Sources: 1950–1976 data after Mengel (1977); 1977–1991 data after Department of Resource Industries (1991).

In the Bowen Basin, following an initial spate of private company exploration and subsequent mine development throughout the 1960s (Hawthorne, 2011), the government determined the need for *"an orderly exploration and development of the coal resources in Central Queensland that would enable the delineation of 'adequate coal reserves' for use by Queensland industries and the generation of electricity in the State"* (Coffey *et al.,* 2017, appendix 6a, page 2). This eventually led to the proclamation of Restricted Departmental Area 55D in 1971 over the Bowen and Galilee basins (Coffey *et al.,* 2017).

Between the early 1970s and early 1990s, the government restrictions on land available for coal exploration in the Bowen Basin, brought about by the proclamation of Restricted Area 55D (RA 55), allowed the Department to progressively undertake regional drilling programs and subsequently, offer selected areas for further exploration and development by private enterprise through a public 'expressions of interest' process (Coffey *et al.,* 2017). This process resulted in many of the exploration areas drilled by the Department in the Bowen Basin being eventually developed as operational coal mines. Mines developed include Clermont, Curragh, Ensham, Gregory–Crinum, Jellinbah East, Lake Lindsay, Kestrel (Gordonstone), Lake Vermont, Minerva, Moranbah North, Grosvenor and Oaky Creek (Figure 4).

From the early 1970s, in conjunction with its regional coal exploration drilling programs, the GSQ's Coal Section also began compiling and maintaining a State-wide inventory of estimated raw coal *in situ* for all mines and identified deposits in Queensland. These compilations were first published in October 1971 (Staines & Koppe, 1980) and, as drilling by the Coal Section continued over the following two decades, were routinely updated and published in the Queensland Government Mining Journal and/or the Annual Reports of the Queensland Coal Board.

In the Bowen Basin, as the basic structural and stratigraphic framework of the coal bearing sequences within it began to be better understood, the approach adopted by the department for these coal drilling programs began to change from the late 1970s and into the early 1980s. Over this period, the nature of the drilling programs shifted away from the type traditionally used by the Department, which largely involved the completion of widely spaced fully cored boreholes, to one focussing on the use of more closely spaced non-cored drilling, supported by the use of downhole geophysics. The latter types of drilling programs completed at this time included those at Curragh, Lake Vermont and Ensham.

Towards the end of the 1970s, when the amount of drilling activity undertaken by the department increased significantly (Figure 3), Mengel (1977) reported that of the 17,295 million tonnes of proven (Measured and Indicated status) black coal 'reserves' estimated in the State by the GSQ at that time, approximately 20% of the coking coal estimates (then totalling about 9900 million tonnes raw coal *in situ*) and 40% of the estimated non-coking coal (totalling about 7300 million tonnes raw coal *in situ* at that time) were identified as a direct result of GSQ drilling programs.

It is significant to note, however, that after all the exploration that had been undertaken by the department and private enterprise in the Bowen Basin over more than 40 years prior to 2010, only one deposit of coal had been identified within the tuff-banded Fort Cooper Coal Measures and its correlatives. This comprised the Curragh West deposit (within coal seams of the Burngrove Formation), adjacent to the Curragh mining leases (see also section 'Curragh West'), subsequently identified for potential use as a thermal coal.

The Fort Cooper Coal Measures exist between the younger Rangal Coal Measures and the older Moranbah Coal Measures / German Creek Formation. They are recognised in the north of the Bowen Basin as a single formation (Koppe, 1978), while further south, the correlatives Burngrove Formation and Fair Hill Formation occur in the central part of the basin.

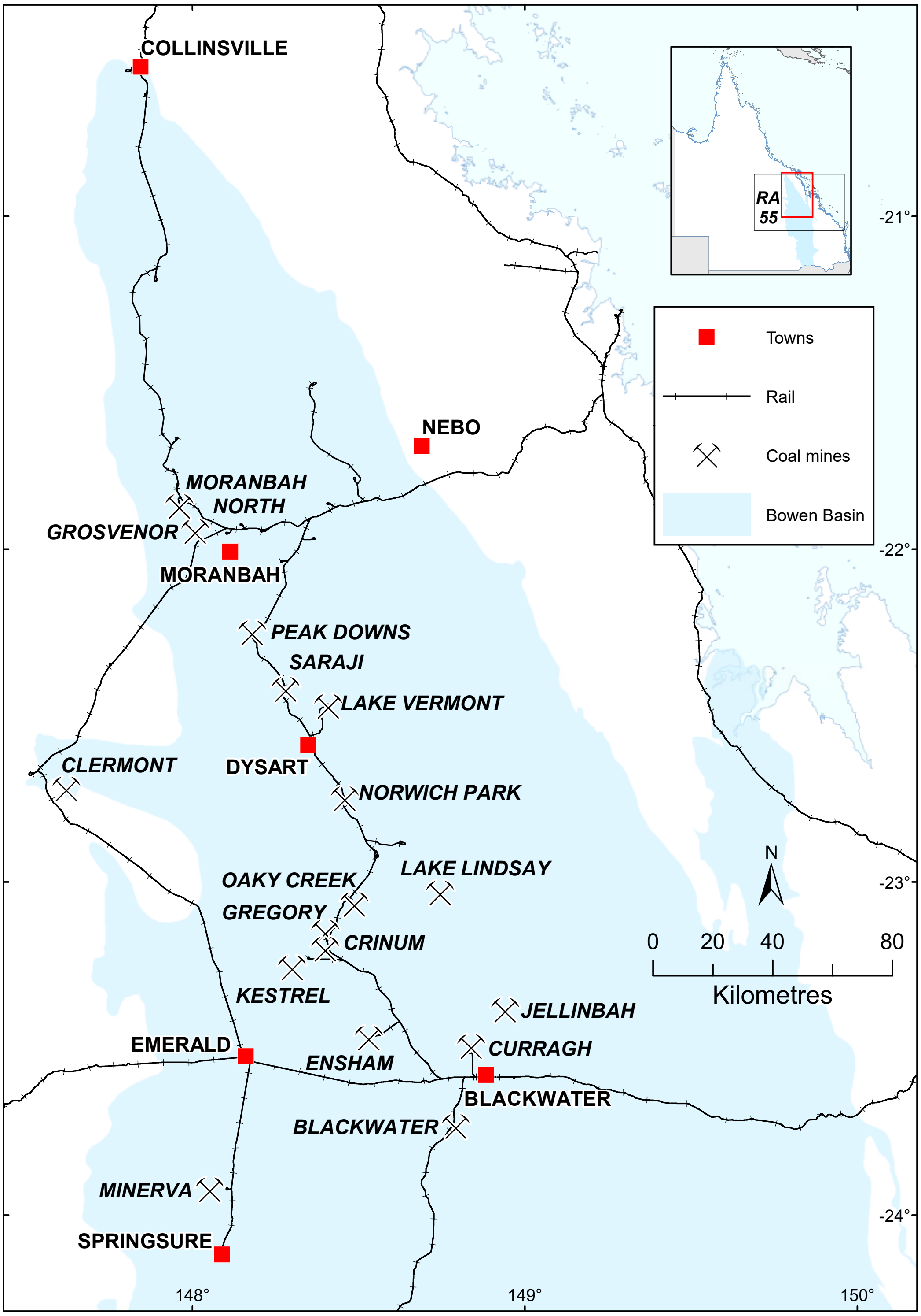

Figure 4. Mines developed through departmental drilling and subsequent land release for coal exploration through 'expressions of interest process'. Restricted Area 55D is shown in the inset.

Although historically regarded as being uneconomic to mine on a stand-alone basis, recent interest by the private sector in the potential commercial development of Fort Cooper/Burngrove/Fair Hill coals as a source of blending coking coal, has prompted the GSQ to undertake this review of the publicly available data relating to their geology and quality.

The three areas being recently targeted for mining comprise the Washpool, Comet Ridge and Wilton project areas (as named at June 2018), which are all located in the central part of the Bowen Basin, on the Comet Anticline/Ridge. The Washpool project is nominally targeting a seam the company has correlated as the Scorpio Seam in the Burngrove Formation, while the Comet Ridge project is targeting development of an open-cut mine on resources the proponent has identified within seams correlated as the Triumph and Fairhill seams in the underlying Fair Hill Formation. The Wilton project appears to be targeting shallow seams in both the Burngrove and Fair Hill formations.

The Initial Advice Statements (IAS) for the Washpool and Wilton coal projects were released in March 2010 (Appendix 1) and April 2012 (Appendix 2) respectively, while the completion of a pre-feasibility study on the Comet Ridge coal project was announced in March 2013 (Appendix 3). The scope of the latter project was for a small open-cut mine designed to produce both 'semi-hard coking' (~66%) and thermal (~35%) products for export at a production rate of between 1 to 2 million tonnes per annum.

These projects were initiated at a time when metallurgical coal was in great demand, coal prices were high and coal exploration activity within the Bowen Basin and the State generally was progressively intensifying (2006–07 through to 2011–12) (Figure 5).

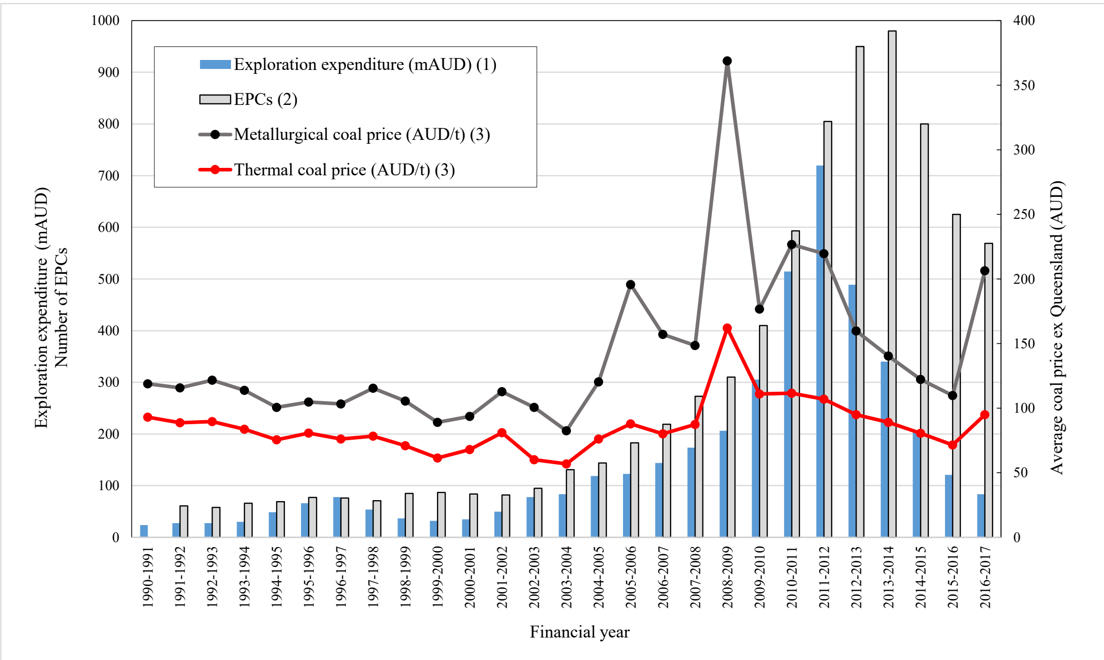

Figure 5. Annual exploration expenditure for coal in Queensland (adjusted mAUD) versus average annual coal prices and number of exploration permits. Sources: (1) Australian Bureau of Statistics 8412.0; (2) DNRM, Spatial and Graphics Group; (3) DNRME, Queensland Coal Annual Statistics.

This review provides a compilation of the departmental data on the Fort Cooper Coal Measure/ Burngrove and Fair Hill formation coals and identifies areas where further exploration effort might be directed, should future demand arise for the coking coal these sequences contain.

1.4 Bowen Basin

The Bowen Basin is the Queensland section of the large intracontinental coal-bearing Bowen-Gunnedah-Sydney Basin System that extends south into New South Wales (Draper, 2013).

During its tri-phase evolution, from the latest Carboniferous – Early Permian to the late Middle Triassic, this basin was shaped by initial dextral transtension, subsequent thermal subsidence and, from the mid-Permian, by a foreland-loading phase. During the latter phase, deformation and thrusting were affected by a series of episodic contractions that have been collectively referred to as the Hunter-Bowen Orogeny (Veevers *et al.,* 1994; Korsch & Totterdell, 2009; Korsch *et al.,* 2009; Draper, 2013).

During the extensional and compressional events, the formation of troughs and platforms (Figure 6 with legend in Figure 7) controlled deposition by changing the location of sedimentation depocentres (Mallett *et al.,* 1995). The environment of sediment deposition, as well as the rate and continuity of sedimentation, was influenced not only by this tectonism, but also by series of marine transgressions and regressions (Draper, 2013).

Deposition during the initial extensional phase was mainly non-marine (Fielding *et al.,* 2001) and saw the deposition of the Group 1 coals of the Reids Dome beds (Table 1, Figure 8).

The subsequent thermal-subsidence phase was extensive and largely marine, and included multiple coal-measure sequences such as the Blair Athol Coal Measures, Collinsville Coal Measures, and equivalents of the Group 2 coals.

The late middle Permian (late Guadalupian) to late Middle Triassic foreland-loading phase has been inferred to have been the cause of subsequent subsidence in the Bowen Basin (Draper, 2013). This period of crustal loading and propagation of thrust sheets associated with the contractional events included offshore marine, shallow-marine delta, prodelta, fluvio-deltaic, lacustrine and alluvial-plain complexes during the late Permian (Lopingian).

The Early and Middle Triassic was characterised by meandering-fluvial, paleosol, braided-fluvial, lacustrine and enclosed fluvial systems with marginal alluvial fans (Draper, 2013). The propagation of the thrust front westwards into the basin caused basin termination, with probable uplift and exhumation at the end of the Middle Triassic (Fielding *et al.,* 2001; Draper, 2013).

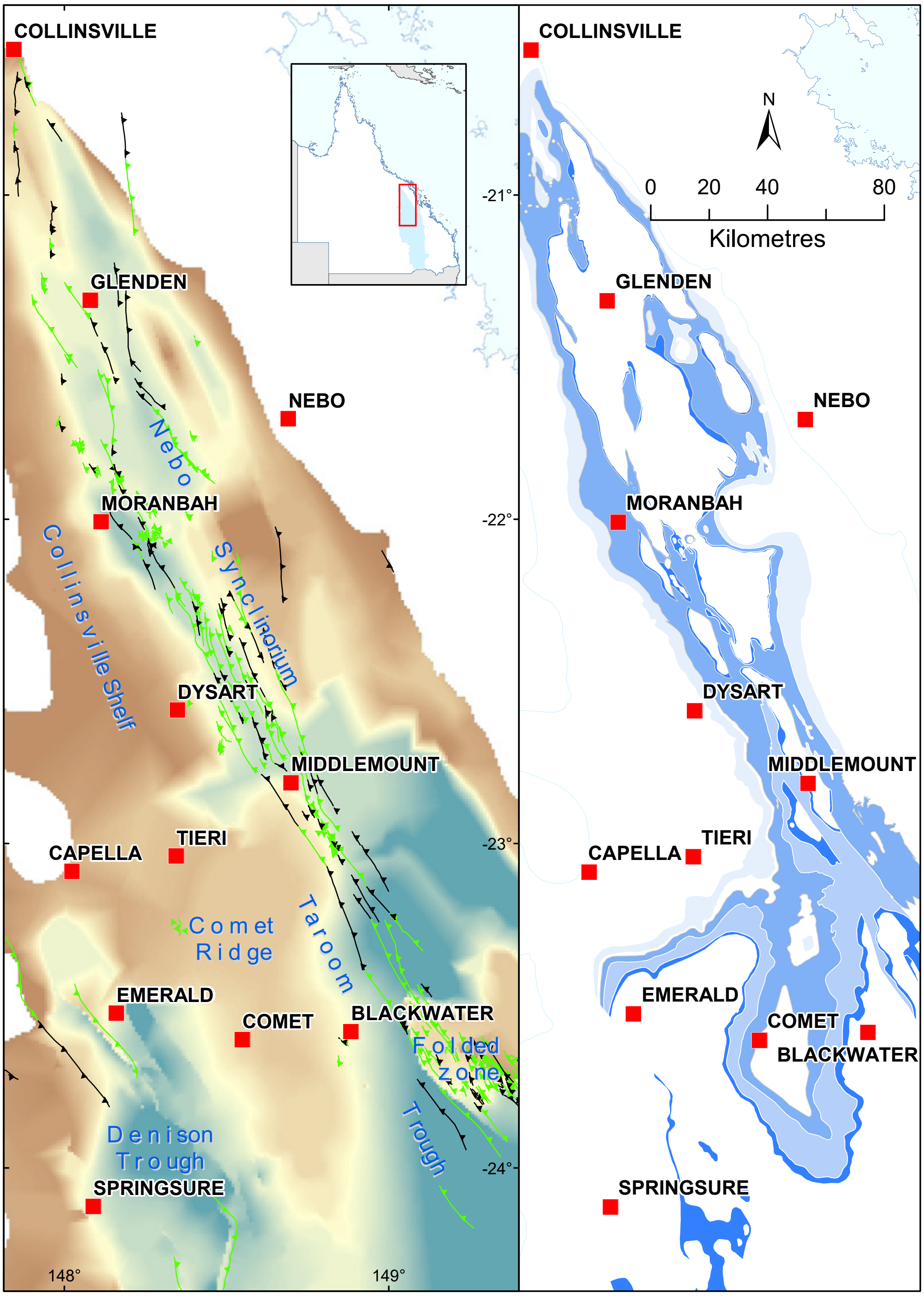

Figure 6. Basement topography, structural features and solid geology of late Permian (Lopingian) coal measures. Legend in Figure 7.

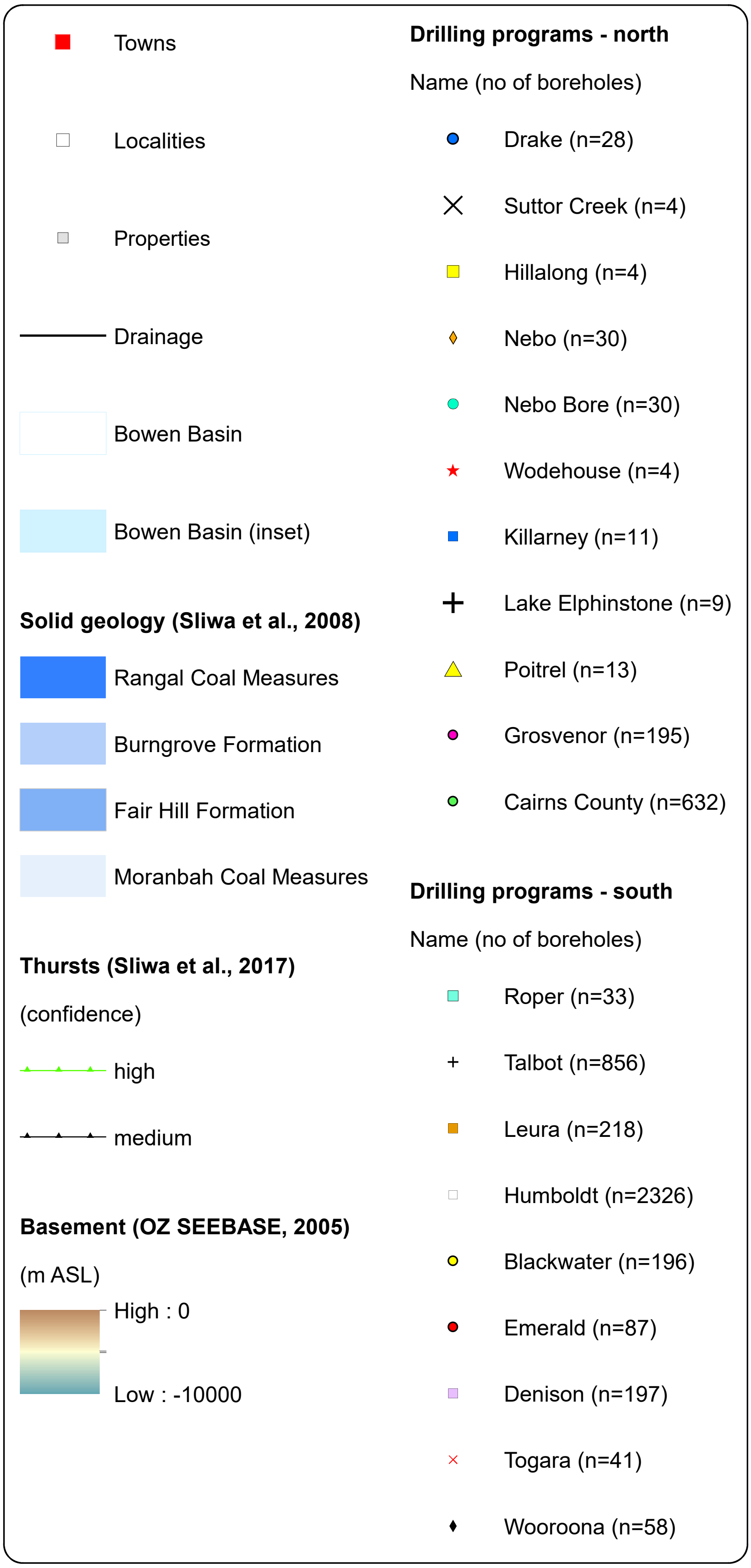

Figure 7. Legend for the following figures: 6, 9, 10, 11, 12, 13, 14, 15, 17, 18, 20, 22, 23, 25, 26, 27, 28, 29, 30, 31, 33, 34, 36, 37, 39, 41, 42, 44, 45, 46, 47, 48, 49, 50, 51, 52, 58, 59, 60, 63, 64, 66, 67, 68, 69, 70, 71, 72, 73, 74 and 75.

The foreland phase of sedimentation caused three southward progradational pulses of fluvial deposition, which provided conditions for coal formation in low-energy lowlands. These pulses corresponded to three major coal-bearing Lopingian formations: Moranbah, Fort Cooper and Rangal coal measures (Fielding *et al.,* 1993; Figure 6). These were designated, respectively, as Group 3, 4 and 5 coals by Draper & Boreham (2006); this classification aimed to integrate both the type of sedimentation and the controlling tectonic phase (Table 1, Figure 8).

Table 1. Coal groups and associated formations (after Draper & Boreham, 2006).

Coal group	Permian coal measures (CM) and formations (Fm)	Environment of deposition	Tectonic phase
5	Rangal CM, Baralaba CM, Bandanna Fm	Fluvial, deltaic	Foreland
4	Fort Cooper CM, Fair Hill Fm, Burngrove Fm	Fluvial, deltaic	Foreland
3	Moranbah CM, German Creek CM	Delta plain, delta	Foreland
2	Collinsville CM Blair Athol CM	Deltaic, back barrier Fluvial	Sag
1	Reids Dome beds	Fluvial, deltaic	Extension

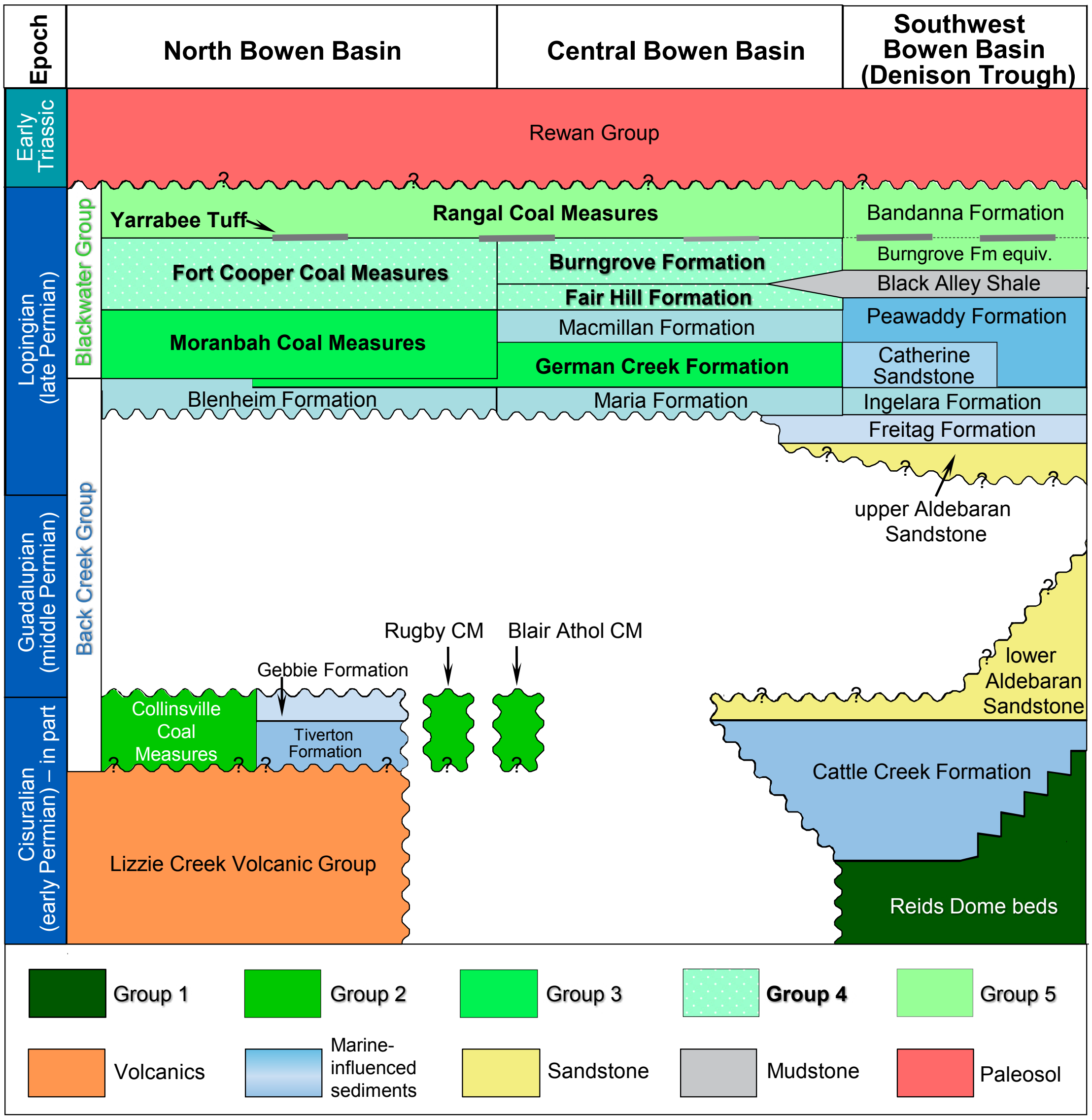

Figure 8. Coal groups in relation to Permian stratigraphy (John McKellar and Russell D'Arcy, personal communication, 2018).

The main focus of this review is the Fort Cooper Coal Measures and its lateral correlatives, the Fair Hill and Burngrove formations which contain the Group 4 coals (Figure 8), with the right rank to include coking coal. While the lower portions of the Baralaba and Bandanna formations (nomenclature used in the far south-eastern part of the basin) are also considered lateral equivalants of the Fort Cooper Coal Measures, these sequences do not have the same coking coal potential and are not considered in this review.

The deposition of the Fort Cooper Coal Measures was contemporaneous with the recurrence of arc volcanism on the eastern margin, which triggered a high influx of volcanolithics and the formation of tuffaceous sediments with high-ash coal beds.

The high inherent ash of the Group 4 coals has historically rendered them unattractive economically, particularly in comparison to the low-ash products of the adjoining Group 3 and Group 5 coals, despite their strong coking coal properties. However, localised trials and mining are currently being undertaken by industry (*e.g.,* Newlands and Hail Creek mines) to test the blending potential of some Fort Cooper seams.

2. Fort Cooper Coal Measures and correlatives

2.1 Early nomenclature and descriptions

Initial stratigraphic placement of the Fort Cooper Coal Measures was as an undifferentiated part of the 'Upper Bowen Series', as defined by Jack (1879) and detailed by Reid (1929) in the Bowen River Coalfield, near Collinsville (Figure 9). This upper series included all the freshwater, coal-bearing formations of the upper Permian, as distinct from the marine influenced sediments of the 'Middle Bowen Series' which underlie them.

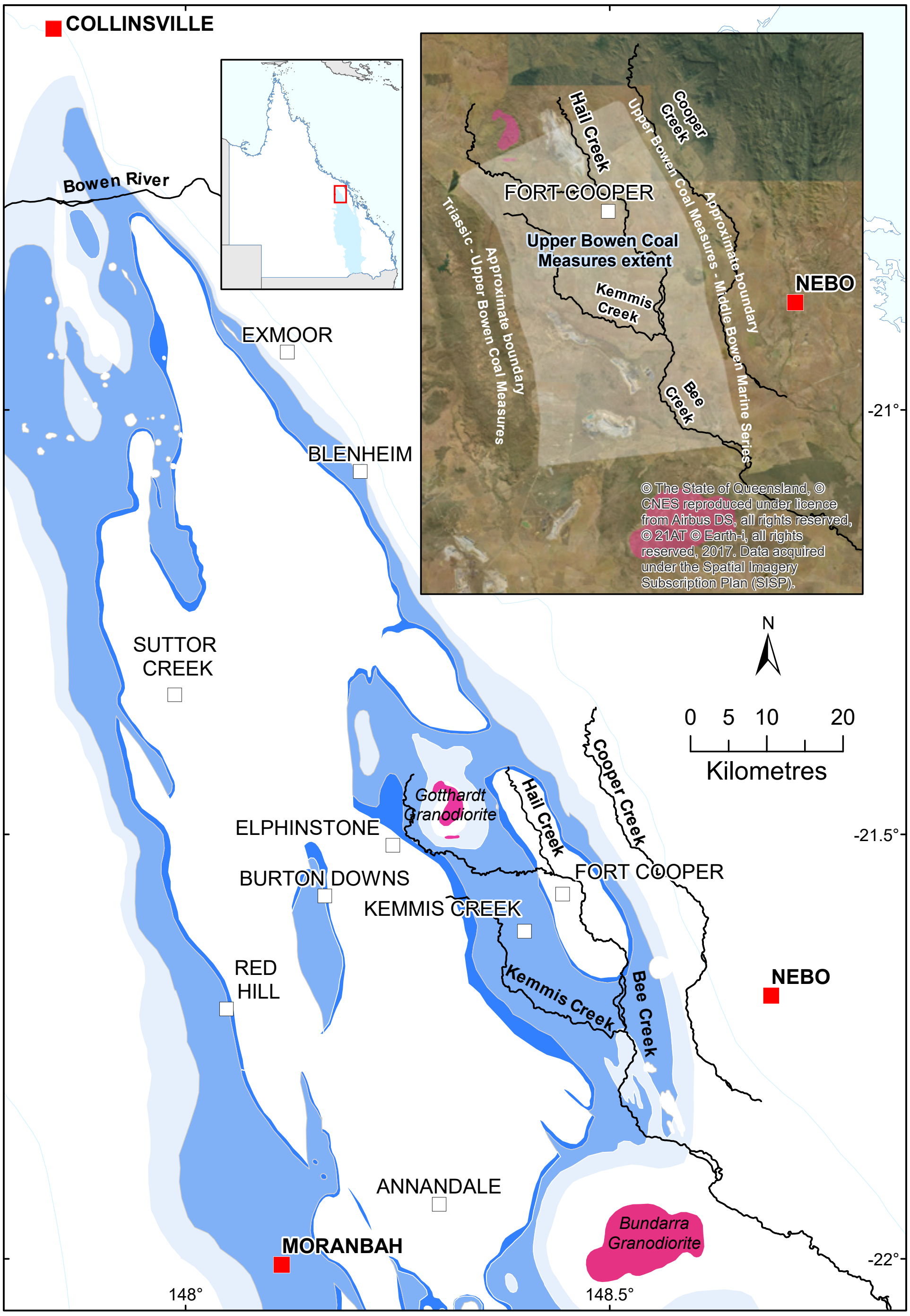

Figure 9. Nebo area and geological boundaries as defined by Reid (1946) with the current solid geology map for comparison. Legend in Figure 7.

While the ‘Upper Bowen’ and ‘Middle Bowen’ terminology persisted, many subsequent workers termed and referred to these units as ‘coal measures’, ‘formations’, or ‘beds’ rather than by their original designation of ‘series’.

While undertaking reconnaissance work to confirm the presence and economic potential of the ‘Upper Bowen Coal Measures’ near Nebo, Reid (1946) found and reported a marked distinction between the units of the Upper Bowen Series. Examining rocks in outcrop in the vicinity of Hail Creek and Cooper Creek (Figure 9), Reid (1946) identified an upper sequence of yellowish to grey sandstone and shale (provisionally named the ‘Elphinstone Coal Measures’), that overlaid a limonitic sandstone and brown cherty shale, which he named the ‘Fort Cooper Coal Measures’. The later formation also contained fossil flora (i.e. *Glossopteris*), fossil wood and coal seams at the base. Reid’s reconnaissance report was the first attempt to subdivide the Upper Bowen Series and to determine the lateral extent of coal seams outside the Bowen River Coalfield at Collinsville.

The extensive field mapping, sampling and dating that was undertaken in the 1960s improved the knowledge and understanding of the chronostratigraphic character of the Permian formations and their coal seams. Initial emphasis was placed on the ‘Middle Bowen Formation’, which consisted of marine sediments and on the Collinsville Coal Measures; later, exploration was extended to the freshwater sediments with coals of the ‘Upper Bowen Formation’ (Dickins *et al.,* 1962; 1964). This early work provided descriptions and attempted correlations between various Permian formations cropping out in the north and north-central Bowen Basin.

Regional mapping of the Duaringa and St Lawrence 1:250 000 geological map sheets enabled further refinement of the upper Permian stratigraphy (Malone *et al.,* 1963). Although the name of ‘Upper Bowen Coal Measures’ was still used, the ‘Burngrove Member’ was distinguished and described for the first time in the Duaringa map sheet (Figure 10). This unit was first recognised as a mappable unit by geologists of the Utah Development Company in their detailed mapping and drilling of the Blackwater area.

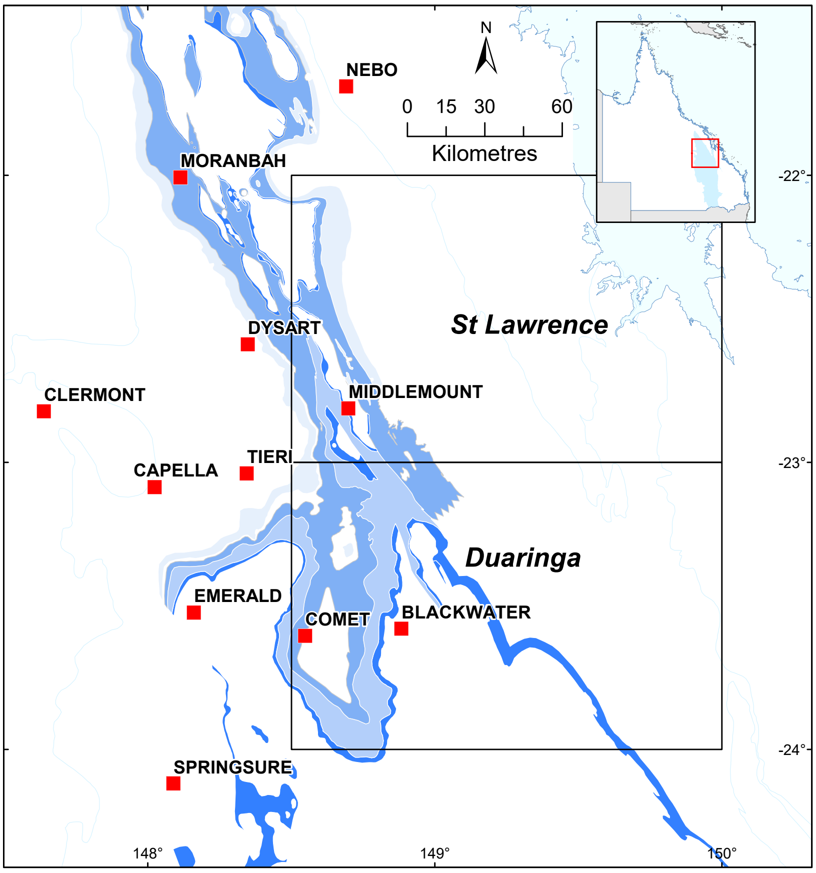

Figure 10. Location of the Duaringa and St Lawrence 1:250 000 geological map sheets. Legend in Figure 7.

Malone *et al.* (1963, page 49) described the Upper Bowen Coal Measures as about 1000 m thick and comprising of *"interbedded argillaceous and arenaceous lithic sediments, calcareous and tuffaceous in places, impure limestone and coal"*. The formation was reported as having a transitional contact with the 'Middle Bowen Beds' and to be conformably overlaid by the Triassic Rewan Formation.

The Burngrove Member consisted of grey-green siltstone interbedded and interlaminated with dark carbonaceous mudstone and fine-grained calcareous lithic sandstone. Fossil plant debris and well-preserved plants were reported as abundant. The sandstone units contained lithics of volcanic origin and frequent calcite veins and cementation. The member was about 100 m thick and was recognised approximately 300 m above the base of the Upper Bowen Coal Measures and between the two main coal-bearing sequences. Distinguishing features were the absence of cross-bedded sandstone units with fossil wood and the lack of coarse clastics, which suggested a low-energy environment of deposition and a slow rate of sedimentation (Malone *et al.,* 1963).

2.2 Seam nomenclature and descriptions

Regional coal exploration programs by the GSQ, following the establishment of Restricted Area 55D, mentioned and described one major seam in the Fort Cooper Coal Measures, the Girrah Seam (*e.g.,* Anderson, 1974; Koppe & Scott, 1981; Dash, 1985a; Matheson & Jameson, 1988). Localised coalescence of the Girrah Seam with the overlying Vermont Seam (i.e. near Moranbah) resulted in this combined seam being named the Vermont-Girrah, which was usually assigned to the Fort Cooper Coal Measures due to the high ash content (Koppe & Scott, 1981; Matheson, 1985). An underlying S Seam was mentioned only near Dysart (Holmes, 1980).

Seam occurrence over the Comet Ridge was much more complex and the first attempt to standardise the nomenclature was made by Staines (1972). Detailed exploration carried out in the 1960s by the Queensland Department of Mines (the Blackwater drilling program, see later sections) and several private companies resulted in a significant amount of geological information being collected on the coal resources centred on the township of Blackwater. Staines (1972) examined hundreds of coal boreholes drilled along of the strike of the Rangal Coal Measures, from the Mackenzie River in the north to Sirius Creek in the south, and proposed a new nomenclature that included previously unrecognised seams (Table 2).

Table 2. Seam nomenclature in the Blackwater area (after Staines, 1972).

<table>
<tr><th>Early names</th><th>Utah Development Company</th><th colspan="2">Broken Hill Proprietary Company Limited</th><th>Clutha Development Pty Limited</th><th>Thiess Bros Pty Limited</th><th colspan="4">Staines (1972)</th></tr>
<tr><td>Mammoth = Blackwater</td><td>Top = Upper = Rider</td><td colspan="2">Rider</td><td>A</td><td>A</td><td rowspan="2">Mammoth</td><td colspan="3">Aries</td></tr>
<tr><td>= Frenchman's Plains</td><td>Middle</td><td>Castor</td><td rowspan="2">Gemini</td><td>Mammoth</td><td>B</td><td>Castor</td><td rowspan="2">Gemini</td><td rowspan="3">Taurus</td></tr>
<tr><td rowspan="3">Mackenzie = Jellinbah</td><td>Main</td><td>Pollux</td><td>Main
Lower</td><td>C</td><td rowspan="3">Mackenzie</td><td>Pollux</td></tr>
<tr><td>Unnamed</td><td colspan="2">Orion</td><td></td><td>D</td><td colspan="2">Orion</td></tr>
<tr><td>Sugarloaf</td><td colspan="2">Pisces</td><td rowspan="6"></td><td rowspan="6"></td><td colspan="3">Pisces</td></tr>
<tr><td rowspan="5"></td><td>Burngrove</td><td colspan="2">Virgo</td><td colspan="4">Virgo</td></tr>
<tr><td rowspan="4"></td><td colspan="2" rowspan="4"></td><td colspan="4">Libra</td></tr>
<tr><td colspan="4">Leo</td></tr>
<tr><td colspan="4">Aquarius</td></tr>
<tr><td colspan="4">Scorpio</td></tr>
</table>

Relevant to the current review is the nomenclature established for the Burngrove Formation seams and their first descriptions by Staines (1972). In addition to departmental borehole data, Staines' (1972) dataset included company data collected in Authority to Prospect (AtP) 6C and 12C; in these areas, the formation was reported to be at least 100 m thick, although the lower boundary was not intersected. The top boundary was set at the top of the Virgo Seam. Boreholes drilled in AtP 10C and 25C (Figure 11) did not intersect the Burngrove Formation.

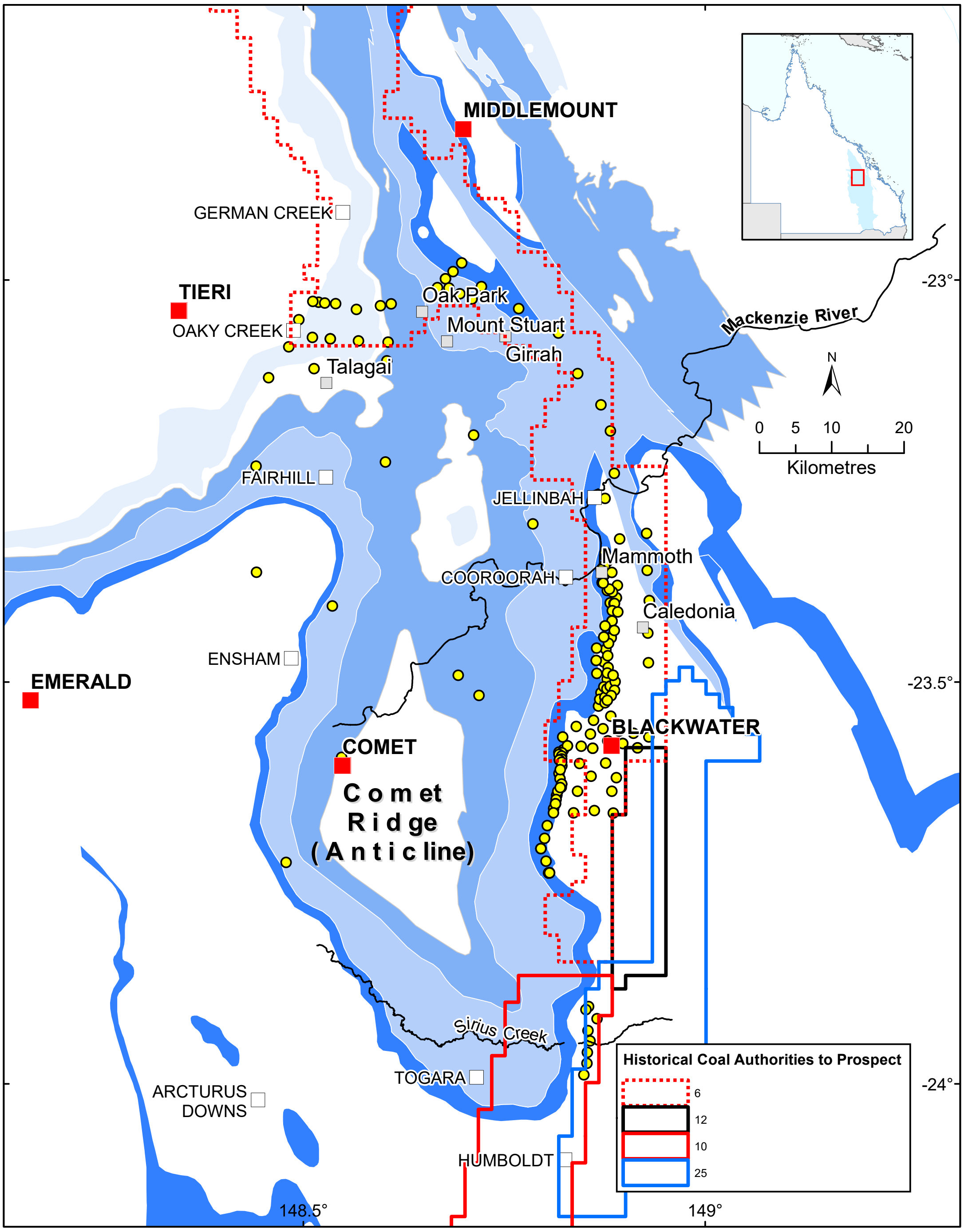

Figure 11. Early departmental and company exploration areas used to establish seam nomenclature. Legend in Figure 7.

In AtP 6C, between the Mackenzie River and the township of Blackwater, the Virgo Seam occurred about 10 m below the Pisces. The two seams were separated by a massive sandstone, which reached 60 m in thickness in the north of the area. Towards the south, the sandstone changed to a 20 m-thick silty sequence, which eventually thinned out and the Virgo and Pisces coalesced. The lower boundary of the Virgo Seam was marked by a 30 to 60 cm-thick light brown tuffaceous mudstone. Four additional seams were intersected in the north. The Libra Seam was about 15 m thick and disappeared near the southern margin, towards Blackwater. The Leo Seam was thicker and consisted of regionally persistent interbedded mudstone and coal; it also included a marker bed like Virgo, consisting of mudstones, which were light brown and friable at the base and changed to a light grey greenish colour towards the top. The deeper Aquarius and Scorpio seams were banded, poorly understood and impossible to correlate regionally at the time.

In AtP 12C (Figure 11), the Virgo Seam was intersected only in a few deep boreholes where it was found to be similar to the Pisces Seam and to consist mainly of brown mudstone.

An important contribution to the seam nomenclature of the Fair Hill Formation was made by Staines (1974) and Prouza (1976; 1977). Although explorers at the time mentioned the presence of between 6 and 11 seams in the Fair Hill Formation, descriptions were sparse and regional correlation was not possible. Staines (1974) mentioned the Phoenix, Pegasus, Hercules, Canis, Lepus and Fairhill seams. Prouza (1976) described them in detail in the Oaky Creek area, while Prouza (1977) investigated their occurrence across the Comet Anticline. A summary is presented in Table 3.

Table 3. Fair Hill Formation seam description (after Prouza, 1976; 1977).

Seam	Thickness (m)	Lithology	Overall quality
Fairhill	8–11	interbeds of tuffaceous mudstones, siltstones and coal	poor coal 10–60% 30–50 tuffaceous layers
Lepus	1.5–2	carbonaceous shale, tuffaceous, minor coal	poor
Canis	6–10	as above	coal <20%
Hercules	15–25	as above	coal <10%
3 unnamed upper seams (Prouza, 1976) Phoenix, Pegasus (Prouza, 1977)	1.5–4	as above	poor

2.3 Type sections

A basin-wide comprehensive synthesis of the upper Permian stratigraphy, including structure and economic significance, was undertaken by Jensen (1968). He subdivided the Upper Bowen Coal Measures into an upper Rewan Formation and a lower Blackwater Group. He introduced the ‘Hail Creek Beds’ as the unit overlying the marine section of the Permian and described the ‘Elphinstone and Fort Cooper coal measures’ in detail, for the first time. All of these changes were introduced in an attempt to formalise nomenclature across the basin, although differences between the northern and southern parts of the basin were recognised (Table 4).

Table 4. Early nomenclature evolution.

<table>
<tr><th>Jack, 1879</th><th colspan="2">Reid, 1946</th><th>Jensen, 1968
(Exmoor – Fort Cooper)</th><th colspan="2">Jensen, 1968
(Blackwater)</th></tr>
<tr><td rowspan="4">Upper Bowen Series</td><td rowspan="4">Upper Bowen Coal Measures</td><td rowspan="2">Elphinstone Coal Measures</td><td>Rewan Formation</td><td colspan="2">Rewan Formation</td></tr>
<tr><td>Elphinstone Coal Measures</td><td>Rangal Coal Measures</td><td rowspan="2">Blackwater Group</td></tr>
<tr><td rowspan="2">Fort Cooper Coal Measures</td><td>Fort Cooper Coal Measures</td><td>Burngrove Formation
Fair Hill Formation</td></tr>
<tr><td>Hail Creek Beds</td><td colspan="2" rowspan="2">German Creek Coal Measures</td></tr>
<tr><td>Middle Bowen Series</td><td colspan="2">Middle Bowen Series</td><td>Back Creek Group</td></tr>
</table>

Jensen (1968) established the type section of the Fort Cooper Coal Measures (380 m thick) in the headwaters of Hail Creek, on the Mount Coolon 1:250 000 geological sheet, Fort Cooper area (Figure 12, insert a). Initially mapped in the 20,000-yard grid, the location of the section has now been converted to GDA94 geographic coordinates. Further detail is presented in section ‘Type section locations’.

Jensen (1968) described the Fort Cooper Coal Measures as *“green lithic sandstone, conglomerate, mudstone, carbonaceous shale and coal, and thin beds of grey white cherty tuff bearing an abundance of fossil leaf impressions… sandy conglomerate appear to be quite massive… thick-bedded sandstone are commonly cross-stratified… fine sediments are generally thin-bedded. The base of the unit is taken as thick beds of pebbly sandstone lying conformably on sediments of the Hail Creek Beds. This is overlain by a thick alternating sequence of carbonaceous shale and pebbly lithic sandstone, but higher in the sequence the sandstone is interbedded with thin beds of grey-white cherty tuff… only in a few places do these tuffs form thick beds. Carbonaceous shale and conglomerate are more common towards the top of the unit than in the middle. Fossil logs are common throughout”* (page 30). The Fort Cooper Coal Measures could be traced from about 40 km north of Kemmis Creek to Blenheim (Figure 12) using the tuff beds, which were found to be reasonably consistent.

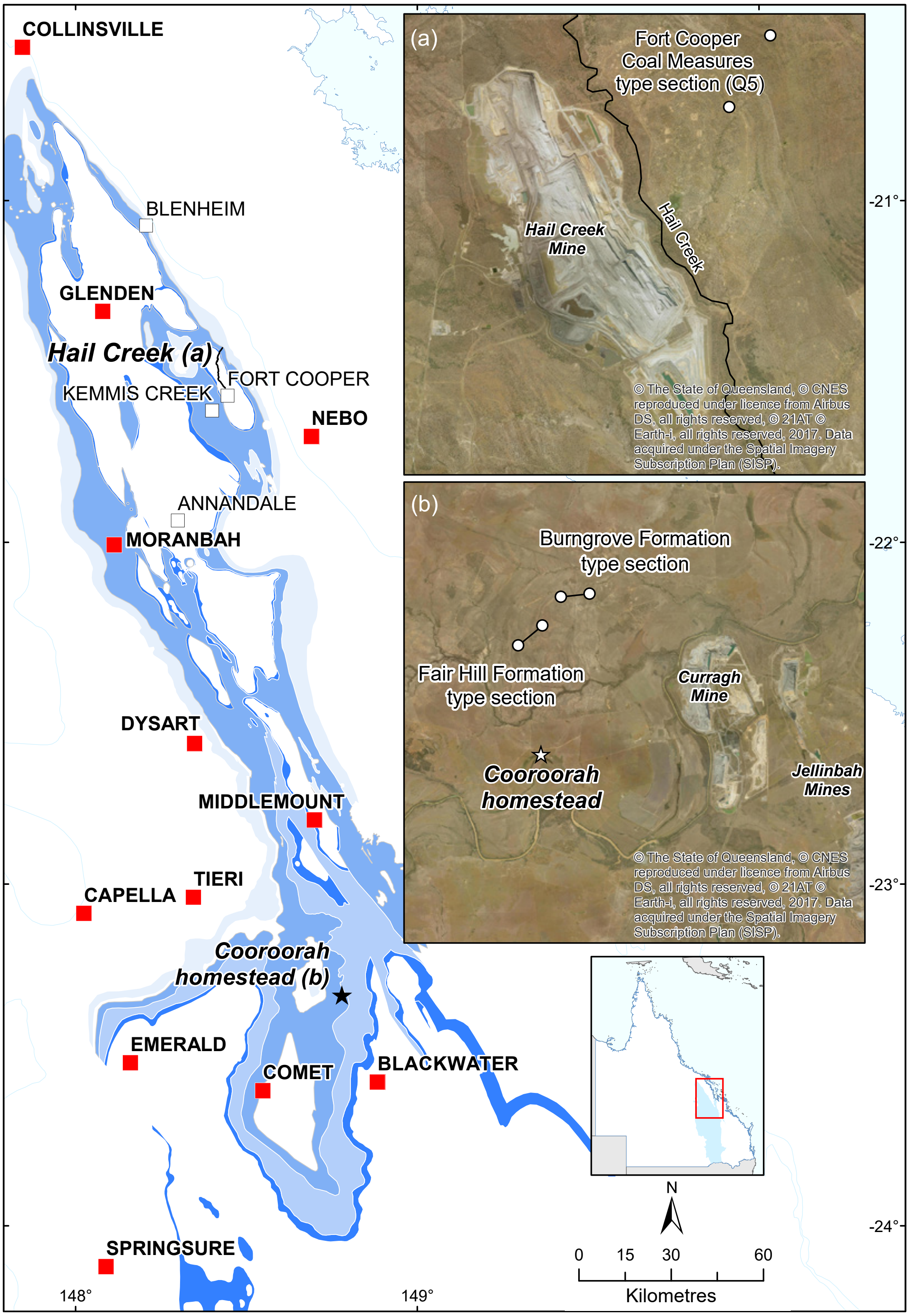

Figure 12. Type section locations: (a) Fort Cooper Coal Measures (Jensen, 1968) and (b) Burngrove and Fair Hill formations (Jensen, 1968 and Malone et al., 1969). Legend in Figure 7.

Further south, in the Blackwater area, Jensen (1968) described the Fort Cooper Coal Measures correlatives for the first time, in a creek gullies situated a few kilometres north of Cooroorah Homestead, in the Duaringa 1:250 000 geological map sheet (Figure 12 and inset b).

The Fair Hill Formation was about 85 m thick and consisted predominantly of fine- to coarse-grained sandstone with minor brown calcareous mudstone. Pebbles were scattered throughout the unit and fossil logs along the bedding plane were common. Cross-stratification was also common and suggested sediment transport in a south and southeast direction. A distinct feature of the formation was the abundance of fresh volcanic rock fragments, which Jensen (1968) considered as reflecting a change in sediment provenance. The Fair Hill Formation was deposited in fluvial channels by strong traction currents.

The boundary with the overlying Burngrove Formation was quite sharp. This unit was about 100 m thick and consisted of hard, well-cemented, grey brown carbonaceous mudstone with beds of grey sandstone, green chert, shaly coal and light green montmorillonitic clay. The thickness of the beds varied between a few millimetres and a few tens of centimetres. The sandstone included volcanic rock fragments and angular quartz and feldspar fragments; the cement consisted of microcrystalline silica. The cherty mudstone was highly tuffaceous with volcanic glass shards. In comparison with the coarser underlying Fair Hill Formation, the Burngrove Formation was deposited in a lower energy environment, unaffected by currents or waves, as suggested by burrowing structures, but close to a continental setting which supplied carbonaceous material (Jensen, 1968).

The formal description of the type sections near Cooroorah Homestead was published by Malone *et al.* (1969), although they added very little to Jensen's (1968) descriptions. The coordinates of the top and bottom section points have been converted from the 20,000-yard grid to GDA94 geographic coordinates and further detail is presented in section 'Type section locations'. Malone *et al.,* (1969) defined the Fair Hill Formation (named after a nearby homestead) as a *"lithic and feldspathic labile sandstone"* (page 44), which was notably different from the underlying quartzose German Creek Formation. The Burngrove Formation consisted of multi-coloured (green, yellow, grey, white) interbedded mudstone, hard and siliceous or tuffaceous in part. Neither Jensen (1968) nor Malone *et al.,* (1969) mentioned coal in their descriptions of the Fair Hill and Burngrove type sections.

2.4 Nomenclature (late 1960s – late-1970s)

Over the following decades, advances in the understanding of the Permian stratigraphy and coal geology of the Bowen Basin were made through regional coal exploration targeting areas with potential for economic mine development, in particular those areas containing coal that had coking potential.

Following the early exploration in the mid to late 1960s within the basin, undertaken by Utah Development Company and Thiess Peabody Mitsui, the Queensland Government imposed restrictions on the access to land for coal exploration in the Bowen Basin by the gazettal of Restricted Area 55D in 1971 (Coffey *et al.,* 2016, appendix 6a). This restriction meant that much of the regional exploration during the 1970s within the basin was initially undertaken by the Geological Survey of Queensland's Coal Section. This and later, supplemented by private sector exploration, as land was progressively released from Restricted Area 55D (Figure 4). This work led to a better understanding of the stratigraphic framework of the basin, the distribution of coal facies within it, as well as the correlations and quality of coal seams within these sequences (see section 'Departmental drilling').

In this context, Hawthorne (1974), then Assistant Chief Government Geologist of the GSQ and a former Supervising Geologist of the GSQ Coal Section, reviewed the coal geology of the Bowen Basin and made reference to and extensively used the "*unpublished information resulting from Department of Mines coal drilling"* (page 371). This review first outlined the general stratigraphic distribution of the coal-bearing sequences of Permian age in the Bowen Basin, which Hawthorne (1974) divided into four different stratigraphic groups, referring to these (from oldest to youngest) as groups 'one' to 'four'. Notably absent from his coal facies scheme were the tuff-banded coals of the Fort Cooper

Coal Measures/ Burngrove – Fair Hill formation sequences. While Hawthorne (1974, page 375) made general reference to them as follows *"Basin-wide volcanism produced tuffs and tuffaceous mudstones. Coals deposited at this time contain numerous tuffaceous mudstone bands"*, these formations were excluded from his scheme seemingly because *"no economically workable seams are known"*.

In the subsequent review of the geology of the northern Bowen Basin, Staines and Koppe (1980) continued with the scheme outlined by Hawthorne (1974), excluding the tuff-banded coals in the Fort Cooper Coal Measures/Burngrove and Fair Hill formations ostensibly because *"None of the seams have proved economic, because of their high content of non-coaly material" (*page 289). Later reviews of the basin stratigraphy by Mallett *et al.* (1995) and Draper (2013) included these banded coals as Group IIIA and Group 4, respectively.

Milligan (1975, page 12) also referred to the tuffaceous character of the upper Permian coal measures in his review of the Bowen and Galilee Basin coalfields. He stated *"The regression continued throughout the Basin under conditions that were generally inimical to coal deposition and a distinctive sequence of fine grained siliceous, carbonaceous and tuffaceous freshwater sediments were deposited throughout. These are represented by the Burngrove shale member of the Fair Hill Formation* [then incorporating the underlying coal-bearing sequence which was later defined as the Moranbah Coal Measures] *in the north west… and the upper part of the Fort Cooper Coal Measures in the north east of the Basin"*.

A significant contribution to the Lopingian coal measures nomenclature resulting from departmental coal exploration in the Bowen Basin was made by Koppe (1978). He reviewed the stratigraphy of the upper Permian succession (i.e. the correlations published by Milligan in 1975) and proposed to replace the name of 'Elphinstone Coal Measures' with 'Rangal Coal Measures' in the northern Bowen Basin. While the name of 'Rangal Coal Measures' was already in use in the south around Blackwater (Table 4), Koppe (1978) extended its use in the north, in an attempt to standardise nomenclature. He also introduced and described a new unit, the 'Moranbah Coal Measures', which extended from Collinsville in the north to the area around Dysart (Figure 13). He also established and described the Moranbah Coal Measures type section in a departmental borehole, DME Grosvenor NS 14, as the interval between 152.4 m and 411.1 m.

The stratigraphic nomenclature proposed by Koppe (1978) was for the name 'Moranbah Coal Measures' to replace the name 'Hail Creek beds' in the northeast and to be used for the lowermost (non tuffaceous) portion of the 'Fair Hill Formation' in the northwest, along the Collinsville Shelf. The nomenclature in use before 1978 (i.e., Milligan, 1975) had the upper part of the formation encompass the tuffaceous coal-bearing unit, which was referred to as the Fort Cooper Coal Measures in the northeast.

Instead, Koppe's proposed amendment was to refer to this tuffaceous coal-bearing unit as the 'Fort Cooper Coal Measures' throughout the northern Bowen Basin and for the name 'Moranbah Coal Measures' to be used for the lower non-tuffaceous part of the 'Fair Hill Formation' in the northwest, as well as the 'Hail Creek beds' in the northeast (Table 5).

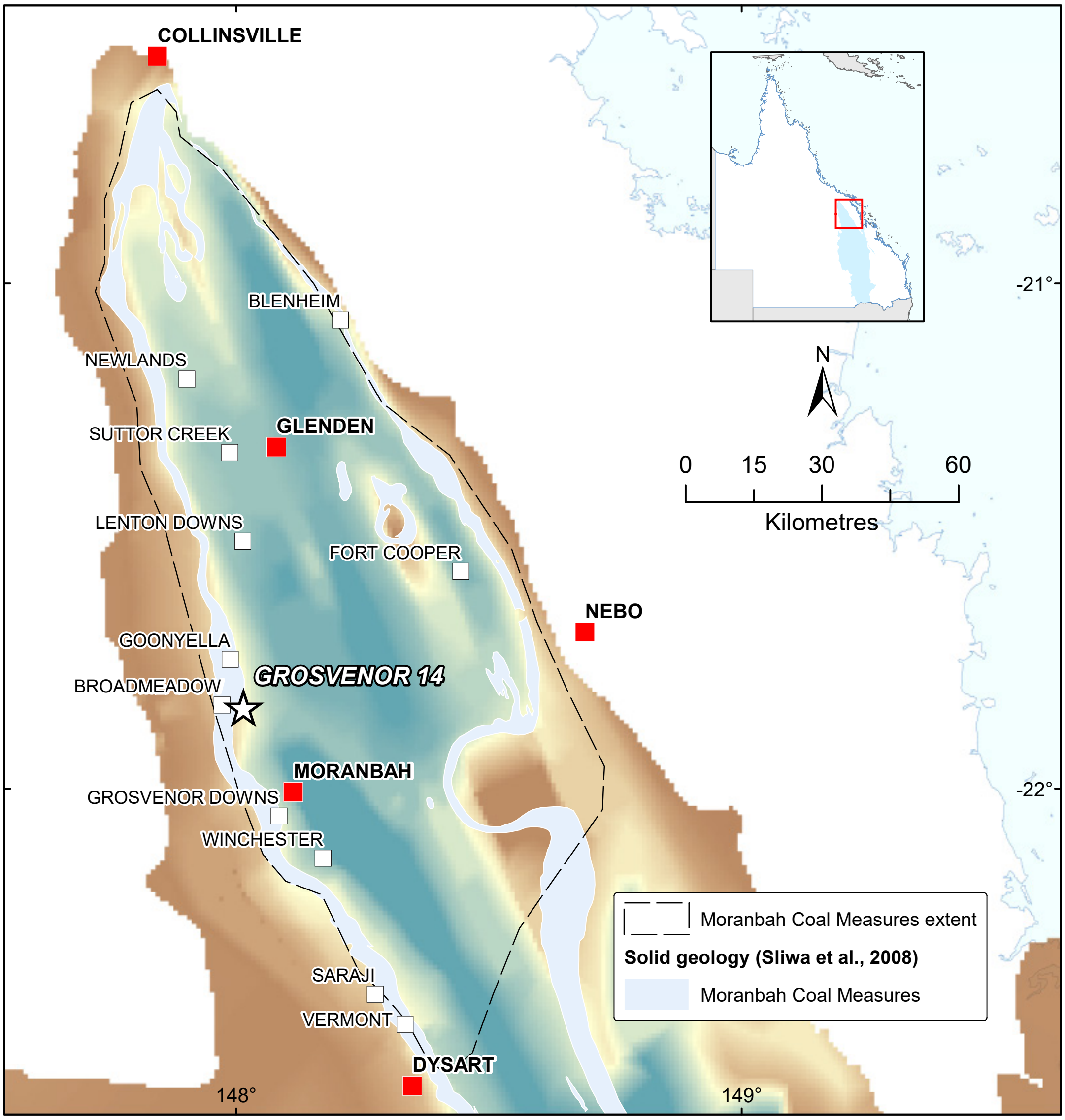

Figure 13. Location of the Moranbah Coal Measures type section - borehole DME Grosvenor NS 14, in relation to the formation extent as defined by Koppe (1978) and current solid geology. Legend in Figure 7.

Table 5. Stratigraphy of the Blackwater Group, north and north-central Bowen Basin.

Milligan, 1975 NW Bowen Basin	Milligan, 1975 NE Bowen Basin	Koppe, 1978 Dash, 1985a
Rangal Coal Measures	Elphinstone Coal Measures	Rangal Coal Measures
Burngrove Formation	Fort Cooper Coal Measures	Fort Cooper Coal Measures
Fair Hill Formation* German Creek Formation	Hail Creek beds	Moranbah Coal Measures

** Moranbah Coal Measures equivalent as later established by Koppe (1978)*

Another significant contribution was made by Matheson (1990a,b) who reviewed the coal geology and exploration of the Rangal Coal Measures. He also provided a synthesis of Fort Cooper Coal Measures knowledge at that time, including description and occurrence. In terms of nomenclature, Matheson (1990 a,b) defined the type section of the Yarrabee Tuff (further details in sections 'Recent advances' and 'Formation boundaries'), which he placed at the boundary between the Fort Cooper and Rangal coal measures.

Reviewing the stratigraphic nomenclature and formation correlations around the Comet Anticline (from German Creek to Emerald and Comet – locations in Figure 11), Prouza and Park (1973) proposed the following:

- The Macmillan Member was no longer considered part of the German Creek Coal Measures and was raised to formation status
- the German Creek Coal Measures were renamed the German Creek Formation
- the Croker Formation near Comet was correlated with the upper German Creek Formation in the Oaky Creek – Parrot Creek area
- the formations underlying the German Creek Formation were correlated with the Ingelara and Freitag formations of the Springsure Shelf and their names extended across the Comet Ridge
- the Maria Formation near Comet was correlated with the lower section of the German Creek Formation and the underlying the Ingelara Formation (Table 6).

Table 6. Evolution of formation nomenclature

<table>
<tr><th>Jensen, 1968 (Exmoor – Fort Cooper)</th><th>Koppe, 1978 (Collinsville–Dysart)</th><th colspan="2">Jensen, 1968 (Blackwater)</th><th>Prouza and Park, 1973 (German Creek – Emerald)</th><th>Prouza and Park, 1973 (Comet)</th></tr>
<tr><td>Rewan Formation</td><td>Rewan Formation</td><td colspan="2">Rewan Formation</td><td>Rewan Formation</td><td>Rewan Formation</td></tr>
<tr><td>Elphinstone Coal Measures</td><td>Rangal Coal Measures</td><td>Rangal Coal Measures</td><td rowspan="4">Blackwater Group</td><td>Rangal Coal Measures</td><td>Rangal Coal Measures</td></tr>
<tr><td rowspan="3">Fort Cooper Coal Measures</td><td rowspan="3">Fort Cooper Coal Measures</td><td rowspan="3">Burngrove Formation
Fair Hill Formation</td><td>Burngrove Formation</td><td>Burngrove Formation</td></tr>
<tr><td>Fair Hill Formation</td><td>Fair Hill Formation</td></tr>
<tr><td>Macmillan Formation</td><td>Macmillan Formation</td></tr>
<tr><td>Hail Creek Beds</td><td>Moranbah Coal Measures</td><td colspan="2">German Creek Coal Measures</td><td>German Creek Formation</td><td>Crocker Formation</td></tr>
<tr><td colspan="4"></td><td>Ingelara Formation</td><td>Maria Formation</td></tr>
<tr><td colspan="4"></td><td>Freitag Formation</td><td>Freitag Formation</td></tr>
</table>

2.5 Recent advances

2.5.1 Regional geology and structure

A 3D model of the Moranbah and German Creek coal measures based on all the available data at that time was published by Esterle & Sliwa (2000). Significantly, the model included, where possible, the overlying formation, the Fort Cooper Coal Measures, and depth and extent on the western side of the basin. The research also demonstrated the control of basement morphology on the thickness and distribution of coal seams and interburden.

Another major contribution was the structural and solid geology mapping of the Bowen Basin, which was based on interpretation of regional airborne magnetics, gravity and radiometrics. The project was a collaborative research between CSIRO Exploration and Mining and the Queensland Department of Mines and Energy and produced a modern solid geology map of the basin and a detailed structural interpretation (Figure 6; Sliwa *et al.,* 2008).

A subsequent regional assessment of Lopingian coals in the Bowen Basin was focused on the extent, seam distribution and patterns of the Rangal Coal Measures (Sliwa *et al.,* 2017b). The study developed on the supersequences and lithostratigraphic units initially defined by Brakel *et al.* (2009) and described Supersequence F1 as a transgressive lower portion of the Supersequence F, which included the Burngrove Formation, Black Alley Shale and the upper Fort Cooper Coal Measures. It was also confirmed that the upper boundary of the Fort Cooper Coal Measures, the high-gamma Yarrabee Tuff, was occurring consistently from Newlands to Blackwater. Used as a boundary marker since the late 1970s, the tuff was regionally described in detail by Matheson (1990a,b); it was found to be 0.6 to 1.6 m thick and often occurred between the splits of the lower seams of the Rangal Coal Measures (the Vermont seams) (Sliwa *et al.,* 2017b).

Recent research in the Bowen Basin has provided an updated version of the basin's structural framework and a characterisation of the Permian to Jurassic tectonic deformation of the coal measure sequences (Sliwa *et al.,* 2017a). The research was based on public and proprietary data and included the determination of faults, folds, fault throws, dykes, sub-surface intrusives and basalt flows, in an attempt to provide the mining industry with relevant information that would assist mine planning and design.

Following up on this research, Ayaz *et al.* (2015) investigated the architecture of the Fort Cooper Coal Measures to define formation extent and seam splitting patterns. The Yarrabee Tuff was found to be extensive and form a regional boundary between the Rangal Coal Measures and the Fort Cooper Coal Measures/Burngrove Formation. The Black Alley Shale, which represented a northward marine incursion, was identified on the Comet Ridge. Based on seam extent and correlations, Ayaz *et al.* (2015) proposed the introduction of a Black Alley correlative in the north, the Middle Main Seams, in an attempt to unify nomenclature across morphotectonics features (Table 7).

Table 7. Proposed revised nomenclature (after Ayaz *et al.,*2015).

<table>
<tr><th colspan="2">Northern area
(Collinsville Shelf and Nebo Synclinorium)</th><th colspan="2">Southern area
(Comet Ridge and central Taroom Trough)</th></tr>
<tr><td colspan="2">Rangal Coal Measures</td><td colspan="2">Rangal Coal Measures</td></tr>
<tr><td colspan="2">Yarrabee Tuff</td><td colspan="2">Yarrabee Tuff</td></tr>
<tr><td>Burngrove Formation</td><td colspan="2" rowspan="3">Fort Cooper Coal Measures</td><td>Burngrove Formation</td></tr>
<tr><td>Middle Main Seams</td><td>Black Alley Shale</td></tr>
<tr><td>Fair Hill Formation</td><td>Fair Hill Formation</td></tr>
</table>

2.5.2 Tuff ages

High-precision U–Pb dating of zircon crystals using the CA-IDTIMS technique (Chemical Abrasion-Isotope Dilution Thermal Ionisation Mass Spectrometry) has assisted the refinement of chronostratigraphy throughout Australia (*e.g.,* see Laurie *et al.,* 2016 for the recalibration of the Guadalupian and Lopingian spore-pollen zones against the geologic time-scale). As part of this program of radioisotopic dating, which is being undertaken by Geoscience Australia, Nicoll *et al.* (2015) analysed and dated tuffaceous material from outcrop and various wells in the Galilee and Bowen basins.

Focussed on the Fort Cooper correlatives and the overlying Yarrabee Tuff, the isotopic ages reported by Nicoll *et al.* (2015) and Ayaz *et al.* (2016a) conclusively placed these strata in the Lopingian (Table 8; locations in Figure 14). The reported dating errors for the core samples ranged 0.08–0.26 million years (Ma).

Table 8. Tuff ages in selected exploration wells (after Nicoll et al., 2015 (bold text) and Ayaz et al., 2016a)

Formation	Emerald 3		Duckworth 11		Peat 1		Crocker Gully 2	
	Depth (m)	Age (Ma)	Depth (m)	Age (Ma)	Depth (m)	Age (Ma)	Depth (m)	Age (Ma)
Yarrabee Tuff			625.8	252.69	786.7	252.58	510.2	253.07
Burngrove Formation	235.3 **241.2** **242.9**	253.52 **253.52** **253.41**	**625.8** **693.2** **715.0** **734.2**	**252.69** **252.85** **253.45** **253.57**	792.0	253.12	591.4	253.77
Fair Hill Formation			**915.4**	**254.03**				

Sliwa *et al.* (2017b) also reported on CA-IDTIMS analysis of zircons that produced ages ranging 252.85–252.92 Ma (error = 0.06–0.07 Ma) for tuff samples collected from the Newlands, Poitrel, Foxleigh and Dawson mine sites (Figure 14). These ages are consistent with previous findings (Table 8).

The stratigraphic relationships between the Lopingian sections containing the coal measures in the Bowen Basin and their equivalents in the adjacent Galilee Basin (Figure 14) have been determined by the application of CA-IDTIMS methodology to tuffaceous intervals across the region (Phillips *et al.,* 2018). This research enabled the differentiation of chronostratigraphic equivalents of the Fort Cooper Coal Measures and their correlatives in parts of the Betts Creek Group, in the Galilee Basin.

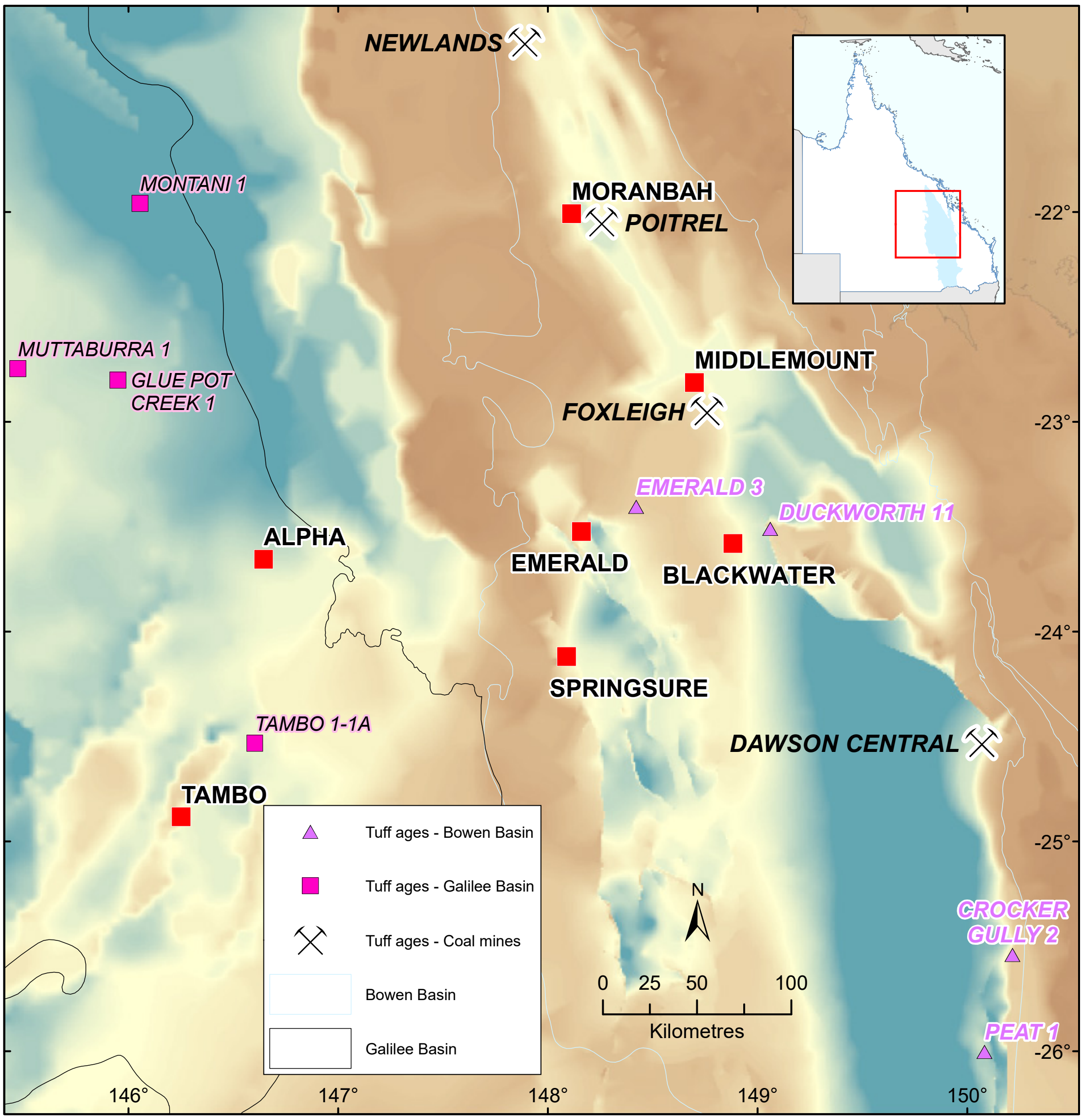

Figure 14. Locations of tuff samples dated using the CA-IDTIMS technique in the Bowen and Galilee basins. Legend in Figure 7.

2.5.3 Mineralogical composition and its implications

Studies of sediment provenance and character are very limited. Baker (1993) analysed particle composition in various Permian formations, with his findings in relation to the Rangal Coal Measures, Burngrove Formation and Fair Hill Formation (stratigraphic relationships in Figure 8) of relevance to the current review.

When assessed in relation to the concentration of quartz and feldspar in the arenitic intervals of those formations, the lithic fragments were found to be in small concentrations (<30%) in the Fair Hill Formation and increased substantially in the Burngrove Formation and the Rangal Coal Measures (up to 90% in relation to both quartz and feldspars). The lithic fragments were predominantly of volcanic origin, with very minor metamorphic contributions. The plagioclase feldspars dominated the K-feldspars in the Fair Hill Formation and became the only feldspar species in the Burngrove Formation and the Rangal Coal Measures (Baker, 1993). This research raised the possibility that a major change in sediment provenance and character occurred after the deposition of the Fair Hill Formation.

Following up on Baker's (1993) work, Michaelson & Henderson (2000) analysed the composition of 200 sandstone samples from the Permian–Triassic succession, including the Fair Hill Formation and the Fort Cooper Coal Measures, and explained the shift in sediment character.

The Fair Hill Formation and all the underlying Permian sandstone intervals were quartz-dominated and interpreted as belonging to Petrofacies A. The sediments were sourced from the cratonic basement rocks to the west and subsequently lost the labile constituents due to reworking.

The upper section of the Blackwater Group and the overlying Rewan Group, was classified as Petrofacies B, due to its volcanolithic character. The sediments were derived from the east and contained lithic fragments in concentrations comparable to those of the quartz component (Michaelson & Henderson, 2000).

The lithologic and maceral composition of the Fair Hill and Burngrove formations, and the associated palaeoenvironmental significance was investigated in a coal seam gas well (Foxleigh 4, near Middlemount—more detail in section 'Vitrinite reflectance') by Ayaz *et al.* (2016b). Their conclusion was that the aggradational Fair Hill Formation was transgressed by the Black Alley Shale and then overlayed by the Burngrove Formation. The coal intervals in both formations were found to be high in vitrinite, with inertinite gradually increasing in the Burngrove Formation. This shift in the composition and proportion of macerals was interpreted as reflecting a change in plant composition, while the overall high content of volcanic mineral matter was responsible for the abundance of dull bands.

Recent geochemical analyses revealed the felsic composition of tuff intervals in the Fort Cooper Coal Measures, with silica ranging 50–80%; the total alkali *versus* silica ratios indicated the magma composition to be within the rhyodacite-dacite and trachyandesite fields (Fricker, 2016; Sliwa *et al.,* 2017b).

Examination of clay speciation of authigenic clay particles in Lopingian coal measures in general (with no specific reference to the Fort Cooper Coal Measures) showed the dominance of illite-smectite mixed layers. The illitic content of the mixed layer clay increased in faulted or fractured zones, presumably due to the precipitation of illite from potassium-rich fluids migrating from deeper parts of the basin (Uysal *et al.,* 2000a). The isotopic signature of these authigenic clays was consistent with hydrothermal activity, which was interpreted to be a result of the Late Triassic extensional tectonic events and found to be more prominent in the northern part of the basin (Uysal *et al.,* 2000b).

2.5.4 Elemental composition

Elemental composition of coal seams can provide an insight into the plant communities involved in the formation of coal, the syngenetic input of detrital material and, in the case of the Fort Cooper Coal Measures, the volcanic ash input to the system. In addition, the elemental composition of the inherent ash can have commercial implications for coal mining, usage, especially power production, as well as cause health issues during operations. Finally, strategic minerals and rare earth are known to occur in association with coal seams and may, in some instances, lead to secondary small-scale extraction operations (Swaine, 1990).

CSIRO research, funded by the Australian Coal Association through the Australian Coal Association Research Program (ACARP), has made significant contributions in this space, including the development of the Australian standard: 'AS 1038.10.0-2002 - Coal and coke - Analysis and testing - Determination of trace elements - Guide to the determination of trace elements'. The main conclusion of that research was that Australian coals contained smaller concentrations of hazardous elements than international coals (*e.g.,* Dale, 2003); however, very little analytical results are publically available for the Bowen Basin coals.

Despite its multi-tiered significance (scientific, commercial and environmental), the elemental composition of coal ash, especially in the case of the Fort Cooper Coal Measures, which are known to have large amounts of volcanic-derived material, has been sparingly determined during coal exploration and, when investigated, it was largely focused on major element concentrations.

The only attempt to elucidate the trace and rare earth element composition of tuffaceous intervals in the Fort Cooper Coal Measures was recently made by Fricker (2016). The main objectives of this geochemical investigation were to establish the type of magmatic source and compare the Yarrabee Tuff elemental composition with other Permian tuff compositions. The magma was found to have a felsic composition, similar to that of the Platypus Tuff (P tuff) analysed by Michaelson et al. (2001) in the Moranbah Coal Measures at Broadmeadow. In addition, the research provided insight on the order of magnitude of element concentrations and their regional variation in tuffs (Figure 15), the main constituent of high-ash coal-bearing formations such as the Fort Cooper Coal Measures. Based on the data published by Fricker (2016), the high-gamma signal of the tuff is predominantly due to thorium (Figure 15).

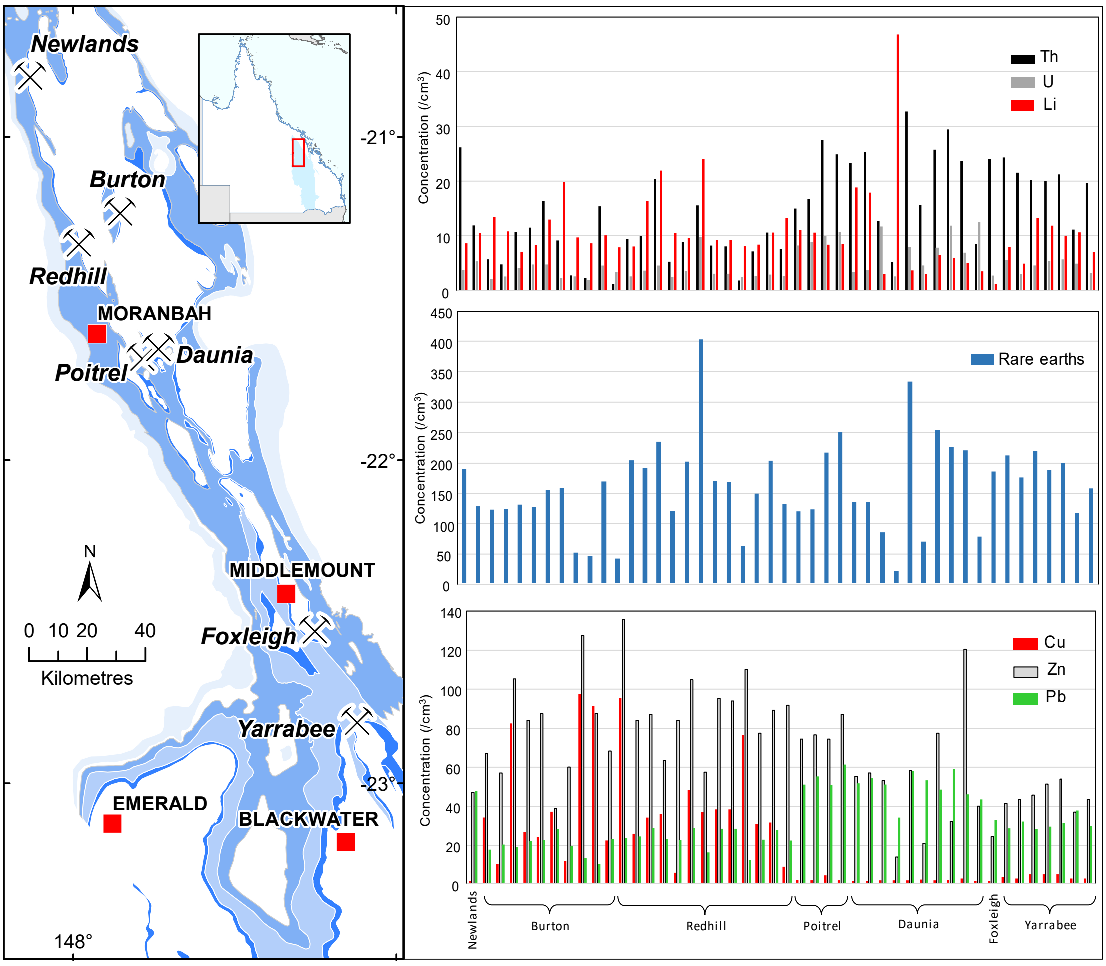

Figure 15. Location of tuff chemical analyses (left). Variation of elemental compositions, from north to south (right).

3. Departmental drilling

3.1 Introduction

The Powell Duffryn Report (Powell Duffryn Technical Services, 1949) highlighted the need for government-lead coal exploration and regional mapping of coal-bearing basins in Queensland. As a result, a Coal Section and a Drilling Branch was created within the Department of Mines in 1950. While most early work by these two groups was concentrated in the southeast, by the latter part of the 1960s, regional coal exploration by the Department began to focus on the Bowen Basin, with peak exploration activity occurring between 1975 and 1982. Over a period of 40 years, coal exploration undertaken by the Department involved the completion of approximately 7800 coal boreholes totalling more than 1 million metres, almost half of which were cored (Figure 16). Some 15,000 coal samples were also taken and analysed during this period. By the late 1980s, the Department's emphasis on discovering and deliniating new coal resources began to wane and the Drilling Branch was closed in 1991 (Department of Resource Industries, 1991). In 1986, the Queensland Government estimated the value of this work undertaken by the Department of Mines at more than $100 million (Gibbs, 1986).

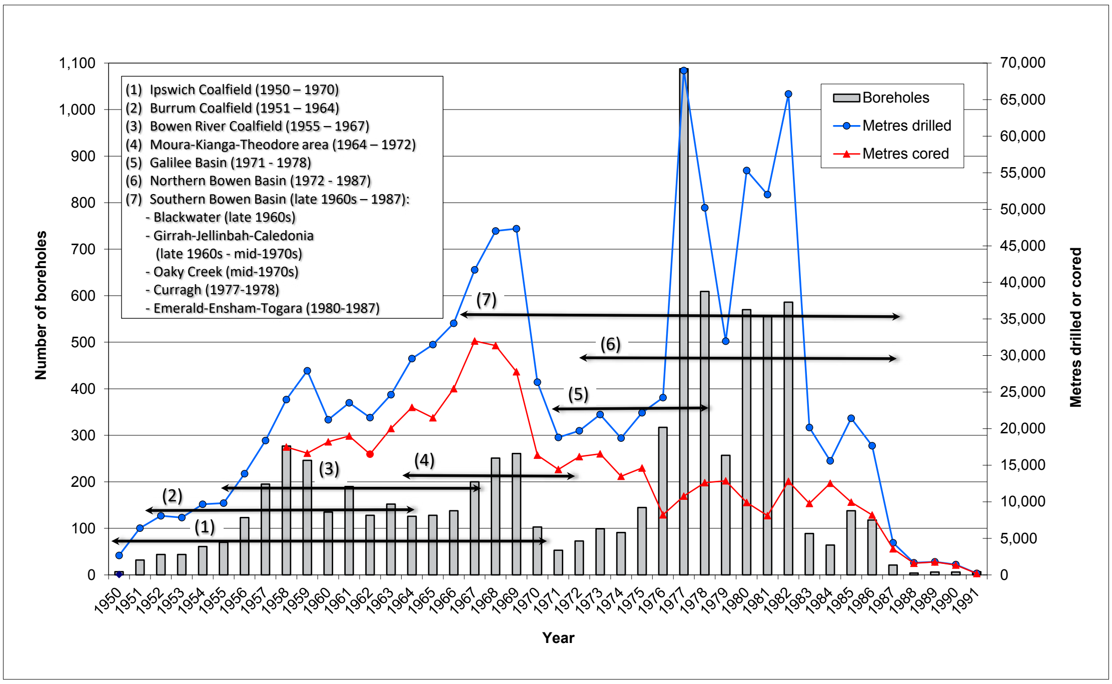

Figure 16. Drilling statistics and explored areas (based on Department of Resource Industries, 1991).

3.2 Methodology

The data collection and discussion presented in this review of departmental exploration is focused on the Fort Cooper Coal Measures and its correlatives, the Burngrove and Fair Hill formations; underlying or overlying coal measures are mentioned or described only to provide context or a basis for comparison. The main aspects summarised and discussed are formation depth (from ground level), thickness, lithology and coal analyses when available. Additional geological data such as detailed core descriptions, cross sections, structural information and coal analyses of seams other than the Fort Cooper Coal Measures have been considered outside the scope of this review but can be found in the referenced QDEX reports (see reference list and company report (CR) numbers).

For simplicity, the terms 'the Department' and 'Departmental' refer to the overarching organisation of which the Geological Survey was part of at the time when exploration was taking place.

The analytical data presented in tables and appendices (section 'Departmental drilling') have not been available in a digital format up until now. The values were extracted from Departmental exploration reports, within which the sampling and analytical procedures were not always described. If not stated in the original departmental reports, it has been assumed that the coal analyses reported are on an air-dried basis (adb), consistent with the laboratory standards at the time. Sample intervals presented in the tables have been rounded to one decimal place.

Due to differences in the types of coal analyses undertaken over time during the Department's exploration in the Bowen Basin, the layout of the various coal analytical tables presented in this review will differ in accordance with these changes.

All of the Departmental coal reconnaissance boreholes presently have the prefix 'DME' assigned to them in the current version of the Department's spatial database. This reflects the name of the Department (Department of Mines and Energy) at the time this data set was incorporated into the database. The 'NS' prefix that follows this code, stands for 'new series' which was incorporated into the department's coal borehole naming system after 1950, to distinguish between those boreholes drilled by the Department arising from the recommendations of the Powell Duffryn Report (1949) and those boreholes that had previously been drilled by the Department; its use was discontinued after 1986.

Initial drilling was named after regional locations (i.e. Blackwater and Emerald) or geographic features (*e.g.,* Suttor Creek) but from the early 1970s, the coal boreholes were named according to the county in which the boreholes were drilled (i.e. Drake, Wodehouse, Grosvenor, Cairns County, Humboldt, etc). Throughout this report, the departmental borehole names have been simplified as follows: 'GR 14' or 'Grosvenor 14' instead of 'DME Grosvenor NS 14'; 'Blackwater 163' or 'BL 163' instead of 'DME Blackwater NS 163', etc. The suffix 'R' denotes a borehole which was redrilled at a nearby site, while the suffix 'A' denotes a deflection within a borehole.

As previously shown (Table 4 and Table 6), both the coal seam and stratigraphic nomenclatures used by the Department's geologists in reporting on the coal reconnaissance exploration undertaken in the Bowen Basin evolved with the progress in geological knowledge. To avoid confusion and for ease of referencing, the following section on departmental drilling programs remains true to the nomenclature used in the associated exploration reports or maps (i.e. 'Elphinstone Coal Measures' and 'Hail Creek beds' instead of 'Rangal Coal Measures' and 'Moranbah Coal Measures', respectively). Similarly, the seam nomenclature used in this review is preserved as it was reported. Comparative comments are made when sufficient information is available.

Throughout this review, comments and quotes are included outlining the results of and the Department's rationale for undertaking some of the coal drilling programs. The terms '(coal) reserves' and '(coal) resources', when presented in single quotation marks, have the meaning relevant to the department's use of these terms at the time. Before 1986, 'coal reserves' referred to estimates of raw coal in place based on 'points of observations'; after 1986, the term of 'coal resources' was used instead, having a similar meaning with the term 'coal reserves' used for that portion of the '(coal) resources' regarded as being either, potentially mineable, recoverable or marketable (refer to section 'Departmental drilling and Queensland's coal resource inventory' for historical context).

In the interest of legibility, the colours used in the following geological maps do not match the Australian Standard Colour Scheme for Geological Maps published in 1974 by the Bureau of Mineral Resources, Geology and Geophysics, Canberra. The formation colours were specifically generated for this review as variations of the Permian colour—PANTONE 300 100%, to ensure the readability of features such as boreholes and their names, structures or localities. Also for clarity, only the boreholes presented and discussed in a certain section are labelled in the associated maps, although locations for the entire borehole series may be displayed for spatial context.

The plates in this review have been selected to show examples of various aspects of the strata and coal seams discussed in the text. These are presented in landscape format with core depths increasing from top to bottom in each tray and from left to right across the page. The depths shown on the marker blocks are a mixture of imperial and metric units of measure. The plate captions usually indicate an approximate depth in metres from surface of the core shown.

For the purpose of this review, which is centred on the Fort Cooper–Burngrove–Fair Hill subcrop (Figure 6), 'northern Bowen Basin' refers to an area extending from Collinsville in the north, to immediately south of the 23° parallel (Nebo Synclinorium), while the 'southern Bowen Basin' extends from the 23° parallel, southwards to about the 24° parallel (Comet Ridge).

3.3 Exploration areas—northern Bowen Basin

The following sections summarise the findings of Departmental drilling programs undertaken over the Nebo Synclinorium and its western boundary with the Collinsville Shelf; these programs are presented in order from north to south (Table 9). The boreholes shown in Figure 17 were selected due to their position in relation to the Fort Cooper Coal Measures outcrop and subcrop, and therefore, an increased likelihood of the holes containing formation descriptions and coal analyses.

Table 9. Exploration areas, boreholes series and associated GSQ publications, northern Bowen Basin.

Area	Borehole series	Reference *(QDEX CR number)*
Collinsville to Suttor Creek	Drake (DR)	Koppe, 1976b *(41683)*; Koppe & Scott, 1979 *(41690)*; Scott, 1987a *(41949)*
	Suttor Creek	Davis, 1972 *(48726)*
Exmoor	Hillalong (HL)	Koppe, 1973 *(41752)*
Elphinstone to Nebo	Nebo/Nebo Bore	Hawthorne, 1961 *(55458)*
	Lake Elphinstone	Beeston, 1974 *(48752)*
	Wodehouse (WO)	Koppe, 1972 *(41750)*; Koppe, 1973 *(41752)*; Koppe, 1976a *(41682)*
East Annandale	Killarney (KL)	Koppe, 1972 *(41750)*; Koppe, 1974 *(41672)*; Scott, 1987a *(41949)*; Dash, 1985b *(41711)*
Lenton Downs to Winchester	Grosvenor (GR)	Koppe, 1974 *(41672)*; Wallin & Koppe, 1978 *(41394)*; Koppe & Scott, 1979 *(41690)*; Koppe & Scott, 1981 *(41698)*; Holmes, 1981 *(41701)*; Dash, 1982 *(41702)*; Matheson, 1985 *(41865)*; Dash, 1985a *(41712)*; Matheson, 1986b *(41715)*; Scott, 1987b *(41717)*; Scott, 1987c *(42032)*; Matheson & Jameson, 1988 *(42035)*
	Poitrel (PO)	Davis, 1973 *(48736)*
Winchester to north Tieri	Cairns County (CC)	Anderson, 1974 *(41675)*; Anderson, 1975b *(41679)*; Galligan, 1975 *(41982)*; Koppe, 1979 *(41691)*; Holmes, 1980 *(41379)*; Carr, 1980 *(41505)*; Sorby, 1981 *(41177)*; Koppe & Scott, 1981 *(41698)*; Anderson & Jameson, 1982 *(41164)*; Sorby & Matheson, 1983 *(41373)*; Sorby et al., 1985 *(41374)* Matheson, 1986a *(41713)*; Sorby, 1986 *(41875)* Coffey & Crosby, 1987 *(41378)*

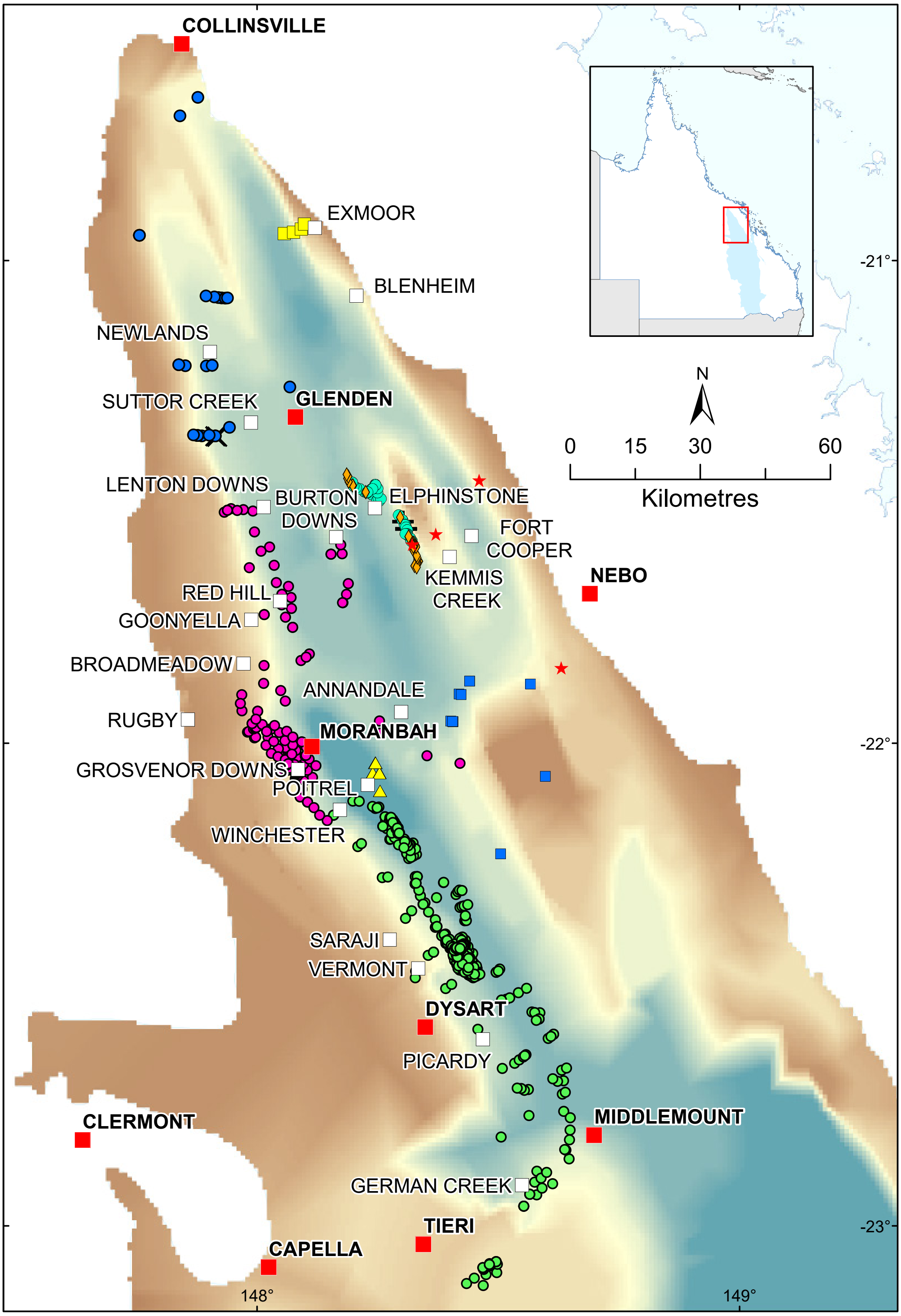

Figure 17. Borehole locations, northern Bowen Basin drilling programs. Legend in Figure 7.

3.3.1 *Collinsville – Suttor Creek*

The Drake (DR) series of boreholes targeted the Moranbah and Rangal coal measures on the northern section of the Bowen Basin, extending south to the Suttor Creek area (Figure 18).

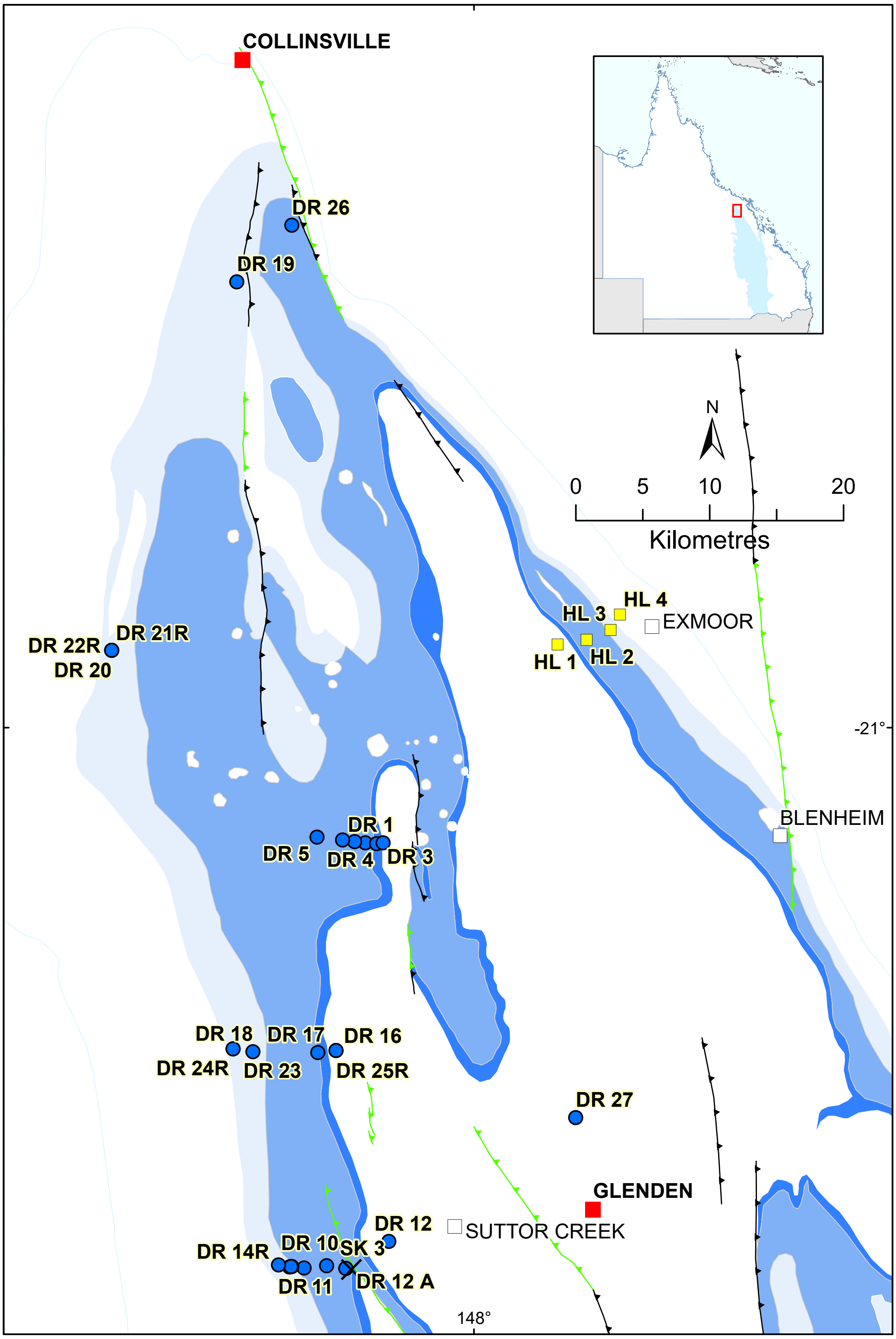

Figure 18. Drake (DR), Suttor Creek (SK) and Hillalong (HL) boreholes in relation to coal measure subcrop and structural features. Legend in Figure 7.

Most of the 28 boreholes of the program were cored (4000+m) and the target seams analysed. Numerous intrusions were reported as affecting the quality of the seams at depths greater than 300 m. The Fort Cooper Coal Measures were intersected at shallow depths (<100 m) in the west and deepened to more than 300 m (i.e. Drake 27) towards the east (Koppe, 1976b; Koppe & Scott, 1979; Scott, 1987a), in the Nebo Synclinorium (Figure 18). The formation was described as a *"poorly sorted pyroclastically-derived labile sandstone, siltstone and waxy mudstone, with lesser thicknesses of petromict conglomerate, tuff, coal and carbonaceous shale"* (Koppe, 1976b, page 5). The coal seams were considered uneconomic due to their poor quality and numerous *"dirt bands"* (Koppe, 1976b, page 5). The Vermont-Girrah Seam was analysed only in Drake 12, near Suttor Creek (Figure 18); the 1.40 and 1.50 float fractions (F 1.40 and F 1.50) presented swelling properties (see crucible swelling numbers (CSN) in Table 10). Plate 1 shows a typical banded coal interval in Drake 12, a few metres below the sampled interval.

Table 10. Cumulative and fractional analytical results—Vermont-Girrah Seam, Drake 12, Suttor Creek area (after Koppe & Scott, 1979).

Borehole	Fraction	Cumulative mass (%)	Depth (m)	Thickness (m)	Specific gravity (g/cm³)	Ash (%)	CSN
DR 12	F 1.40	22.8	236.1	1.28	1.33	8.6	8
	F 1.50	43.4			1.40	15.5	6
	F 1.60	63.1			1.45	20.5	2½
	Raw	100			1.59	30.7	-
	F 1.40	6.1	237.9	1.05	1.33	8.2	8½
	F 1.50	17.6			1.43	18.4	2½
	F 1.60	46.8			1.52	26.6	1
	Raw	100			1.67	39.5	-
	F 1.40	5.7	238.9	1.29	1.34	10.1	8½
	F 1.50	9.2			1.39	15.4	8
	F 1.60	21.3			1.50	25.4	1½
	Raw	100			1.81	50.7	-

Plate 1. Banded predominantly dull/stony coal in Drake 12 (depth ~ 140 m).

Most of the Drake boreholes were located in disturbed or faulted areas with steep dips, which resulted in the top of the Fort Cooper Coal Measures being intersected at highly different depths (i.e. near the ground surface in Drake 9 and plunging to 238 m deep in Drake 12, Figure 18). The maximum vitrinite reflectance in oil ($R_{o\,max}$) results also varied and ranged between 0.88% at 50 m depth and 1.18% at depths of more than 400 m (Beeston, 1981).

Drake 27 was drilled north of Glenden (analyses in Table 11), where the Fort Cooper Coal Measures also occurred at depth. Andesitic intrusions were reported at 336 and 353 m, immediately above and below the Elphinstone-Fort Cooper boundary (345.7 m). Vitrinite reflectance ranged 1.03–1.44% (Scott, 1987a), being slightly higher than that reported by Beeston (1981).

Table 11. Raw coal analytical results—upper seam, Drake 27, Glenden area (after Scott, 1987a).

Borehole	Depth (m)	Thickness (m)	Cumulative mass (%)	Specific gravity (g/cm³)	Proximate analysis (adb)				Specific energy (MJ/kg)
					M (%)	Ash (%)	VM (%)	FC (%)	
DR 27	349.6	1.15	91.0	1.73	2.2	46.8	13.5	37.5	17.0
	352.2	1.31	89.0	1.69	1.5	40.5	20.3	37.7	18.4
	354.1	0.98	86.0	1.57	1.4	36.1	21.0	41.5	21.3
	355.1	0.97	100	1.79	1.9	50.4	14.3	33.4	15.8
	356.2	1.15	100	2.04	2.5	66.2	7.6	23.7	8.2
	359.4	1.10	95.5	2.19	3.0	74.8	7.5	14.7	5.0
	360.5	1.02	100	1.75	2.1	50.1	18.0	29.8	15.7

M - inherent moisture, VM - volatile matter, FC - fixed carbon

3.3.2 Exmoor

The Hillalong (HL) borehole series aimed to investigate a complete section from the base of the Rewan Formation to the base of the Blackwater Group, near Exmoor (Koppe, 1973). Four boreholes (Hillalong 1 to 4 inclusive; Figure 18), totalling just over 1810 m of drilling (about 1760 m cored) intersected a total of about 1100 m of Blackwater Group strata, including the Hail Creek beds, Fort Cooper Coal Measures and the Elphinstone Coal Measures.

The structurally complex Nebo Synclinorium and the numerous intrusions observed in the area have resulted in dislocation of strata, steep dips (10–20°) and natural cindering ('coking') of coal seams (Koppe, 1973).

The Fort Cooper Coal Measures were distinguishable by the abundance of tuffaceous sediments and high proportion of lithic material of volcanic origin. Two units were identified in Hillalong 2, which intersected 480 m of Fort Cooper Coal Measures. The top unit (A) was generally coarser containing poorly sorted arenites and polymictic conglomerates. The lower unit (B) contained medium-grained arenites, tuffaceous mudstone, carbonaceous shale and dull coal. It was concluded that the abundance of tuffaceous mudstone, along with steep dips and large intervals where the coal seams were coked would restrict the usefulness of seams in the Fort Cooper Coal Measures and Hail Creek beds (Koppe, 1973).

Vitrinite reflectance data in Hillalong 2 indicated the existence of a higher rank coal interval at depths greater than 330 m (Figure 19). Heat-affected coal was present in Hillalong 4, along with a marine influence (finely laminated mudstone with yellow intercalations due to pyrite oxidation) in the Blenheim Formation.

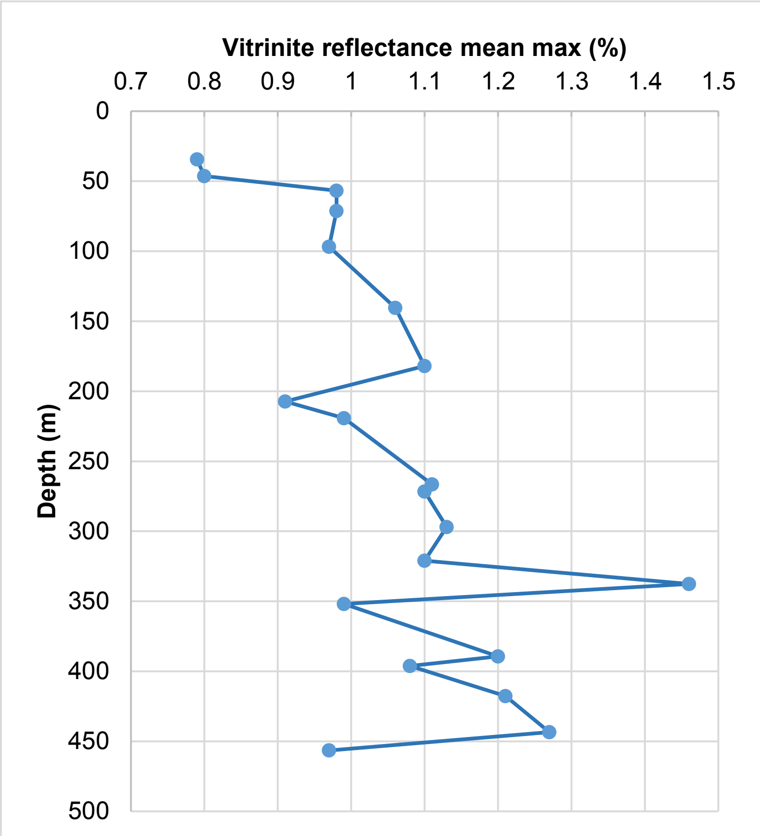

Figure 19. Vitrinite reflectance profile of the Fort Cooper Coal Measures, Hillalong 2 (after Beeston, 1981).

3.3.3 Elphinstone—Nebo

The drilling of the Nebo (30 boreholes) and Nebo Bore (28 boreholes) borehole series took place in the late 1950s with the aim of determining the extent of the Elphinstone Seam in a NW–SE direction, in the Elphinstone and Kemmis Creek areas (Figure 20). The drilling was very shallow (Nebo 10 was the deepest terminating at 123 m). Not all boreholes intersected the Elphinstone Seam and splitting was reported in the southern-most holes. Fault-related breccias were documented in Nebo 23 and 26 (10 km northwest of Kemmis Creek). Although the Fort Cooper Coal Measures were reported in the area by previous explorers (*e.g.,* Reid, 1925; 1946), the Nebo programs did not intersect these coal measures, presumably due to the shallowness of the drilling (Hawthorne, 1961).

Similarly, the Lake Elphinstone drilling program targeted the Elphinstone Coal Measures and no information relevant to the Fort Cooper Coal Measures was collected (Beeston, 1974).

Four Wodehouse (WO) boreholes were drilled in the Kemmis Creek area (Figure 20). The aim of that drilling program was to map the solid geology of the area and clarify the vertical extent of the local coal measures. The total depth of the Wodehouse boreholes ranged from 750 to 1200 m, which enabled the intersection of all of coal-bearing sequences that were expected to be encountered (namely the Elphinstone Coal Measures, Fort Cooper Coal Measures and the Hail Creek beds). The base of the lowest tuffaceous mudstone was adopted as the boundary between the Fort Cooper Coal Measures and the Hail Creek beds (Koppe, 1976a).

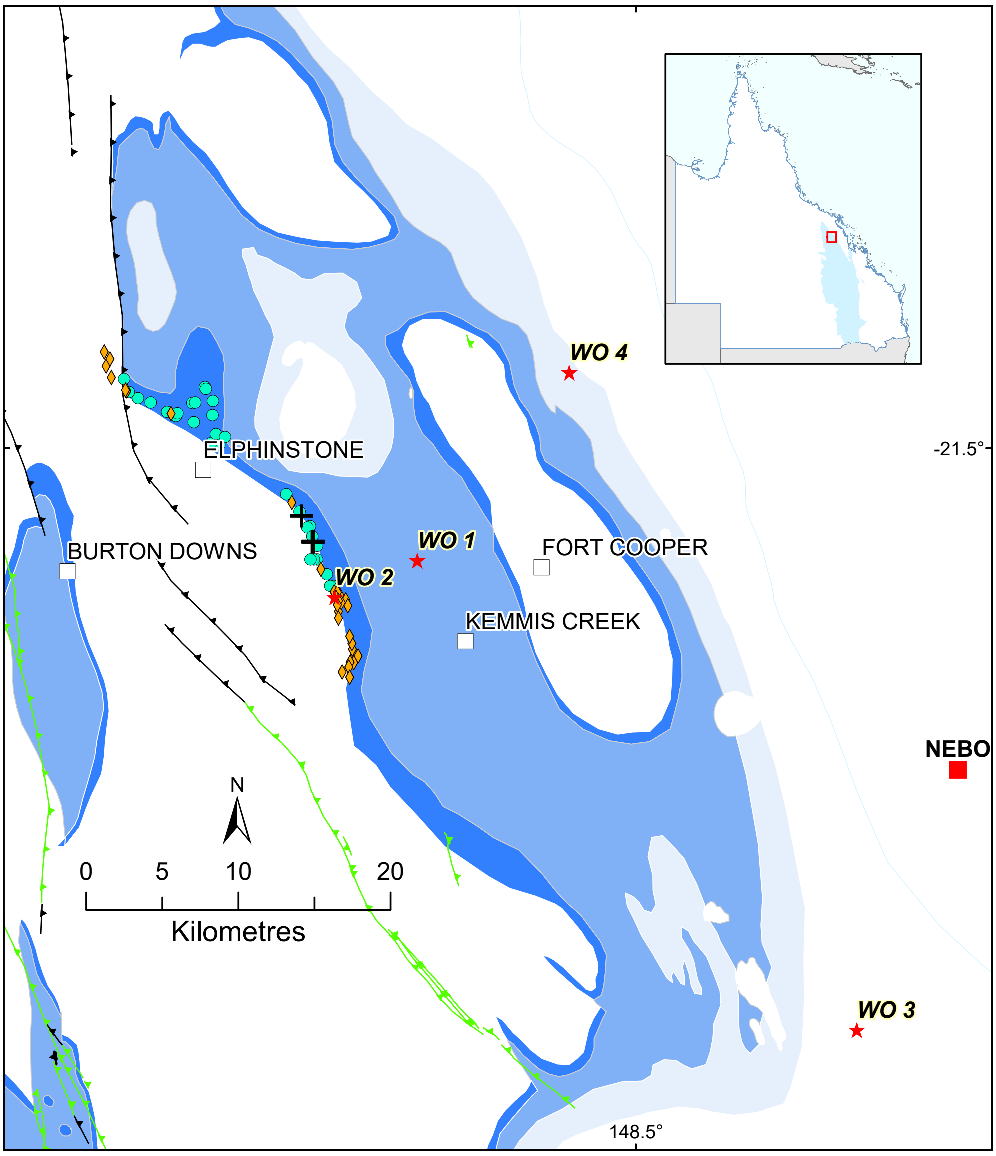

Figure 20. Wodehouse (WO) boreholes in relation to previous drilling and structural features. Legend in Figure 7.

The Fort Cooper Coal Measures extended between 17 and 158 m in Wodehouse 1 and between 188 and 680 m in Wodehouse 2 (Koppe, 1976a). The formation was described as rich in pyroclastic material; sandstone and conglomerate dominated in the upper unit while the lower unit was more argillaceous. A similar distinction was made by Koppe (1973) in the Hillalong boreholes, at Exmoor. According to Koppe (1976a), *"the high extraneous ash content of the seams in the Fort Cooper Coal Measures renders them unsuitable for conventional utilisation"* (page 7–8). Wodehouse 3 did not intersect coal (total depth = 229.2 m, stratigraphy not reported; Koppe, 1972); the Fort Cooper Coal Measures were not reported as having been intersected in Wodehouse 4, which was drilled to a total depth of 367.3 m (Koppe, 1973).

Similar to that found at Exmoor and Hail Creek, igneous activity intruded the coal seams in the Kemmis Creek area, evidenced by high vitrinite reflectance values, as shown in Figure 21. An example of an intrusion and its effect on coal is displayed in Plate 2.

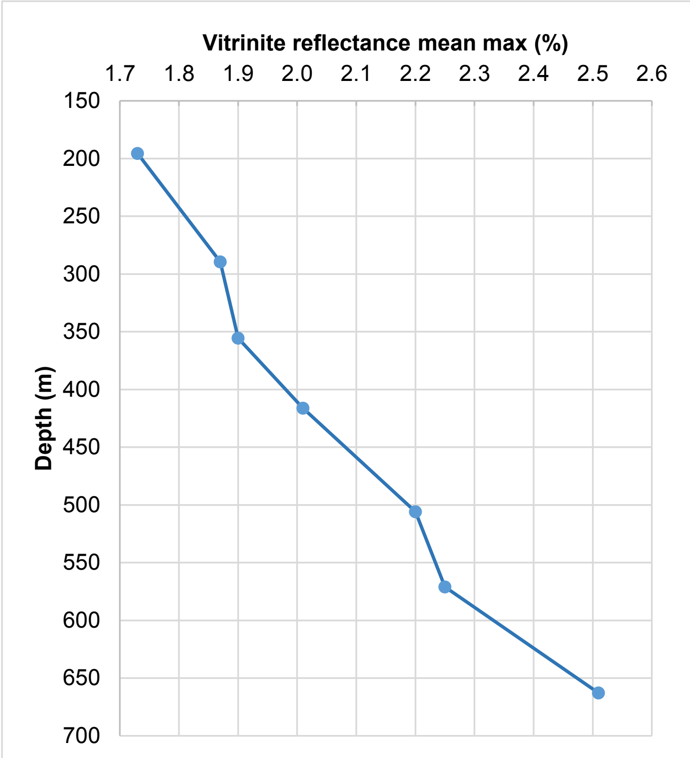

Figure 21. Vitrinite reflectance profile of the Fort Cooper Coal Measures, Wodehouse 2 (after Beeston, 1981).

Plate 2. Heat-affected and banded coal proximal to intrusion in Wodehouse 1 (depth ~ 60–65 m).

East Annandale

The Killarney (KL) series of boreholes were drilled to the south of the Nebo and Wodehouse boreholes to determine the southward extent of local coal seams (Figure 22).

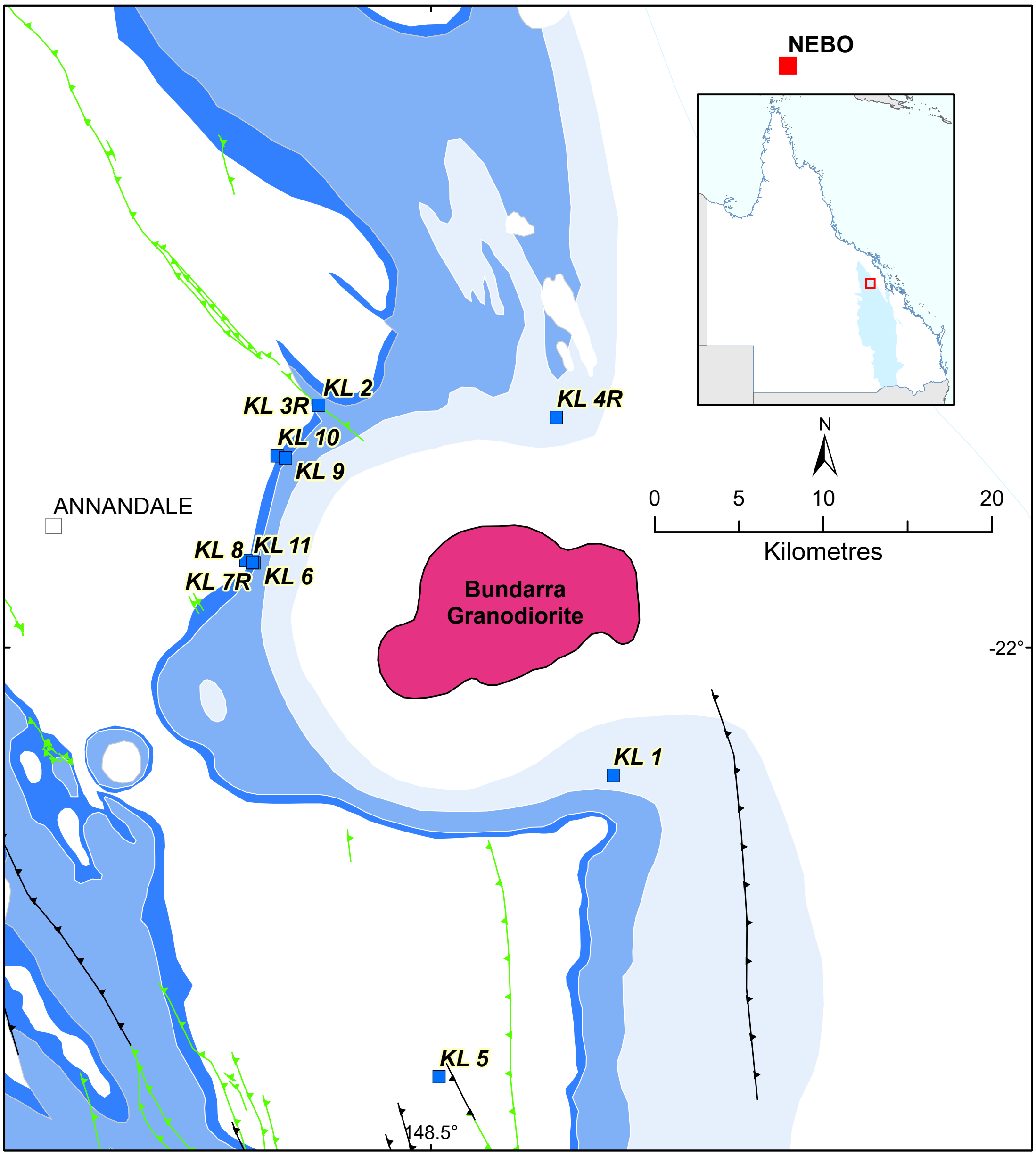

Figure 22. Killarney (KL) boreholes in relation to structural features. Legend in Figure 7.

Killarney 1 intersected about 30 m of Tertiary sediments and 360 m of undifferentiated Permian. Seven coal seams were intersected (98.7 to 305.7 m depth) ranging in apparent thickness from between 0.7 and 1.4 m. The coal was generally dull with thin laminae of bright coal and interbeds of carbonaceous shale. The strata were intensely slickensided and fractured, with steep dips ranging between 35° to 55° observed in the upper parts of the borehole, increasing to around 75° towards the bottom of the borehole. The arenites were labile and contained abundant volcanic clastics. Of note was the presence of brachiopods (224–256 m deep) which, along with the occurrence of coal seams, suggested a near-shore environment of deposition with a fluctuating brackish-freshwater interface. Overall, the sequence intersected in Killarney 1 did not present similarities with the Blackwater Group sequence described further north at Exmoor. The steep dips, slickensiding and fracturing observed in the core could be explained by the proximity of the borehole to the Folded Zone (Figure 6), while the influence from the intrusion of the Bundarra Granodiorite might explain the increased rank of the coal locally (Koppe, 1972).

Killarney 2 and 3R were drilled northeast of Annandale; the Fort Cooper Coal Measures were intersected between 188.3 m and 256.6 m (total depth) and consisted of grey, poorly sorted arenites with a clayey matrix and minor conglomerate, mudstone and tuff (Koppe, 1974). Three major seams were intersected in Killarney 2, but only the top one was analysed (Table 12).

Table 12. Cumulative and fractional analytical results—upper seam, Killarney 2, Annandale area (after Koppe, 1974).

Fraction	Cumulative mass (%)	Depth (m)	Thickness (m)	Specific gravity (g\cm³)	Proximate analysis (adb)				S (%)	CSN	Specific energy (MJ/kg)	Ash fusion temperatures (°C) (reducing atmosphere)		
					M (%)	Ash (%)	VM (%)	FC (%)				Deform.	Hemi.	Flow
F 1.40	48.1	184.1	0.9	1.37		8.6				½				
F 1.50	81.7			1.41		12.0				½				
F 1.60	88.3			1.42	1.6	13.1	11.6	73.7	0.38	½	30.24	1380	>1600	>1600
Raw	100			1.49		18.4				½				
F 1.40	31.6	185.0	0.74	1.37		9.7				1				
F 1.50	66.8			1.42		14.5				½				
F 1.60	85.1			1.45	1.5	17.6	11.0	69.6	0.39	½	28.73	1370	1450	1470
Raw	100			1.50		22.2				½				
F 1.40	28.0	186.4	0.65	1.37		9.6				1				
F 1.50	72.2			1.43		14.7				½				
F 1.60	84.1			1.45	1.7	16.7	11.3	70.3	0.40	½	29.14	1420	1520	1530
Raw	100			1.51		21.6				½				
F 1.40	51.9	187.1	0.43	1.36		8.0				1				
F 1.50	82.9			1.40		11.8				1				
F 1.60	89.0			1.41	1.5	12.8	12.4	73.3	0.48	½	30.87	1410	1570	1590
Raw	100			1.47		17.8				½				
F 1.40	10.5	187.51	0.8	1.34		7.6				3				
F 1.50	31.0			1.43		16.4				½				
F 1.60	53.5			1.49	1.4	22.5	11.1	64.9	0.42	½	27.05	1440	1530	1550
Raw	100			1.71		39.7				½				

Although the ash content was quite low for a coal seam in the Fort Cooper Coal Measures, the CSNs were also uncharacteristically low. Based on the thickness and the low ash value of the seam, Koppe (1974) considered the area as a potential resource of thermal coal. Steep dips and fracturing were also observed in core from Killarney 2 (Plate 3).

Plate 3. Steep dips in smectitic (based on the desiccation cracks) Fe-rich mudstones in Killarney 2 (depth ~ 125 m).

Killarney 4 and 5 were drilled more than 10 years later to better delineate the extent of the Moranbah Coal Measures, which were known to be deformed and intruded in the area (Scott, 1987a). Neither of these boreholes intersected the Fort Cooper Coal Measures. Killarney 4 was terminated at 311.2 m and Killarney 5 terminated at a depth of 917.8 m in strata of the Rangal Coal Measures, suggesting that the Fort Cooper Coal Measures would be present at a depth greater than 920 m.

Boreholes Killarney 6 to 11 were drilled close to Annandale (Figure 22) to further investigate the occurrence of seams in the Moranbah and Fort Cooper coal measures (Dash, 1985b). The Fort Cooper Coal Measures were described as tuff-rich and ashy. The Vermont Upper Seam occurred at shallow depths (18 to 36 m) and consisted of two plies of dull coal, around 2 m thick. The Vermont Lower was about 10 to 12 m below the Vermont Upper and between 2.5 to 4 m thick. It was banded, graded to inferior coal at base and determined as being much ashier than the upper seam. This was the case in boreholes Killarney 9, 10 and 11, where both the Vermont seams were present. Previous exploration showed that the Rangal-Fort Cooper boundary was marked by a prominent tuff bed with a high gamma response. Due to the distinct tuffaceous character of the Vermont Lower Seam in some of the Killarney boreholes, the boundary was established between the Vermont Upper and Lower, although a noticeable tuff bed was not present between these seams. The Girrah Seam occurred about 30 m below the Vermont Lower in the south and more than 60 m in the north. Although quite thick (9 to 14 m), it was strongly banded with tuffaceous sandstone and carbonaceous mudstone. Overall, the coal (including the Rangal seams) was deemed uneconomic due to high ash in the raw coal (up to 30% in the Rangal seams and greater than 35% in the Fort Cooper seams, Table 13), as well as faulting and doming of sediments. In addition, some of the coal was heat-affected; i.e. the Vermont Lower coal in Killarney 8 had a vitrinite reflectance of 1.79% (Dash, 1985b). The coal interval immediately below the sampled section in Killarney 6 is shown in Plate 4.

Table 13. Cumulative and fractional analytical results, Killarney 6, 8, and 11, Annandale area (after Dash, 1985b).

Borehole	Seam	Fraction	Depth (m)	Thickness (m)	Cumulative mass (%)	Specific gravity (g/cm^3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	P (%)
							M (%)	Ash (%)	VM (%)	FC (%)			
KL 6	Girrah	F 1.80	88.5	2.36	48.5			29.6					
		Raw			100	1.84		51.0					
		F 1.80	93.0	1.72	74.4			26.9					
		Raw			100	1.69		38.5					
KL 8	Vermont Lower	F 1.80	95.6	1.79	59.5			32.2					
		Raw			100	1.80		48.4					
	Girrah	F 1.80	131.2	1.58	68.0			29.8					
		Raw			100	1.72							
		F 1.80	135.2	1.55	78.6		2.1	23.8	10.5	63.6	27.0	0.46	0.053
		Raw			100	1.60							
KL 11	Girrah	F 1.80	262.4	1.87	58.5	1.77		27.9					
		Raw			100			43.9					

Plate 4. Bright coal underlying tuffaceous siltstones, Killarney 6.

3.3.4 Lenton Down—Winchester

This large area was explored by the Grosvenor (GR) drilling program which extended over 17 years (1970–1987) and consisted of 207 boreholes drilled mostly on the western flank of the Bowen Basin, over the Collinsville Shelf – Nebo Synclinorium boundary (Figure 23).

The explored areas included Annandale (Koppe, 1974), Moranbah (Wallin & Koppe, 1978), Suttor Creek and Lenton Downs (Koppe & Scott, 1979), Broadmeadow (Koppe & Scott, 1981), Goonyella East (Holmes, 1981), Red Hill (Matheson, 1985), Rugby (Matheson, 1986b), Moranbah-Peak Downs (Dash, 1982; Scott, 1987b; 1987c) and Burton Downs (Dash, 1985a; Matheson & Jameson, 1988).

The main exploration target was the Moranbah Coal Measures and therefore, the Fort Cooper Coal Measures were rarely described, sampled or analysed. Only one third of the Grosvenor borehole logs mentioned the Fort Cooper Coal Measures, with 15% of the total stopping before reaching the Moranbah Coal Measures and therefore, not providing a bottom depth for the Fort Cooper Coal Measures; this was the case in boreholes where the latter were intersected at depths greater than 200 m and the drilling stopped soon after. Of note were boreholes GR 3 and GR 12 (Figure 23), which intersected a thick and complete sequence of Fort Cooper Coal Measures, while most boreholes intersected sections thinner than 100 m, due to localised surface erosion or basalt cover.

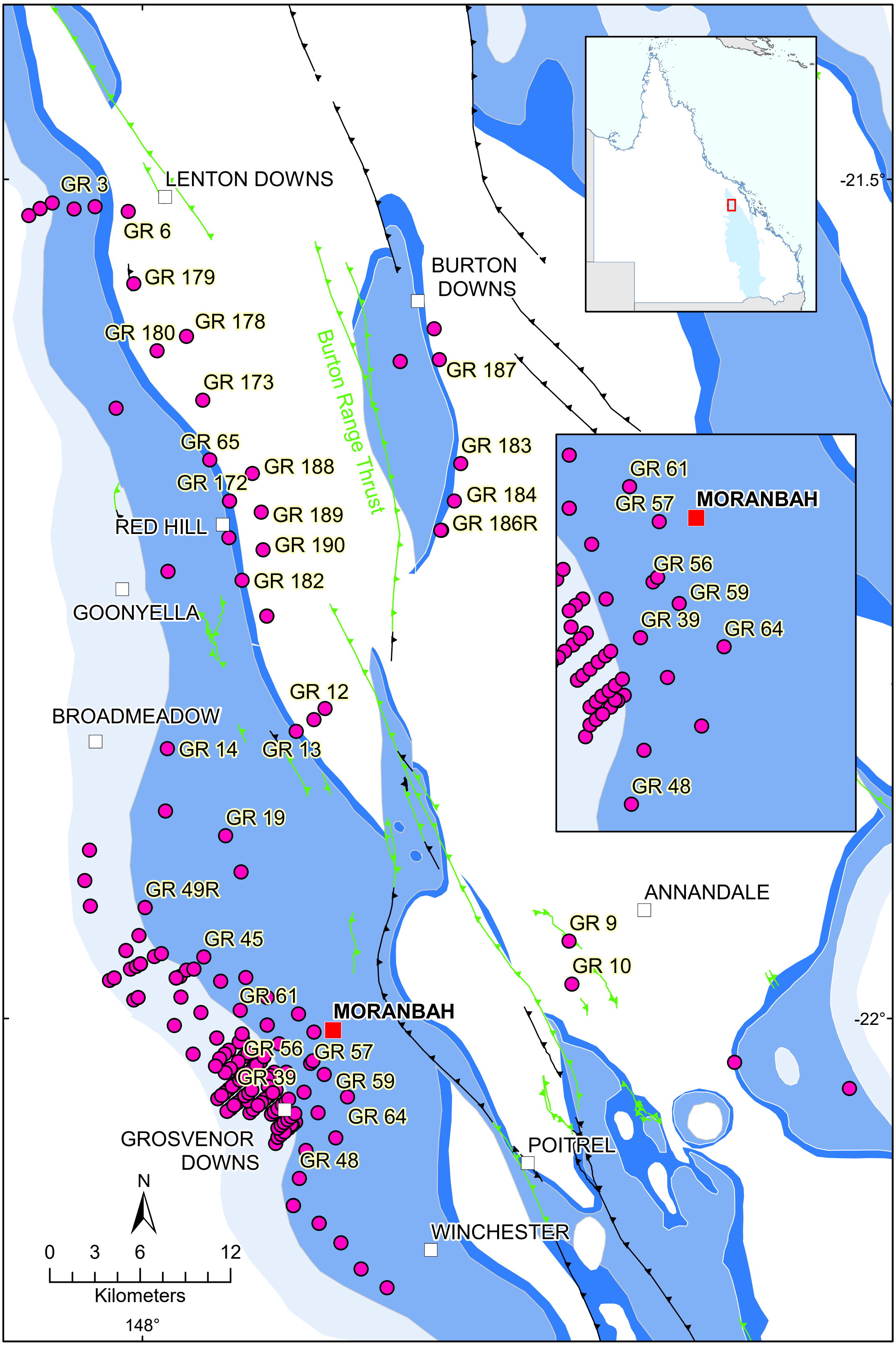

Figure 23. Grosvenor (GR) boreholes in relation to subcrop and structural features. Legend in Figure 7.

3.3.4.1 Lenton Downs

Grosvenor 1 to 7 were drilled in the Lenton Downs area, proximal to the Drake boreholes (Koppe & Scott, 1979). Little relevant information was acquired through these Grosvenor boreholes, except for GR 3 (Figure 23), which intersected 350 m of Fort Cooper Coal Measures (85–436 m); several seams were present but only the top one was analysed (Table 14). Additional data are presented in Appendix 4. The banded and tuffaceous character of the seams is shown in Plate 5. Post-depositional calcite infilling is common in the bright coal intervals (Plate 6).

Table 14. Cumulative and fractional analytical results—upper seam, Grosvenor 3, Suttor Creek area (after Koppe & Scott, 1979).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)			
GR 3	F 1.40	40.5	178.9	179.6	1.36		14.3					8
	F 1.50	49.7			1.38		16.0					8
	F 1.60	68.0			1.43	2.5	19.9	24.8	52.9	27.5	0.45	5½
	Raw	100			1.68	2.6	35.7	21.7	39.8	21.1	0.36	3
	F 1.40	70.3	179.6	180.9	1.33		10.8					8½
	F 1.50	74.2			1.47		11.6					8½
	F 1.60	76.9			1.56	2.1	12.3	29.1	56.7	30.6	0.56	8½
	Raw	100			2.20	2.8	26.4	24.8	45.8	24.8	0.47	6

Plate 5. Banded coal with thick intervals of tuffaceous siltstones and carbonaceous mudstones, Grosvenor 3 (depth ~174 m).

Plate 6. Calcite precipitation in cleats of bright coal bands, Grosvenor 3.

3.3.4.2 Red Hill

Twelve Grosvenor boreholes (GR 172, 173, 176R, 178 to 181, 181R, 182 and 188 to 190) were drilled further south in the Red Hill area, north of Moranbah (Figure 23). The boreholes were fully cored (~2500 m) and intersected the Fort Cooper Coal Measures, Rangal Coal Measures, Rewan Formation, as well as minor basalt and Paleogene–Neogene (Tertiary) sediments (Matheson, 1985).

The Fort Cooper Coal Measures comprised green lithic sandstones and conglomerates with a clayey matrix and reworked tuffaceous material. The sandstones were interlaminated with siltstones and the mudstones were bioturbated in places. The formation also included numerous interbedded coal seams (Matheson, 1985).

The Vermont Seam consisted of two plies, 1.47 and 0.88 m thick, separated by a 0.35 m-thick tuffaceous and carbonaceous band, which was considered the boundary between the Rangal and the Fort Cooper Coal Measures. The composite seam had raw ash (adb) ranging between 35 and 42% and the F 1.60 fraction had 16% ash with a 50% yield. The underlying Girrah Seam was the first interval to contain abundant tuff; it was also highly banded and split in some areas, while in others coalesced with the lowermost seam in the Rangal Coal Measures to form a Vermont-Girrah Seam (Matheson, 1985). Table 15 presents analytical data for the Vermont seam, as well as the underlying Girrah Seam (Figure 23; complete dataset in Appendix 4) as reported by Matheson (1985) at Red Hill. The F 1.40 fraction presented coking properties in both seams, although the yields were under 10% in about half of the Girrah samples analysed.

Table 15. Comparative cumulative and fractional analytical results—Vermont and Girrah seams, Grosvenor boreholes, Red Hill area (after Matheson, 1985).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
GR 172	Vermont	F 1.40	2.3	93.2	93.8		9.4	9
		F 1.60	6.0				20.3	6
		Raw	100			1.90	53.6	0
	Girrah	F 1.40	9.8	176.6	178.1		5.9	9
		F 1.60	32.2				23.2	7
		F 1.80	72.3				35.0	1½
		Raw	100			1.72	44.9	1
GR 173	Girrah	F 1.40	14.4	290.4	292.3		9.8	8½
		F 1.60	54.9				22.9	2
		F 1.80	74.6				27.7	1
		Raw	100			1.67	35.5	1
GR 178	Vermont	F 1.40	18.4	360.4	362.1		9.0	8½
		F 1.60	49.7				18.8	3
		Raw	100			1.76	44.6	1
GR 179	Vermont	F 1.40	2.3	224.9	226.2		6.6	9
		F 1.60	61.6				22.8	½
		Raw	100			1.64	32.5	½
GR 180	Girrah	F 1.40	19.2	275.0	276.8		9.8	8½
		F 1.60	66.4				22.5	2
		F 1.80	81.9				26.4	1
		Raw	100			1.59	33.4	1
GR 182	Vermont	F 1.40	32.3	117.1	118.8		8.8	8½
		F 1.60	64.9				16.4	6
		Raw	100			1.59	31.4	2
GR188	Vermont	F 1.40	35.2	226.0	227.2		9.8	8
		F 1.60	77.5				15.4	4
		Raw	100			1.52	24.5	2
	Girrah	F 1.40	6.4	299.8	301.7		6.9	9
		F 1.60	31.6				26.4	6½
		F 1.80	68.7				35.7	1
		Raw	100			1.78	44.2	1
GR 189	Vermont	F 1.40	38.9	234.0	235.5		9.4	6½
		F 1.60	72.2				14.1	2½
		Raw	100			1.56	24.4	1½
GR 190	Vermont	F 1.40	21.9	304.2	305.7		7.1	8½
		F 1.60	67.2				15.5	4
		Raw	100			1.55	26.4	1½

Further west, at Goonyella, exploration was limited to a few Grosvenor boreholes (GR 72, 72R, 73 and 74), of which only GR 72R was analysed (Table 16, Figure 23).

Table 16. Comparative cumulative and fractional analytical results—Fort Cooper Coal Measures seam and Goonyella Upper Seam, Grosvenor 72R, Goonyella East area (after Holmes, 1981).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
GR 72R	Unnamed Fort Cooper	F 1.40	0.1	113.9	116.78		5.2	1
		F 1.50	0.8				11.5	1½
		F 1.60	15.9				23.7	0
		Raw	100			1.98	56.5	0
	Goonyella Upper	F 1.40	31.1	243.7	244.5		10.2	9
		F 1.50	46.3				14.5	8½
		F 1.60	55.3				17.3	8
		Raw	100			1.68	40.6	3½

3.3.4.3 Burton Downs

Boreholes GR 183 to GR 187 were drilled in a faulted region of the Nebo Synclinorium, the Burton Downs area (Figure 23), to investigate the occurrence of the Rangal Coal Measures. The Fort Cooper Coal Measures comprised *"tuffaceous sandstone, siltstone, mudstone, coal and conglomerate with abundant petrified fossil wood… the tuffaceous material is common in coal seams but also distributed throughout the other sediments"* (Dash, 1985a, page 3). The top boundary could not be placed according to Koppe (1978) at the top of a highly tuffaceous interval, as it was absent in 4 of the 5 boreholes drilled at Burton Downs; it was picked at the top of the Girrah Seam instead. The lower boundary of the Fort Cooper Coal Measures was placed at the base of the lowermost tuff-rich unit. The Girrah Seam presented good swelling properties in the F 1.40 and F 1.60 fractions (Table 17, Dash, 1985a). Additional data (ash fusion temperatures and ash analyses) were also reported by Dash, 1985a.

Table 17. Comparative cumulative and fractional analytical results—Vermont and Girrah seams, Grosvenor 183, 184, 186 and 187, Burton Downs area (after Dash, 1985a).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
GR 183	Vermont (Rangal)	F 1.40	22.3	197.4	199.1		8.0	8½
		F 1.60	49.5				14.1	2½
		F 1.80	57.8				16.2	2
		Raw	100			1.67	32.0	1
	Girrah	F 1.40	8.7	238.3	240.1		8.0	8½
		F 1.60	26.5				16.1	2
		F 1.80	52.4				22.8	1
		Raw	100			1.69	37.7	1
GR 184	Vermont (Rangal)	F 1.40	65.3	174.6	176.1		7.4	8½
		F 1.60	83.6				9.4	6½
		F 1.80	90.0				10.5	6
		Raw	100			1.42	13.9	3½
	Girrah	F 1.40	20.6	270.2	272.1		7.5	>9
		F 1.60	54.1				16.1	7
		F 1.80	70.7				19.3	4½
		Raw	100			1.56	28.5	1½
GR 186R	Girrah	F 1.40	10.3	298.8	300.1		7.7	>9
		F 1.60	28.9				17.5	9
		F 1.80	55.3				24.4	5
		Raw	100			1.67	38.3	1
GR 187	Girrah	F 1.40	15.6	252.5	254.3		6.8	>9
		F 1.60	49.7				16.4	4½
		F 1.80	69.2				20.4	2½
		Raw	100			1.58	29.7	1
	Girrah	F 1.40	22.3	260.4	262.5		6.7	>9
		F 1.60	47.5				15.1	>9
		F 1.80	64.3				19.7	8½
		Raw	100			1.59	32.7	4

The area investigated was proximal to the Burton Range Fault and the strata dipped to the east, at up to 30°. An intrusion was apparent in GR 183 (Figure 23) where it had heat-affected the Girrah Seam, and also in GR 184 where it altered an interval immediately above the Leichhardt Seam. All seams presented coking properties, although the ash value increased with depth, being the highest in the Girrah Seam (Table 17).

A few years later, GR 71 and 71A (Figure 23) were spudded in the Fort Cooper Coal Measures in an attempt to intersect the Moranbah Coal Measures and possibly confirm the presence of coal of semi-anthracite rank (Scott, 1987a). No testing of the Fort Cooper Coal Measures was undertaken.

The Grosvenor drilling program ended with GR 207, drilled near Burton Downs (Figure 23), to provide CSIRO with a test hole to conduct hydraulic fracturing measurements as part of a program aimed at determining the regional stress. The borehole intersected the Fort Cooper Coal Measures at 391.8 m (boundary established at the top of the Girrah Seam) and was terminated at 432.5 m, about 9 m below the seam. The formation consisted primarily of tuffaceous sandstone; the Girrah Seam was a tuff-rich 32m-thick interval, increasingly banded at depth (Matheson & Jameson, 1988).

3.3.4.4 Broadmeadow

Grosvenor 12 and 13 were spudded on the subcrop of the Fort Cooper Coal Measures (Broadmeadow area, Figure 23), where the formation was intersected at shallow depths. The sequence consisted of fine- to coarse-grained clayey sandstone interbedded with carbonaceous shale, coal, tuffaceous mudstone and minor conglomerate. In this area, the Vermont and Girrah seams coalesced and contained predominantly dull coal with tuffaceous bands, including a prominent tuff which marked the top of the formation (Koppe & Scott, 1981; Plate 7). Bright coal intervals were also present (Plate 8), although the dull bands of coal were more frequent at depth (Plate 9).

Plate 7. Yarrabee Tuff overlying the Vermont-Girrah Seam, Grosvenor 12.

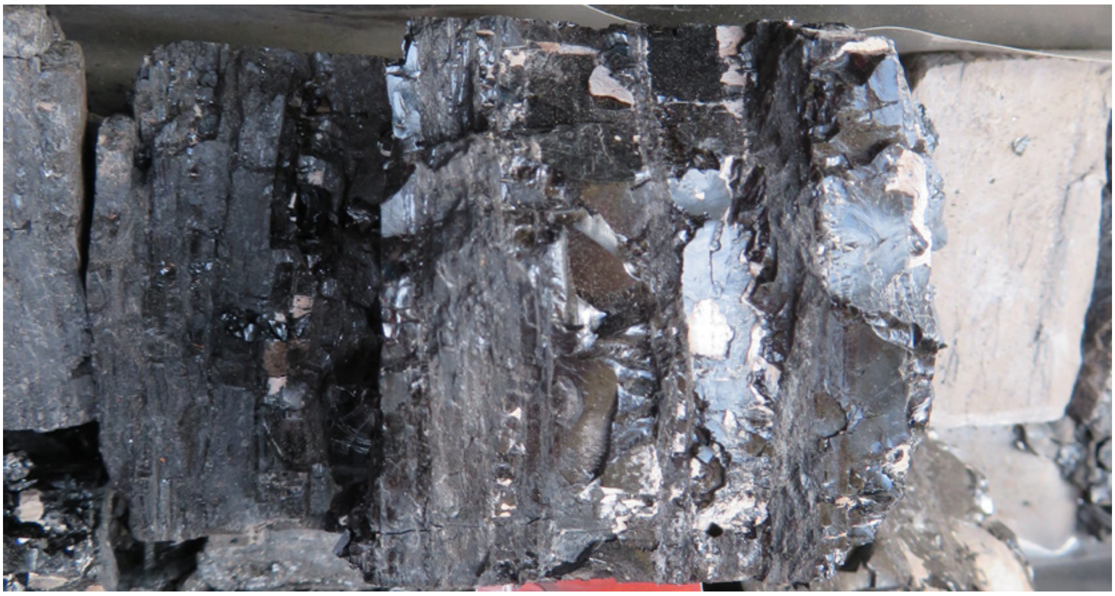

Plate 8. Bright coal in Grosvenor 12 (depth ~ 75 m).

Plate 9. Banded coal and tuffaceous siltstones/mudstones in Grosvenor 12.

When comparing the quality of seams occurring at depth (*e.g.* Table 15) with the quality of the shallow Vermont-Girrah Seam (Table 18 and Appendix 4) it could be seen that, although the ash values in raw coal were comparable, coking properties improved in the deeper coal.

Table 18. Cumulative and fractional analytical results—Vermont-Girrah Seam, Grosvenor 12 and 13, Broadmeadow area (after Koppe & Scott, 1981).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
GR 12	F 1.40	12.3	67.7	68.5	1.32	11.0	8½
	F 1.50	23.7			1.44	15.6	3½
	F 1.60	40.5			1.54	20.9	1
	Raw	100			1.74	34.9	1
	F 1.40	15.9	71.3	71.9	1.30	9.3	8
	F 1.50	28.6			1.43	15.4	4½
	F 1.60	40.8			1.52	20.1	2
	Raw	100			2.02	45.1	1
GR 13	F 1.40	18.0	157.0	158.4	1.34	11.7	6½
	F 1.50	48.7			1.41	17.8	1½
	F 1.60	72.4			1.45	21.1	1
	Raw	100			1.56	28.1	1
	F 1.40	12.6	159.7	160.3	1.31	9.7	8
	F 1.50	26.8			1.38	17.0	4
	F 1.60	50.6			1.44	23.7	1
	Raw	100			1.73	45.9	1

Grosvenor 14 was located a few kilometres west of GR 12 and GR 13 (Figure 23) and established as the type section for the Moranbah Coal Measures by Koppe (1978). He referred to the Fort Cooper Coal Measures as the overlying sequence with abundant tuffs. Comparative coal analyses show similarities between the quality of the (unnamed) Fort Cooper Seam and Goonyella Upper (as an example), although the top coal seam of the Moranbah Coal Measures had less ash and greater yields for the fractions with high CSNs (Table 19).

Table 19. Comparative cumulative and fractional analytical results—Fort Cooper Coal Measures seam and Goonyella Upper Seam, Grosvenor 14, Goonyella East area (after Holmes, 1981).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
GR 14	Fort Cooper	F 1.40	5.5	142.7	143.6	1.32	10.4	>9
		F 1.50	11.5			1.40	19.2	9
		F 1.60	24.5			1.49	27.4	7½
		Raw	100			2.11	58.0	1
		F 1.40	30.2	143.6	144.5	1.33	11.5	>9
		F 1.50	52.8			1.38	17.1	9
		F 1.60	69.6			1.42	20.5	8
		Raw	100			1.62	32.9	4½
		F 1.40	7.4	144.5	146.3	1.30	9.9	>9
		F 1.50	16.9			1.39	18.6	8½
		F 1.60	29.7			1.46	24.6	7
		Raw	100			1.85	49.0	1
	Goonyella Upper	F 1.40	32.4	185.2	186.2	1.35	12.6	9
		F 1.50	56.8			1.40	17.4	8
		F 1.60	65.8			1.42	19.6	7½
		Raw	100			1.68	38.3	1½
		F 1.40	15.9	186.8	187.4	1.36	13.5	9
		F 1.50	35.1			1.44	19.5	7½
		F 1.60	46.5			1.49	23.0	6½
		Raw	100			1.71	49.3	1
		F 1.40	9.3	187.4	188.1	1.33	11.9	9
		F 1.50	35.8			1.44	22.0	5
		F 1.60	60.9			1.49	26.1	1½
		Raw	100			1.71	41.0	1
		F 1.40	52.0	188.1	189.1	1.34	10.5	8
		F 1.50	66.3			1.37	13.0	7½
		F 1.60	73.7			1.39	14.8	7
		Raw	100			1.54	26.8	3½

Vitrinite reflectance was generally around 1% in a few boreholes in the area, except for GR 8, located near the axis of the synclinorium, where coal reflectance values were considerably higher (Figure 24).

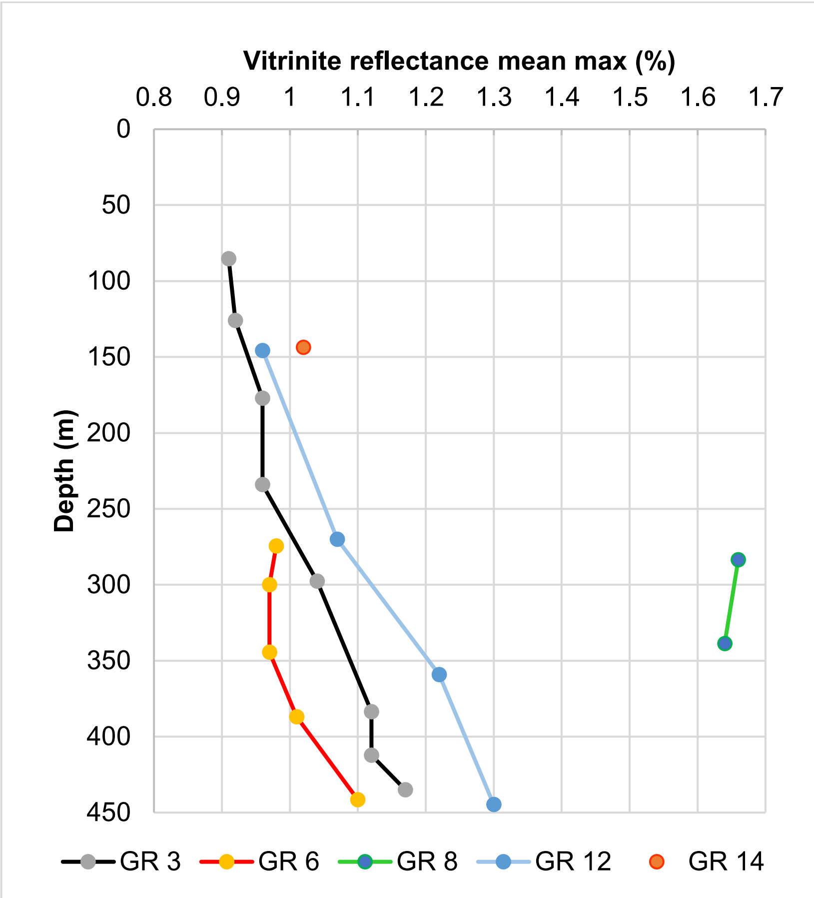

Figure 24. Vitrinite reflectance in selected Grosvenor boreholes (after Beeston, 1981).

3.3.4.5 Moranbah

In the mid-1970s, a large number of Grosvenor boreholes (GR15 to GR53) were drilled in the Moranbah area (Figure 23) to assess the coking coal reserves and the quality of underground coking coal (Wallin & Koppe, 1978). Most of those boreholes were spudded in the Moranbah Coal Measures and did not intersect the Fort Cooper Coal Measures.

A small number of analyses were performed on the Fairhill Seam intersected by the boreholes spudded in the Fort Cooper Coal Measures; the results showed good swelling properties (CSN values) for the 1.40 and 1.60 fractions, although some of the yields were lower than 30% (Table 20, Figure 23, Appendix 4).

Table 20. Cumulative and fractional analytical results—Fairhill Seam, Grosvenor 19, 39, 45, 48 and 49R, Moranbah area (after Wallin & Koppe, 1978).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)			
GR 19	Raw	100	171.5	172.8		1.4	38.7	19.9	40.0	20.2	3.2	3½
	Raw	100	172.8	173.6		1.9	34.1	20.3	43.7	22.3	0.5	4½
GR 39	F 1.40	7.9	93.9	95.6	1.31		8.2					>9
	F 1.50	17.3			1.39		17.9					9
	F 1.60	33.0			1.48		26.3					7½
	Raw	100			1.76		50.0					1
GR 45	F 1.40	28.8	119.9	122.2	1.32		9.0					>9
	F 1.50	40.1			1.39		16.0					8½
	F 1.60	65.9			1.44		20.9					8
	Raw	100			1.61		33.6					5½
GR 48	F 1.40	43.6	129.8	130.9			11.1					>9
	F 1.50	58.5				2.3	14.6	22.8	60.8	30.2	0.57	9
	F 1.60	65.5					16.5					8½
	Raw	100			1.58		31.8					6½
GR 49R	F 1.4	30.6	157.4	158.7			12.4					9
	F 1.5	55.4					18.2					8½
	F 1.6	73.4				2.0	21.9	23.8	52.2	27.2	0.77	7½
	Raw	100			1.56		32.2					5½

The next series of Grosvenor boreholes (GR 54 to GR 70) were drilled closer to the township of Moranbah and they all intersected the Fort Cooper Coal Measures at shallow depths; some sequences were more than 100 m thick and extended to depths of almost 200 m. The majority of the Moranbah Coal Measure seams were found to be economic, including the basal seam of the Fort Cooper Coal Measures—the Fairhill Seam (Table 21, Figure 23, Appendix 4).

Table 21. Cumulative and fractional analytical results—Fairhill Seam, Grosvenor 56R, 57, 59, 61, 64 and 65, Moranbah area (after Scott, 1987b).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
							M (%)	Ash (%)	VM (%)	FC (%)			
GR 56R	Fair Hill	F 1.40	25.5	100.2	101.7			9.6					>9
		F 1.50	48.6					17.1					8
		F 1.60	68.4				2.0	22.0	22.5	53.4	27.0	0.52	7½
		Raw	100			1.59		35.3					4
GR 57		F 1.60	75.9	127.3	128.6		1.6	21.2	21.4	55.8	27.7	0.57	8½
		Raw	100			1.51							7
		F 1.60	49.0	154.5	156.1								7½
		Raw	100			1.72							1
		F 1.60	57.8	156.1	157.4								7½
		Raw	100			1.61							3
GR 59		F 1.40	16.6	172.5	173.8			13.6					>9
		F 1.50	44.6					21.7					8½
		F 1.60	68.6					26.4					7½
		Raw	100			1.59		36.9					3½
GR 61		F 1.40	30.1	142.0	143.75			10.5					9
		F 1.50	52.4					16.2					9
		F 1.60	69.3				1.7	20.3	22.1	55.9	27.6	0.62	8½
		Raw	100			1.60		33.1					5½
GR 64		F 1.40	14.5	188.1	189.7			8.2					9
		F 1.50	28.3					16.8					9
		F 1.60	47.0				1.7	23.8	21.1	53.4	26.7	0.64	8½
		Raw	100			1.70		41.9					8½
GR 65	Vermont Upper (Rangal)	F 1.40	55.2	96.6	97.8		2.8	9.9	27.9	59.3		0.36	7½
		F 1.50	75.8					12.9					6½
		F 1.60	80.9					14.1					6
		Raw	100			1.49		22.8			25.4		4½
	Vermont Lower (Fort Cooper)	F 1.40	35.3	99.4	100.7			10.1					6
		F 1.50	58.5					14.5					5
		F 1.60	69.6					16.8					3½
		Raw	100			1.54	2.7	28.7	19.7	48.8	23.3	0.34	1½

The exploration of the Moranbah area continued with a large number of shallow boreholes (GR 76 to GR 171), which were all spudded in the Moranbah Coal Measures (Dash, 1982).

Similarly, the boreholes GR 191 to GR 206, drilled further west in the Back Creek Group cropping out in the Rugby area (Figure 23), did not intersect the Fort Cooper Coal Measures (Matheson, 1986b).

3.3.4.6 Annandale

East of Moranbah, in the Annandale area, GR 8 to GR 10 intersected the Fort Cooper Coal Measures at depths greater than 300 m (Figure 23). The formation was described as grey, poorly sorted, fine to coarse-grained arenites with beds of petromict conglomerate and tuffaceous material (Koppe, 1974). The coal seams had a large ash content, except for a section between 453.8 and 457.3 m, which presented high CSNs and high yields on washing at specific gravity 1.60 (bold text in Table 22; additional data in Appendix 4). Note the depth difference between GR 9 and 10, which was presumably caused by a fault running in between the two boreholes (Figure 23).

Table 22. Cumulative and fractional analytical results, Fort Cooper Seam, Grosvenor 9 and 10, Annandale area (after Koppe, 1974).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)			
GR 9	F 1.40	30.5	453.4	453.8	1.34		11.0					6 ½
	F 1.50	50.2			1.39		14.5					2
	F 1.60	64.7			1.52	1.7	17.4	16.3	64.6	28.8	0.37	1
	Raw	100			1.58		26.6					1
	F 1.40	**37.6**	**453.8**	**455.6**	**1.34**		**9.4**					**9**
	F 1.50	**57.4**			**1.38**		**13.4**					**7½**
	F 1.60	**72.6**			**1.42**	**1.4**	**16.9**	**17.3**	**64.4**	**29.0**	**0.42**	**6**
	Raw	100			1.54		26.3					1
	F 1.40	**16.8**	**455.6**	**457.3**	**1.35**		**10.5**					**9**
	F 1.50	**33.1**			**1.41**		**16.1**					**6½**
	F 1.60	**48.0**			**1.46**	**2.0**	**20.6**	**15.3**	**62.1**	**28.1**	**0.46**	**4**
	Raw	100			1.67		37.6					1
	F 1.40	**19.6**	**457.3**	**458.5**	**1.31**		**8.0**					**>9**
	F 1.50	**47.4**			**1.40**		**16.3**					**7**
	F 1.60	**65.4**			**1.45**	**2.1**	**20.0**	**15.4**	**62.5**	**28.2**	**0.49**	**4**
	Raw	100			1.63		32.8					1
GR 10	F 1.40	6.6	334.7	335.2	1.28		6.3					>9
	F 1.50	10.7			1.35		13.0					9
	F 1.60	28.6			1.48		24.8					3½
	Raw	100			1.74		42.9					1
	F 1.40	5.8	335.2	336.1	1.33		10.2					>9
	F 1.50	26.4			1.43		19.4					3
	F 1.60	59.6			1.50		24.8					1
	Raw	100			1.64		36.1					1

The dull character of some of the coal is shown in Plate 10.

Plate 10. Predominantly dull coal in Grosvenor 10 (depth ~ 340 m).

More than a decade later, Grosvenor 75 was spudded in the Rangal Coal Measures to better delineate the formation (Scott, 1987a). No testing of coal within the Fort Cooper Coal Measures was undertaken.

3.3.4.7 Poitrel

This drilling program targeted the Elphinstone Coal Measures and no information relevant to the Fort Cooper Coal Measures was collected (Beeston, 1974).

3.3.5 Winchester—Tieri

The Cairns County (CC) drilling program was the largest undertaken in the northern Bowen Basin. It comprised 632 boreholes which were drilled over almost 15 years, in 1972–1986. The majority were located on the western flank of the Nebo Synclinorium, from Winchester in the north to immediately southeast of Tieri (Figure 25).

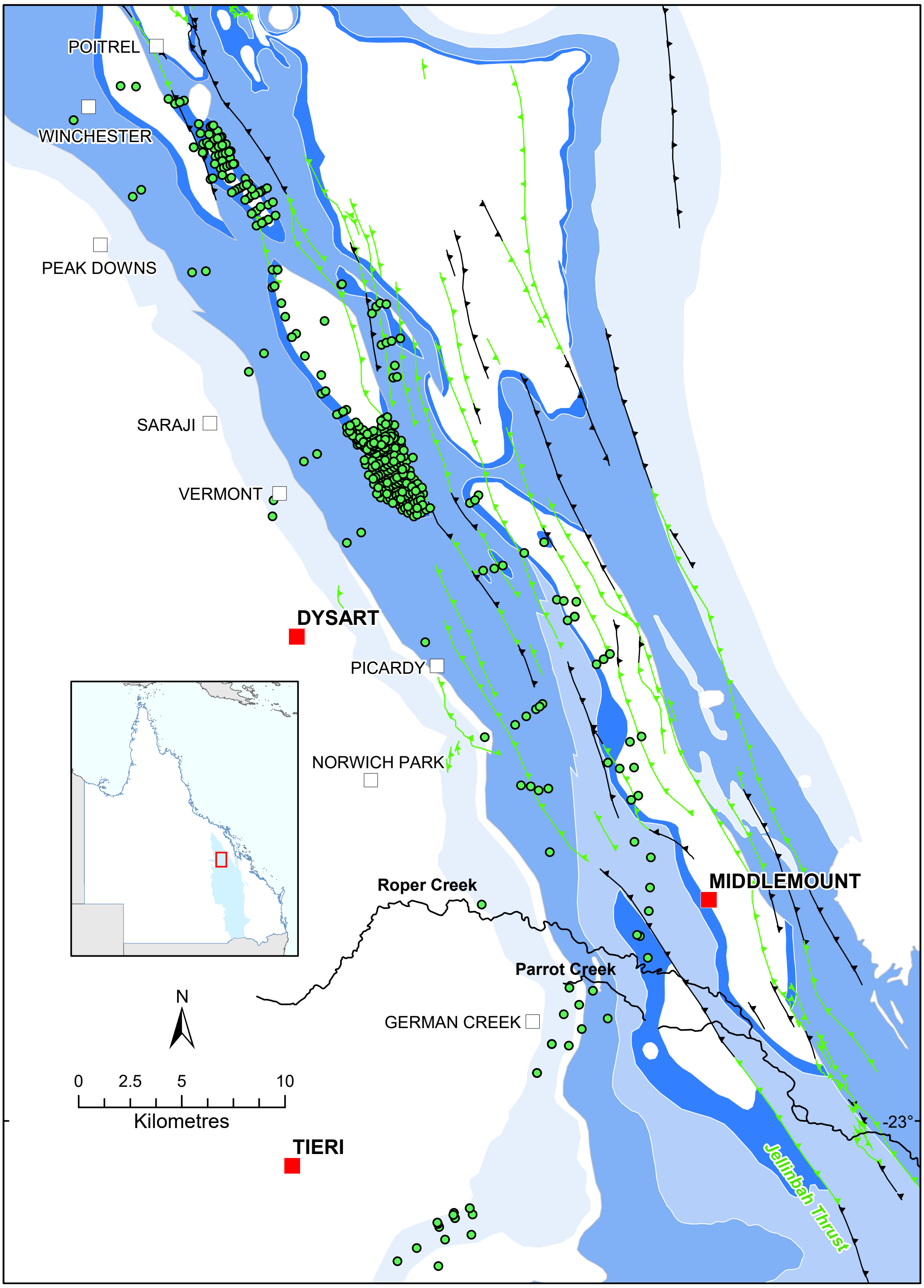

Figure 25. Cairns County (CC) boreholes in relation to subcrop and structural features. Legend in Figure 7.

The target formations were the Moranbah and Rangal coal measures in the Roper Creek area (Anderson, 1974; Anderson & Jameson, 1982), Parrot Creek area (Galligan, 1975), Picardy (Anderson, 1975b; Coffey & Crosby, 1987), Winchester (Koppe, 1979; Carr, 1980; Koppe & Scott, 1981), Peak Downs – Norwick Park (Holmes, 1980), Lake Vermont (Sorby, 1981; Sorby & Matheson, 1983; Sorby *et al.,* 1985; Sorby, 1986) and Vermont (Matheson, 1986a).

3.3.5.1 *Winchester*

The Winchester area was initially explored as part of the Grosvenor drilling program but also included two Cairns County boreholes, CC 15 and CC 16, drilled immediately northeast of Winchester (Figure 26).

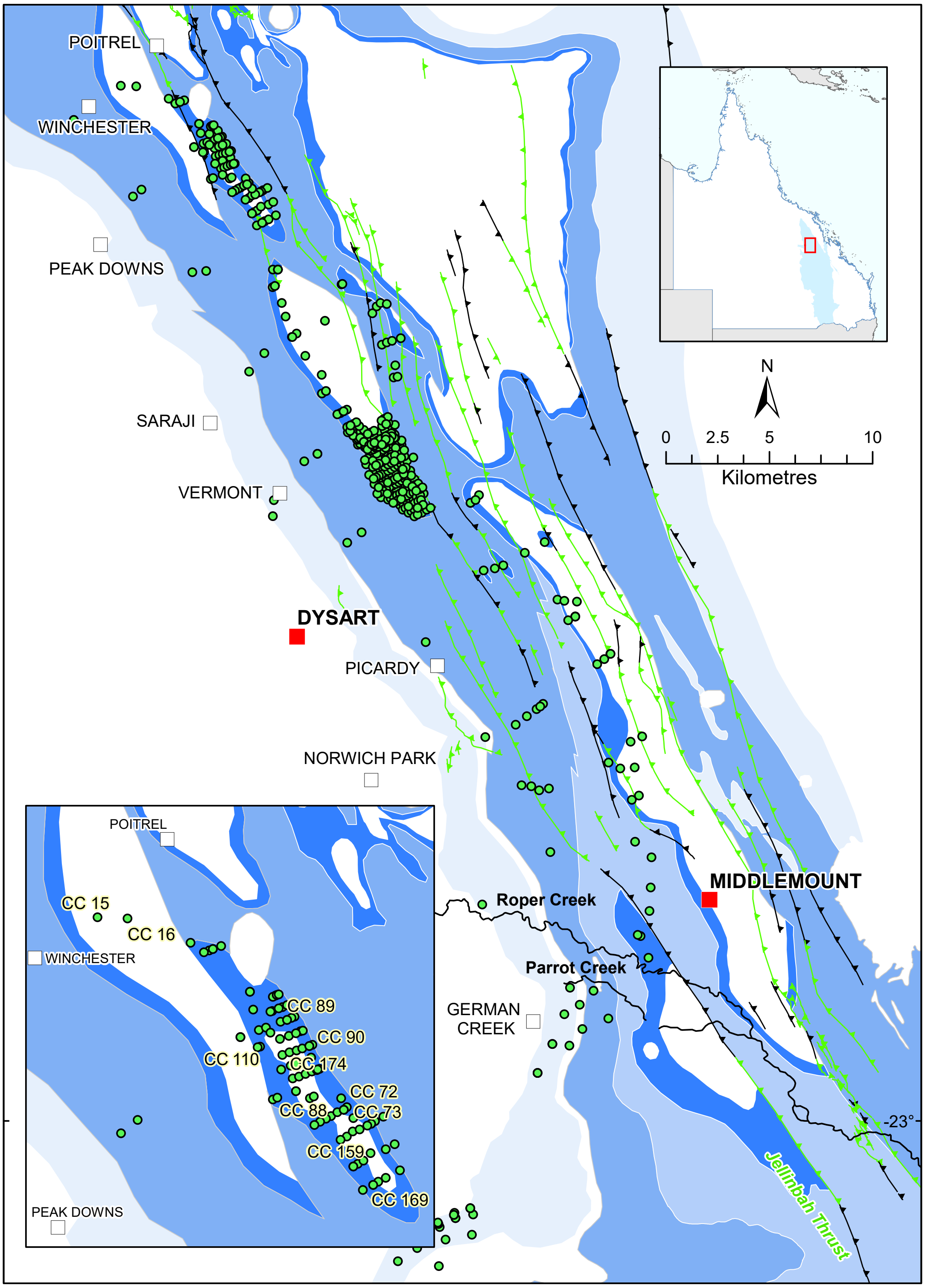

Figure 26. Cairns County boreholes in the Winchester area. Legend in Figure 7.

The Fort Cooper Coal Measures consisted of poorly sorted, fine- to coarse-grained sandstone interbedded with carbonaceous shale, tuffaceous mudstone and coal (Koppe & Scott, 1981). The Vermont-Girrah Seam comprised several plies which were analysed, with the upper ply considered to be part of the Rangal Coal Measures. The analytical results were similar, although the Rangal ply had higher yields and lower ash (Table 23, Appendix 4).

Table 23. Cumulative and fractional analytical results—Vermont-Girrah Seam, Cairns County 15 and 16, Winchester (after Koppe & Scott, 1981).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g\cm³)	Ash (%)	CSN
CC 15	Vermont-Girrah (Rangal)	F 1.40	33.2	84.9	86.6	1.35	9.7	7½
		F 1.50	62.2			1.42	14.8	3½
		F 1.60	79.6			1.45	17.8	1½
		Raw	100				23.8	1
	Vermont-Girrah (Fort Cooper)	F 1.40	13.6	87.0	88.1	1.33	10.7	8½
		F 1.50	38.7			1.41	17.5	3
		F 1.60	55.2			1.46	20.6	1
		Raw	100				33.2	1
		F 1.40	9.8	88.1	89.6	1.33	9.5	8½
		F 1.50	30.5			1.42	17.5	4
		F 1.60	42.8			1.46	21.4	2½
		Raw	100				42.7	1
CC 16	Vermont-Girrah (Rangal)	F 1.40	38.7	149.2	151.0	1.34	9.5	
		F 1.50	75.3			1.41	14.8	
		F 1.60	92.1			1.43	17.3	
		Raw	100			1.46	19.8	
	Vermont-Girrah (Fort Cooper)	F 1.40	18.2	151.9	152.7	1.34	10.8	
		F 1.50	44.1			1.41	17.1	
		F 1.60	63.8			1.45	20.8	
		Raw	100			1.69	34.0	

Boreholes CC 89 to CC 174 (Carr, 1980) were drilled in the Winchester South area to reassess the coal ‘reserves’ (Indicated status) within the Rangal Coal Measures, which had previously been estimated by Koppe (1979; boreholes CC 72 to CC 88). Only CC 174 was fully cored (Figure 26). Carr (1980) described the Leichhardt Seam, two plies of the Vermont Seam and the Girrah Seam in the Fort Cooper Coal Measures. The latter contained high ash and it was considered of no commercial interest by both Koppe (1979) and Carr (1980). No analyses were performed.

3.3.5.2 Peak Downs – Norwick Park

This area, which broadly ran parallel to the strike of the Fort Cooper Coal Measures was drilled by the department to evaluate the underground mining potential of the Moranbah Coal Measures at depth. The program involved the completion of ten deep fully cored boreholes, CC 62 to CC 71, located to the east and between the Peak Downs and Saraji mines (locations in Figure 27). The results obtained were assessed together with information gathered from a few previously drilled Cairns County boreholes (10, 11, 13 and 38), which expanded the assessment area south to Norwich Park (Figure 27). Most boreholes were commenced in strata of the Fort Cooper Coal Measures and the boundary with the Moranbah Coal Measures was intersected at depths of between 100 and 200 m (Holmes, 1980).

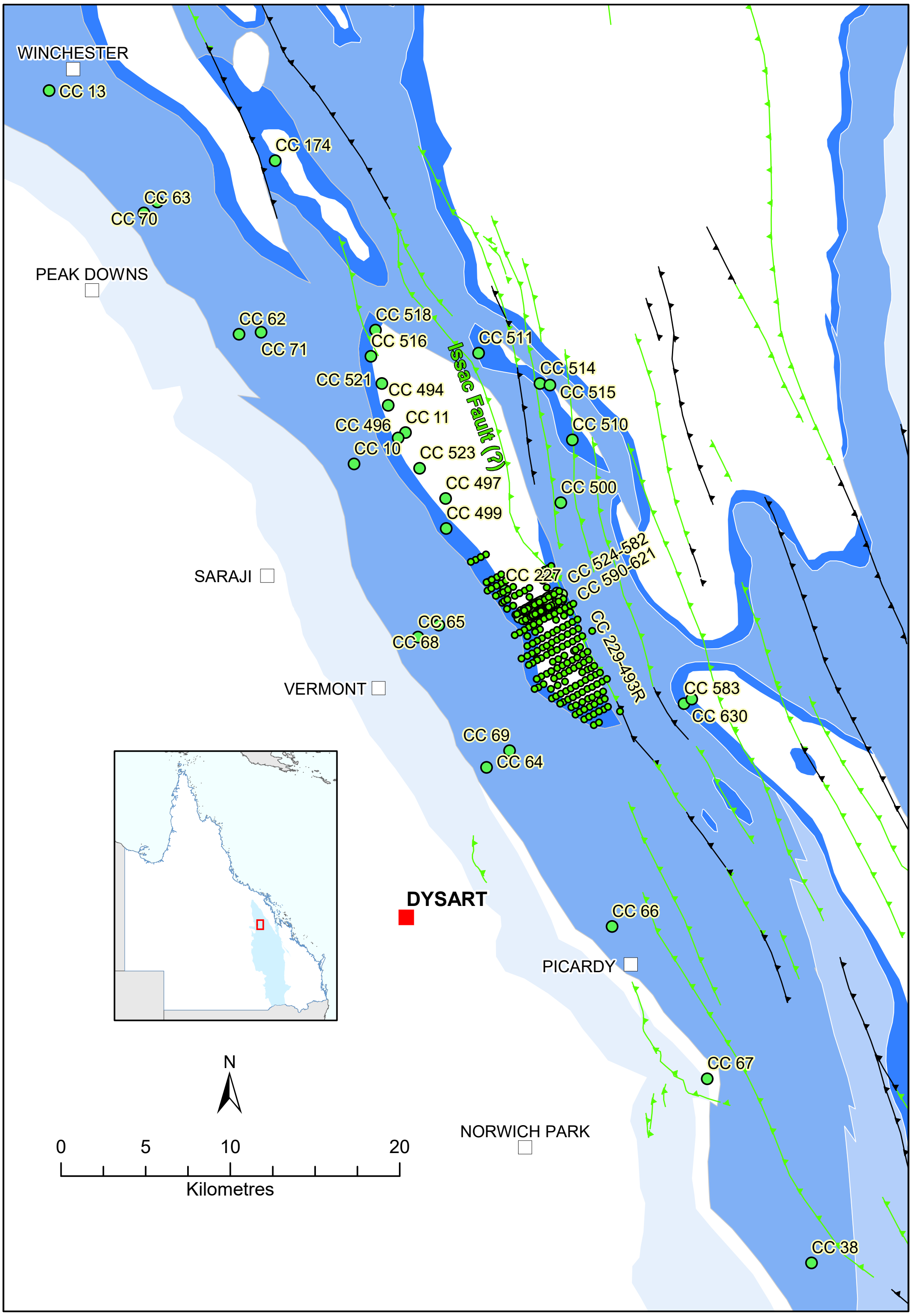

Figure 27. Cairns County boreholes from Peak Downs to Norwich Park. Legend in Figure 7.

Vitrinite reflectance values of coal were determined only in CC 10, 11 (Plate 11) and 38 and ranged from 1.3 to 1.7% (Beeston, 1981), being presumably caused by heat.

Plate 11. Intrusion in Cairns County 11 (depth ~ 445 m).

The lower seam of the Fort Cooper Coal Measures (S Seam) was analysed and described as tuffaceous and uneconomic to mine (Table 24, Appendix 4; borehole locations in Figure 27).

Table 24. Analytical results—S seams, Cairns County 62, 63, 68, 69 and 70, east of Peak Downs (after Holmes, 1980).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g\cm³)	Proximate analysis (adb)				S (%)	Specific energy (MJ/kg)	CSN
							M (%)	Ash (%)	VM (%)	FC (%)			
CC 62	S Upper	F 1.40	13.1	90.7	91.9			8.9					>9
		F 1.50	34.0					17.8					8½
		F 1.60	59.7				2.3	23.7	19.9	54.3	0.57	26.8	7½
		Raw	100			1.65		38.1					2½
	S Lower	F 1.40	19.0	125.5	126.7			9.4					>9
		F 1.50	39.9					16.6					9
		F 1.60	57.0				2.1	21.3	21.1	57.8	0.54	28.4	8
		Raw	100			1.68		41.2					3
CC 63/63A	S Lower	F 1.40	19.6	95.2	96.6			11.5					
		F 1.50	40.8					18.5					
		F 1.60	59.3				2.2	23.3	23.1	54.2	0.48	26.6	
		Raw	100			1.65		41.6					
CC 68/68A	S	F 1.60	31.2	186.2	188.3			23.2					
		Raw	100			1.82		53.2					
		F 1.60	57.6	190.1	191.6			20.6					
		Raw	100			1.61		36.5					
CC 69	S	F 1.40	11.9	147.1	149.2			9.4					
		F 1.50	27.9					17.5					
		F 1.60	42.7					22.5					
		Raw	100			1.74		48.3					
CC 70	S Lower	F 1.40	18.1	179.4	180.8			11.2					>9
		F 1.50	40.1					18.7					9
		F 1.60	62.7					24.1					8
		Raw	100			1.62		38.2					3½

3.3.5.3 Lake Vermont—Vermont

Fifty four Cairns County boreholes (CC 174 to CC 227) totalling more than 5000 m (350 m cored) were drilled along strike in the Lake Vermont area, to estimate the quality and 'reserves' in the Leichhardt and Vermont seams (Sorby, 1981). The Fort Cooper Coal Measures were cored only in CC 227 (Figure 27), where they were intersected at 110 m (Table 25, Appendix 4). Sorby (1981, page 3) stated *"Analysis revealed a ply towards the top of the seam may provide a source of steaming coal. Further exploration in the area is recommended to examine resources within the Girrah and other seams within the Fort Cooper Coal Measures."*

Table 25. Comparative cumulative and fractional analytical results—Vermont and Girrah seams, Cairns County 227, Lake Vermont (after Sorby, 1981).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Ash (%)	CSN
CC 227	Vermont (Rangal)	F 1.40	84.5	88.2	91.2		8.1	½
		F 1.60	94.5				8.7	½
		F 1.80	95.8				9.0	½
		Raw	100			1.48	10.5	½
		F 1.40	81.2	91.2	94.4		8.2	5
		F 1.60	88.3				8.9	3½
		F 1.80	90.4				9.3	3
		Raw	100			1.54	14.7	2
	Girrah	F 1.40	1.6	161.9	163.5		9.4	
		F 1.60	3.0				15.5	
		F 1.80	7.0				26.4	
		Raw	100			2.01	62.3	
		F 1.40	20.1	165.8	167.1		8.2	
		F 1.60	57.9				17.0	
		F 1.80	73.9				20.8	
		Raw	100			1.55	29.3	
		F 1.40	2.0	167.1	168.3		8.9	
		F 1.60	3.9				15.5	
		F 1.80	7.5				23.6	
		Raw	100			2.01	61.6	
		F 1.40	5.3	170.6	172.95		7.4	
		F 1.60	16.2				18.5	
		F 1.80	29.6				24.5	
		Raw	100			1.82	50.1	

Two years later, 265 shallow Cairns County boreholes (CC 229 to CC 493R, Figure 27), totalling more than 10,000 m were drilled in the Lake Vermont area; only ten were analysed to further assess the quality of the Leichhardt and Vermont seams (Sorby & Matheson, 1983). The Fort Cooper Coal Measures in the area were described as a grey siltstone and mudstone, and light grey, fine- to very fine grained sandstone, interbedded with carbonaceous or tuffaceous mudstone. The environment of deposition was interpreted to be continental with still poorly drained lakes (Sorby *et al.,* 1985). A slight greenish colour distinguished these coal measures from the overlying Rangal Coal Measures. The Fort Cooper – Rangal boundary was placed at the top of a 0.5 to 3.3 m-thick tuffaceous mudstone, which occurred about 10 m below the Vermont Seam and 35 m above the Girrah Seam. This seam and its splits were intersected in a few boreholes but not analysed as part of this exploration program (Sorby *et al.,* 1985).

Thirty boreholes were drilled in the Vermont North area (CC 494 to CC 523, Figure 27) to assess the potential commercial value of the Leichhardt and Vermont seams in the Rangal Coal Measures. Approximately 7000 m were drilled, of which about 3800 m was cored, described, and sampled for analysis (Matheson, 1986a). The Fort Cooper Coal Measures comprised predominantly sandstone, carbonaceous and tuffaceous mudstone and siltstone. Greenish coarse arenites were observed to underlie the coal intervals. A 1–2 m thick tuffaceous bed with a high-gamma wireline log response was equated with the Yarrabee Tuff. The Girrah Seam occurred immediately underneath this tuff bed in the north and from 3 to 50 m beneath this marker bed towards the south. Cairns County 499 (Figure 27; Plate 12) was the only borehole which was drilled through the entire Fort Cooper Coal Measures (92–478 m) and finished in the Moranbah Coal Measures at 562.0 m. Intrusions were observed in 5 boreholes: CC 494, 496, 510, 511 and 515 (Figure 27), the latter containing 14 separate occurrences (Matheson, 1986a).

Plate 12. Fe-rich tuffaceous bands interbedded with predominantly dull/stony coal, Cairns County 499.

A major northwest-trending regional fault up-thrown to the east was interpreted as crossing the Vermont area leading to depth anomalies in some boreholes (i.e. CC 505 and CC 510, and CC 514 and CC 515, Figure 26). Cairns County 515, in particular, showed evidence of faulting with numerous slickensides and steep dips around of around 45°. Seam character was also variable, especially when compared to the Lake Vermont area (Sorby & Matheson, 1983), suggesting the existence of numerous faults which displaced seams within separate blocks (Matheson, 1986a).

Although considered highly tuffaceous, the Girrah Seam was analysed in 9 boreholes, along with the Vermont Seam, which was considered part of the Rangal Coal Measures in the Vermont North area (Table 26, Table 27, Appendix 4, locations in Figure 27).

Table 26. Cumulative and fractional analytical results—Girrah Seam, Cairns County 494, 496, 497 and 499, Vermont (after Matheson, 1986a).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Ash (%)	CSN
CC 494	Girrah	F 1.40	22.8	186.0	187.6		8.1	9
		F 1.60	55.1				19.1	7½
		F 1.80	69.4				23.6	7
		Raw	100			1.64	39.1	1½
		F 1.40	32.0	193.1	194.6		9.8	9
		F 1.60	82.8				18.9	3½
		F 1.80	91.2				20.8	2½
		Raw	100			1.47	24.7	1½
CC 496	Girrah	F 1.40	21.8	206.9	208.3		6.9	>9
		F 1.60	49.3				18.2	8
		F 1.80	63.9				23.9	7
		Raw	100			1.69	42.2	1
		F 1.40	20.2	208.3	209.2		7.9	>9
		F 1.60	69.2				21.2	7½
		F 1.80	84.9				24.9	6
		Raw	100			1.53	31.0	3
CC 497	Girrah	F 1.40	20.8	300.2	301.4		7.1	>9
		F 1.60	61.5				20.9	7½
		F 1.80	81.9				26.4	5½
		Raw	100			1.56	33.3	2
		F 1.40	8.2	302.1	303.3		6.7	>9
		F 1.60	48.8				24.3	1
		F 1.80	75.2				31.0	1
		Raw	100			1.66	40.5	1
CC 499	Girrah	F 1.40	6.5	114.1	115.5		8.1	>9
		F 1.60	33.1				24.3	8
		F 1.80	62.5				33.5	3
		Raw	100			1.75	46.7	1
		F 1.40	3.4	122.9	124.0		5.5	>9
		F 1.60	18.4				25.7	7
		F 1.80	62.0				39.7	1
		Raw	100			1.72	48.6	1
	S Upper	F 1.40	5.9	459.1	460.3		4.2	>9
		F 1.60	9.7				7.0	>9
		F 1.80	28.8				20.8	8½
		Raw	100			1.73	46.6	1
		F 1.40	4.2	460.3	460.7		4.5	>9
		F 1.60	8.6				8.4	>9
		F 1.80	37.7				22.1	5
		Raw	100			1.71	44.3	1

Table 27. Cumulative and fractional analytical results—Girrah Seam, Cairns County 500, 510, 511, 516, 518, 521 and 523, Vermont (after Matheson, 1986a).

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
CC 500	Girrah	F 1.40	21.6	150.0	152.0		9.2	>9
		F 1.60	71.3				19.4	3
		F 1.80	84.7				22.9	2
		Raw	100			1.54	28.2	1½
		F 1.40	2.6	153.6	154.5		7.3	>9
		F 1.60	18.1				25.3	7
		F 1.80	64.2				39.8	1
		Raw	100			1.76	49.3	1
CC 510	Girrah	F 1.40	14.1	380.3	381.7		4.9	>9
		F 1.60	46.1				20.5	7½
		F 1.80	69.4				28.2	4
		Raw	100			1.69	42.1	1
		F 1.40	1.7	385.7	386.4		6.1	>9
		F 1.60	7.9				23.6	>9
		F 1.80	43.8				40.2	1
		Raw	100			1.92	58.8	½
CC 511	Girrah	F 1.40	10.6	209.2	211.7		5.8	>9
		F 1.60	44.0				22.4	6½
		F 1.80	67.4				29.3	2
		Raw	100			1.70	42.0	1
		F 1.40	10.2	218.2	221.2		6.1	>9
		F 1.60	49.8				20.3	2
		F 1.80	74.5				27.2	1
		Raw	100			1.67	37.9	1
CC 516	Girrah	F 1.40	23.4	139.5	142.4		9.1	9
		F 1.60	54.4				19.6	7½
		F 1.80	75.1				25.6	4½
		Raw	100			1.63	36.6	2
CC 518	Girrah	F 1.40	22.6	96.7	99.3		9.0	9
		F 1.60	51.5				20.1	7
		F 1.80	71.3				26.0	4½
		Raw	100			1.67	37.7	1½
CC 521	Vermont (Rangal)	F 1.40	51.9	160.7	162.1		5.9	4
		F 1.60	74.0				7.5	2
		Raw	100			1.39	11.2	1
	Girrah	F 1.40	14.5	212.0	214.0		12.5	9
		F 1.60	32.3				22.1	8
		F 1.80	49.7				29.4	5½
		Raw	100			1.89	54.9	1
		F 1.40	32.4	217.6	219.0		12.3	9
		F 1.60	67.7				19.8	5½
		F 1.80	80.8				23.5	3½
		Raw	100			1.57	30.7	1½

Table 27. (continued)

Borehole	Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
CC 523	Vermont (Rangal)	F 1.40	16.8	243.6	245.2		5.7	9
		F 1.60	42.3				9.9	5½
		Raw	100			1.50	23.3	1
	Girrah	F 1.40	26.1	301.2	302.9		9.0	>9
		F 1.60	77.6				19.2	4
		F 1.80	86.3				21.3	3½
		Raw	100				27.0	2

Lake Vermont area was further investigated with a series of 91 boreholes (CC 524-582 and CC 590-621, Figure 27) to confirm the previously estimated resources (Measured status) of thermal coal in the Rangal Coal Measures (*e.g.* Sorby & Matheson, 1983) and to provide further detail on the structural geology of the area (Sorby, 1986). The boreholes were shallow, with total depths of less than 150 m. The Fort Cooper Coal Measures were found relatively undisturbed to the west but affected by faulting to east, with inferred displacements of at least 100 m, presumably caused by an equivalent of the Isaac Fault (Sorby, 1986).

3.3.5.4 Picardy

Located southeast of Lake Vermont, the Picardy area was explored through the drilling of 17 cored boreholes totalling more than 5000 m (CC 583-589 and CC 622-631, Figure 28).

The main purpose was to determine the continuity of coal seams within the Rangal Coal Measures at depth (Coffey & Crosby, 1987). The Fort Cooper Coal Measures were intersected by the majority of boreholes and comprised predominantly labile lithic sandstone interbedded with tuffaceous material and high-ash coal seams. Of note is CC 583, which is the deepest borehole in the area and intersected a full sequence of Fort Cooper Coal Measures (53–475 m). The name of 'Fort Cooper' was preferred, as the finer grained strata, that included a large argillaceous component characteristic of the Burngrove Formation further to the south, was not recognisable in this area (Coffey & Crosby, 1987). The upper boundary of the Fort Cooper Coal Measures was placed at the top of a tuffaceous band with a high gamma ray wireline log response. The banded and tuffaceous character of the seams is shown in Plate 13 and Plate 14.

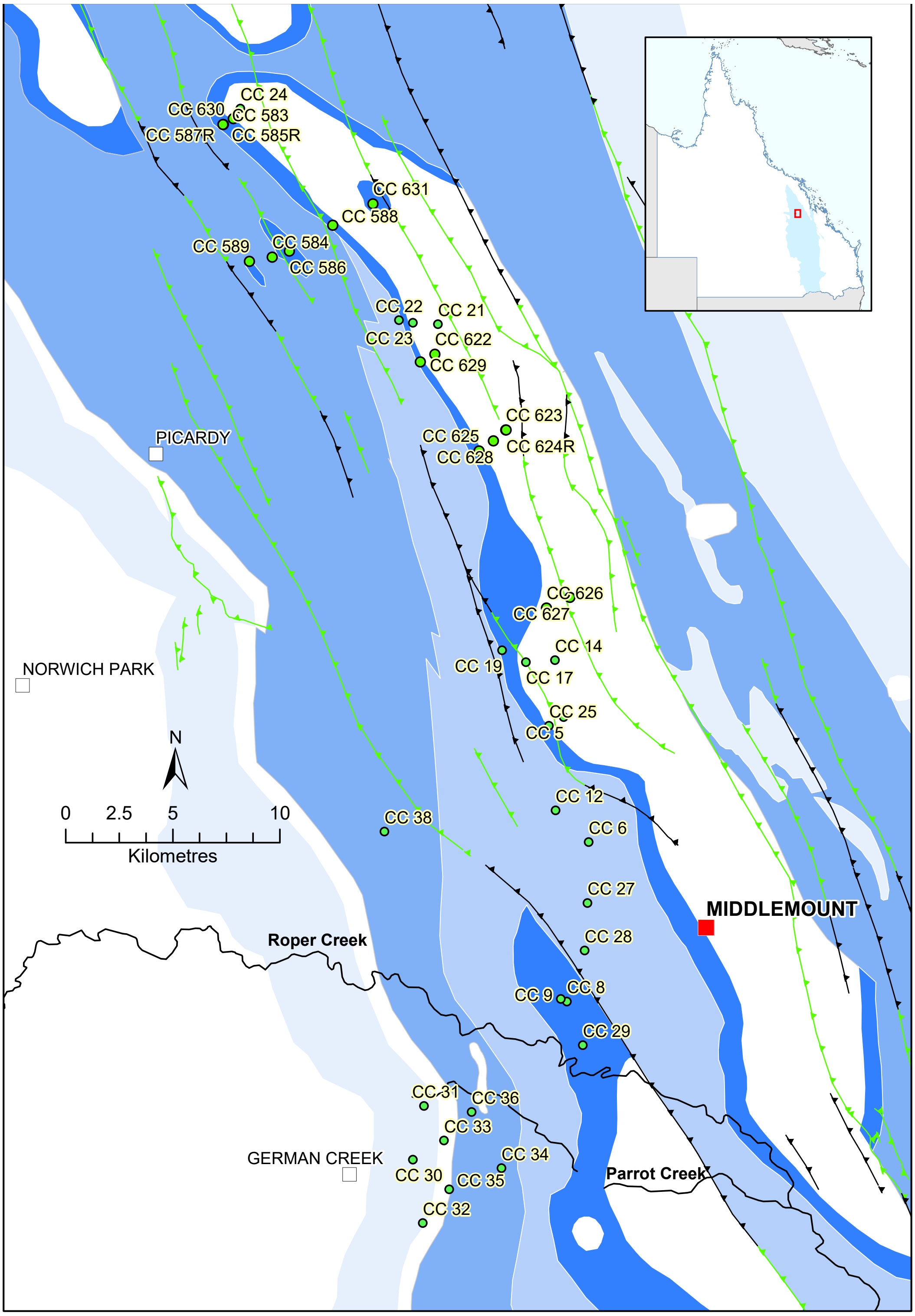

Figure 28. Cairns County boreholes from Picardy to German Creek. Legend in Figure 7.

Plate 13. Typically dull coal, thinly interbedded with Fe-rich or tuffaceous mudstones, Cairns County 583.

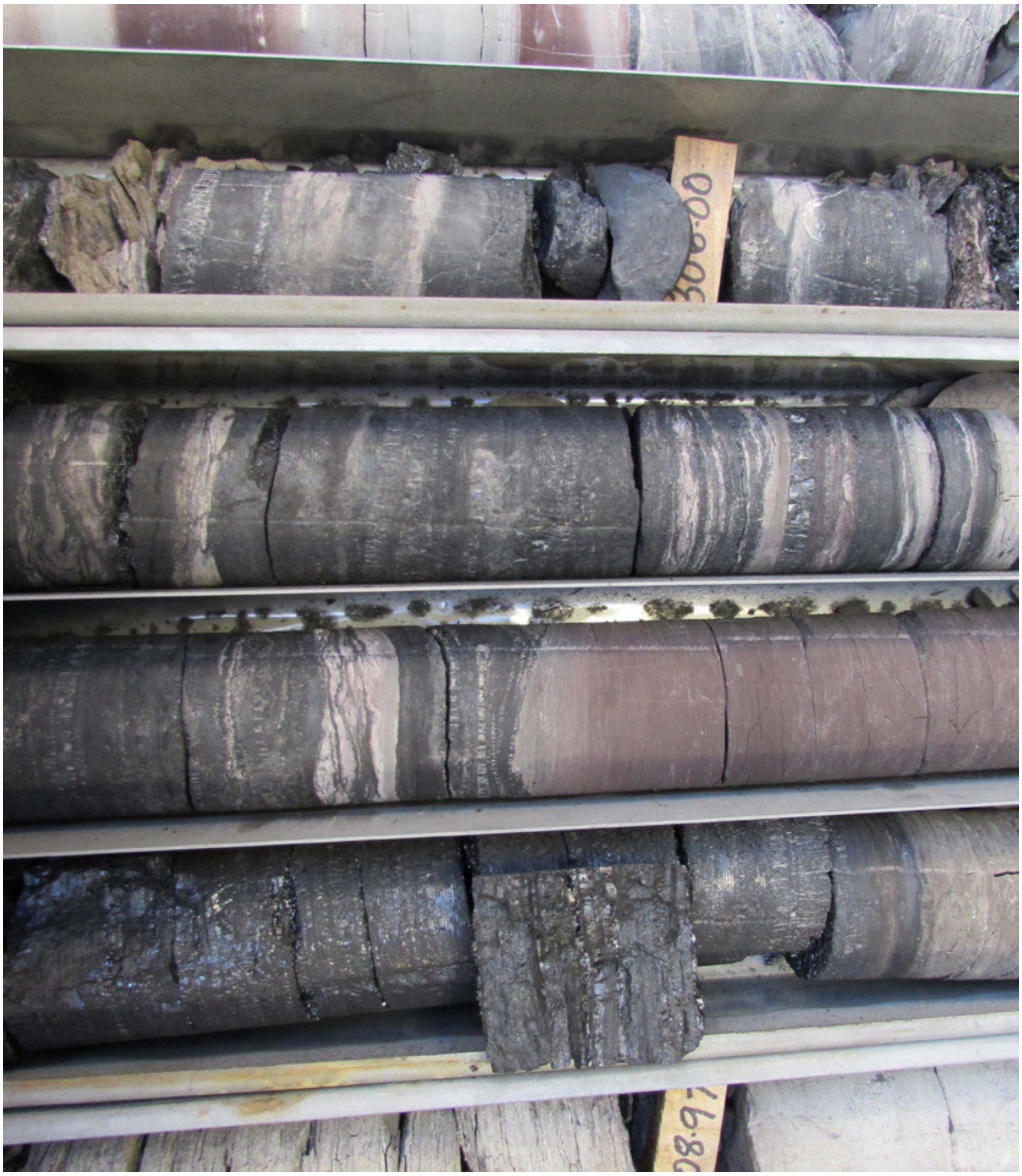

Plate 14. Sideritic intervals, Cairns County 583.

While the correlation of a few coal seam intervals within the Fort Cooper Coal Measures was tentatively suggested in some of the boreholes drilled, the correlation of seams within the Fort Cooper Coal Measures overall was not undertaken, largely because of the lack of stratigraphic control and the structural complexity of the region investigated, evidenced by the structural features (fault zones, mylonite zones and steep apparent dips) observed in the core taken from most of the boreholes drilled.

Sampling and analyses were only undertaken on four coal plies from Fort Cooper Coal Measure seams intersected during the program. These were from boreholes CC 583, CC 626 and CC 630 (Table 28). In addition to these coal samples and to assist with the visual logging of the banded seams within the Fort Cooper Coal Measures, a number of other samples of the coal and carbonaceous mudstones (i.e. CC 584 and CC 586) were also taken and analysed for ash and relative density. Faulting was apparent in a few boreholes such as CC 583, CC 603 and CC 627 (locations in Figure 28), where formation repeats occurred. A fault zone was also interpreted between CC 584 and CC 586, and CC 586 and CC 588, with vertical displacements of between 100 to 200 m inferred. Coal was intruded in CC 626 (Table 28), CC 627 and CC 629 (Coffey & Crosby, 1987).

Table 28. Cumulative, fractional and 'spot sample' analytical results, unnamed Fort Cooper seams, Cairns County 583, 584, 586, 626 and 630, Picardy (after Coffey & Crosby, 1987).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Proximate analysis (adb) M (%)	Ash (%)	VM (%)	FC (%)	Specific energy (MJ/kg)	S (%)	CSN
CC 583	F 1.60	44.2	116.4	117.7		1.3	20.7	14.4	63.6	28.1	0.50	2½
	Raw	100			1.67		41.6					1
	F 1.60	34.5	118.1	119.2		1.3	18.9	14.9	64.9	28.7	0.53	3
	Raw	100			1.73		46.2					1
CC 584	Raw	100	92.2		1.92		64.6					
	Raw	100	92.8		1.70		45.8					
	Raw	100	100.0		2.01		63.7					
	Raw	100	100.2		1.95		63.4					
	Raw	100	174.2		1.60		33.2					
	Raw	100	175.4		1.50		26.6					
	Raw	100	178.4		1.78		52.7					
	Raw	100	235.4		1.97		65.9					
	Raw	100	237.1		2.14		77.1					
CC 586	Raw	100	109.3		1.95		59.1					
	Raw	100	110.6		1.77		50.8					
	Raw	100	144.5		1.50		25.4					
	Raw	100	171.8		1.94		63.2					
	Raw	100	171.9		1.51		35.4					
	Raw	100	172.1		1.77		52.9					
	Raw	100	189.3		1.66		10.9					
	Raw	100	190.6		1.90		62.2					
	Raw	100	190.7		1.75		48.0					
CC 626*	Raw	100	205.7	206.1	1.47	2.0	21.0	11.7	64.9			0
	F 1.30	4.3	206.1	207.8			3.4					1
	F 1.40	8.0					7.1					½
	F 1.50	22.5					14.9					½
	F 1.60	45.6					21.3					0
	Raw	100			1.74		43.9					0
CC 630	F 1.60	44.9	215.5	216.7			22.3					3
	Raw	100			1.69		41.5					1

**heat-affected*

3.3.5.5 Roper and Parrot creek areas

The first of the Cairns County series of boreholes (CC 5, 6, 8, 9 and 12) were drilled in the Roper Creek area, west of Middlemount (Figure 28), to explore the Rangal Coal Measures occurring east of the Jellinbah Fault (Anderson, 1974). The Burngrove Formation was the lowermost unit drilled and consisted mostly of fine-grained grey-green sandstone and siltstone with minor mudstone. The arenites contained abundant plant material and were characterised by contorted bedding. In relation to the Girrah Seam, Anderson (1974, page 9) noted: *"Although the seam as a whole is high in ash, there are lenticular plies of relatively clean coal. These plies consist of coal which, although higher in ash content than commercial grade coal, has high swelling properties"* (Table 29).

Table 29. Cumulative and fractional analytical results—Girrah Seam, Cairns County 8 (after Anderson, 1974).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Ash (%)	CSN
CC 8	F 1.40	10.2	220.2	220.8	1.31	7.6	9
	F 1.60	34.8			1.45	21.3	6½
	Raw	100			1.77	46.2	1
	F 1.40	53.2	220.8	221.6	1.30	6.8	>9
	F 1.60	67.8			1.34	10.9	8½
	Raw	100			1.56	28.6	5
	F 1.40	46.5	221.6	222.8	1.32	9.1	9
	F 1.60	84.5			1.39	15.9	7½
	Raw	100			1.47	21.9	6

The next in this series of boreholes (CC 14, 17, 19 and CC 21–25) were drilled further north, towards the Picardy area, also targeting the Rangal Coal Measures. The eight completed boreholes totalled more than 2200 m of drilling, of which about 2000 m was cored (Figure 28). The Burngrove Formation consisted of grey-green arenites and a high proportion of interbedded tuffaceous material (Anderson, 1975b).

Cairns County 27, 28 and 29 (Figure 28) were drilled as part of the Roper Creek East Stage II program, with the purpose of determining 'reserves' of coal in the Rangal Coal Measures to an indicated level of confidence in accordance with the Departmental parameters used at that time—refer to section 1.3. The upper most part of the Burngrove Formation was intersected and the Rangal–Burngrove boundary was placed at the top of the Yarrabee Tuff, although previous reports had placed it at the top of the Girrah Seam (Anderson & Jameson, 1982). The Burngrove Formation was described as consisting mainly of coarse-grained lithic labile sandstone, with minor mudstone and coal. While the coal seams had considerable thickness, the abundance of tuff interbeds rendered them of no commercial value (Anderson & Jameson, 1982).

Further south of Middlemount, in the Parrot Creek area, a few Cairns County boreholes (CC 30 to CC 38) were drilled to explore for coal seams in the German Creek Formation (Figure 28).

Although the coal was not analysed, the formations were described in detail. The Burngrove Formation consisted of a grey to dark grey siltstone and mudstone with some fine-grained sandstone and a 10 m thick coal seam intersected at 60 m depth in CC 34. The Fair Hill Formation (between 90–195 m) comprised medium-grained, light grey, labile sandstone with bands of grey mudstone at the top, grading into mudstone and siltstone with coal seams and tuffaceous layers. The Fairhill Seam was about 12 m thick at a depth of around 175 m (Galligan, 1975).

3.4 Exploration areas—southern Bowen Basin

The following sections summarise the findings of exploration programs undertaken by the Department from German Creek to Springsure, presented in order from north to south (Table 30; Figure 29).

Table 30. Exploration areas, boreholes series and associated GSQ publications, southern Bowen Basin.

Area	Borehole series	Reference *(QDEX CR number)*
Roper Creek	Roper (RO)	Anderson, 1974 *(41675)*; Anderson & Jameson, 1982 *(41164)*
Parrot Creek	Talbot (TA)	Galligan, 1975 *(41982)*; Anderson & Jameson, 1982 *(41164)*
Oaky Creek	Talbot	Zillman, 1976 *(41685)*
	Blackwater (BL)	Staines, 1973 *(41665)*; Prouza, 1976 *(41681)*; Prouza 1977 *(41764)*
Jellinbah—Caledonia	Talbot	Carr, 1981 *(41700)*; Balfe, 1983 *(41704)*
	Leura (LE)	Staines, 1978 *(41395)*; Balfe, 1983 *(41704)*; Staines, 1987 *(41377)*
	Humboldt (HU)	Staines, 1978 *(41395)*; Carr, 1981 *(41700)*; Balfe, 1983 *(41704)*; Staines, 1987 *(41377)*
	Blackwater	Staines, 1972 *(55545)*; Park, 1973a *(41661)*; Carr, 1973 *(41663)*; Staines, 1974 *(55549)*; Staines, 1977 *(41760)*
Curragh	Humboldt	Galligan, 1977 *(41502)*; Galligan, 1978 *(7059)*; Galligan & Turner, 1979 *(41689)*; Thornton, 1982 *(41703)*
Northeast Blackwater	Humboldt	D'Arcy, 1985 *(41722)*
Minyango	Blackwater	Carr, 1975 *(41677)*
Emerald	Emerald (EM)	Park, 1973b *(41664)*; Park, 1974 *(41667)*; Park & Galligan, 1974 *(41668)*; Galligan, 1976 *(41684)*
	Talbot	Galligan, 1976 *(41684)*; Wallin & Tuttle, 1982 *(41191)*; Slater et al., 1983 *(41706)*; Staines et al., 1983 *(41809)*
	Denison (DE)	Wallin, 1979 *(41692)*; Wallin & Tuttle, 1982 *(41191)*; Slater et al., 1983 *(41706)*; Staines et al., 1983 *(41809)*; Thornton, 1983 *(41372)*
Ensham	Talbot	Wallin, 1982 *(41190)*; Wallin & Tuttle, 1982 *(41191)*; Coffey, 1983 *(41705)*
	Denison	Wallin & Tuttle, 1982 *(41191)*; Coffey, 1983 *(41705)*; Coffey et al., 1983 *(42020)*
Denison (Arcturus)	Denison	Anderson, 1975a *(41678)*; Thornton, 1987 *(41954)*
Togara (Comet River)	Humboldt	Zillman, 1978 *(41766)*; Thornton, 1986 *(41716)*
	Denison	Wallin, 1980 *(41695)*; Thornton, 1986 *(41716)*
	Togara	Zillman, 1978 *(41766)*
	Wooroona	Zillman, 1978 *(41766)*; Thornton, 1986 *(41716)*

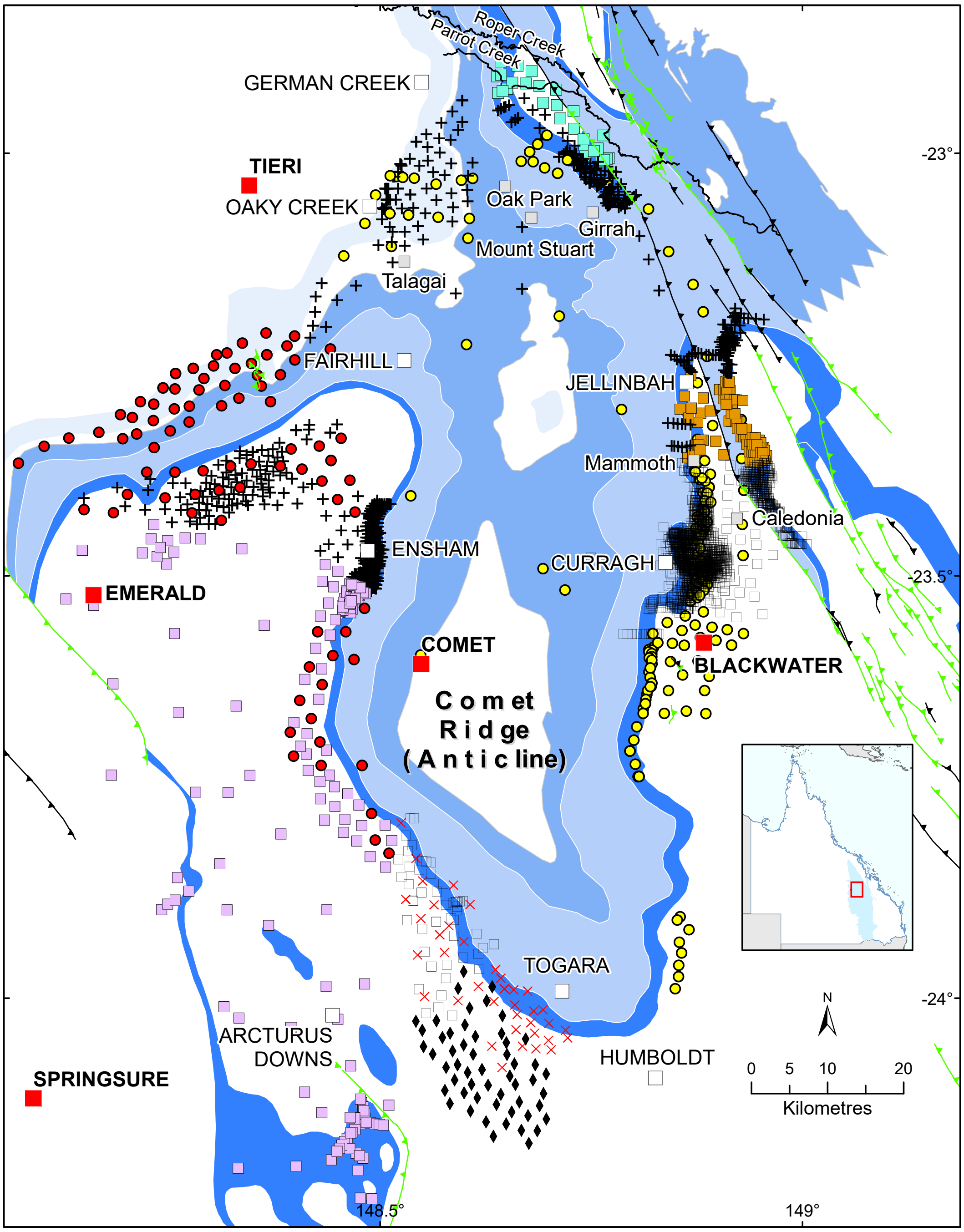

Figure 29. Borehole locations in relation to solid geology, southern Bowen Basin. Legend in Figure 7.

3.4.1 Roper and Parrot creeks

The Roper and Parrot creek areas, explored by the Department between the mid-1970s and early 1980s, were investigated with a combination of Cairns County, Roper and Talbot series boreholes. The results of these coal reconnaissance drilling programs have been reported by Anderson (1974), Galligan (1975) and Anderson & Jameson (1982) (Figure 30).

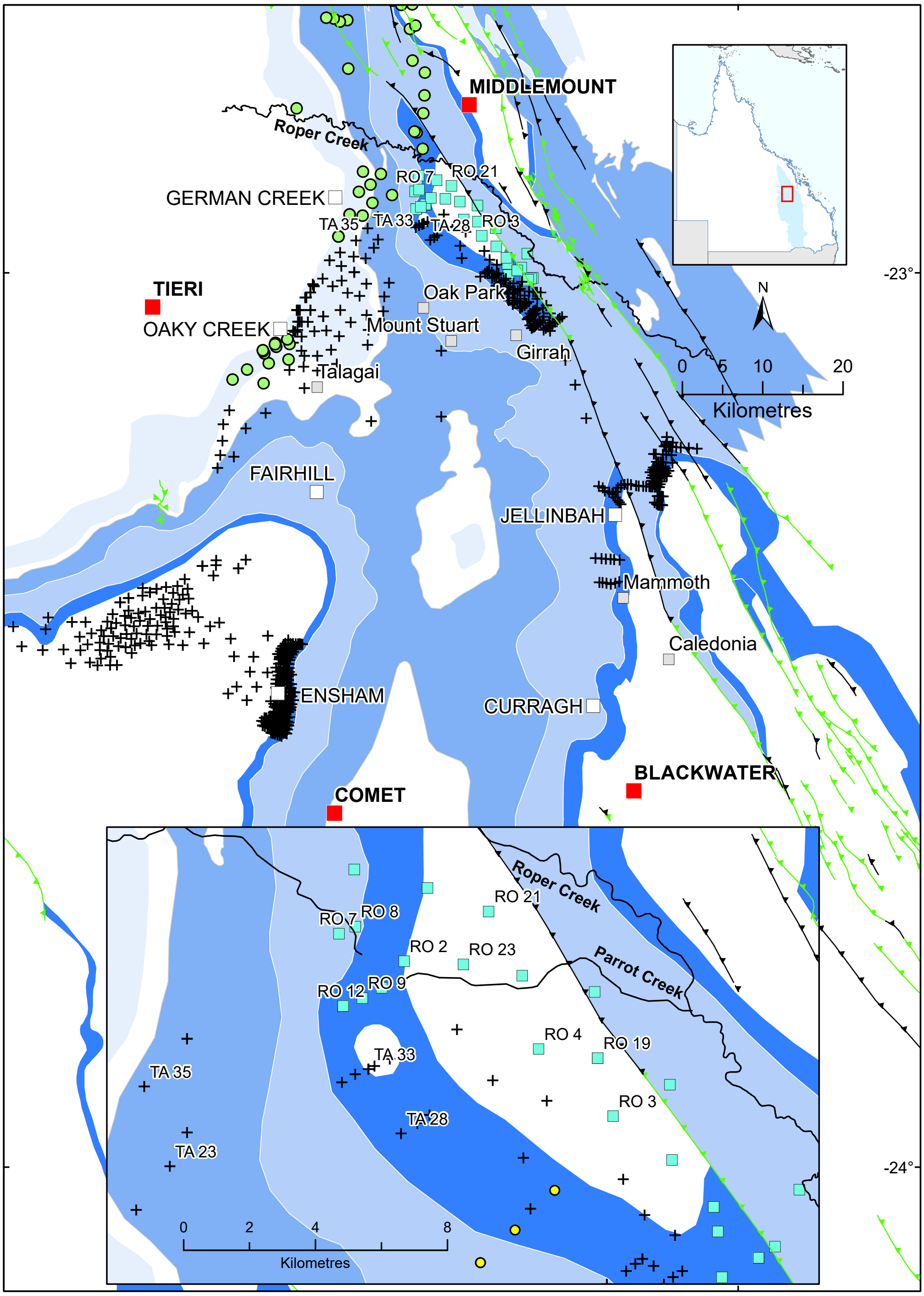

Figure 30. Roper (RO) and Talbot (TA) boreholes in the Roper and Parrot creek areas. Legend in Figure 7.

The Roper Creek drilling program was undertaken in two stages. The first stage was to investigate the possible occurrence of coal seams in the Rangal Coal Measures and the second to estimate 'reserves' of coal in the seams delineated in the first stage (Anderson, 1974; Anderson & Jameson, 1982). During these programs, the uppermost section of the Burngrove Formation was also intersected in places and described. This upper sequence consisted mainly of coarse-grained labile sandstone with minor mudstone and coal. While the coal seams were of considerable thickness, the numerous fine-grained tuffs, which usually occurred within the coal seams, were regarded to "*render them of no commercial value*" (Anderson & Jameson, 1982, page 5).

The first coal seam underlying a thick tuffaceous unit (presumably the Yarrabee Tuff, although not named as such at the time) was identified as the Girrah Seam. This seam was intersected only in Roper 2, 3, 12, 21 and 23 (Figure 30) and one Cairns County borehole (CC 8, Figure 28), where Anderson (1974) noted the coking properties of the coal (Table 29). Intrusions were reported in Roper 4, 19 and 23 (substantial occurrences noted in the latter), as well as in Talbot 23 and 28. With a few exceptions (i.e., Roper 7, 8, 9 and 12, and Talbot 35), where the top of the formation was less than 100 m deep, all the other boreholes intercepted the Burngrove Formation at depths of between 200 and 350 m (i.e., Talbot 23 and 33). Limited coal quality analyses were performed in the Roper boreholes (Table 31), although the thermal coal potential of the Girrah Seam was investigated in the area around Roper 2 and 21 (Anderson & Jameson, 1982).

Table 31. Raw coal analytical results—Girrah Seam, Roper 2 and 21, Roper Creek area (after Anderson & Jameson, 1982).

Boreholes	Depth from (m)	Depth to (m)	Specific gravity (g\cm^3)	Proximate analysis (adb)				S (%)	P (%)	CSN	Specific energy (MJ/kg)	Ash fusion temperatures (°C) (reducing atmosphere)		
				M (%)	Ash (%)	VM (%)	FC (%)					Deform	Hemi	Flow
RO 2*	206.7	209.2	1.68	-	38.5	-	-	-	-	-	-	-	-	-
RO 21	310.8	314.7	1.44	1.7	15.5	16.8	66.0	0.29	0.05	1	29.37	1460	>1600	>1600

** calculated from raw coal analyses of individual plies*

Further southwest, the Talbot boreholes drilled in the Parrot Creek area were mainly commenced in the German Creek Formation and did not intersect the Burngrove Formation (Galligan, 1975).

3.4.2 Oaky Creek – Girrah

The exploration of the northern Comet Ridge covered the Oaky Creek, Oak Park and Mount Stuart areas (Figure 31) and comprised boreholes of the Cairns County, Talbot and Blackwater series. Most were spudded in the target formation, the German Creek Formation, and only a few intersected the Fair Hill Formation and/or the Burngrove Formation.

The Fairhill, Lepus, Canis and Hercules seams were encountered in Blackwater 174, southwest of Mount Stuart (Figure 31), which was spudded in the Girrah Syncline (a structural feature introduced by Madden, 1968). All seams consisted of carbonaceous shales with numerous tuffaceous bands and minor poor quality coal (Zillman, 1976).

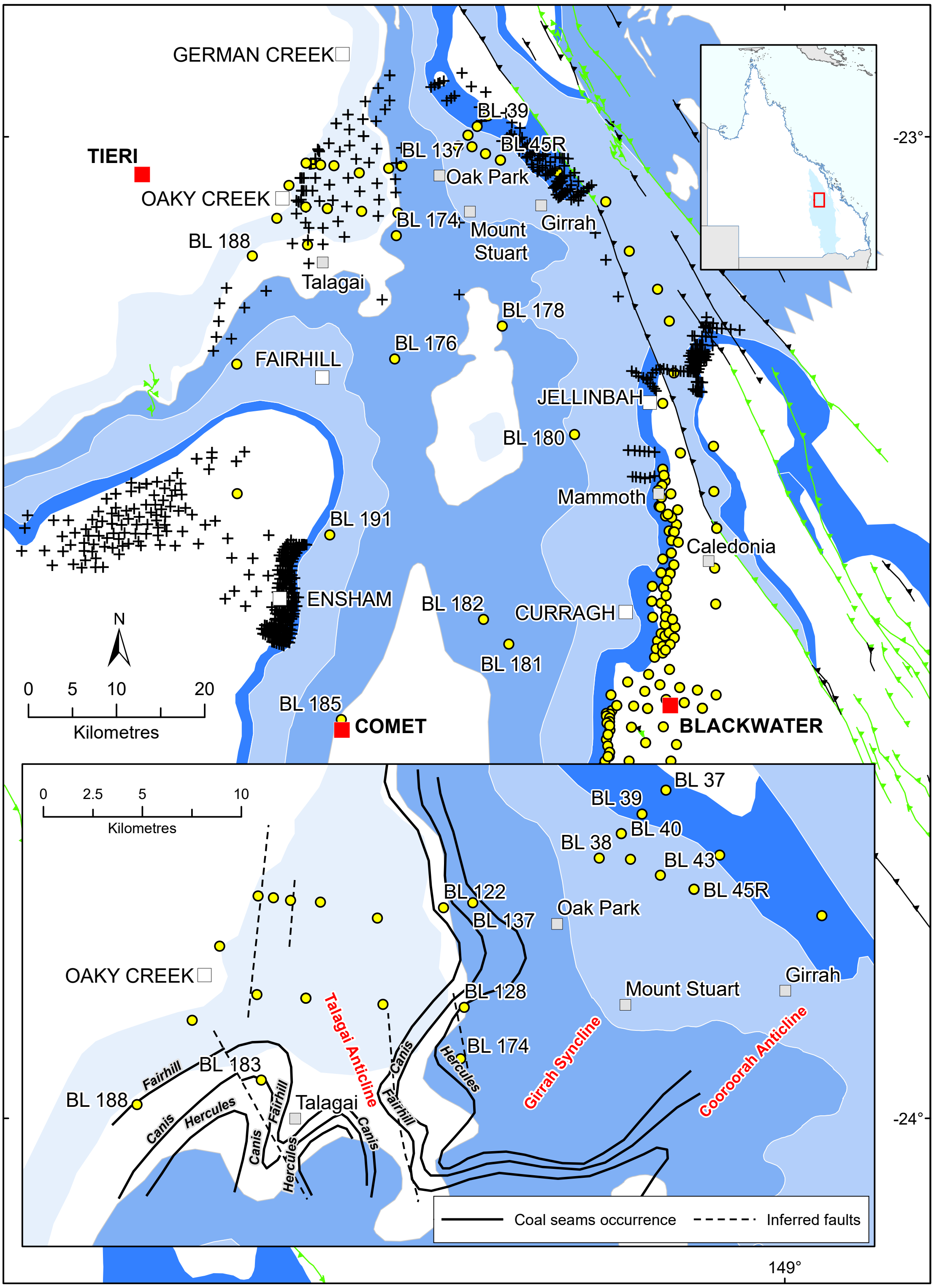

Figure 31. Talbot (TA) and Blackwater (BL) boreholes, Oaky Creek area. Inset shows the faults (after Prouza, 1976), in relation to local structure (after Madden, 1968).

Further east, towards Oak Park and Mount Stuart, Staines (1973) and Prouza (1976; 1977) drilled several Blackwater boreholes, which penetrated both the Fair Hill and the Burngrove formations.

The Fair Hill Formation was intersected at shallow depth in Blackwater 38 (Figure 31, inset), where it consisted of calcareous lithic labile sandstones interbedded with mudstones and siltstones. The sandstone was fine- to medium-grained and characteristically greenish from lithic fragments. The mudstone was light to dark grey and carbonaceous, with minor 0.3 m-thick coal seams (Staines, 1973).

The Burngrove Formation was conformable with the underlying Fair Hill Formation and composed of siltstone, fine-grained sandstone and mudstone (carbonaceous in places). The colour grey became greenish towards the base. The sandstones contained green lithic grains and the coal seams were mudstone-dominated, with light brown tuffaceous beds, some 1 m thick. A dark shale encountered at a depth of 189 m in Blackwater 38 was taken as the base of the Burngrove Formation (Staines, 1973).

The Virgo Seam was analysed in BL 39, 40, 43 and 45R (Table 32). In BL 39 and 45R (Figure 31, inset), the seam consisted of two coal intervals separated by a bed of carbonaceous mudstone. Staines (1973) considered that despite the seam's coking properties, the ash content could not be reduced to economically acceptable levels by washing.

Table 32. Cumulative and fractional analytical results—Virgo Seam, Blackwater 39, 40, 43 and 45R, Oaky Creek area (after Staines, 1973).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Proximate analysis (adb)				S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)		
BL 39	F 1.40	18.4	132.1	132.5	1.30		6.9				9
	F 1.60	43.8			1.38	1.6	16.2	20.0	62.2	0.69	8
	Raw	100			1.63	1.7	31.3	20.7	47.3	0.65	4
	F 1.40	36.0	132.7	133.8	1.30		8.7				9
	F 1.60	66.3			1.37	1.8	14.9	19.5	63.8	0.73	6½
	Raw	100			1.51	1.4	24.5	19.6	54.5	0.62	4½
	F 1.40	14.1	135.7	136.2	1.32		5.7				
	F 1.60	57.8			1.42	1.4	21.3	18.3	59.0	0.52	2½
	Raw	100			1.62	1.5	33.2	18.3	47.0	0.58	2½
	F 1.40	24.6	136.2	137.0	1.33		6.8				
	F 1.60	75.6			1.41	1.1	19.0	19.8	60.1	0.60	5½
	Raw	100			1.51	1.8	26.8	18.2	53.2	0.51	3½
BL 40	F 1.40	18.5	47.9	48.6	1.30		6.1				9
	F 1.60	49.3			1.38	1.9	17.6	19.9	60.6	0.79	7
	Raw	100			1.66	2.2	40.0	17.4	40.4	0.87	2½
	F 1.40	38.5	48.6	49.8	1.31		7.4				8½
	F 1.60	83.1			1.38	1.0	15.8	21.0	62.2	1.08	7
	Raw	100			1.30	1.2	21.9	20.7	56.2	1.30	5
	F 1.40	45.8	49.8	50.0	1.36		9.3				7½
	F 1.60	80.4			1.39	1.0	15.2	20.5	63.3	0.97	7
	Raw	100			1.34	0.9	21.7	19.5	57.9	1.34	5½
BL 43	F 1.40	32.8	19.5	20.0	1.32		9.2				
	F 1.60	61.4			1.40	2.3	16.3	19.3	62.1	0.40	5½
	Raw	100			1.58	2.5	26.5	17.6	53.4	0.64	3
	F 1.40	76.9	20.0	21.0	1.28		8.1				
	F 1.60	96.4			1.31	2.3	11.2	20.3	76.2	0.61	7½
	Raw	100			1.33	2.2	13.3	19.9	64.6	0.57	8
	F 1.40	21.6	21.0	21.2	1.34		7.1				
	F 1.60	21.8			1.35	2.0	7.1	15.0	75.9	0.53	4
	Raw	100			1.42	2.0	33.5	14.7	49.8	0.60	3½
	F 1.40	36.2	23.3	23.9	1.24		8.0				
	F 1.60	83.8			1.35	2.0	15.9	18.3	63.8	0.86	4
	Raw	100			1.42	1.9	21.3	18.2	59.6	0.69	3½
	F 1.40	44.8	23.9	24.8	1.27		8.1				
	F 1.60	80.6			1.35	1.8	14.0	19.1	65.1	0.58	5½
	Raw	100			1.42	2.0	23.0	18.4	56.6	0.52	5
	F 1.40	19.2	25.2	26.2	1.30		27.6				
	F 1.60	49.5			1.42	1.7	19.3	19.2	59.8	0.63	6½
	Raw	100			1.61	2.0	39.4	17.2	41.4	0.6	3½

Table 32 (continued)

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Proximate analysis (adb)				S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)		
	F 1.40	42.7			1.35		10.9				
	F 1.60	70.3	43.3	43.9	1.41	1.5	16.9	18.0	63.6	0.62	6½
	Raw	100			1.54	1.7	29.0	15.9	53.4	0.59	2
	F 1.40	72.2			1.35		10.3				
	F 1.60	86.7	43.9	45.0	1.37	1.3	13.4	18.4	66.9	0.62	7
	Raw	100			1.43	1.1	18.7	17.6	62.6	0.60	5
	F 1.40	65.4			1.34		12.3				
	F 1.60	82.7	46.5	48.4	1.37	0.9	15.6	18.7			6
BL 45R	Raw	99.2			1.45	1.3	23.5	17.3	57.9	0.62	3
	F 1.40	60.0			1.36		13.8				
	F 1.60	86.9	51.5	52.8	1.42	1.3	17.9	16.1	64.7	0.67	2
	Raw	100			1.47	1.6	22.9	16.3	59.2	0.69	1½
	F 1.40	66.9			1.36		13.6				
	F 1.60	89.8	52.8	54.2	1.39	1.4	17.9.4	16.3	64.4	0.67	3
	Raw	100			1.42	1.6	20.5	15.7	61.8	0.70	2
	F 1.40	15.8			1.34		14.0				
	F 1.60	49.0	54.7	55.8	1.44	1.1	20.6	15.3	59.3	0.49	3
	Raw	100			1.67	2.0	42.7	13.0	42.3	0.62	1

A slight increase in vitrinite reflectance with depth was also determined (Figure 32).

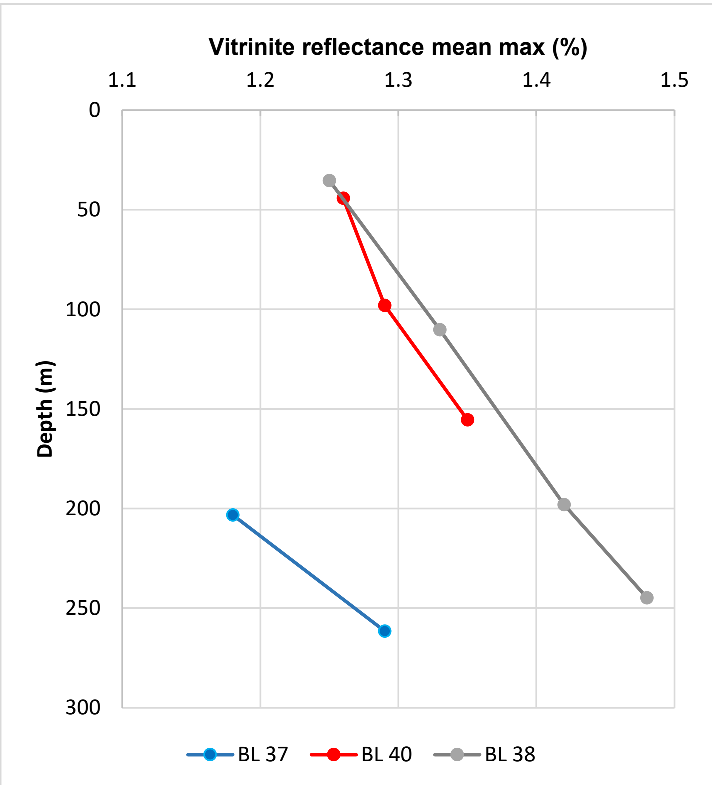

Figure 32. Vitrinite reflectance profiles of the Burngrove Formation (BL 37 and BL 40) and the Fair Hill Formation (BL 38), Oaky Creek (after McKillop, 2016).

Prouza (1976) did not analyse the Fair Hill Formation around Oak Park (Figure 31), but provided detailed descriptions of the lower section of the formation and the coal seams within it. A summary is presented in Table 33.

Table 33. Seams intersected and their approximate depth, Oak Park (Prouza, 1976).

Borehole	Seam(s) intersected	Approximate depth (m)
BL 122	Fairhill	17.5–22.9
BL 128	Canis, Fairhill	No details provided in lithological log
BL 137	Canis, Fairhill	14-19(?), 54-65.2
BL 174	Hercules, Canis, Fairhill	14-22(?), 52-60(?), 91-99(?)
BL 183	Fairhill	27–35.7
BL 188	Fairhill	10–23

The Fair Hill Formation comprised sandstone with minor siltstone, mudstone and coal. The lower boundary was established at the lowest sandstone layer of the formation, which was found to be 7–15 m below the lowest coal seam.

Of note was Prouza's (1976) theory of cyclic sedimentation of the formation, a cyclothem consisting of the following in the Oak Park area:

1. sandstone, medium- to coarse-grained, pebbly at base, 3–7 m thick
2. siltstone, interlaminated with mudstone and fine-grained sandstone, grey to dark grey, up to 12 m thick—shallow water deposition
3. siltstone, massive, dark grey, with fossil plant roots, becoming finer and darker at the top, a few cm thick—alluvial or coastal plain swamps
4. "*Coal seam, consisting mostly of carbonaceous shale, numerous interbeds of light brown tuffaceous and siltstone, and subordinate high-ash coal. Such seams in the Fair Hill Formation were undoubtedly deposited in situ, and are usually thick (up to 55 feet in this area) but dirty, and therefore uneconomic*" (Prouza, 1976, page 14)
5. shale, dark grey, plant fossil, 1–5 m thick—isolated, stagnant freshwater or brackish lagoon.

Not all cycles were complete, presumably due to uplift and subsequent erosion. The seams were banded, with limited amounts of coal and considered to be uneconomic (Prouza, 1976).

3.4.3 Mount Stuart – Comet

The extent of coal seams across the Comet Anticline was investigated by Prouza (1977), who drilled 8 Blackwater series boreholes, extending from Mount Stuart to Comet (BL 176, 180, 181, 182, 185 and 191, Figure 31). The main exploration target, the German Creek Formation, was found to thin out southwards. The Fair Hill and Burngrove formations were found to crop out on both flanks of the anticline but their seams were of poor quality and no further exploration was recommended.

The Fair Hill Formation was described as comprising between 50 to 70% sandstones, interbedded and interlaminated with mudstones and siltstones. Several depositional phases were observed, each starting with a coal seam. The arenites were interpreted as channel or bar deposits and, due to the good sorting and roundness of the quartz grains, were considered to have formed in a transitional environment. Swamp sedimentation represented about 8–17% of the formation thickness, while the seams consisted predominantly of tuffaceous mudstones.

The Burngrove Formation that was intersected across the Comet Anticline was deposited in four phases (Prouza, 1977), described from the base upwards as follows:

1. Grey black mudstone, finely interbedded or massive, with thin beds of whitish tuff:
    - up to 20 m thick in the southern section of the anticline
    - correlated this basal mudstone with the Black Alley Shale of the Springsure Shelf (Anderson, 1971)
    - deposition—anoxic lake.
2. Dark grey mudstone, interbedded with grey siltstone:
    - common organic burrows, plant debris and various types of lamination
    - rare pale-coloured tuffaceous beds
    - thickness up to 20 m
    - deposition—alluvial or tidal plain.
3. Green siltstone interbedded with silty mudstone and fine sandstone:
    1. limited burrowing
    2. thickness 30–55 m
    3. deposition—fluviolacustrine environment.
4. Coal seam overlying sandstones:
    - six coal seams on the eastern flank (total thickness = 60–90 m)
    - three to four seams on the western flank (total thickness = 120–180 m)
    - sub-labile lithic sandstones, with angular coarse grains of different provenance
    - deposition—deltaic environment, with fluvial and paludal influences.

As previously described by Prouza (1976) in the Oak Park area, the coal seams of the Fair Hill and Burngrove formations, cropping out on the flanks of the Comet Anticline, contained abundant carbonaceous shales and tuffs, and were considered of no economic interest (Prouza, 1977).

Vitrinite reflectance was determined only in BL 181 where the values varied between 1.2 and 1.3% at shallow depths ranging from 37 to 76 m (McKillop, 2016).

3.4.4 Blackwater and surrounds

From the mid 1960s onwards the government's policy of proving up 'reserves' of coal to meet targets for future power requirements of Queensland was continued with the commencement of further coal drilling programs in the southern Bowen Basin around the Moura, Theodore and Blackwater areas.

Consequently, exploration on the eastern flank of the Comet Ridge, at the boundary with the central Taroom Trough, was undertaken in the Jellinbah, Caledonia, Curragh, Blackwater and Minyango areas over the next 20 years. In the early 1970s, Staines (1972; 1974), Carr (1973; 1975) and Park (1973a) reported on the findings of the Blackwater series of boreholes drilled in various parts of the region. In the late 1970s, Staines (1977; 1978; 1987), Galligan (1977, 1978) and Galligan & Turner (1979) continued this work, primarily north of the township of Blackwater, with the Leura and Humboldt series of boreholes. Throughout the 1980s, Carr (1981), Thornton (1982), Balfe (1983) and D'Arcy (1985) undertook drilling at Curragh, Curragh East and Northeast Blackwater with the Talbot, Leura and Humboldt series of boreholes. The primary target for all of this drilling was the Rangal Coal Measures but a significant number of boreholes also intersected seams of the underlying Burngrove Formation.

Staines (1972) used earlier departmental drilling information, in conjunction with company exploration data, to correlate seams in the Rangal Coal Measures over a strike length of about 70 km, extending to the north and south of Blackwater (Figure 33). Subsequent departmental drilling was aimed at determining the extent and quality of these coal seams in this region.

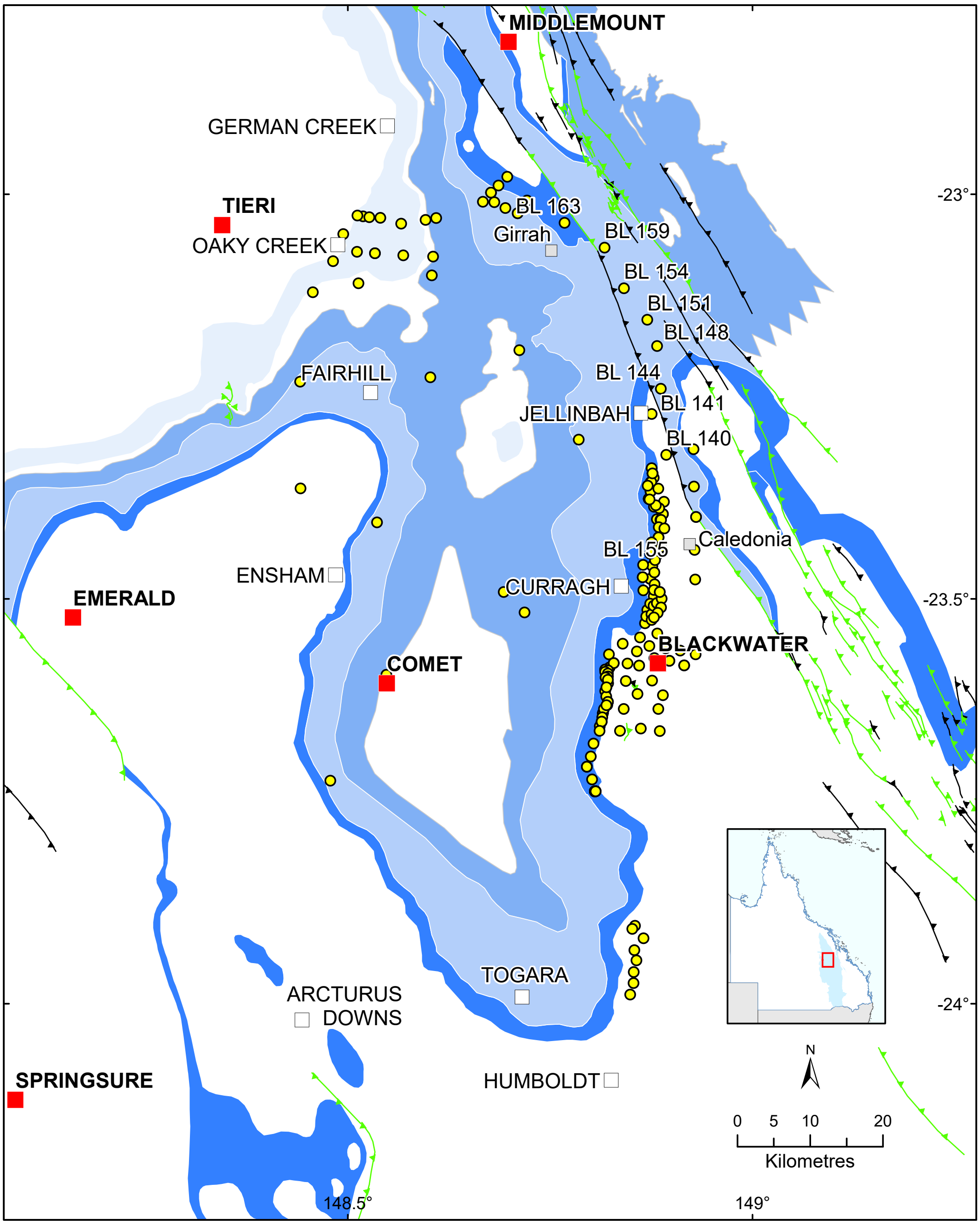

Figure 33. Blackwater (BL) boreholes drilled along strike, north and south of Blackwater (after Staines, 1972 and Carr, 1973). Legend in Figure 7.

3.4.4.1 Girrah – Jellinbah

Carr (1973) reported on 8 Blackwater series boreholes (BL 140, 141, 144, 148, 151, 154, 159 and 163), which were drilled in an attempt to trace the Rangal Coal Measures between the Girrah and Jellinbah homesteads (Figure 33).

The Fair Hill Formation was found to be conformable with the underlying German Creek Formation and at least 200 m thick (base of the latter formation not reached). The upper part of the formation comprised fine-grained liable sandstone interbedded with siltstone. The lower sequence was predominantly mudstone with fawn tuffaceous beds and micaceous sandstone intervals. Eleven coal seams were identified but none was considered workable (Carr, 1973).

The Burngrove Formation was found to conformably overly the Fair Hill Formation, consisting of fine-grained sandstone at the top. As with the Fair Hill Formation, the sandstone was noted as becoming finer and interbedded with siltstone and mudstone towards the base. The sandstones were predominantly green, labile and calcareous in part. The siltstones were described as being green, grey or light grey with tuffaceous intervals. Plant fragments were common in both the sandstones and the siltstones. The seven coal seams intersected were similar to those present in the Fair Hill Formation, being banded and with a high percentage of fawn tuffaceous mudstone or carbonaceous partings.

The Virgo (Girrah) Seam, located at the top of the Burngrove Formation, comprised dull and bright coal; it was the thickest near Girrah homestead (approximately 23 m) and included three 0.5 m-thick brown mudstone bands. This seam was analysed only in Blackwater 163 (Table 34; Figure 33). Carr (1973, page 11) expressed the view that *"Although the Virgo seam at Girrah has a relatively high percentage of bright coal, and correspondingly high crucible swelling numbers, even allowing for discards in washing in excess of 50%, ash percentages of the washed coal still be prohibitively high for coking coal. This seam cannot, therefore, be regarded as a coking coal prospect"*.

Table 34. Cumulative and fractional analytical results—Virgo Seam, Blackwater 163, Girrah area (after Carr, 1973).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Proximate analysis (adb)				CSN	Ash fusion temperatures (°C) (reducing atmosphere)		
						M (%)	Ash (%)	VM (%)	FC (%)		Deform	Hemi	Flow
BL 163	F 1.40	16.0	241.3	241.8	1.32		6.4			>9			
	F 1.50	50.1			1.42		17.2			8			
	F 1.60	72.5			1.46		21.1			7			
	Raw	100			1.58	1.7	31.7	12.7	53.8	3	1330	1480	1520
	F 1.40	50.0	242.8	243.4	1.32		7.4			9			
	F 1.50	69.3			1.36		10.9			8½			
	F 1.60	80.7			1.39		13.8			7½			
	Raw	100			1.47	1.3	21.2	14.3	63.0	5½	1310	1460	1500
	F 1.40	7.4	245.2	246.0	1.31		5.7			>9			
	F 1.50	19.0			1.39		15.5			8½			
	F 1.60	35.			1.47		23.0			7			
	Raw	100			1.74		46.2			1			
	F 1.40	29.7	246.0	248.3	1.33		7.4			9			
	F 1.50	55.0			1.9		13.4			8			
	F 1.60	71.0			1.42		17.2			5½			
	Raw	100			1.54	1.6	27.6	13.2	57.4	2½	1390	1510	1550
	F 1.40	17.5	252.7	254.3	1.31		5.6			>9			
	F 1.50	42.6			1.40		15.4			8			
	F 1.60	58.5			1.44		19.5			7½			
	Raw	100			1.60	1.4	31.0	14.4	52.9	2½	1240	1330	1380
	F 1.40	15.6	254.3	255.2	1.32		6.2			>9			
	F 1.50	46.9			1.41		17.1			8			
	F 1.60	73.9			1.47		21.9			6			
	Raw	100			1.59	1.7	31.5	12.9	53.8	3	1310	1450	1490
	F 1.40	12.5	255.2	254.3	1.31		4.3			>9			
	F 1.50	28.2			1.40		14.5			9			
	F 1.60	46.0			1.46		21.1			8			
	Raw	100			1.67	1.9	39.9	11.5	46.5	2	1330	1480	1520
	F 1.40	12.9	258.4	260.2	1.31		5.9			>9			
	F 1.50	27.5			1.39		14.9			9			
	F 1.60	43.8			1.45		21.1			8			
	Raw	100			1.67		38.1			2½			

3.4.4.2 Jellinbah–Caledonia

Following up on Carr's (1973) work, Park (1973a) drilled 6 boreholes (Blackwater 168, 173, 175, 177, 179 and 184R—a redrill of Blackwater 175), with the intention of testing the eastern extension of the Rangal Coal Measures seams in the Jellinbah–Caledonia area (Figure 34).

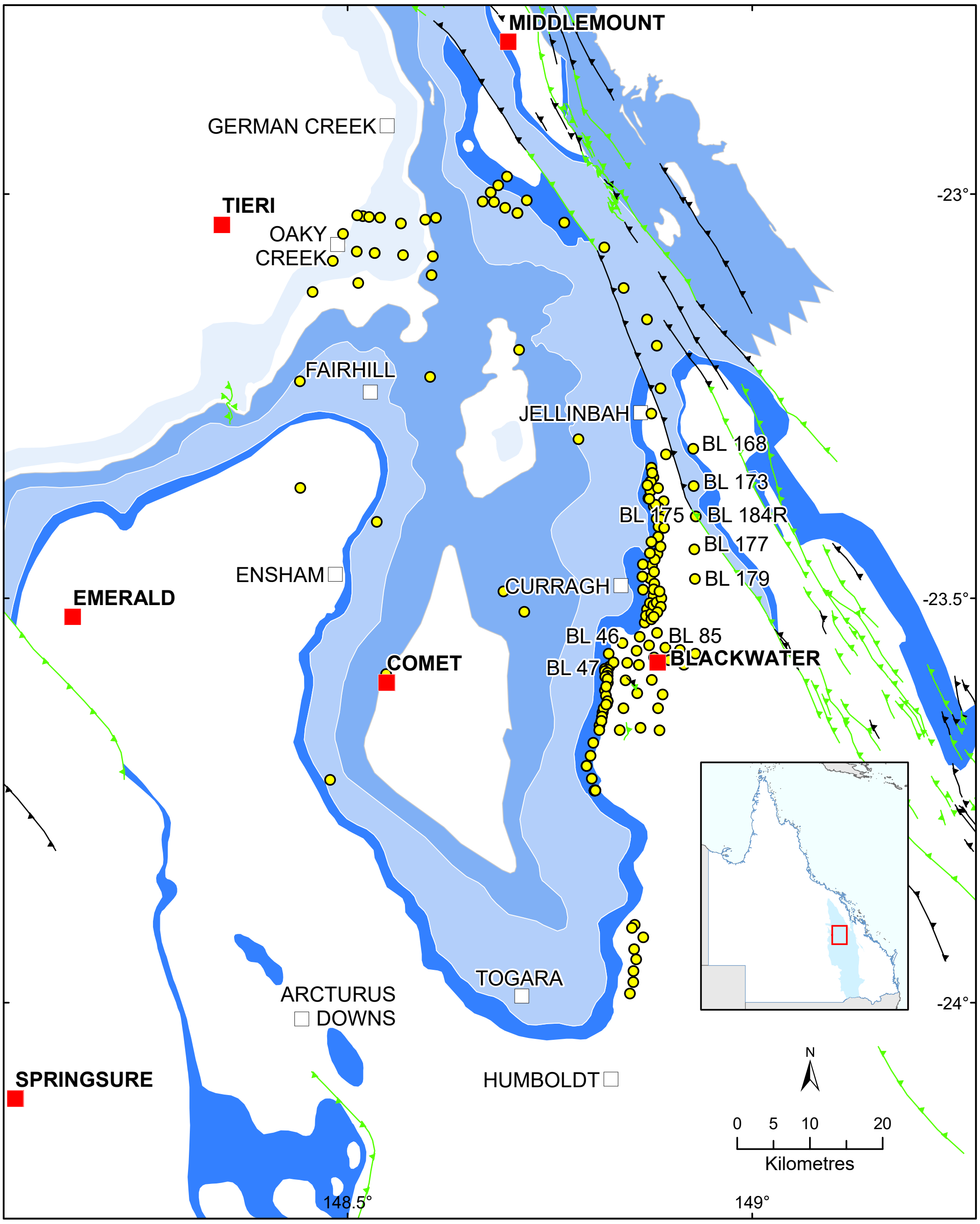

Figure 34. Blackwater boreholes drilled in the Caledonia area (after Park, 1973a). Legend in Figure 7.

Only the Burngrove Formation was intersected by boreholes drilled at Caledonia. The maximum thickness encountered was 240 m in BL 173, although the lower boundary was not reached. The formation comprised greenish-grey mudstones and siltstones, interbedded with light green fine- to medium-grained labile sandstones. The upper part of the formation contained banded seams of up to 10 m in thickness and abundant fossil leaves (Park, 1973a). The lower part consisted of dark grey mudstones with pale-coloured tuffaceous bands, which were correlated with the Black Alley Shale on the Springsure Shelf, as previously described by Anderson (1971).

Park (1973a) interpreted the deposition in the Caledonia area as occurring during a regressive phase. The fine sediments of the lower Burngrove Formation represented a pro-delta, which was eventually encroached by channel sands and interdistributary facies that formed the upper Burngrove Formation and the overlying Rangal Coal Measures. During times of exposure, vegetation growth allowed development of peat swamps.

The coal seams identified in the Caledonia area differed substantially, in terms of thickness and quality (Table 35). The Virgo Seam was about 10 m thick in BL 179, thinning to around 5 m northward in BL 173, and splitting into two 2 m sections further north in BL 168 (Figure 34). The coal was analysed for its coking potential in BL 177 and BL 179, where washing selected samples to a specific gravity of 1.45/cm^3 produced a low ash, high CSN coal with yields exceeding 50% (Table 35).

Table 35. Raw and fractional analytical results—Blackwater 173, 177, 179 and 184R, Caledonia area (after Park, 1973a).

Borehole Seam	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)			
BL 173 Virgo	Raw	100	52.3	53.4	1.64	1.8	36.0	10.9	51.3	22.3	1.01	1
	Raw	100	53.4	55.1	1.94	3.2	60.6	8.6	27.6	11.3	0.43	0
	Raw	97.4	55.1	56.7	1.63	1.7	35.0	13.0	50.3	22.2	0.69	1
	Raw	93.9	56.7	57.5	1.67	2.0	39.4	11.3	47.3	20.6	0.57	1
Leo	Raw	100	106.2	107.0	1.68	1.3	37.6	13.5	47.6	20.7	0.66	1
Scorpio	Raw	91.5	193.0	194.2	1.75	1.6	43.9	11.6	42.9	18.4	0.36	½
BL 177 Virgo	F 1.45	32.8	391.8	393.0	1.37	1.7	10.1	16.8	71.4		0.6	9
	Raw	100			1.62	2.2	36.8	13.4	47.6			
	F 1.45	33.0	395.2	396.8	1.38	1.7	11.2	16.8	70.3		0.54	8½
	Raw	100			1.64	2.2	35.9	13.9	48.1			
	F 1.45	77.1	397.8	399.3	1.35	1.4	8.9	17.8	71.9		0.54	>9
	Raw	100			1.42	1.4	16.4	17.6	64.6			
	F 1.45	22.6	399.3	400.0	1.30	1.3	9.4	18.1	71.2			>9
	Raw	100			1.65	1.9	39.1	13.7	45.3			
BL 179 Virgo	Raw	100	310.5	311.6	1.69	2.6	42.6	13.8	41.0			
	Raw	100	313.6	314.9	1.65	2.2	39.6	12.3	45.9			
	F 1.45	53.4	316.1	317.5	1.39	1.5	15.4	15.6	67.5		0.33	5½
	Raw	100			1.54	2.0	28.0	14.1	55.9			2½
	F 1.45	90.4	317.5	318.8	1.37	1.2	13.1	17.3	68.4		0.52	9
	Raw	100			1.44	1.9	17.7	16.1	64.3			7½
BL 184R Virgo	F 1.40	42.3	395.1	396.9	1.35		7.4					4½
	F 1.50	70.3			1.39		10.9					1½
	F 1.60	80.2			1.40	1.6	12.5	14.8	71.1	30.0	0.39	1
	Raw	100			1.51	1.5	19.4	16.4	62.7	26.9		1
	F 1.40	39.5	398.2	399.5	1.33							8
	F 1.50	71.0			1.38							3½
	F 1.60	81.3			1.40	1.5	13.4	15.1	70.0	30.6	0.38	2
	Raw	100			1.51	1.5	19.9	16.5	62.1	27.3	0.36	1

Three boreholes were selected for vitrinite reflectance determinations (Figure 35). The results showed that the coal samples taken from BL 168 and BL 173 fall outside the coking window.

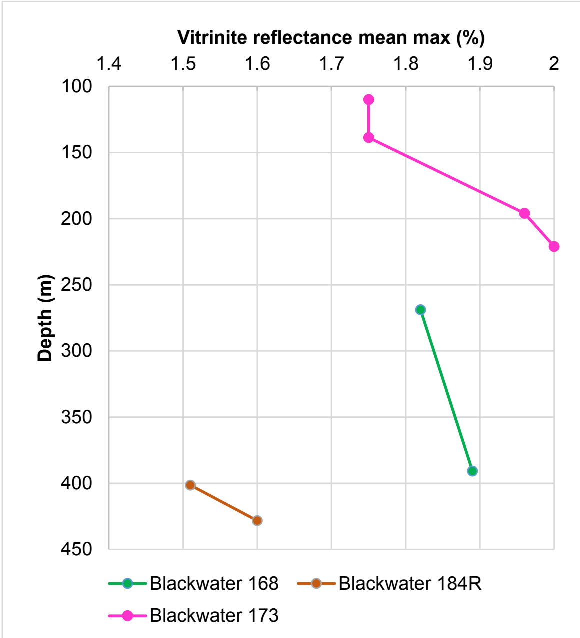

Figure 35. Vitrinite reflectance profile of the Burngrove Formation, northeast of Caledonia (after McKillop, 2016).

Further departmental drilling in the area was undertaken by Staines (1977; 1987) in order to determine estimates of coal 'reserves/resources' in coal seams of the Rangal Coal Measures to 'measured' and 'indicated' levels of confidence, in accordance with the departmental parameters and national codes in use at that time. He did not add to the formation descriptions published by his predecessors for the area, but he mentioned that the green colouration of the Burngrove Formation was uniform to mottled and some sections contained *"distinctive elliptical pea-sized dark green patches with lighter rims"* (Staines, 1977, page 10). The formation was thickest near Jellinbah Homestead (366 m) and thinned towards Blackwater (134 m), although none of the Blackwater boreholes intersected the bottom of the formation. The seams encountered (descending stratigraphic order) were the Virgo, Libra, Leo, Aquarius and Scorpio. All were banded with the in-seam partings comprised of light brown, grey-brown or cream-coloured tuffaceous mudstones.

The Virgo Seam was the most persistent in the area ranging in thickness from about 3.7 to 12.2 m, although most frequently was about 6 m thick. Three brown mudstone bands separated the coal plies. The ash content was found to be too high for the seam to be saleable at the time (Table 36; Figure 34). The other seams were occurring inconsistently and, although they had some good quality sections, they were also considered uneconomic (Staines, 1977). The vitrinite reflectance of coal sampled in BL 85 was approximately 1.3% (McKillop, 2016).

Table 36. Raw and fractional analytical results—Virgo Seam, Blackwater 85, Blackwater area (after Staines, 1977)

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g\cm^3)	Proximate analysis (adb)				S (%)	CSN	Ash fusion temperatures (°C) (reducing atmosphere)		
						M (%)	Ash (%)	VM (%)	FC (%)			Deform.	Hemi.	Flow
BL 85	F 1.40	37.1	275.7	277.1			7.2							
	F 1.50	51.7					11.4							
	F 1.60	65.5					15.2							
	Raw	100			1.58	2.1	31.6	18.5	47.5	0.51	4	1080	1135	1360

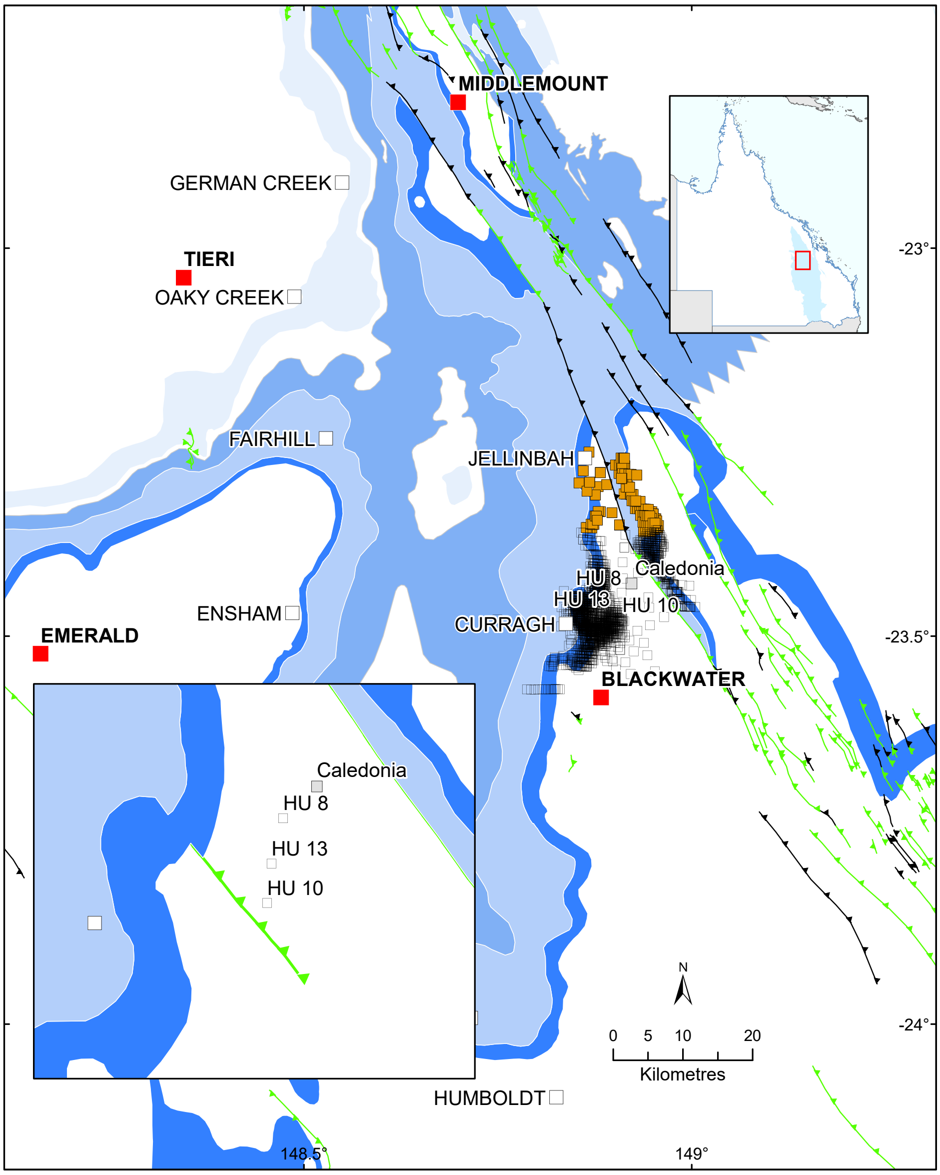

Figure 36. Humboldt (HU) boreholes near Caledonia Homestead. Legend in Figure 7.

Additional testing was carried out by Staines (1978) in a few Humboldt boreholes (Table 37; Figure 36), where the coal presented good swelling properties.

Table 37. Raw and fractional analytical results—Virgo Seam, Humboldt 8, 10 and 13, Caledonia area (after Staines, 1978).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g\cm^3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	P (%)	CSN	Ash fusion temperatures (°C) (reducing atmosphere)		
						M (%)	Ash (%)	VM (%)	FC (%)					Deform	Hemi.	Flow
HU 8	Raw	100	255.2	256.5	1.81	1.9	47.9	11.7	38.5	17.1	0.27	0.04	2½			
HU 10	F 1.60	80.7	160.5	161.8		1.1	16.1	18.0	64.8	29.6	0.49	0.02	8	1400	1520	1590
	Raw	100			1.48								7			
	F 1.60	60.4	162.5	163.7		1.3	20.8	17.1	60.8	27.8	0.50	0.04	8	1300	>1600	>1600
	Raw	100			1.61								3			
HU 13	F 1.40	15.9	179.6	181.5			7.7						>9			
	F 1.50	28.9				1.5	14.4	17.3	66.9	30.6	0.56	0.02	8½	1380	>1600	>1600
	F 1.60	44.0					20.3						8			
	Raw	100			1.74		44.5						1½			
	F 1.40	19.5	181.9	183.7			7.0						>9			
	F 1.50	31.5				1.3	12.5	18.4	67.7	31.3	0.59	0.01	9	1380	>1600	>1600
	F 1.60	42.0					17.3						8½			
	Raw	100			1.72		43.0						2			

In 1980, a new program of shallow drilling was commenced in the area between Jellinbah and Blackwater. The main objectives of the program were to understand the local structure, in particular the nature of the Jellinbah Fault, to determine 'reserves' of coal potentially suitable for open-cut mining and to ascertain whether or not a coking fraction might be obtained from the seams of the Rangal Coal Measures. The drilling consisted of more than 230 Talbot and Humboldt boreholes (Figure 37), totalling about 25,000 m of drilling, of which about 500 m was cored (Carr, 1981). No descriptive information on the Burngrove or Fair Hill formations was provided in the geological report on this work.

To upgrade the estimated 'reserves' of coal to 'measured' status (in accordance with the departmental parameters in use at that time) and examine structural features in more detail, another program of more than 330 Talbot, Leura and Humboldt series boreholes was drilled at Jellinbah. Based on this drilling, Balfe (1983) subdivided the Pisces Seam into an upper *"working section"* (page 12), comprising a relatively unbanded ('clean') upper portion of the seam he placed within the Rangal Coal Measures. The underlying Pisces Lower Seam, which comprised the higher ash more banded portion of the Pisces coal interval, was placed by Balfe (1983) as the upper most seam in the underlying Burngrove Formation. The Pisces 'working section' had an average thickness of about 2 m and was best represented near Humboldt 2116 (Figure 37, inset a). The Pisces Lower had a highly variable thickness of up to 12 m. The two sections were separated by a tuffaceous horizon (presumably a Yarrabee Tuff equivalent), which was well-developed in places (i.e., between Humboldt 1992 and Humboldt 1940; Figure 37, inset b). The boundary between the Rangal Coal Measures and the Burngrove Formation was thus interpreted to be at the top of a tuffaceous layer within the Pisces Seam and not at the base of this seam interval as Staines (1972) had initially done.

Further north, in Humboldt 1937, 1941 and 2072 (Figure 37, inset b), the Pisces Seam was found to coalesce with the Virgo Seam, reaching a combined thickness of about 15 m. Where separated, the Virgo Seam was up to 7 m thick but was banded and tuffaceous throughout.

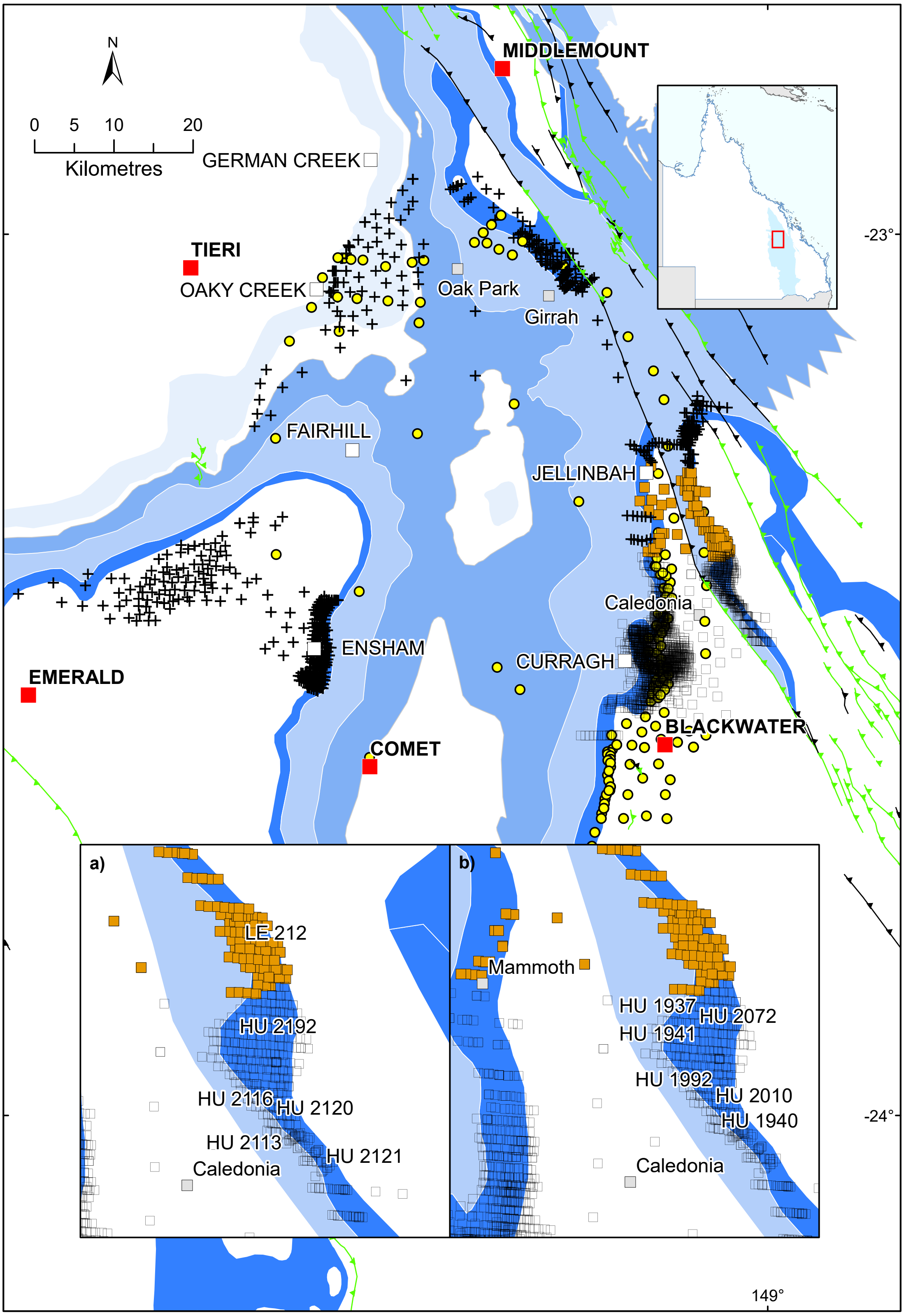

Figure 37. Humboldt (HU) and Leura (LE) boreholes, Caledonia area. Legend in Figure 7.

Although Balfe (1983) did not consider the Pisces seams to be of economic significance, raw coal samples were selected for proximate and ultimate analyses (Table 38; locations in Figure 37, inset a). Ash was significantly higher in the Pisces Lower than in the overlying working section of the Pisces Seam. The maceral group analysis revealed the dominance of vitrinite and semi-inertinite. The vitrinite reflectance of the coal sampled ranged from 1.75 to 1.80%.

Table 38. Comparative raw coal analytical results—Pisces working section (Pws; Rangal Coal Measures) and Pisces Lower (PL, Burngrove Formation), Humboldt 2121, 2113, 2120, 2116, 2192 and Leura 212, Caledonia area (after Balfe, 1983).

Borehole	Seam	Depth from (m)	Depth to (m)	Specific gravity (g\cm³)	Proximate analysis (adb)				S (%)	P (ppm)	Specific energy (MJ/kg)
					M (%)	Ash (%)	VM (%)	FC (%)			
HU 2121	Pws	72.2	74.1	1.53	2.0	22.2	13.6	62.0	0.60	580	26.6
	PL	74.7	76.2	1.78	1.7	46.6	11.0	40.7	0.43	280	17.6
HU 2113	Pws	75.3	77.9	1.44	1.5	14.11	14.5	69.9	0.53	570	30.0
	PL	78.8	80.4	1.78	1.3	47.8	10.4	40.5	0.38	150	17.3
	PL	80.9	81.6	1.57	1.5	28.8	12.0	57.7	0.58	500	24.5
HU 2120	Pws	61.3	63.6	1.43	1.7	14.9	13.4	70.0	0.49	560	29.8
	PL	64.3	66.5	1.66	1.4	37.1	12.3	49.2	0.50	240	21.3
HU 2116	Pws	55.9	57.9	1.42	2.2	13.6	13.5	70.7	0.50	550	30.3
	PL	58.3	59.6	1.60	1.4	32.7	12.5	53.4	0.61	270	23.2
HU 2192	Pws	46.5	48.1	1.53	1.6	22.9	16.2	59.3	0.50	880	25.8
	PL	48.9	50.9	1.75	1.7	44.0	12.7	41.6	0.53	270	18.2
LE 212	Pws	62.6	63.3	1.55	2.0	21.4	15.4	61.7	0.73	360	26.4
	PL	63.8	69.2	1.77	1.8	42.7	11.9	43.6	0.33	1470	18.7

The ultimate analyses showed an overall drop in the atomic ratios of hydrogen to carbon, as well as oxygen to carbon, between samples taken from the Pisces Lower Seam, in comparison to those taken from the stratigraphically higher (younger) Pisces 'working section' (Figure 38). According to van Krevelen (1981, figure VI,3) such a pattern may indicate dehydration as part of the coalification process, although given that the samples are, stratigraphically, only a few metres apart, this seems unlikely. The proximity of the two sets of samples probably also rules out effects caused by heating due to intrusions. The decrease of the atomic ratios is, therefore, considered more likely to be a reflection of the maceral composition. In addition, it is possible that the higher frequency of tuffaceous and argillaceous influx in the lower Pisces Seam might have prevented oxidation of the plant material in the peat mire, which has resulted in higher vitrinite content and the difference between the seams (Ray Smith, pers. comm).

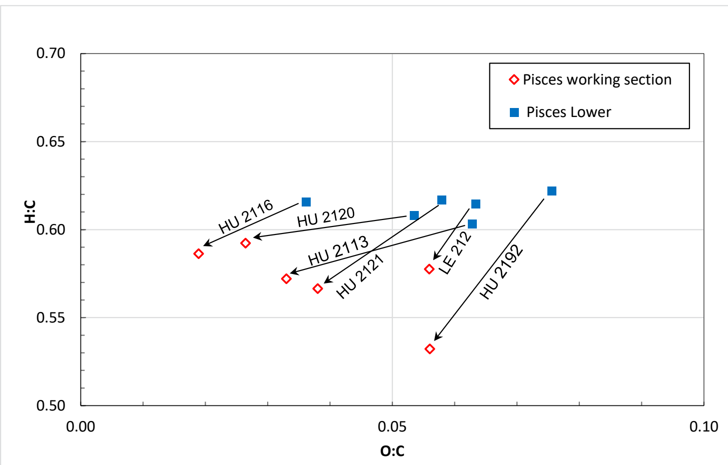

Figure 38. Comparative atomic ratios for selected boreholes (data from Balfe, 1983).

3.4.4.3 Curragh

The exploration of the Curragh area (~10 km north of Blackwater) started in the mid-1970s with the completion of more than 2000 Humboldt and Leura boreholes, totalling approximately 80,000 m of drilling. Only 344 boreholes (~3300 m) were fully cored. The drilling program targeted the shallow seams (<55 m deep) in the Rangal Coal Measures. Galligan (1977) initially provided estimates of raw coal 'reserves' regarded to be at a 'measured' confidence level, comprising both thermal and coking coal. Galligan (1978) later published the results of analyses undertaken on these coals that included washability data, as well as thermal and coking properties. He also provided detailed descriptions as follows: *'The Burngrove Formation consists of light green, light grey and grey mudstone and siltstone, with subordinate fine sandstone and seams of coal and carbonaceous mudstone with tuffaceous bands. The greenish colour and banded coal seams are two easily recognizable characteristics of the formation. As the boundary between the Burngrove Formation and overlying Rangal Coal Measures is gradational, for convenience, the top of the uppermost coal seam, the Virgo seam, is nominated as the top of the Burngrove Formation. In the southern half of the area the Virgo seam is up to 40 m thick and lies immediately below the Pisces seam which is the lowermost seam of the Rangal Coal Measures. Some good coal plies are present but do not appear to have wide lateral extent. Numerous and often thick interbands of tuff and tuffaceous mudstone are present. Several thin banded seams below the Virgo seam have been intersected on the western extent of some drill traverses'* (Galligan, 1978, page 13–14). The nature and extent of the seams within the Rangal Coal Measures further towards the east was later investigated and reported on by Galligan & Turner (1979) and Thornton (1982).

As previously mentioned by explorers of the eastern flank of the Comet Ridge, the greenish colour of the sediments and the banded nature of the seams were commonly described as being defining characteristics of the formation. Galligan (1978) placed the boundary with the Rangal Coal Measures at the top of the Virgo Seam. This seam was found to be up to 40 m thick in places and occurred immediately below the Pisces seam in the south, towards Blackwater. Although some good coal plies were present, they were not laterally extensive. The conclusion was that, despite their thickness and the occasional good quality, the seams were *"extremely banded and are not of economic interest at present"* (Galligan, 1977, page 6).

3.4.4.4 Blackwater

Following up the discovery of coking coal south of Blackwater in 1962 by Utah Development Company, the Department commenced the drilling of the Blackwater series of boreholes.

Over the next 20 years, regional exploration was initially focused on shallow thermal and coking coal, potentially suitable for open-cut mining. Over time, and as the region was progressively evaluated, attention was increasingly focussed on areas where coal seams were deeper or those areas where limited exploration had previously been undertaken.

These programs drew to a close in 1984 with the drilling of ten Humboldt boreholes 5 km northeast of Blackwater, to investigate seams within the Rangal Coal Measures likely to be present at depths more suited to underground mining (D'Arcy, 1985). This program also intersected the top of the Burngrove Formation, which was described and sampled. The drilling program included HU 2328 to HU 2338, of which HU 2328 and HU 2332 were fully cored (Figure 39).

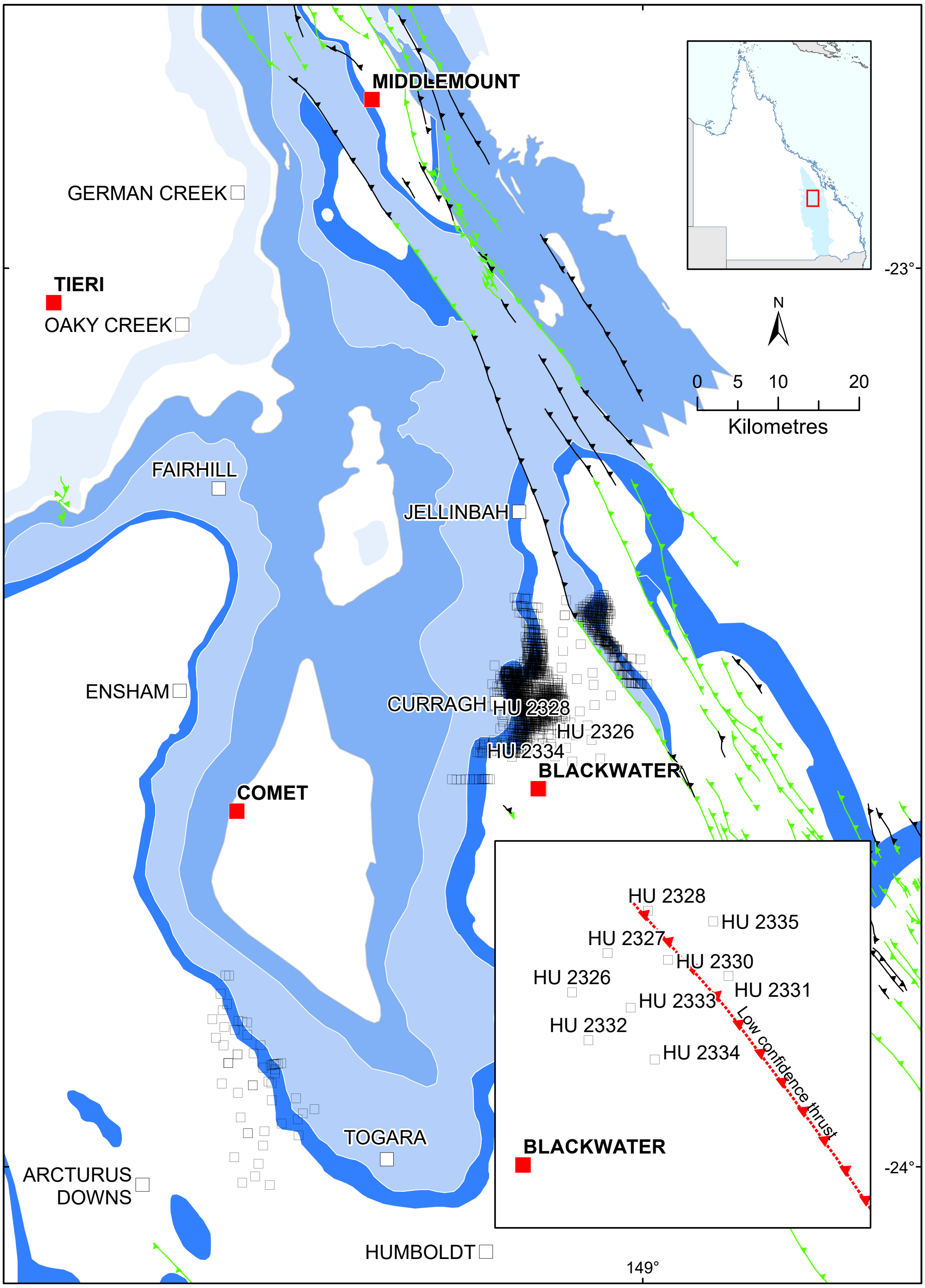

Figure 39. Humboldt (HU) boreholes near Blackwater. Legend in Figure 7.

The top of the Burngrove Formation consisted mainly of fine- to medium-grained labile sandstone, with siltstone and mudstone interbeds. The sandstones were typically light grey-green, while the siltstones were darker shades of green-grey, which was the typical colour of the formation. Mudstone and cream to fawn tuffaceous interbeds were common and generally concentrated in the coal seams (D'Arcy, 1985).

The boundary with the overlying Rangal Coal Measures was gradational and established by D'Arcy (1985) at the top of a tuffaceous marker horizon, which was a section of the Pisces Seam. The choice of an intraseam tuffaceous boundary was also made by Balfe (1983) at Caledonia, a few kilometres north of Blackwater.

The basal section of the Pisces Seam was considered part of the Burngrove Formation and was intersected in all the boreholes. It was 1.7 to 3.6 m thick and consisted primarily of carbonaceous and tuffaceous mudstone.

The Virgo Seam was found in the north but not in HU 2332 and HU 2334 (Figure 39 inset). It was only 1.2 to 2.3 m thick and, although similar lithologically to the lower Pisces Seam, it was highly variable in terms of coal content. The most coaly intersection was found in HU 2327 (Table 39; Figure 39), while in HU 2331, the seam had no coal plies at all.

The Leo Seam was the thickest and most consistent seam intersected and typically located about 10 m below the Virgo Seam. It ranged from 4 m thick in HU 2327 to more than 8 m in HU 2333. Five distinct sections were described in the Leo Seam:

1. upper coaly interval: 0.6 to 1.8 m thick, comprising interbedded coal, carbonaceous mudstone, tuffaceous sediments with minor siltstone and sandstone
2. upper tuffaceous interval: 0.4 to 2.5 m thick, comprising interbedded carbonaceous and tuffaceous mudstone
3. middle coaly interval (sampled in HU 2332 and 2333, Table 39): 0.3 to 1.3 m thick, comprising moderately bright coal with thin beds and laminae of carbonaceous and tuffaceous mudstone
4. lower tuffaceous interval: 0.3 to 1.7 m thick, comprising dominantly tuffaceous mudstone and siltstone
5. lower coaly interval (sampled in HU 2326, 2328, 2332 and 2333, Table 39): 0.9 to 4.0 m thick, comprising relatively bright clean coal and further subdivided in a 'banded section' and a 'basal section'.

The raw ash content was high even in the sections with bright coal, such as the middle and lower coaly intervals (Table 39). High CSN values were characteristic of the 1.60 fraction, although some of the yields were below 50%. The ash fusion (initial deformation, reducing atmosphere) temperatures were all under 1600 (D'Arcy, 1985).

Table 39. Raw and fractional analytical results—Virgo and Leo seams, Humboldt 2327, 2326, 2328, 2332 and 2333, Blackwater (after D'Arcy, 1985).

Borehole	Seam (section)	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
							M (%)	Ash (%)	VM (%)	FC (%)			
HU 2327	Virgo (coaly top)	Raw	95	256.6	257.2	1.58		32.0					
	Virgo (prime)	F 1.40	32.4	257.3	258.9			7.9					>9
		F 1.60	70.8				1.4	16.8	18.0	63.9	29.2	0.51	8½
		Raw	100			1.52		27.4					6½
HU 2326	Leo (banded upper)	Raw	82	266.4	267.8	1.81		49.7					
	Leo (banded lower)	F 1.40	10.0	267.8	268.8			3.9					
		F 1.60	35.0					21.0					
		Raw	100			1.77		48.4					
	Leo (basal)	F 1.40	26.0	268.8	270.4			6.0					>9
		F 1.60	79.8					16.4					7
		Raw	100			1.51		23.8					3
	Leo (banded lower + basal)	F 1.40	19.6	267.8	270.4			7.5					
		F 1.60	61.8				1.2	17.4	18.3	63.1	29.2	0.48	
		Raw	100			1.61		33.4					
HU 2328	Leo (basal)	F 1.40	22.1	247.4	248.8			6.2					>9
		F 1.60	71.3				1.4	17.0	17.8	64.0	29.2	0.47	6
		Raw	100			1.55		27.5					2
HU 2332	Leo (middle coaly)	F 1.40	9.9	305.5	306.5			4.8					>9
		F 1.60	53.3					22.4					7
		Raw	100			1.66		40.9					1
	Leo (banded)	Raw	100	307.5	308.0	1.83		50.7					
	Leo (basal)	F 1.40	20.6	308.0	309.4		0.8	6.5	21.8	70.9		0.54	>9
		F 1.60	73.6					18.7					7
		Raw	100			1.58		28.3					2½
HU 2333	Leo (middle coaly)	F 1.40	9.9	348.9	350.1			4.1					9
		F 1.60	45.5					22.2					4½
		Raw	100			1.71		42.2					1
	Leo (banded)	Raw	100	351.0	351.6	1.76		44.8					
	Leo (basal)	F 1.40	21.5	351.6	353.2			4.5					9
		F 1.60	78.7				1.4	17.9	17.3	63.4	28.9	0.46	4½
		Raw	100			1.54		24.5					2½

Vitrinite reflectance values ranged between 1.41 and 1.46% in the Burngrove Formation seams. Of note and based upon the vitrinite reflectance values, was the difference inferred in geothermal gradient between HU 2328 and HU 2326 (Figure 40; locations in Figure 39), which appeared to be located on opposite flanks of a thrust fault inferred by Sliwa *et al.* (2008). Although D'Arcy (1985) did not find evidence of duplication or removal of strata in the Burngrove Formation intersections, the slikensides and fractures observed in core were interpreted as fault-related disturbance.

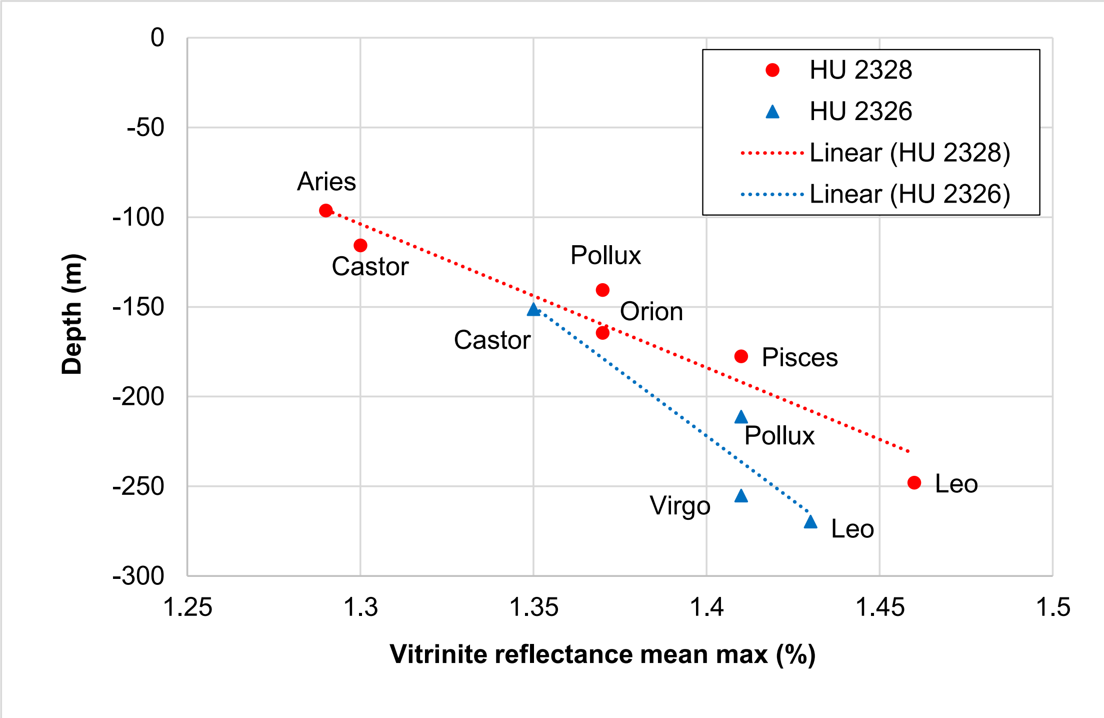

Figure 40. Vitrinite reflectance variation with depth in coal seams north of Blackwater (data from D'Arcy, 1985).

In conclusion, while the Virgo Seam and the 'middle coaly interval' of the Leo Seam were considered thin and inferior in quality northeast of Blackwater, D'Arcy (1985, page 45) considered "*Some potential exits for the lateral extension of the Leo seam 'basal section' up dip to the west. At shallow depth suitable for open-cut mining this seam may be economically viable, as although it is relatively high in ash it has a number of good coking properties and may have some application as a blending coal. A shallow drilling program may be warranted to investigate this possibility at a future date*".

3.4.4.5 Minyango

Eight boreholes (BL 115 to 121 and BL 124; Figure 41 inset) were drilled in the Minyango area, proximal and to the south of Blackwater township, with the aim of proving 'reserves' of coal in seams of the Rangal Coal Measures (Carr, 1975). Intersections of the underlying Burngrove Formation in the area consisted of light greenish-grey, fine to medium-grained labile sandstone interbedded with greenish-grey tuffaceous siltstones and fawn coloured mudstones. Only the upper three seams were intersected (Virgo, Leo and Aquarius), with the entire Pisces Seam considered part of the Rangal Coal Measures.

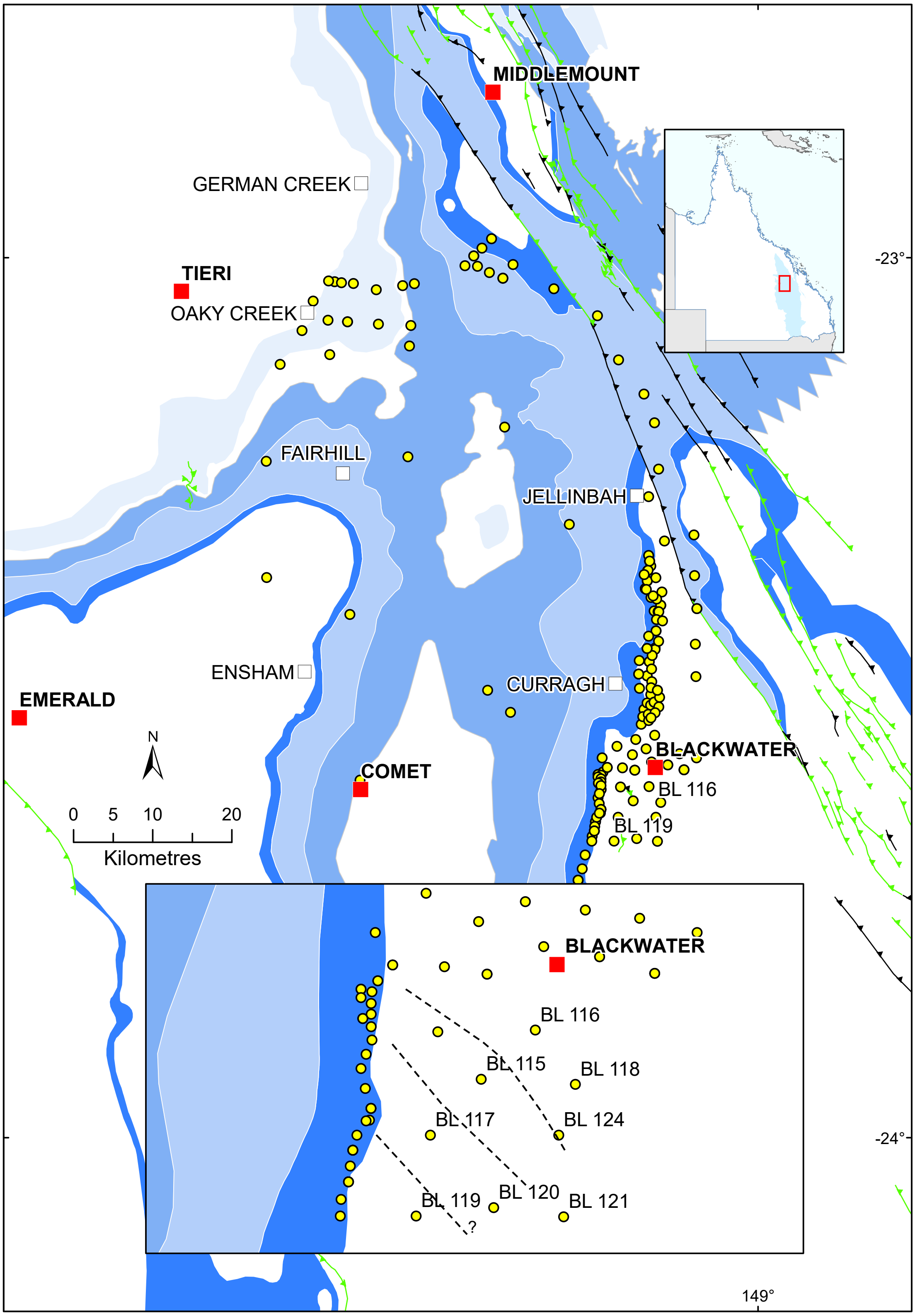

Figure 41. Blackwater boreholes and inferred faults in the Minyango area (after Carr, 1975). Legend in Figure 7.

The Virgo Seam contained tuffaceous mudstones and dull coal. It was split by a thick sandstone bed and consequently, considered unworkable. The Leo Seam was found only in BL 116 and 120, about 30 m below the Virgo. It was almost 4 m thick and split by a greyish-fawn tuffaceous mudstone. Although Carr (1975) considered the upper section of better quality than the lower section, the Virgo Seam was deemed uneconomic based on thickness and scarcity. Only BL 116 was deep enough to reach the Aquarius Seam, located about 26 m below the Leo Seam. It was only 2 m thick and thinly interbedded with coal and carbonaceous mudstones.

3.4.4.6 Summary

A comprehensive summary of the Blackwater exploration drilling program (eastern flank of the Comet Anticline) up until the early 1970s and its findings was provided by Staines (1974). Along with 'proven reserves' in the Rangal Coal Measures, he also published the most detailed formation and seam descriptions of the Comet Ridge, based on all the Blackwater boreholes drilled from Oaky Creek and Girrah in the north, to south of Blackwater. Subsequent exploration has not challenged the basic stratigraphic understanding acquired at that time, other than to place the boundary between the Rangal Coal Measures and the underlying Burngrove Formation at the top of the marker tuff within the Pisces Seam (Balfe, 1983; D'Arcy, 1985), rather than at the top of the underlying Virgo Seam. Presented below is Staines' (1974, pages 5, 6, 11) summary on exploration findings.

"The Fair Hill Formation consists predominantly of fine-grained lithic arenite and siltstone, minor mudstone, and coal. It sub-crops beneath the Cainozoic cover in the Oaky Creek area. A complete section has not been drilled, but in adjacent area its thickness ranges from 90 to 150 m. Cyclic sedimentation is recognizable, though many cycles are incomplete (Prouza, 1974 (sic) [refers to Prouza (1976) which was in preparation at the time]. *The arenites are commonly calcareous, and in places greenish, and contain a few fossil logs. Thinly interbedded sections of siltstone, mudstone, and fine sandstone occur, and show abundant evidence of organic activity. Plant fossils of the Glossopteris flora are common in the mudstone. The formation contains six coal seams. They are commonly thick (up to 16m) and contain numerous beds of carbonaceous mudstone and light coloured tuffaceous mudstone.*

The arenites are probably fluvial, while the lutaceous sediments probably represent a brackish coastal environment with periods of swampy conditions during which the coaly sections accumulated.

The Burngrove Formation comprises light green, light grey, and grey mudstone, siltstone, and subordinate fine arenite, and minor seams of coal and carbonaceous mudstone. The green coloration where it occurs is characteristic, especially where it appears as dark green patches with lighter rims. Much of this formation is calcareous (Staines, in Davis, ed., 1971).

Thickness increases northwards and eastwards from 135 m around Blackwater (Staines, ibid.) to 250 m at Oak Park (Staines, 1973) and 365 m at Jellinbah (Carr, 1973).

The lower third of the formation consists of grey laminated strata which contain organic burrows, but are devoid of coal. A middle section of variable thickness comprises green massive sediments with rare burrows. The remaining upper part of the formation consists usually of grey laminated sediments".

"Coal seams occur at six or seven levels in the formation, but none is workable. They characteristically contain bands of light brown tuffaceous mudstone. Beds of white siliceous mudstone crowded with plant fossils, mostly Glossopteris, crop out conspicuously in some places.

"The Virgo seam, the topmost of the Burngrove Formation, persists throughout the area. Its thickness varies widely, but commonly about 8 m. The seam consists of interbedded carbonaceous mudstone, brown tuffaceous mudstone, and coal, in roughly equal proportions. It is thickest (up to 23.5 m) in the Girrah area, where the proportion of coal is also greater (Carr, 1973). Three of the brown mudstone

bands are 0.4 to 0.8 m thick and are characteristic of the seam. Despite the thickness of some the coal plies, the ash content is high, and the seam is generally unworkable.

These five seams [Libra, Leo, Aquarius, Scorpio, Centaur] *occur, in descending order, below the Virgo seam. They also consist of interbedded carbonaceous mudstone and coal, and typically include a number of bands of light brown tuffaceous mudstone. Their thicknesses are quite variable, but the Leo seam is generally thicker (4 to 9 m) and more coaly than the others. It has a distinctive marker band similar to those in the Virgo seam. Although these seams contain some sections of good quality coal, such sections are impersistent, and consequently none of the seams would in practice be workable.*

The Fair Hill Formation includes from six seams, in the Oaky Creek area (Prouza, 1973), to at least eleven seams, in the Jellinbah-Girrah area (Carr, 1973). The seams consist of carbonaceous mudstone, minor coal, usually inferior, and numerous interbeds of light coloured tuffaceous mudstone.

Names applied to the six seams in the Oaky Creek area are, in descending order, Phoenix, Pegasus, Hercules, Canis, Lepus, and Fair Hill. The Hercules in the thickest (16.7 m) and the basal seam, the Fair Hill, ranges from 8.0 to 11.3 m. It is difficult to correlate the eleven seams in the Jellinbah-Girrah area with the named seams".

3.4.5 Emerald

The Emerald area was explored in several stages, initially north of the town and subsequently continuing east and southeast along strike. Initial boreholes were named 'Emerald' after the locality but later boreholes were prefixed 'Talbot' and 'Denison' after the counties in which they were located. The exploration primarily targeted the Rangal Coal Measures at depths that might be suitable for either open cut or underground mining but also extended into the underlying Burngrove and Fair Hill formations to provide stratigraphic control.

Park (1973b) reported on boreholes Emerald (EM) 1 to 17 and also provided very detailed descriptions of core taken from both the Fair Hill and Burngrove formations. The next series of Emerald boreholes (EM 18 – EM 34) was drilled and reported by Park (1974) who analysed the Virgo Seam in boreholes EM 25 and EM 30 (Figure 42). The drilling continued with boreholes EM 35 to EM 65, from which Park & Galligan (1974) analysed the Virgo Seam in EM 55. The following stage of the drilling program included EM 76 to EM 88 and a number of Talbot boreholes (Galligan, 1976). The main purpose of this latter program was to improve the level of confidence of the 'coal reserve' estimates in the area to 'indicated' status by reducing the borehole spacing throughout the area.

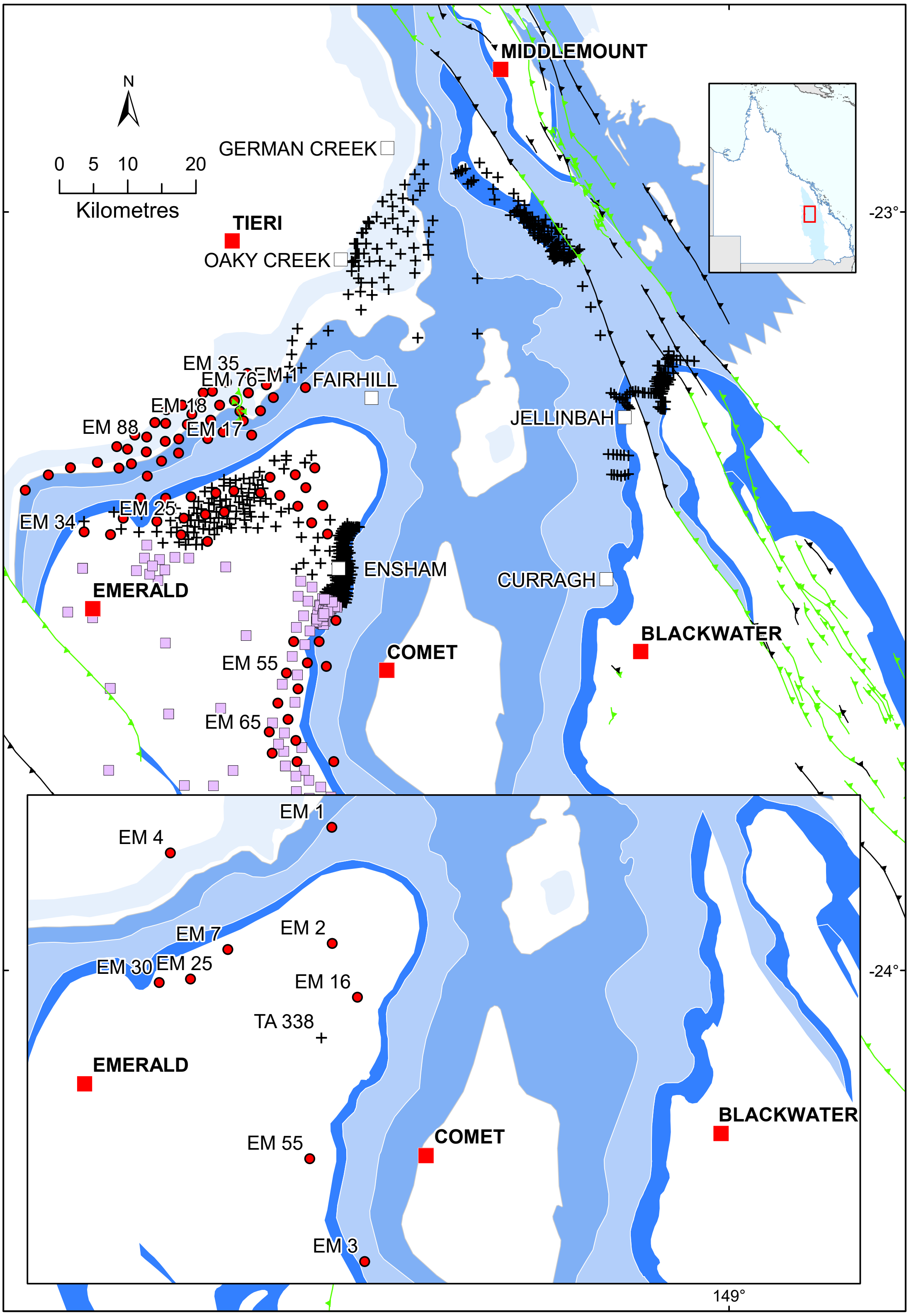

Figure 42. Emerald (EM) and Talbot (TA) boreholes, Emerald area. Legend in Figure 7.

Park (1973b) reported that the Fair Hill Formation consisted mainly of light grey, fine- to medium-grained feldspatho-lithic sandstones. Rare laminae of carbonaceous fragments and a few pebbly bands were also observed. The argillaceous units contained leaf impressions, rootlets and evidence of burrowing.

The lower boundary of the Fair Hill Formation was placed by Park (1973b) at 2 to 25 m below the lowermost coal seam within the formation. He placed the upper boundary at the top of the stratigraphically highest sandstone layer below the first of the dark grey argillaceous strata of the overlying Burngrove Formation (Park, 1973b). The thickness of the Fair Hill Formation varied between 140 m in EM 1, 2 and 3, and 100 m in EM 4 (locations shown in Figure 42 inset).

The seams of the Fair Hill Formation were found to be typically thick and banded. They comprised carbonaceous mudstone, interbedded with fawn to brown, thick tuffaceous mudstones. Four seams were recognised in the Emerald area (Fair Hill, Lepus, Canis and Hercules) but none was considered economic at the time. Park (1973b) interpreted the depositional setting as a dominantly subaerial deltaic environment with periods of swamp development and pyroclastic material deposition.

The lower boundary of the Burngrove Formation was described as a sharp change from the sandstones of the Fair Hill Formation to dark grey marine siltstones and mudstones, which dominate the upper unit. Lithologically, the Burngrove Formation contained numerous mudstone interbeds, especially towards the base. The basal dark grey to black mudstones, interbedded with pale tuffaceous layers, were equated with the Black Alley Shale occurring on the Springsure Shelf, as proposed by Anderson (1971). Park (1973b), however, included the marine sequence as part of the Burngrove Formation. The rare sandstones were coarse-grained in places and contained volcanic pebbles and mudstone clasts. Fossil wood and leaf fragments occurred in bands. Worm burrows suggested a marine influence during coal deposition (Park, 1973b).

The colour of the strata within the Burngrove Formation was also noted to have changed to light green and greenish-grey, particularly towards the top, in the sandy and silty interbeds. The upper boundary of the Burngrove Formation was taken at the top of the Virgo Seam. The formation thinned westward from 180 m in EM 16 to 150 m in EM 7 (Figure 42 inset). Complete sequences were drilled in EM 2, 7 and 16 (Park, 1973b).

Only three seams were routinely intersected (Virgo, Leo and Aquarius), as generally only the upper section of the Burngrove Formation was drilled. They were found to be persistent throughout the Emerald area but contained predominantly carbonaceous sandstone, with tuffaceous bands up to 1 m thick.

Park (1973b) interpreted the initial deposition of the Burngrove Formation as occurring during a transgressive phase, when clay-rich sediments were being deposited in an open marine setting. He suggested that this was followed by a regressive phase, with the development of a delta, where water fluctuations triggered alternating episodes of swamp formation and clastic deposition, both accompanied by pyroclastic activity.

The quality of the Virgo Seam was tested in three boreholes (Table 40; Figure 42): EM 25, EM 30 (Park, 1974) and EM 55 (Park & Galligan, 1974). Other than the F 1.40 fraction from EM 55, which returned a CSN value of 5 with an ash value of 9.5% (adb), none of the coal sampled presented swelling properties worthy of note.

Coal rank drops off considerably between Oaky Creek and Emerald and most of the coals near Emerald are too low a rank to provide coking coals, with vitrinite reflectance of 0.8% or lower. A detailed profile was determined in EM 7 (Figure 43).

Table 40. Raw and fractional analytical results—Virgo Seam, Emerald 25, 30 and 55, (after Park, 1974 and Park & Galligan, 1974).

Borehole	Fraction	Cumulative mass (%)	Depth from (m)	Depth to (m)	Specific gravity (g/cm^3)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	CSN
						M (%)	Ash (%)	VM (%)	FC (%)			
EM 25	F 1.40	21.1	210.7	211.9	1.38		9.0					1½
	F 1.60	62.4			1.58	7.2	20.2	26.4	46.0	24.0	0.37	1
	Raw	100			1.85	6.7	33.7	22.9	36.4			1
EM 30	Raw	100	235.9	236.9	1.50	10.2	27.8	24.2	37.8	19.8	0.34	
EM 55	F 1.40	50.2	226.1	227.1			9.5					5
	F 1.60	79.0					15.2					2½
	Raw	100				6.6	23.9	27.2	42.3	23.3	0.23	1

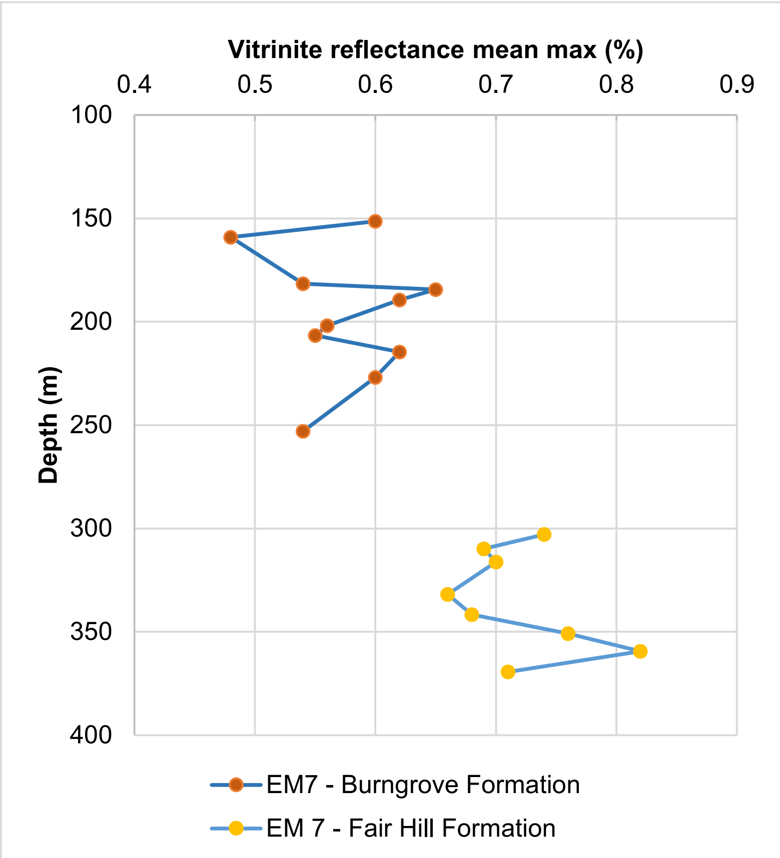

Figure 43. Vitrinite reflectance profile in EM 7, northeast of Emerald (after McKillop, 2016).

The extent of the Rangal Coal Measures seams south of Emerald and towards Springsure was investigated a few years later by Wallin (1979), who drilled 13 Denison boreholes. The Burngrove Formation was intersected at the base of all boreholes but not penetrated fully. The uppermost section comprised green grey, lithic sandstones with a tuffaceous matrix and rare carbonaceous coal seams. The deeper intersections were more argillaceous, highly bioturbated and with numerous tuff beds.

The area east of Emerald and towards Ensham was explored by Wallin and Tuttle (1982) and Slater *et al.* (1983) who drilled more than 70 Talbot and Denison boreholes. Similar to the previous drilling, only the upper Burngrove Formation was intercepted. The Virgo Seam was found to be carbonaceous with coal of poor quality (Wallin & Tuttle, 1982). Slater *et al.* (1983) described the Virgo Seam intersected at 235 m in TA 338 (Figure 42) and approximately 30 m below the Pollux Seam, as containing about 2 m of relatively clean coal, interlayered with three mudstone bands, aggregating to one metre in thickness. The ash content of the raw coal, excluding the thickest mudstone band, was 42.8% (Slater *et al.,* 1983).

The area northeast of Emerald was drilled by Staines *et al.* (1983), with the aim of raising the level of confidence of the estimates of 'coal reserves' in the Rangal Coal Measures to 'measured' status. The drilling program included 79 Talbot and 8 Denison series boreholes and principally targeted the Aries Seam. Where intersected during the drilling program, the Virgo Seam was found to be highly tuffaceous and to provide a useful marker horizon, indicating the base of the Rangal Coal Measures had been reached. The Leo Seam (where intersected) was about 40–50 m below the Virgo and presented a high stone/coal ratio. Only limited analytical testing was undertaken on coal samples taken from the Virgo Seam and that did not include testing of coking parameters.

Staines *et al.* (1983, page 7) commented that *"Sections of the Virgo seam from thirteen holes* [Table 41; Figure 44 inset]*, which on visual inspection appeared to be of possible workable quality and thickness, were sampled and analysed, but their very high ash content renders this seam quite unworkable"*.

Table 41. Raw coal analytical results—Virgo Seam, Denison and Talbot boreholes, Emerald area (after Staines *et al.,* 1983).

Borehole	Depth from (m)	Depth to (m)	Specific gravity (g/cm³)	Proximate analysis (adb)				Specific energy (MJ/kg)	S (%)	P (%)
				M (%)	Ash (%)	VM (%)	FC (%)			
DE 153	238.1	239.2	1.58	7.8	31.0	25.0	36.2	19.7	0.54	0.016
DE 155	297.5	298.9	1.57	9.0	31.5	24.3	35.2	18.3	0.27	0.028
DE 159	305.4	306.4	1.54	10.4	30.9	23.4	35.3	19.1	0.35	0.024
TA 600	258.4	259.5	1.63	5.6	34.3	25.2	34.9	19.1	0.39	0.029
TA 604	261.1	262.1	1.57	5.6	28.8	25.4	40.2	21.5	0.39	0.017
	268.9	269.8	1.53	6.0	26.8	23.9	43.3	21.9	0.40	0.009
TA 605	203.9	204.9	1.54	6.8	28.5	23.7	41.0	21.1	0.35	0.017
TA 606R	223.1	224.1	1.64	6.7	32.2	27.2	33.9	18.9	0.63	0.067
TA 613	239.9	241.8	1.60	7.0	36.2	22.3	34.5	18.9	0.53	0.017
TA 621	251.7	252.8	1.57	8.0	29.0	24.1	38.9	20.2	0.31	0.014
TA 622	360.8	361.8	1.54	7.6	27.0	24.5	40.9	21.0	0.36	0.014
TA 624	296.2	297.3	1.64	6.7	37.4	22.3	33.6	18.0	0.39	0.017
TA 823	303.9	305.0	1.60	6.7	35.1	22.8	35.4	18.9	0.68	0.015
TA 836	325.4	326.4	1.61	6.1	35.3	24.0	34.6	18.8	0.38	0.028

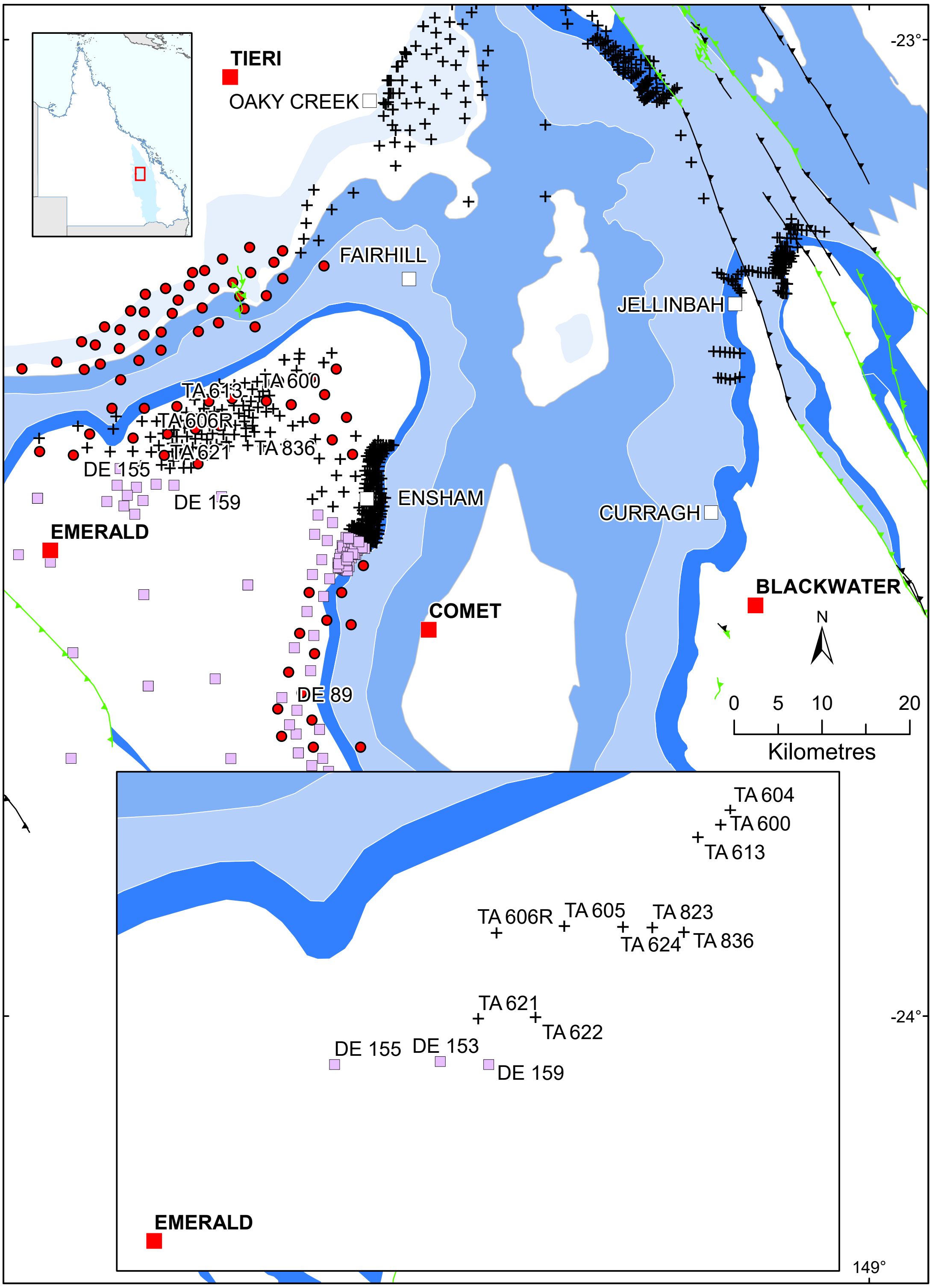

Figure 44. Talbot (TA) and Denison (DE) boreholes, Emerald. Legend in Figure 7.

Further departmental exploration in the Emerald area was undertaken to the south of Comet. The aim was to reassess the underground reserves of the Rangal Coal Measures on the western flank of the Comet Anticline, to the south of Ensham. The Virgo Seam was intersected only in DE 89 at a depth of 180.6 m (Figure 44). Analysis of the raw coal returned an ash value of 30% (adb), a sulphur content of 0.48% (adb) and a specific energy of 21.3 MJ/kg (Thornton, 1983).

3.4.6 Ensham

Following up on exploration between 1978 and 1979 to the east of Emerald, near Ensham homestead (Wallin & Tuttle, 1982) and a subsequent follow-up program in the latter part of 1980 (Wallin, 1982), the department undertook a much more extensive drilling program of closely spaced boreholes to assess the shallow resource potential of the coal seams in the Rangal Coal Measures. This program was undertaken along a strike length of about 15 km, to improve the level of geological knowledge of the area and to enable preliminary mining studies to be undertaken, upgrading the confidence level of 'coal reserve' estimates in the area to 'measured' status (Coffey, 1983; Coffey *et al.,* 1983). Collectively, more than 400 Talbot and Denison series boreholes were drilled during these three separate programs, of which about 100 boreholes were cored with selected coal seams sampled for analysis.

The programs targeted coal seams within the Rangal Coal Measures and only the upper section of the Burngrove Formation was drilled. The formation was described as comprising light green sandstone and greenish grey siltstone with banded coal seams; interbeds of tuff and tuffaceous mudstone were frequent. Dark grey mudstones, equivalent to the Black Alley Shale, prevailed towards the basal parts of the sections drilled (Coffey *et al.,* 1983). While most explorers of the Comet Ridge at that time placed the upper boundary of the Burngrove Formation with the overlying Rangal Coal Measures at the top of the Virgo Seam, as proposed by Staines (1972), Coffey *et al.* (1983) noted a tuffaceous horizon with a high gamma-ray log response, present about 2.5 m above the Virgo Seam, which they considered to be the upper boundary of the Burngrove Formation. This was in accordance with an unpublished proposal by Anderson & Koppe (1979) (details in section 'Formation boundaries'), who considered the tuff a significant boundary marker.

The Virgo Seam was encountered about 30 m below the Pollux Seam (the lowermost coal seam in the Rangal Coal Measures in the area) and consisted of interbedded coal, carbonaceous mudstone and tuffaceous mudstone, the latter having a high natural gamma response. The seam was more than 4 m thick in TA 236 and TA 151, but between 3 and 4 m in most other boreholes (i.e., TA 239, 240, 241, 424, 481, 486R and 522). The seam also thinned to less than 2.5 m thick in the south, in DE 121 (Figure 45). No coal testing of the Virgo Seam was undertaken in this latter drilling.

3.4.7 Denison Trough – Arcturus

About 30 km east of Springsure, the department drilled 12 Denison series boreholes in 1971 and 1972, to investigate the coal potential of the Rangal Coal Measures (Bandanna Formation) in the central Denison Trough (Anderson, 1975). The program comprised about 1850 m of drilling, of which about 1600 m was cored.

Many of these holes were terminated in thick basalt (i.e., DE 6, 7 and 9) or Rewan Formation sediments (i.e., DE 5, 8 and 11R), but four holes (DE 1 through DE 4) intersected both the Rangal Coal Measures and the Burngrove Formation. DE 12 also intersected the German Creek Formation although no coal seams were found (locations in Figure 46).

The Burngrove Formation consisted of an upper sandy section and a lower clayey and tuffaceous section. No coal seams were intersected in the Burngrove sediments and, in the absence of the Virgo Seam or equivalent, the boundary with the Rangal Coal Measures was taken as the top of the most tuffaceous unit.

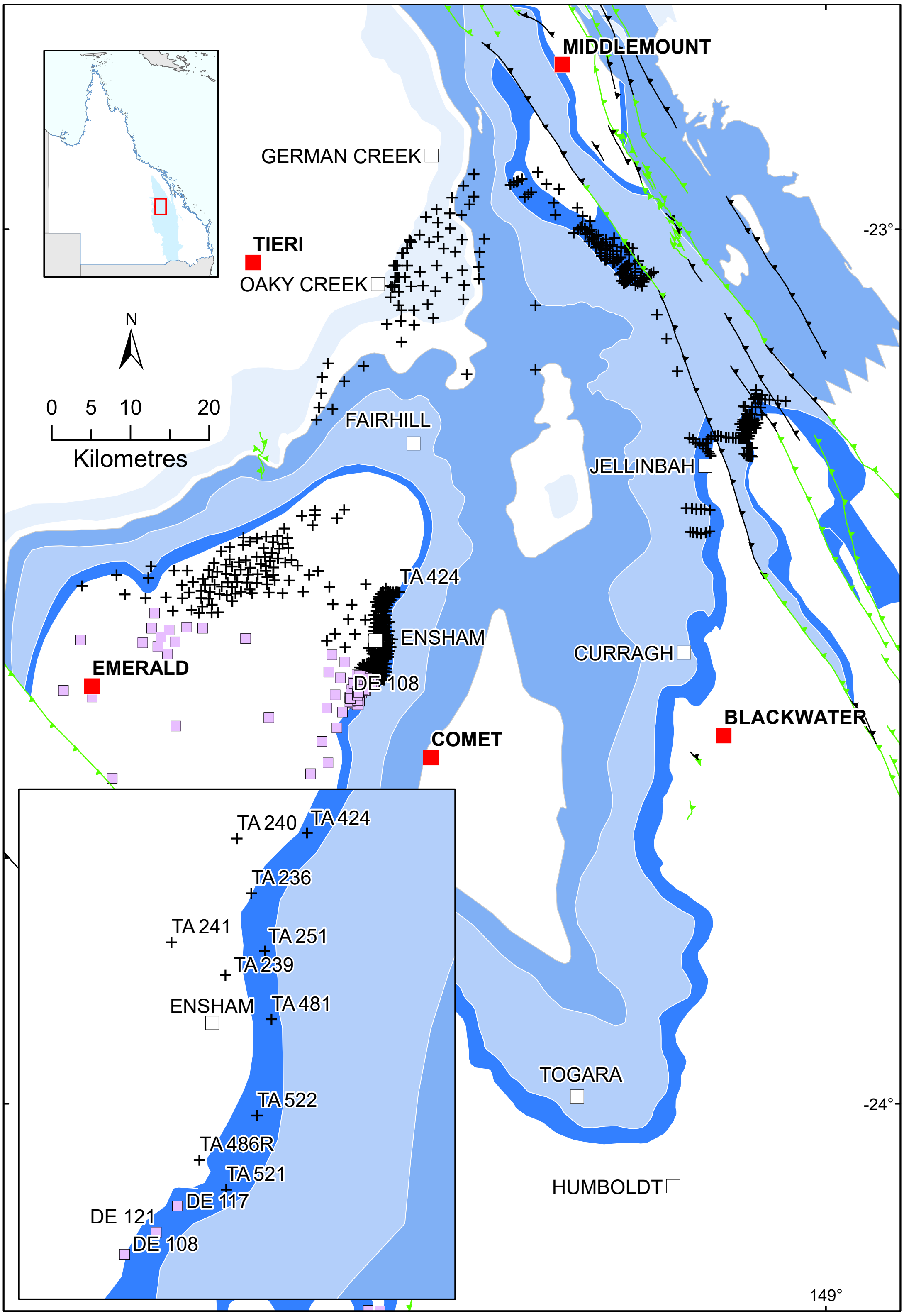

Figure 45. Talbot and Denison boreholes, Ensham. Legend in Figure 7.

Ten years later, 25 additional Denison series boreholes were drilled in the south-west Bowen Basin in the Arcturus area (named after the property Arcturus Downs), about 40 km east of Springsure. Eight of the Denison series boreholes drilled were fully cored (Denison 166 to Denison 172; Figure 46 inset). The greenish-grey silty sandstone sequence containing coal fragments and creamy tuffaceous intervals intersected in some of these holes was interpreted as the Burngrove Formation, and as being deposited in a pro-deltaic setting (Thornton, 1987).

The presence of tuffaceous material commencing about 20 m below the lowermost coal seam encountered in the Rangal Coal Measures (presumably an equivalent of the Yarrabee Tuff) was obvious from the cuttings and core obtained, as well as the *"significant gamma log deflections"* (Thornton, 1987, page 2) in the geophysical logs. The poorly sorted, slumped, bioturbated sequence encountered in association with these tuffs was interpreted by Thornton (1987) as being the Black Alley Shale.

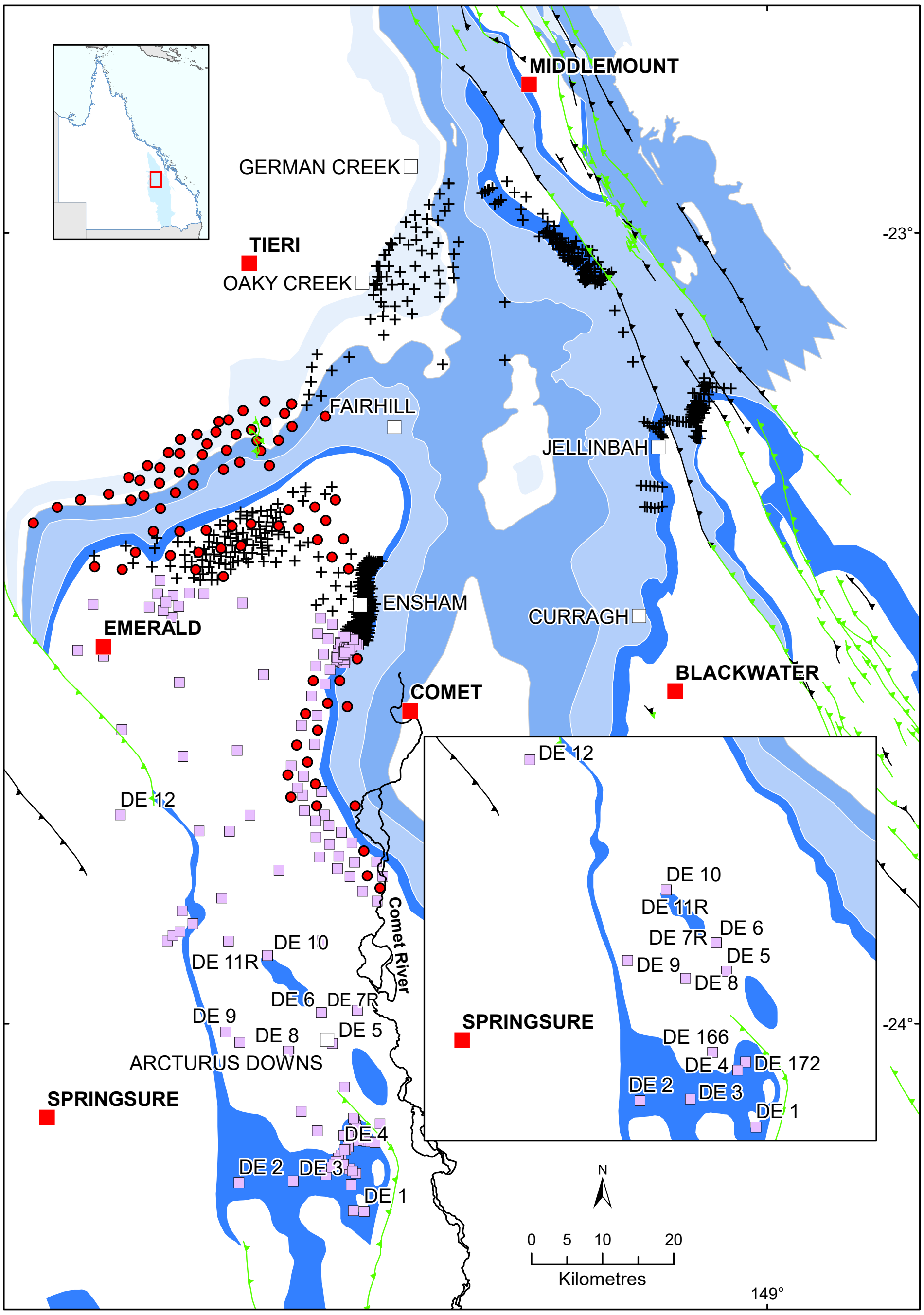

Figure 46. Denison boreholes, Arcturus Downs area. Legend in Figure 7.

3.4.8 Togara

Company exploration by Bellambi Coal Company Ltd and Clutha Development Pty Ltd on the western flank of the Comet Anticline, to the east of Emerald, in the late 1960s, targeted shallow occurrences of coking coal, but was soon abandoned as only coal of non-coking quality was encountered.

Between 1971 and mid-1977, the Department subsequently undertook a two-stage drilling program in the Togara area, to investigate the geology and thermal coal resource potential of the Rangal Coal Measures in this area.

The first stage of drilling included the completion of 44 boreholes totalling about 8400 m of drilling (~ 6400 m cored) comprising Humboldt, Togara and Wooroona series boreholes. The program provided initial stratigraphic and structural information sufficient to delineate coal 'reserves' of coal to 'indicated' status in the Aries and Pollux seams. This early drilling program also penetrated the Burngrove and Fair Hill formations, but as seams in these latter formations were found to be banded, they were considered of no economic interest, and the next stage focused only on the Pollux and Aries seams (Zillman, 1978).

The second stage of 29 boreholes, while enabling the Department to prove up additional 'reserves' of thermal coal in the Aries and Pollux seams, did not intersect deeper formations except for Togara 6, which penetrated the Fair Hill Formation (Figure 47). The unit was reported as consisting of medium- to fine-grained sublabile sandstone, interbedded with grey mudstone and siltstone, with rare conglomeratic bands. Burrows and plant debris occurred in thinly interbedded mudstone and siltstone sections (Zillman, 1978).

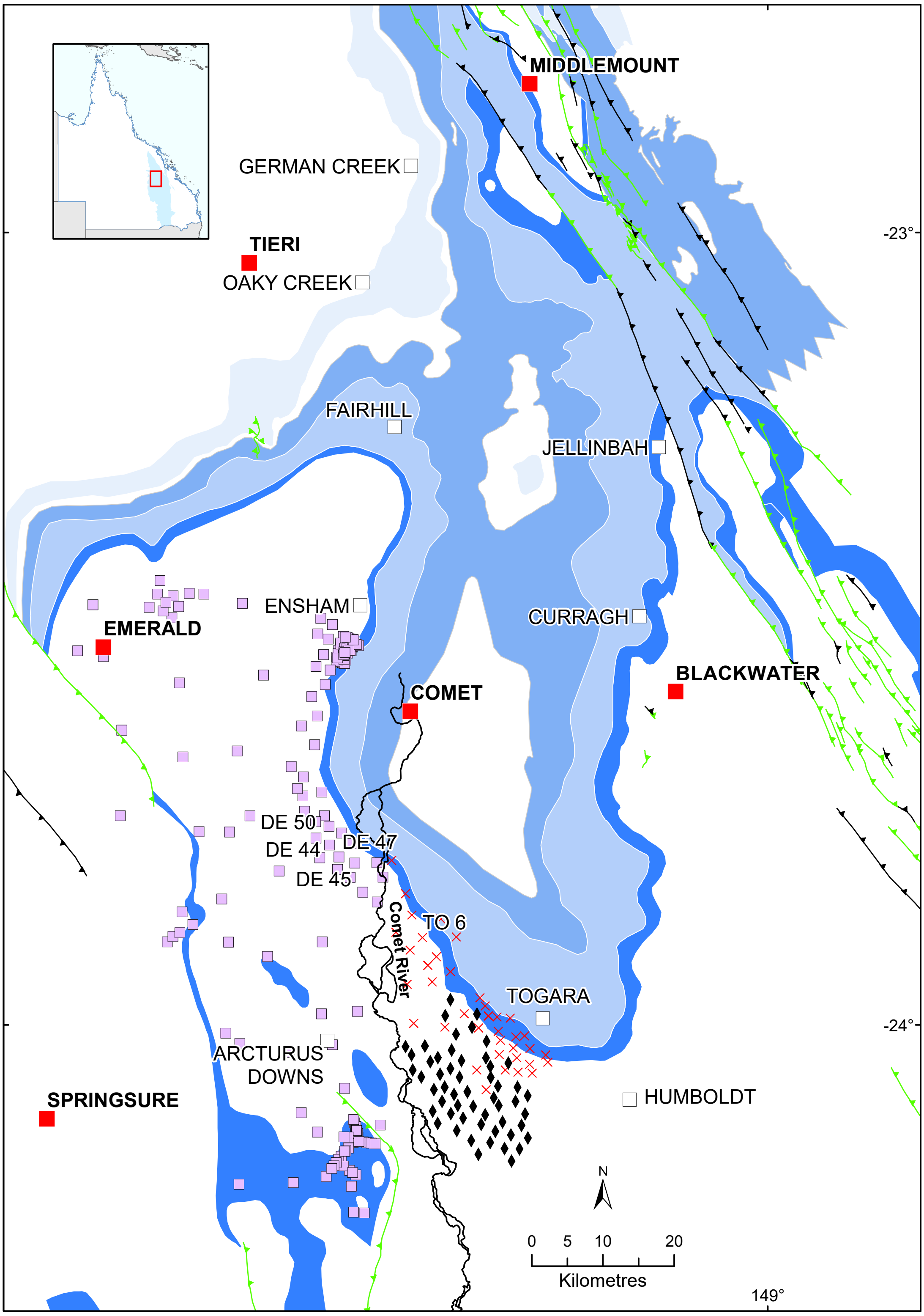

Figure 47. Boreholes west of Togara. Legend in Figure 7.

Three Fair Hill Formation seams were recognised in Togara 6. The Phoenix and Pegasus seams comprised tuffaceous mudstone, while the Hercules Seam was predominantly carbonaceous mudstone with coal bands (Zillman, 1978).

The Burngrove Formation was intersected by most of the early Togara boreholes and was reported by Zillman (1978) of consisting of three distinct lithologic units:

- basal mudstone section:
    - dark grey to black mudstone interbedded with biotitic or green bentonitic tuffs
    - up to 30 m in thickness
    - transgressive, quiet and euxinic (lagoonal) environment of deposition
    - equivalent to the Black Alley Shale
- middle greenish barren section:
    - green grey siltstone and silty mudstone with rare sandstone beds
    - grey and whitish mottles
    - up to 70 m in thickness
    - regressive environment
- upper coal-bearing section:
    - siltstone and mudstone, minor sandstone
    - coal seams thickening towards the north
    - up to 70 m thick
    - transgressive environment, nearshore marches.

The three Burngrove Formation seams identified at Togara were the Virgo, Leo and Aquarius. All these seams were reported as consisting mainly of tuffaceous mudstone with coal bands of no economic importance. Of note was that the sediments above Leo were described as grey to dark grey, while the sediments underlying the seam were generally greenish grey with white mottling. The Virgo Seam was not encountered in the southern part of the Togara area (Zillman, 1978).

Two further Departmental drilling programs were undertaken in the Togara area in 1979 (Wallin, 1980; DE 44, 45, 47, and 50) and between 1981 and 1983 (Thornton, 1986; 70 Denison, Humboldt and Wooroona boreholes series) but neither program penetrated below the Rangal Coal Measures (borehole locations in Figure 47).

Synthesising the findings of the departmental coal drilling undertaken between Emerald and Springsure, Thornton (1985) concluded that the upper section of the Burngrove Formation can be divided into three deposition zones that reflect a transition from a fluvio-deltaic environment in the north, to a marginal pro-delta environment in the south:

- Zone 1—near and immediately south of Emerald:
    - at least 3 seams present, including the Virgo Seam
    - interlaminated and interbedded grey-green sandstones and siltstones with tuffaceous bands
    - minor bioturbation in lower siltstones
- Zone 2—south of Comet to Togara:
    - no coal seams, only carbonaceous bands
    - interbedded grey-green sandstones and siltstones with tuffaceous or mudstone bands
    - moderate bioturbation in siltstones from the top of the formation

- Zone 3—Arcturus:
    - coal seams with reworked coal and mudstone fragments
    - poorly sorted mottled green and white silty and tuffaceous sandstones
    - intense bioturbation and slumping.

No analyses of any of the Burngrove Formation coal seams intersected at Togara was undertaken.

4. Regional review

4.1 Formation boundaries

Although the tuffaceous nature of the Fort Cooper Coal Measures was viewed by numerous workers as a correlatable feature when logging and mapping, the criteria for picking the boundaries of this unit and its correlatives has varied regionally. The main reason appears to have been the proportion of tuff present within a specific interval and how sharp and distinguishable the contact was with other strata. The introduction of wireline logging of coal boreholes eventually provided an objective method of identifying Fort Cooper-equivalent tuffaceous intervals through their high-gamma signal, although validation of this identification method using drill core remains uncertain in many cases.

The lower boundary of the Fort Cooper sequence with the underlying Moranbah Coal Measures has consistently been placed by GSQ coal geologists at the base of the lowermost tuffaceous interval (*e.g.,* Koppe, 1976a; Koppe, 1978; Anderson, 1985; Dash, 1985a).

Placement of the upper boundary in relation to the overlying Rangal Coal Measures has, however, been more variable. Current practice is to place this boundary at the top of a high gamma-response tuffaceous interval, referred to as the Yarrabee Tuff. Early proponents of this approach were Coffey *et al.* (1983), Anderson (1985) and Matheson (1985). More recently, this generalisation has been adopted by Ayaz *et al.* (2016a) and Sliwa *et al.* (2017a).

However, prior to the widespread use of geophysical logging, the presence of the Yarrabee Tuff was not always recognised or mentioned. In these instances, the boundary was often placed at the top of uppermost banded coal seam in the sequence. Names given to this uppermost coal seam have varied depending on locality and include the: Fort Cooper (Koppe, 1974), Girrah (Anderson, 1974), Pisces Lower (Balfe, 1983) and Vermont Lower seams (Matheson, 1985).

Kempton (1971) was the first coal exploration geologist working in the Bowen Basin to note a *"fawn-coloured claystone"* with *"a higher than background gamma radiation"*, which he *"believed to be of tuffaceous origin"* (pages 88-89). He considered that his success in correlating coal seams using the claystone at Bluff and Yarrabee in the central Bowen Basin, was *"persuasive evidence that the gamma marker is, in fact, a reliable time plane"* (Kempton, 1971, page 89). It took many decades of regional exploration for Kempton's visionary statement to be widely accepted: *"If this claystone does indeed represent a volcanic ash deposit, involving airborne distribution, it should be a widespread time-stratigraphic marker that could also be used in correlation of the Rangal Coal Measures from one locality to another"* (Kempton, 1971, page 89).

Over the next few years however, no recognition of such a marker bed was made by departmental coal geologists while investigating the Rangal Coal Measures and underlying upper Fort Cooper Coal Measures in the northern Bowen Basin at Exmoor, Fort Cooper, Kemmis Creek or Suttor Creek.

The following is a summary of findings in these areas:

- Koppe (1972) drilled Killarney 1 and Wodehouse 3; he did not provide detailed descriptions or mention a tuff marker.
- Koppe (1973) published one of the most detailed descriptions of the Fort Cooper Coal Measures at Exmoor on the eastern flank of the basin, while drilling the Hillalong boreholes. He referred to the high gamma-ray response of the entire formation, especially of the carbonaceous intervals interbedded with tuffs, but he did not remark on any specific tuff layer; his method of picking the coal measures was based on the overall abundance of tuffs.

- Koppe (1976a) was not able to correlate the Fort Cooper Coal Measures sequences in Wodehouse 1 and 2, and also pointed out differences in thickness estimations by Koppe (1973) and Jensen (1971) at Exmoor and Kemmis Creek; this was despite all authors documenting the abundance of volcanic-derived material as a defining characteristic of the coal measures; the differences in estimates may have been caused by the absence of sharp easily-distinguishable boundaries or intervals that would enable reliable correlations.
- Similarly, Koppe (1976b) did not define the boundary between the Fort Cooper and Rangal coal measures in the Drake boreholes at Suttor Creek.

The first explicit reference to the top boundary of the Fort Cooper Coal Measures, in the eastern Bowen Basin, was provided by Koppe (1974), while drilling at Annandale (Killarney 2-3R, Grosvenor 8, 9 and 10; Figure 22 and Figure 23). He stated that *"The upper boundary of the Fort Cooper Coal Measures has been put at the top of the readily identifiable Fort Cooper seam, which is characterised both by an abundance of interbedded tuffaceous sediments, and by its thickness (greater than 10m)"* (Koppe, 1977, page 7). He identified splits of the Fort Cooper Seam and also in seams of the overlying Rangal Coal Measures, which varied in number and character from one borehole to another. Koppe (1974) concluded that the tonstein layer identifiable in the Fort Cooper Seam was a *"useful marker"* (page 10), although its stratigraphic position in relation to the coaly interval varied; for example, in Killarney 2-3R, the tuff separated a clean and a banded section of the seam.

In the same period, Anderson (1974, 1975) was exploring the Roper Creek and Picardy areas, respectively. Although he did not refer to a marker bed or describe the way he defined the top boundary, he concluded that the tuffaceous mudstone in the Girrah Seam represented *"the end of pyroclastic activity in the Permian"* (Anderson, 1974, page 9).

Over the next 14 years, departmental coal exploration continued to be undertaken primarily on the western flank of the basin, focussing to a large extent on prospective coal seams in the Moranbah Coal Measures and German Creek Formation along the western flank of the Nebo Synclinorium. As such, many of the departmental boreholes drilled did not encounter the Fort Cooper sequence at all. During this period, reference to the Fort Cooper Coal Measures extent, its formation boundaries, or the 'tuffaceous marker' in departmental geological reports was limited and sporadic. Awareness that a useful tuffaceous marker interval was found in the central part of the Bowen Basin meant that departmental coal geologists, reporting on work undertaken on the western flank of the basin, also made reference to it when it was observed. These references include:

- Anderson & Koppe (1979) apparently proposed the type section of the Yarrabee Tuff as the interval between 358.70–362.64 m, in Cairns County 5, Roper Creek area; although several other workers from the 1980s refer to this proposal as Anderson & Koppe (in preparation), it does not appear to have ever been published. Matheson (1990b), however, referenced the Anderson & Koppe draft and used it as the basis of his definition of the Yarrabee Tuff Bed.
- Koppe & Scott (1981) reported on drilling undertaken at Red Hill, Broadmeadow and Winchester and placed the top Fort Cooper Coal Measures at the top of highly tuffaceous sediments. At Red Hill, the Vermont and Girrah occur as separate seams, while at Winchester, these coalesce into a 14 m-thick Vermont-Girrah Seam.
- Anderson & Jameson (1982) placed the top boundary of the Fort Cooper Coal Measures at the top of the Yarrabee Tuff and referenced Anderson & Koppe (in preparation) in the text of their report.
- Sorby *et al.* (1985) mentioned a *"thick tuffaceous band"* (page 7) at the top of the Fort Cooper Coal Measures at Lake Vermont and named this interval as the Yarrabee Tuff 'Member' in reference to 'Anderson and Koppe (unpublished)'.
- Anderson (1985) reviewed the Fort Cooper Coal Measures and stated that tuffs provide *"the best correlation evidence"* (page 87). *"A distinctively radioactive tuff occurs at the top of the Fort Cooper Coal Measures. It is in the process of being named the Yarrabee Tuff Bed, the topmost member of the Fort Cooper Coal Measures and the Burngrove Formation. The bed usually occurs within a coal seam, which unfortunately places the formation boundary within the* [Vermont] *seam"* (page 88).

- Dash (1985a) and Matheson & Jameson (1988) placed the top of the Fort Cooper Coal Measures at the top of the Girrah Seam, because a highly tuffaceous interval was not apparent in the overlying strata in boreholes at Burton Downs.
- Similarly, Dash (1985b) did not notice a tuff bed between the Vermont Upper and Vermont Lower in the Annandale area, but he placed the Rangal-Fort Cooper boundary between the two Vermont seams, based on the overall tuffaceous character of the Lower Seam.
- Matheson (1985) revisited the Red Hill area and found that a 35 cm-thick gamma marker occurred between two plies of the Vermont Seam and about 45 m above the Girrah Seam.
- Matheson (1986a) described a 1–2 m thick high gamma mudstone located 3 to 50 m above the Girrah Seam in the Vermont North area.
- Finally, Scott (1987a) stated that Drake 27 (north of Glenden) passed through the Yarrabee Tuff Bed (and cited 'Anderson and Koppe, unpublished'), which *"separates the basal seam of the Rangal Coal Measures from the uppermost seam of the Fort Cooper Coal Measures"* (page 3).

Following up on these accounts, a formal definition of the Yarrabee Tuff, along with detailed descriptions of its occurrence, was published by Matheson (1990 a,b), who established the type section as the interval from 93.96–94.34 m depth in Grosvenor 176R (a redrill of GR172), at Red Hill. His work followed up on the draft report of Anderson & Koppe (1979), who had proposed the type section of the tuff marker to be in Cairns County 5, Roper Creek area. Matheson (1990a), however, considered that occurrence to be unrepresentative, due to local faulting and intrusions, and instead, chose Grosvenor 176R as the type section.

Unfortunately, the Yarrabee Tuff intersected by Cairns County 5, Grosvenor 172 and Grosvenor 176R can no longer be viewed in core or be dated as the core from boreholes CC 5 and GR 176R has been discarded and the relevant tuff interval in GR 172 has been removed along with the surrounding coal for analysis (Table 15).

This review of observations of the Yarrabee Tuff in departmental geological reports has indicated a tendency to generalise its existence. Discrete tuff intervals at the top of the Fort Cooper Coal Measures having a sharp contact have been in fact, rarely observed, although tuff bands of various thicknesses are commonly dispersed throughout the formation. The high gamma signal, apparent on natural gamma wireline logs, is also characteristic of many tuffaceous layers within the Fort Cooper Coal Measures, not just the uppermost tuff bed. Recent work places the average age of the Yarrabee Tuff at around 252.76 Ma, although there are other tuff intervals with similar ages lower down the sequence in the Burngrove Formation (Table 8). This suggests that the uppermost (stratigraphically highest) tuff, either may not always represent the same volcanic ash-fall event at a regional scale or indicate the last significant Lopingian volcanic episode over the entire basin. Factors involved in the removal of an easily distinguishable tuffaceous mudstone at the top of the Fort Cooper Coal Measures in certain areas such as Exmoor, Suttor Creek, Burton Downs, Fort Cooper, Kemmis Creek and Annandale may include post-depositional processes such as erosion and redistribution of volcanic ash by water or wind.

On the Comet Ridge, information in departmental reports relating to the placement of stratigraphic boundaries of correlatives of the Fort Cooper Coal Measures is localised and incomplete because drilling was aimed at exploring for coal in the more economically prospective formations, comprising the Rangal Coal Measures (mainly) and in places, the German Creek Formation.

In the early 1970s, Staines (1972) established the upper boundary of the Burngrove Formation at the top of the Virgo Seam in an area including the northern section and the eastern flank of the anticline, to the Mackenzie River. This approach was used in subsequent exploration programs: *e.g.,* Park (1973b) at Emerald and Galligan (1978) at Curragh.

The report on drilling undertaken at Caledonia by Balfe (1983), however, set the boundary between two splits of the Pisces Seam, dividing the seam into an upper 'working section' (placed in the Rangal Coal Measures) and a Pisces Lower Seam, which was considered to be part of the Burngrove Formation due to its tuffaceous character. Similarly, D'Arcy (1985) set the upper boundary at an intraseam tuff within the Pisces Seam, northeast of Blackwater.

On the northern part and western flank of the Comet Ridge, another approach taken was to place the boundary at a high gamma ray tuffaceous horizon. This was the case at Roper Creek (Anderson & Jameson, 1982) and at Ensham where the boundary between the Rangal Coal Measures and Burngrove Formation was placed above the seam correlated as the Virgo Seam, at *"the top of a stratigraphically higher tuff bed which gives a high gamma-ray log response and forms a widespread marker horizon"* (Coffey *et al.,* 1983, page 18).

Finally, in the absence of the Virgo Seam or a clear marker, the boundary was set at the top of the most tuffaceous unit (*e.g.,* Anderson, 1975, the Denison boreholes, Figure 46).

The Burngrove – Fair Hill boundary was rarely intersected in departmental boreholes drilled on the Comet Ridge. Where it was encountered, such as at Oak Park (Staines, 1973), it was placed at the base of dark grey shales. Near Emerald, Park (1973b) established the boundary at the first sandstone layer underlying the dark grey mudstones of the Burngrove Formation.

The lower boundary of the Fair Hill Formation with the German Creek Formation was mentioned only by Prouza (1976) at Oak Park, where the formation was thin and shallow. This boundary was established at the base of the lowest sandstone layer, which was 7–15 m below the lowest coal seam.

4.2 Type section locations

4.2.1 Background

Jensen (1968) and Malone *et al.* (1969) originally recorded the location of the type section tops and bottoms of the Fort Cooper Coal Measures and equivalent formations as 8-digit numbers based on the 20,000 yard Transverse Mercator grid in the original 1:250 000 geology notes. As part of this review, the type section locations of the Fort Cooper Coal Measures and the Fair Hill and Burngrove formations have been converted to the current Geocentric Datum of Australia (GDA94), using geographic coordinates.

The original coordinates were recorded as follows:

- Fort Cooper Coal Measures: *"between points 67533209 and 67413188 Mount Coolon 1:250,000 Sheet"* (Jensen, 1968, page 30); this section was in the 20,000 yard Transverse Mercator grid, zone 7.
- Fair Hill Formation: *"4 miles north of Cooroorah homestead (Grid reference: base, 15000987; top, 15141000) in the Duaringa 1:250 000 Sheet area"* (Malone *et al.,* 1969, page 44); this section was in the 20,000 yard Transverse Mercator grid, zone 8.
- Burngrove Formation: *"in a small creek 6 miles north of Cooroorah homestead (Grid reference: base 15251019, top 15421021) in the Duaringa Sheet area"* (Malone *et al.,* 1969, page 51); this section was in the 20,000 yard Transverse Mercator grid, zone 8.

The 8-digit coordinate representation is an abbreviated way of expressing locations in the Universal Transverse Mercator projection. The first four numbers refer to the easting and the second four to the northing of the location (Table 42).

Table 42. Abbreviated and complete display of coordinates.

Formation	Reported points	Complete 20,000 yard eastings and northings
Fort Cooper Coal Measures	67533209 67413188	675,300–2,320,900 674,100–2,318,800
Fair Hill Formation	15000987 15141000	150,000–2,098,700 151,400–2,100,000
Burngrove Formation	15251019 15421021	152,500–2,101,900 154,200–2,102,100

4.2.2 Methodology

The conversion of the 20,000-yard grid coordinates into GDA94 geographic coordinates comprised several steps:

1. The 1:250 000 Mount Coolon (Malone & Jensen, 1968) and Duaringa (Malone *et al.,* 1970) geological map sheets were registered in the original 20,000-yard grid. This was achieved using ArcMap v.10.4.1. and establishing the four corners of one grid square as 4 control points for registration.
2. A new shape file with the points defining the sections (see complete coordinates in Table 42) was created and overlaid on the geological maps.
3. The section points and the geological basemaps were then saved as image files, one for each map sheet.
4. The image files were registered in AGD66 (Australian Geodetic Datum 1966, the projection in use at the time the original maps were produced) by selecting and registering 4 control grid points with known geographic coordinates.
5. After registration, the section points were digitised from the registered image in AGD66 and new point shape files were created, one for each set of top and bottom section points.
6. The final step was to convert the section points from AGD66 to GDA94 (Table 43).

Table 43. Original section points and their respective converted coordinates.

Formation	Reported points	GDA94 coordinates
Fort Cooper Coal Measures	67533209 67413188	21.446838°S–148.418743°E 21.428978°S–148.429017°E
Fair Hill Formation	15000987 15141000	23.266795°S–148.767643°E 23.256148°S–148.780532°E
Burngrove Formation	15251019 15421021	23.240826°S–148.790420°E 23.239215°S–148.805773°E

4.2.3 Fort Cooper type section

The type section of the Fort Cooper Coal Measures has its base at 21.446838°S; 148.418743°E and its top at 21.428978°S; 148.429017°E. According to Jensen (1968), these sites are located in the headwaters of Hail Creek, clearly visible on the 1-second hillshade map (Figure 48, inset a). Overlying the points on a recent drainage and satellite image, the points do not appear to fall within a gully but they are proximal to a left side tributary of Hail Creek (Figure 48, inset b). In addition, the base of the section is about 700 m southwest of the closest point to the relevant boundary of the Fort Cooper Coal Measures, as shown in the solid geology map by Sliwa *et al.* (2008) (Figure 48). These discrepancies could be due to rounding in the original 8-digit coordinates or errors in the current geological linework, or a combination of the two. Based on the hillshade and satellite images of the area, the most likely location of the type section is along a gully shown by the double red line in Figure 48.

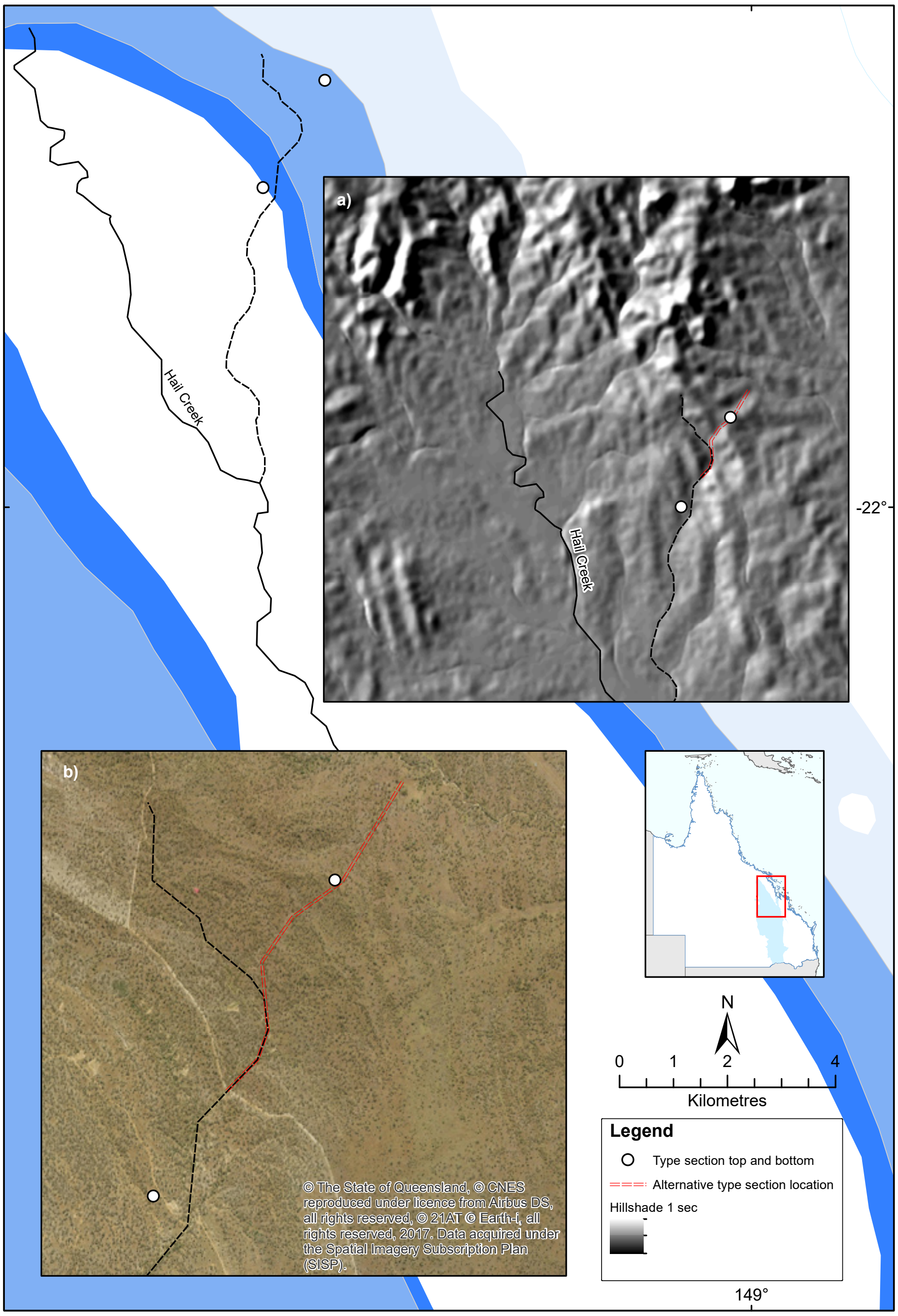

Figure 48. Fort Cooper Coal Measures type section location as described by Jensen (1968) in relation to solid geology, a) terrain elevation as 1-second hillshade and b) satellite image. Legend in Figure 7.

4.2.4 Fair Hill type section

The type section for the Fair Hill Formation has its base at 23.266795°S; 148.767643°E and the top at 23.256148°S; 148.780532°E. This line does not match any gullies, but it is possible that the type section could be along the creek to the north of the base of the section (Figure 49, inset a). About 800 m to the west-northwest of the currently identified base of type section, the gully seems to intersect a distinctive ridge of rock that may be the quartzose sandstone (Figure 49, inset b) mapped on the 1970 Duaringa 1:250 000 map sheet as the German Creek Coal Measures. To the east of this ridge is a flat area that appears to have no outcrop, which may fit the description of Malone *et al.* (1969) where they note that the lower half of the formation is not exposed in the type section.

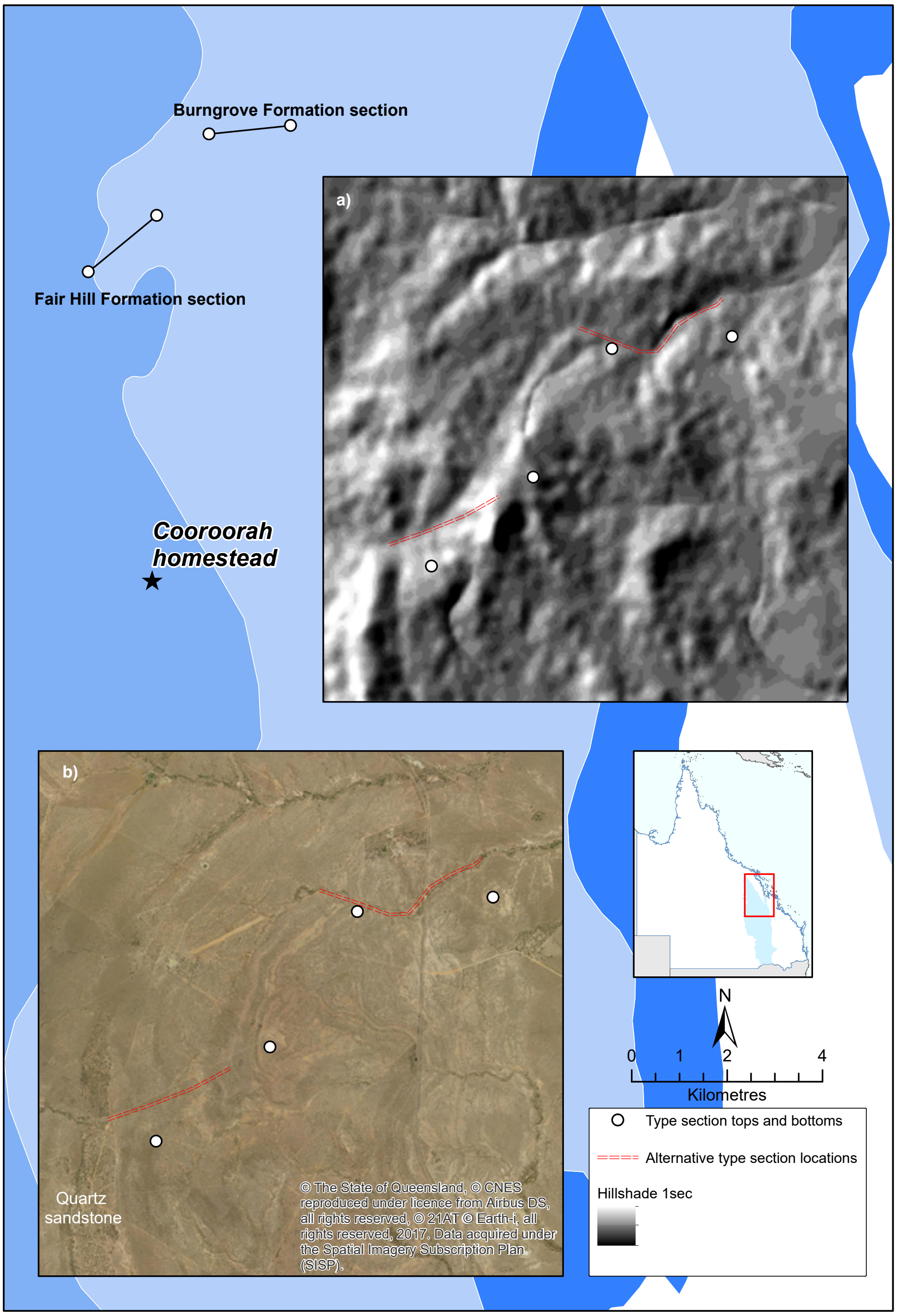

Figure 49. Fair Hill and Burngrove formation type section location as described by Malone et al. (1969) in relation to solid geology and a) terrain elevation as 1-second hillshade and b) satellite image. Legend in Figure 7.

To further complicate the matter with the Fair Hill Formation, on the latest solid geology map (after Sliwa *et al.,* 2008), the base of the Fair Hill Formation in the area of the type section has been moved 4 km to the west of where Malone *et al.* (1969) had placed it. This means that the quartzose sandstone at the top of the top of the German Creek Coal Measures, which was used to define the base of the overlying Fair Hill Formation type section, is now included in the Fair Hill Formation.

The oldest mapping that could be found showing this boundary occurring far to the west of Malone *et al.* (1969) was by Geological Survey of Queensland (1988). However, this issue on the base of the formation, similar to the exact location of the type section, could only be resolved by a field investigation, though examining core of boreholes that intersect these units may help in understanding the lithological differences at these formation boundaries and allow the establishment of reference sections of these formations.

The top of the type section currently plots inside the Burngrove Formation, but if the point was about 800 m to the southwest then it would plot within the same gully as suggested for the base of the type section above, and would be at the boundary between the Fair Hill and Burngrove Formation as shown in Malone *et al.* (1969). The current placement of the top of the type section could be due to rounding in the original 8-digit 20,000-yard grid reference; a possible section location along a nearby gully is shown in Figure 49 insets.

4.2.5 Burngrove type section

The type section for the Burngrove Formation has been plotted at 23.240826°S; 148.790420°E as the base and 23.239215°S; 148.805773°E as the top. Like the Fair Hill Formation type section, these points do not plot within any gullies. However, if the base of the section is moved 600 m to the west-northwest, it would plot in a gully that intersects prominent bedding trends visible in aerial photography and may have good outcrop (Figure 49 insets). Moving the top of the type section about 500 m to the northwest would plot within the same gully and in an area fitting the description by Malone *et al.* (1969, figure 15), who stated that the top of the section is in a flat area of no outcrop. The difference between the plotted top and bottom of the type section and the location of the gully may be due to rounding in the original grid references.

Unfortunately, none of the discrepancies, mapping/digitising errors or the proposed locations can be checked or confirmed without a field visit, which is not possible at this time.

4.3 Drilling summary

Departmental coal exploration of the northern Bowen Basin spanned over 20 years, from the early 1970s to the late 1980s, principally targeting the Rangal Coal Measures, the Moranbah Coal Measures and to lesser extent, the German Creek Formation. Out of the 960 boreholes drilled as part of nine regional exploration programs undertaken in the north of the basin, over the Nebo Synclinorium, only 57 were sampled to determine the coal quality of the Fort Cooper coal seams; a third of those samples were deeper than 200 m (Table 44, Figure 50).

Table 44. Drilling programs, references and analyses of Fort Cooper Coal Measures coal samples.

Borehole series	Area	Reference (QDEX CR number)	Analysed boreholes	Approx. testing depth (m)*
Drake (DR)	Collinsville to Suttor Creek	Koppe & Scott, 1979 *(41690)*	DR 12	236–239
		Scott, 1987a *(41949)*	DR 27	350–360
Killarney (KL)	east Annandale	Koppe, 1974 *(41672)*	KL 2	184–188
		Dash, 1985b *(41711)*	KL 6 KL 8 KL 11	88–95 131–133 262–264
Grosvenor (GR)	Lenton Downs to Winchester	Koppe & Scott, 1979 *(41690)*	GR 3	177–180
		Koppe, 1974 *(41672)*	GR 9	450–457
			GR 10	335–338
		Koppe & Scott, 1981 *(41698)*	GR 12	68–73
			GR 13	157–162
		Holmes, 1981 *(41701)*	GR 14	143–146
		Wallin & Koppe, 1978 *(41394)*	GR 19	171–173
			GR 39	94–95
			GR 45	120–126
			GR 48	130–131
			GR 49R	157–165
		Scott, 1987b *(41717)*	GR 56R	100–102
			GR 57	127–157
			GR 59	172–174
			GR 61	142–144
			GR 64	188–190
			GR 65	97–101
		Holmes, 1981 *(41701)*	GR 72R	112–117
		Matheson, 1985 *(41865)*	GR 172	159-180
			GR 173	290-315
			GR 180	275-280
		Dash, 1985a *(41712)*	GR 183	238-240
			GR 184	270-272
			GR 186R	299-300
			GR 187	252–262
		Matheson, 1985 *(41865)*	GR 188	283–302

**below ground level (m)*

Table 44 (continued)

Borehole series	Area	Reference (QDEX CR number)	Analysed boreholes	Approx. testing depth (m)*
Cairns County (CC)	Winchester to Tieri	Anderson, 1974 *(41675)*	CC 8	220–223
		Koppe & Scott, 1981 *(41698)*	CC 15	87–98
			CC 16	149–153
		Holmes, 1980 *(41379)*	CC 62	91–128
			CC 63	95–97
			CC 68	186–192
			CC 69	143–149
			CC 70	179–181
		Sorby, 1981 *(41177)*	CC 227	162–179
		Matheson, 1986a *(41713)*	CC 494	186-198
			CC 496	207–216
			CC 497	300–312
			CC 499	114–128
			CC 500	150–157
			CC 510	380-390
			CC 511	209–221
			CC 516	124–142
			CC 518	97–99
			CC 521	212–219
			CC 523	295–303
		Coffey & Crosby, 1987 *(41378)*	CC 583	116-119
			CC 584	92–238
			CC 586	109–191
			CC 626	206–208
			CC 630	215–217

**below ground level (m)*

Of the 4000 boreholes drilled in the southern section of the Bowen Basin, around the Comet Ridge, as part of 9 regional exploration programs, only 43 were sampled to determine the coal quality of the Burngrove Formation coal seams; three quarters of those samples were deeper than 200 m. The Fair Hill Formation coal seams were rarely intercepted and never analysed for coal quality (Table 45, Figure 50).

Table 45. Drilling programs, references and analyses of Burngrove Formation coal samples.

Borehole series	Area	Reference (QDEX CR number)	Analysed boreholes	Approx. testing depth (m)*
Roper (RO)	Roper Creek	Anderson & Jameson, 1982 *(41164)*	RO 2 RO 21	207–209 310–315
Blackwater (BL)	Oaky Creek	Staines, 1973 *(41665)*	BL 39 BL 40 BL 43 BL 45R	132–136 48–50 20–26 43–56
Blackwater	Jellinbah—Caledonia	Staines, 1977 *(41760)*	BL 85	276–277
		Carr, 1973 *(41663)*	BL 163	241–260
		Park, 1973a *(41661)*	BL 173 BL 177 BL 179 BL 184R	52–194 392–400 310–319 395–400
Humboldt (HU)		Staines, 1978 *(41395)*	HU 8 HU 10 HU 13	255–267 161–164 180–184
		Balfe, 1983 *(41704)*	HU 2121 HU 2113 HU 2120 HU 2116 HU 2192	72–74 75–82 61–67 56–60 47–51
Leura (LE)		Balfe, 1983 *(41704)*	LE 212	63–69
Humboldt	Blackwater	D'Arcy, 1985 *(41722)*	HU 2327 HU 2326 HU 2328 HU 2332 HU 2333	257–259 266–270 274–249 306–309 349–353
Emerald (EM)	Emerald	Park, 1974 *(41667)*	EM 25 EM 30	211–212 236–237
		Park & Galligan, 1974 *(41668)*	EM 55	226–227
Denison (DE) Talbot (TA)		Staines et al., 1983 *(41809)*	DE 153 DE 155 DE 159 TA 600 TA 604 TA 605 TA 606R TA 613 TA 621 TA 622 TA 624 TA 823 TA 836	238–239 298–299 305–306 259–260 261–270 204–205 223–224 240–242 252–253 361–362 296–297 304–305 325–326
Denison		Thornton, 1983 *(41372)*	DE 89	180.6

**below ground level (m)*

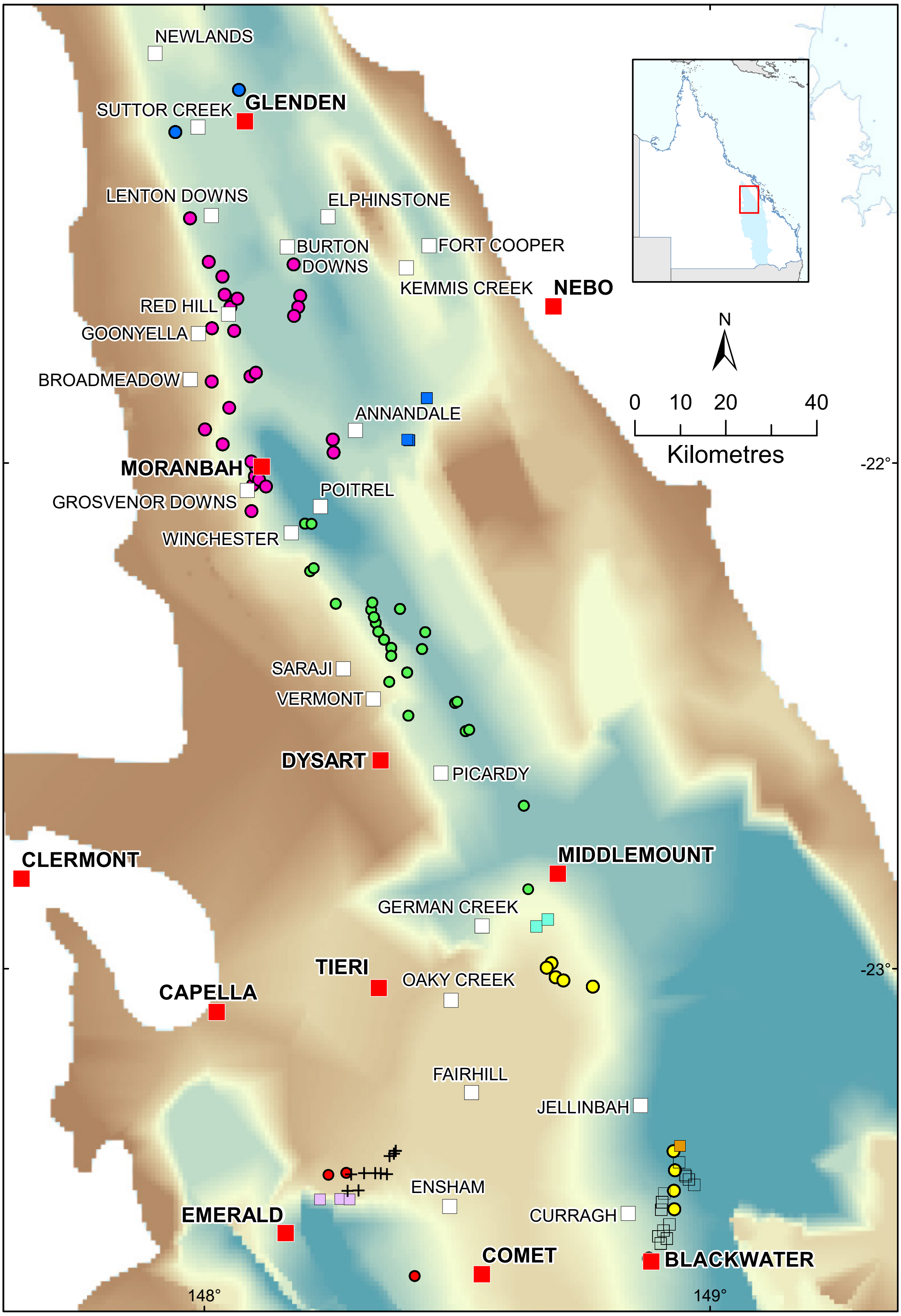

Figure 50. Spatial distribution of coal analyses (Fort Cooper Coal Measures and Burngrove Formation). Legend in Figure 7.

4.4 Geological setting and coal quality

4.4.1 Eastern Nebo Synclinorium

Although limited, the departmental drilling undertaken on the eastern flank of the northern part of the Bowen Basin (Hillalong, Wodehouse and Killarney borehole series) was able to reveal intense strata disturbance in the area. Faulting resulted in displacements of hundreds of metres and the Fort Cooper Coal Measures were intersected at variable depths (*e.g.,* Wodehouse 1 and 4, Figure 20). Volcanic and igneous activity produced highly tuffaceous sediments with high dips and emplaced sills which heat-affected the coal at depth (Figure 21). That was particularly the case east at Annandale, where proximity to the Folded Zone and emplacement of the Bundarra Granodiorite (Figure 22) has caused strata faulting, shearing and strata deformation. The effect of faulting was demonstrated by Killarney 5, which terminated at 920 m without intersecting the Fort Cooper Coal Measures, although the common depth to top formation was around 200 m in the area.

The Fort Cooper Coal Measures were distinguishable by the abundance of tuffs and volcanolithics. Two units were apparent at Exmoor (Hillalong boreholes) and Kemmis Creek (Wodehouse boreholes); the upper unit was dominated by sandstone and conglomerate (Plate 15), while the lower unit was a tuffaceous mudstone with dull coal (Koppe, 1973, 1976b). This coarsening up sequence was different from the fining up strata found further south, where a fine-grained Burngrove Formation and a coarser underlying Fair Hill Formation could be differentiated.

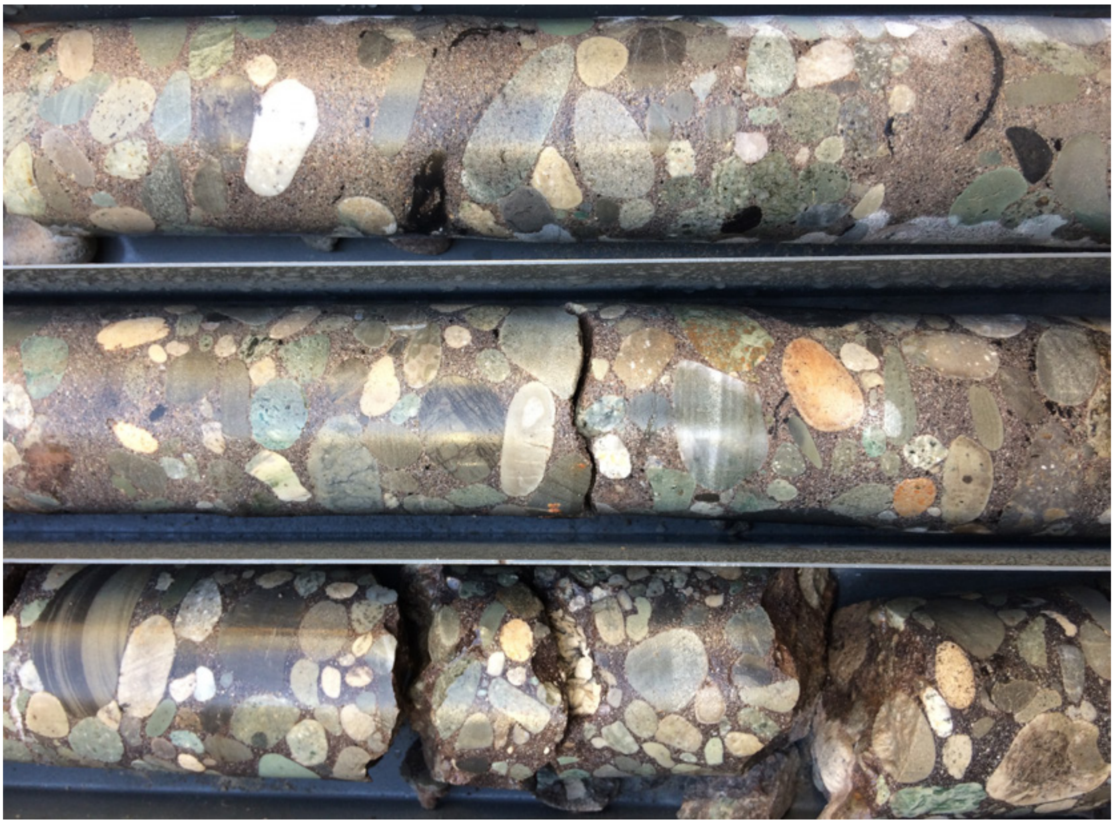

Plate 15. Fort Cooper Coal Measures conglomeratic unit, Exmoor-Kemmis Creek area (depth ~ 180 m in Hillalong 4).

Another localised characteristic of the Fort Cooper sediment composition was the presence of oxidised pyrite in Hillalong 4, near Exmoor (Figure 18) and brachiopods in Killarney 1, southeast of Annandale (Figure 22). These occurrences suggested occasional marine incursions that reached as far west as Suttor Creek (i.e., up to 5% sulphur in the Suttor Creek boreholes) and disturbed the fluvial sedimentation locally.

The coal quality was tested in only a few Killarney boreholes, east of Annandale, where the raw coal ash was greater than 30%; the CSNs were generally low, presumably due to intrusions and the specific energy ranged from 15–21 MJ/kg.

Judging by these findings, the Fort Cooper Coal Measures occurring on the eastern flank of the Nebo Synclinorium would appear to have little prospectivity for economic coal; however, shallow basement and the development of a structural feature like the Hail Creek Syncline (30 x 7 km, Figure 51) created conditions for the deposition of minable Fort Cooper seams. The Hail Creek Mine (ML 4738) operates within the Hail Creek Syncline and mines the Rangal Coal Measures, the Elphinstone and Hynds seams. Although the Fort Cooper top seam (Plate 16) contains high ash, it is 25–30 m thick and comprises several plies, which are mined when they occur close to the Hynds Seam, the lowermost coal seam in the Rangal Coal Measures at this locality (Resource Strategies Pty Ltd, 2014).

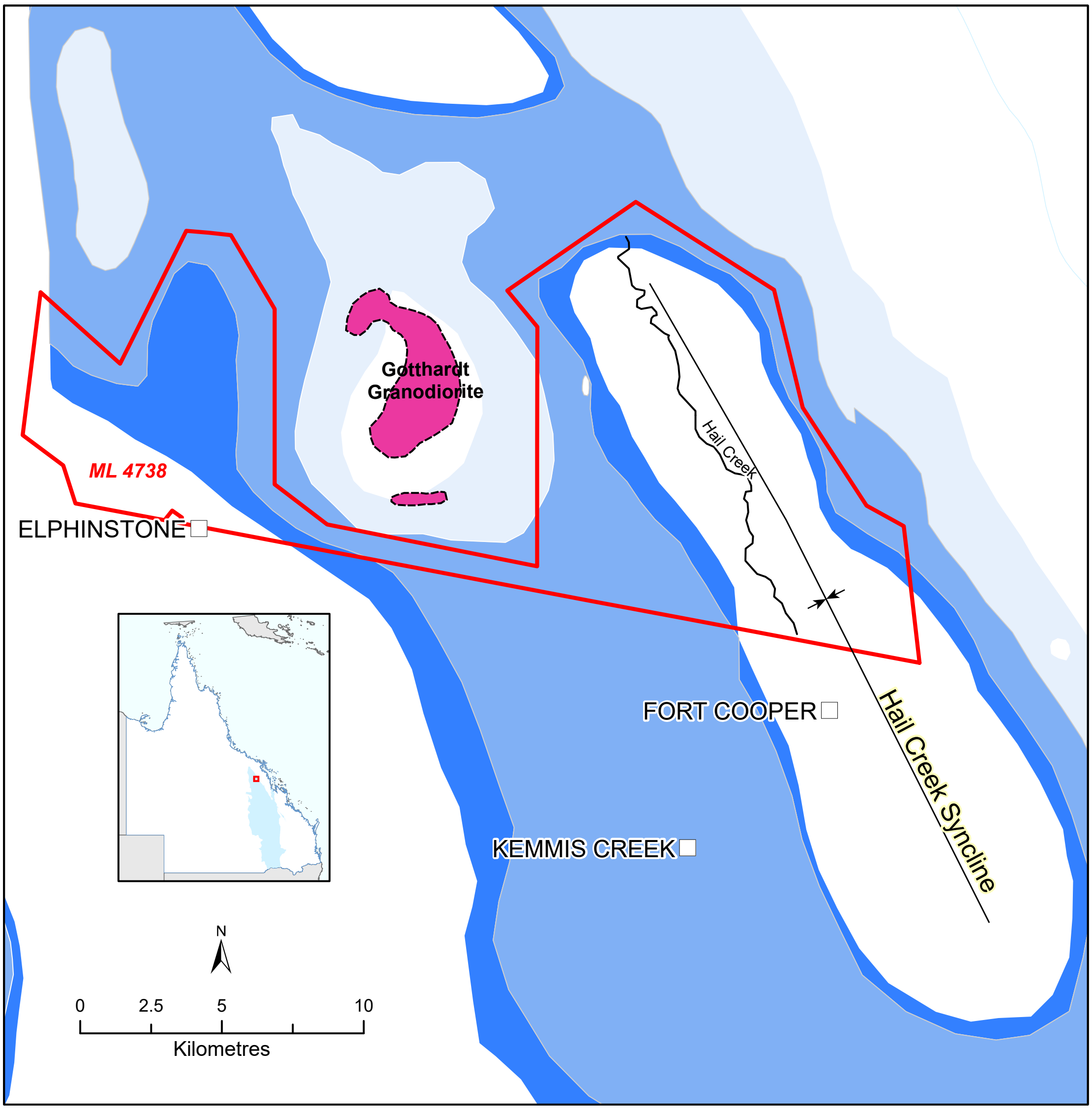

Figure 51. Hail Creek Syncline.

Plate 16. Mineable ply, Fort Cooper Coal Measures (sample size 10 x 10 cm), Hail Creek Syncline.

4.4.2 Western Nebo Synclinorium

The GSQ Coal Section explored the area situated at the boundary between the Collinsville Shelf and the western Nebo Synclinorium with the Drake, Grosvenor and Cairns County series of boreholes. As drilling generally followed the subcrop, some boreholes were located towards the axis of the synclinorium, enabling the delineation of faults and localised characteristics over deeper sections of the synclinorium. Geological interpretation based on intersections within GR 9 and GR 10, situated west of Annandale (Figure 23) for example, revealed strata displacements of up to 100 m. Further south, near Picardy, fault repetition of strata with displacements of up to 100–200 m were inferred in several of the Cairns County boreholes (Figure 28).

In the Drake boreholes, the Fort Cooper Coal Measures contained poor quality seams similar to those described at Exmoor, a few kilometres to the east. Faulting, steep dips and andesitic intrusions were common and similar to those mapped on the eastern side of the synclinorium. However, Fort Cooper seams are mined in open cut at Newlands (Bronwyn Leonard, personal communication).

At Eastern Creek South (ML 4755, Figure 52), the Girrah Seam lies immediately below the Lower Newlands Seam (LNS - Vermont Seam equivalent). At this location, the LNS has two plies (LN1 and LN2) which are separated by the Yarrabee Tuff. The LNS/Girrah sequence was exposed in the Girrah Trial Pit at Eastern Creek South in 2015 (Plate 17). In this area, the LNS/Girrah sequence is approximately 25 m-thick although the trial pit only investigated the top 18 m of the sequence. As expected, the Girrah coal plies had a high raw ash values (35–45% adb).

At Eastern Creek North (ML 4754, Figure 52), the Lower Newlands Seam is mined in the Bangarra Pit but the Girrah sequence is not present. To the north and south of the pit, gamma spikes indicate that the Girrah Seam marker tuffs are associated with carbonaceous material but no significant coal bands. It is inferred that the thick Girrah sequence observed at Eastern Creek South was not deposited at Eastern Creek North.

Further south at Wollombi (western part of the Suttor Creek mining lease - ML 4761, Figure 52), where coal is extracted from the Moranbah Coal Measures, a small section of the Fort Cooper Coal Measures is exposed in the open-cut where it overlies the Moranbah Coal Measures. The coal seam exposed in the lower section of the Fort Cooper Coal Measures in this area is assumed to be the Fairhill Seam equivalent. Although the Fort Cooper Coal Measures are highly weathered over the majority of the Wollombi Pit, at the eastern limit of the pit, a small portion of the basal seam has been mined from immediately below the base of weathering (Bronwyn Leonard, pers. comm.).

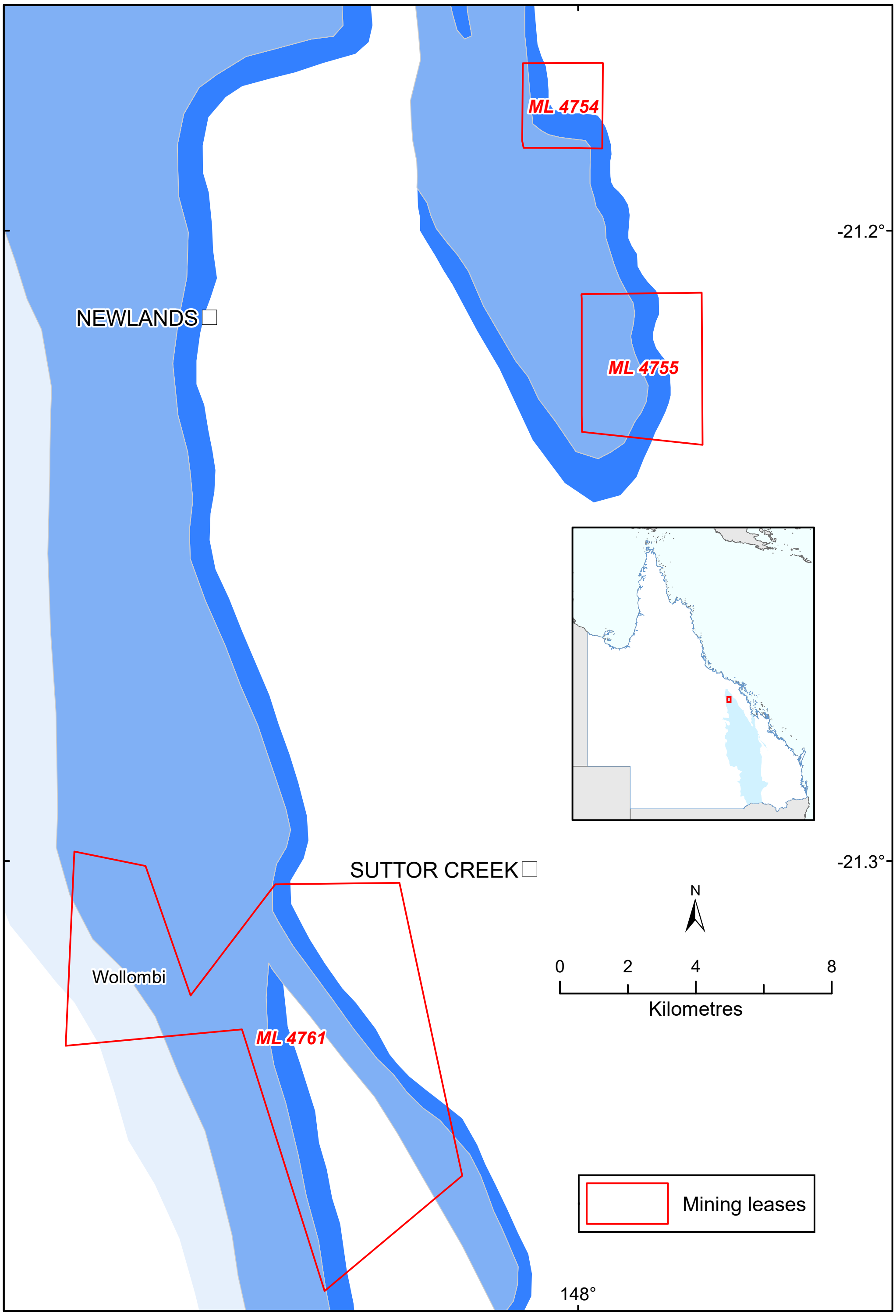

Figure 52. Newlands, Eastern Creek, Suttor Creek (incorporating Wollombi) mining leases with Fort Cooper Coal Measures trial pits. Legend in Figure 7.

Plate 17. Fort Cooper Coal Measures profile (~5 m deep) in the Girrah Trial Pit, Eastern Creek South mining lease, Newlands Mine (photo used with permission).

Most of the Grosvenor boreholes were drilled along the strike of the Moranbah and Rangal coal measures, between Lenton Downs in the north to Winchester South, further south, although a few were commenced in the Fort Cooper Coal Measures. Very little attention was given to investigating the quality of coal seams in the Fort Cooper Coal Measures at this stage of the department's coal exploration drilling, since interest was primarily being focussed on the coking coal of the Moranbah Coal Measures and to a lesser extent, on the seams within the Rangal Coal Measures. Limited sampling of coal seams within the Fort Cooper Coal Measures was undertaken as a result.

The formation was generally described as fine- to coarse-grained arenites interbedded with carbonaceous shale, tuffaceous mudstone and coal. Where present, conglomerate beds were often described as polymictic and where intersected at depth, such as at Burton Downs, also contained petrified wood (Figure 23). The colour green was often mentioned as a distinguishable characteristic (Plate 18), which suggests a deep-water reducing environment of deposition. Tuffs were ubiquitous and occurred as bands, beds or distributed throughout the coal and interburden. Fe-rich bands or intervals were also common within the coal seams, especially in the fine-grained sediments (Plate 19).

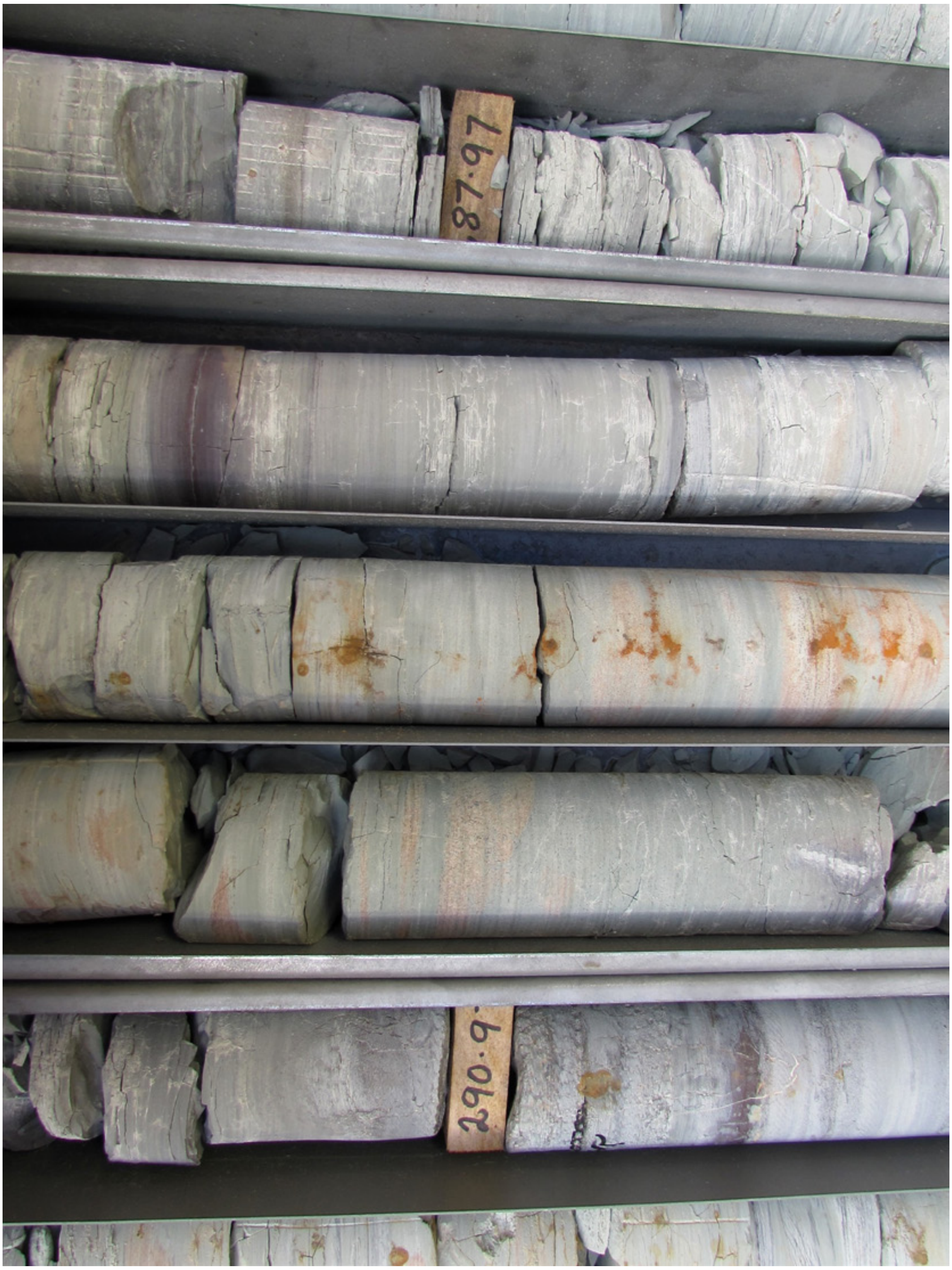

Plate 18. Green-purple finely laminated mudstones; an example from Cairns County 583.

Plate 19. Fe-rich laminae, bands or intervals; an example from Cairns County 16.

Over 300 coal samples were analysed in 25 Grosvenor boreholes (Figure 50, Appendix 4), with washability testing undertaken at specific gravities 1.40, 1.50, 1.60, 1.80 g/cm^3 and on raw coal (adb). About 75% of the raw coal samples contained ash values ranging from 30 to 50% (adb). Although the 1.40, F 1.50 and 1.60 fractions had high CSN values, ranging from 7 to 9, the cumulative yields were relatively low (i.e., >50% yield in 70% of analytical results for the F 1.60). Specific energy was rarely analysed and ranged from 20.2–24.8 MJ/Kg for raw coal and 26.6–30.6 MJ/Kg in F 1.60. Coking properties seemed to improve with increased depth in some areas (*e.g.,* Broadmeadow; Figure 23) as did the thickness of the Girrah Seam in other areas (*e.g.,* 32 m at Burton Downs).

Analytical results of coal samples of the Fort Cooper Coal Measures taken from the Cairns County series of boreholes demonstrated that the overall lithology and coal quality of the Fort Cooper Coal Measures did not change further south and along strike.

At Winchester, east of the Peak Downs and Saraji mining leases and at Lake Vermont (Figure 25), the Fort Cooper Coal Measures were described as consisting predominantly of poorly sorted, fine- to coarse-grained sandstones, very similar to the material described during the Grosvenor exploration drilling. In the Lake Vermont area, however, the formation became dominated by grey siltstones and mudstones, which were interpreted by Sorby *et al.* (1985) as deposited in still, poorly drained lakes.

In the region between Dysart and Middlemount, in the southern part of the north Bowen Basin, the partial correlative of the Fort Cooper Coal Measures, the Burngrove Formation, was mentioned for the first time at Picardy by Anderson (1974), when he described a green-grey highly tuffaceous arenite However, in later departmental drilling undertaken in the region in the late 1980s, other geologists (Coffey & Crosby, 1987) preferred using the name of ‘Fort Cooper Coal Measures’, since they could not clearly recognise a fine-grained argillaceous unit suggestive of the Burngrove Formation further to the south, in core taken from the Cairns County boreholes drilled during their program. Observations in core from the later drilling program at Picardy indicated that the region had undergone significant structural deformation (observed faulting, mylonites and steep dips in core), to the extent of unduly complicating stratigraphic correlations in that part of the Bowen Basin.

Further south, in the Roper and Parrot creeks area, the southern correlatives of the Fort Cooper Coal Measures were easily differentiated. The Burngrove Formation was described as a grey-green siltstone and mudstone interbedded with fine-grained sandstone. The underlying Fair Hill Formation comprised medium-grained sandstone grading into tuffaceous siltstone and mudstone.

In the Cairns County series of departmental boreholes, over 300 Fort Cooper coal analyses (F 1.40, 1.60, 1.80 and raw coal) were obtained from 25 boreholes, mainly concentrated in the Lake Vermont area (Figure 50). Overall, the ash values of the raw coal were similar to those determined in the areas covered by the Grosvenor boreholes further to the north, with about 70% of samples having raw coal ash values of between 30 to 50% (adb) Although the CSN values were high, the yields were lower than those obtained from samples taken from the Grosvenor boreholes further north (i.e. >50% yield in about 60% results for the 1.60 fraction).

4.4.3 Comet Ridge

Most of the departmental coal drilling undertaken in the southern part of the Bowen Basin has been located on the Comet Ridge, with only a few boreholes extending southwest into the Denison Trough (Figure 29). The Comet Ridge, which has also sometimes been referred to as either the 'Comet Platform' or (Comet) 'Anticline', was described by Galligan (1977, page 5) as *"a broad eroded anticlinorium plunging gently to the south. To the east the* [sediment] *sequence is interrupted by the Jellinbah Fault, an easterly-dipping reverse fault with a displacement of at least several hundred metres."*

Seam descriptions and coal quality data of the southern correlatives of the Fort Cooper Coal Measures are broadly clustered in three areas around the Comet Ridge as:

1. the northern section, east of Oaky Creek
2. the eastern flank, north and around Blackwater
3. the western flank, primarily north of Emerald (Figure 50).

4.4.3.1 Northern section

This area extends from the properties of Roper Creek in the north, Oaky Creek in the west and Girrah in the east (Figure 29). Departmental exploration in this region was undertaken with the Roper, Talbot and Blackwater series of boreholes, which mainly targeted seams within the Rangal Coal Measures (Roper Creek) or the German Creek Formation (Oaky Creek).

At Roper Creek, Anderson & Jameson (1982) found an atypical sandstone-dominated Burngrove Formation. They also reported the presence of several thick tuffaceous bands and inferred the thermal coal potential of the top seam, the Girrah Seam, at depths of 200–300 m.

Further south, near Oak Park, the Burngrove Formation was intersected at much shallower depths (<130 m deep), where it was described as being predominantly silty, with interbeds of sandstones or mudstone. The sandstones contained green lithic fragments at base, while the coal seams were dominated by mudstones with thick light brown tuffaceous intervals. The top seam was named the Virgo Seam by Staines (1973), a name that was subsequently used throughout the Comet Ridge. The seam consisted of two plies with coking properties but with ash values of between 20 to 42% (adb), which was considered unacceptably high at the time.

The sedimentation of the Fair Hill Formation appeared to be cyclic in this area and consisted predominantly of labile sandstone with greenish lithic fragments, followed by interlaminated siltstone, massive siltstone and coal at the base of the sequence (Prouza, 1976). The coal seams (Fairhill, Lepus, Canis and Hercules) were carbonaceous with thin and poor-quality coal intervals (Staines, 1973; Prouza, 1976; Zillman, 1976).

4.4.3.2 *Eastern flank*

Collectively, thousands of the Talbot, Leura, Humboldt and Blackwater series boreholes were drilled by the department along the eastern flank of the Comet Ridge, primarily to delineate the resources and coal quality of seams in the Rangal Coal Measures. Areas drilled included locations such as Jellinbah, Caledonia, Curragh and Blackwater. Over a period of almost two decades, coal exploration was undertaken in these areas by the GSQ's Coal Section on behalf of the State Electricity Commission. Most of the work was located within Departmental Area 56D—an area that was specifically reserved by the State for the possible supply of thermal coal for use in domestic power generation.

The Burngrove Formation was described as consisting of several sedimentary sequences with medium to fine sandstones at the top, numerous silty interbeds and dark grey massive mudstone at base, the latter being correlated with the Black Alley Shale on the Springsure Shelf (Anderson, 1971). The colour green and the carbonaceous nature of the coal seams were considered a ubiquitous characteristic by many of the geologists who reported on the department's coal exploration drilling in the region (*e.g.,* Carr, 1973; Park, 1973a; Staines, 1977, 1978).

The formation was the thickest at Jellinbah, at around 365 m (Carr, 1973) and thinned towards the north to about 250 m at Oak Park (Staines, 1973) and also southwards towards Blackwater, where it was reported at about 135 m thick (Staines, 1974).

The coal seams were highly variable in terms of presence, thickness and character. The Virgo Seam was the thickest near Girrah (>23 m; Carr, 1973), thinned and split north of Caledonia, and then coalesced with the Pisces near Caledonia (Park, 1973; Balfe, 1983). Around Blackwater, the Virgo was found to be only a few metres thick (Carr, 1975; D'Arcy, 1985). The greatest thickness was reported near Curragh (~ 40 m, Galligan, 1978). Highly interbedded with carbonaceous mudstone, the seam also contained several thick (~0.5 m) tuffaceous bands.

Due to the high incidence of carbonaceous and tuffaceous material, the raw coal had high ash values (30–50% adb), although coking properties were reported at Girrah (Carr, 1973), Caledonia (Park, 1973a; Staines, 1978) and northwest of Blackwater, near Curragh (D'Arcy, 1985).

The seams below the Virgo (Leo, Aquarius, Scorpio) were predominantly carbonaceous and of no economic interest, with one exception; at Blackwater, D'Arcy (1985) found good coking properties in a couple of coaly intervals in the Leo Seam.

The Fair Hill Formation was initially mentioned by Carr (1974) near Girrah, where the formation was predominately arenitic with silty interbeds. The scarcity of information on the northern and eastern sides of the anticline was due to the fact that the drilling undertaken in this area did not penetrate the entire Burngrove Formation to reach the Fair Hill Formation.

However, the boreholes drilled on the subcrop of the formation at Oak Park, enabled Prouza (1977) to describe the cyclicity of sedimentation as mudstone–siltstone–coal. A sequence containing from three to six seams, up to 180 m thick, was encountered, although the coal seams intersected were considered to be uneconomic due to their carbonaceous and tuffaceous character. No analyses of the seams intersected was undertaken.

4.4.3.3 *Western flank*

The lithology and character of the Burngrove Formation on the western flank of the anticline differs from those described on the eastern flank, due to episodes of marine-influenced sedimentation. Where intersected, the formation consisted predominantly of dark grey marine mudstones similar to the Black Alley Shale, although coarse-grained sandstone interbeds were also present north of Emerald (Park, 1975b). At Ensham, the formation comprised light green sandstones and siltstones interbedded with tuffaceous bands, becoming muddy at the base (Coffey *et al.,* 1983).

Further south, between Comet and Togara, the character of the Burngrove Formation reflected a transition from fluvio-deltaic to lagoonal sedimentation (Zillman, 1978; Thornton, 1986).

Of the three seams intersected in the Burngrove Formation north of Emerald (Virgo, Leo and Aquarius), only the Virgo Seam was analysed. There, it was a few metres thick, more than 300 m deep, and the coal did not present coking properties (Park, 1974; Park & Galligan, 1974; Staines *et al.,* 1983; Thornton, 1983). The Virgo Seam was absent at Ensham and further south at Togara (Anderson, 1975a; Zillman, 1978), presumably due to the marine influence which became more prominent over the Denison Trough.

The Fair Hill Formation was briefly mentioned at Emerald (Park, 1973b) and Togara (Zillman, 1978). It was described as feldspathic, sublabile, lithic sandstones interbedded with siltstone and argillaceous units (Park, 1973b; Zillman, 1978). The three seams intersected at Togara (Phoenix, Pegasus and Hercules) were tuffaceous and/or carbonaceous (Zillman, 1978).

4.4.4 Summary

As previously mentioned, there are 100 coal boreholes located in both the northern and southern section of the basin which have been analysed for coal quality; the resultant coal quality dataset comprises 880 analyses (Figure 53), most of which are of raw coal (Appendices 4 and 5). The relationship between ash (% adb) and CSN is of significance (Figure 54). Analysis of the entire dataset shows that the fractions at specific gravity less than F 1.60 may contain ash values below 25% (adb), increasing to around 35% (adb) in the F 1.80 fraction, while ash values of the raw coal can reach up to 60% (adb).

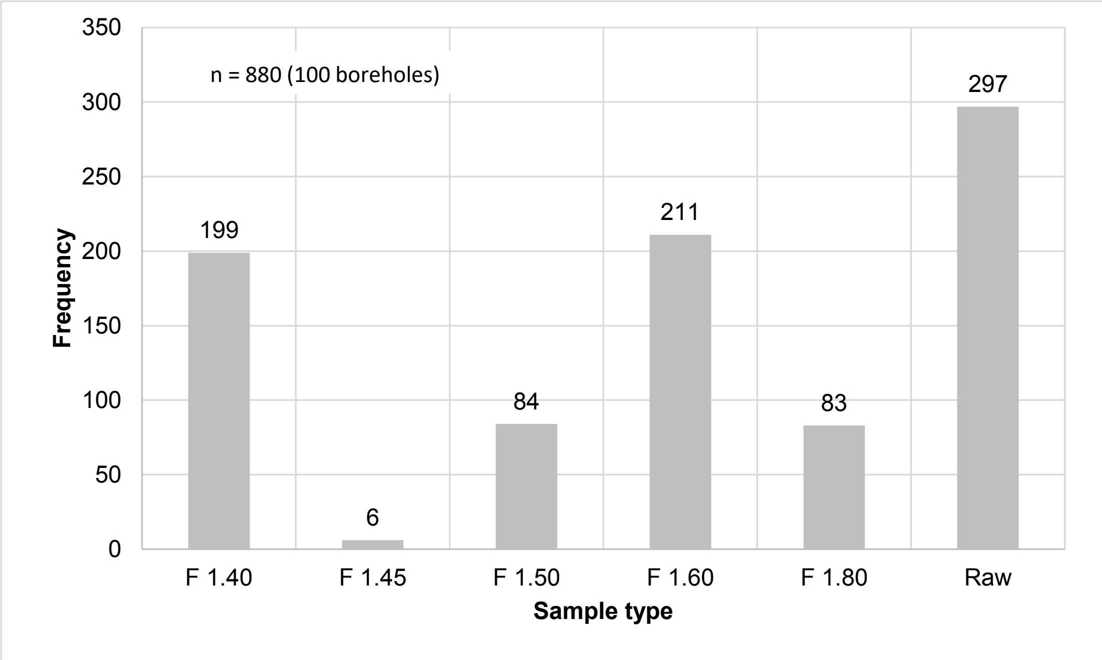

Figure 53. Type and number of Group 4 coal analyses, north and south Bowen Basin.

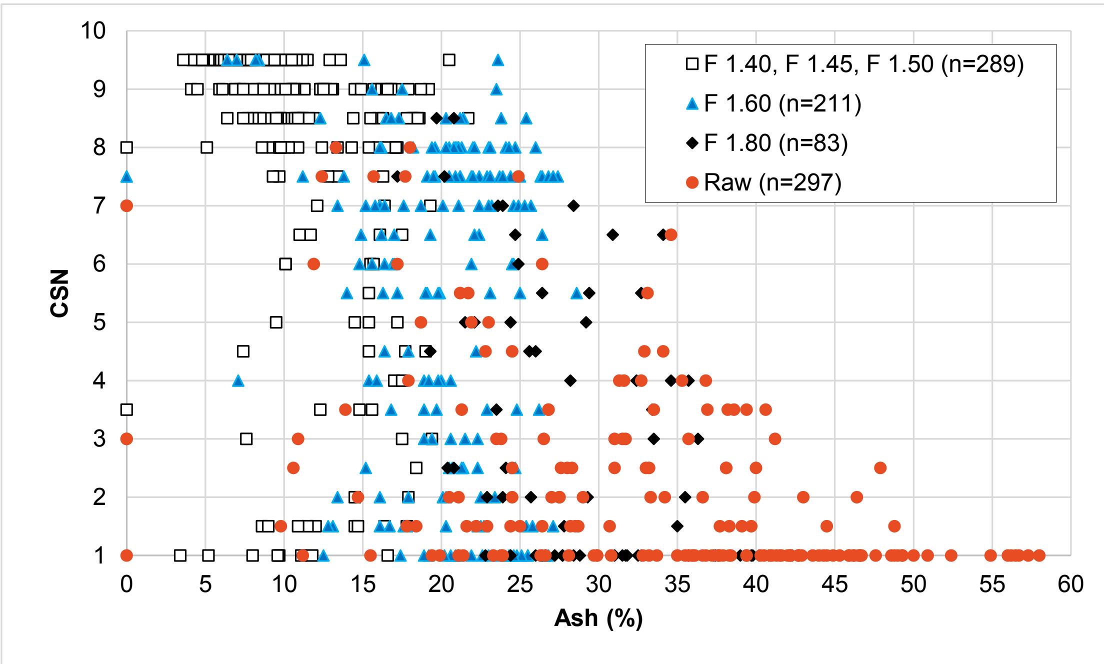

Figure 54. Relationship between ash values (adb) and CSN of Group 4 coal, north and south Bowen Basin.

4.5 Coal depth and thickness

The cumulative sample thickness in a particular borehole was calculated for the entire dataset.

These thickness estimates represent plies which were visually considered of better quality and warranted sampling for analyses. Samples were largely consecutive, with a few exceptions when up to 2 m partings/stone bands occurred between coal layers. When larger intervals occurred, for example between the Vermont Lower and the Girrah seams or the Virgo and the Leo seams, only the seam with the greater thickness was considered in the thickness analysis—Girrah/Virgo Seam in most cases.

Analysis of this cumulative coal thickness against depth (the top of the upper most sample in each borehole) reveals a few areas where thick sections of clean coal are found at depths shallower than 250 m (Figure 55): Red Hill (GR 173), Winchester (CC 15; Plate 20), Lake Vermont (CC 227; Plate 21) and Oak Park (BL 163).

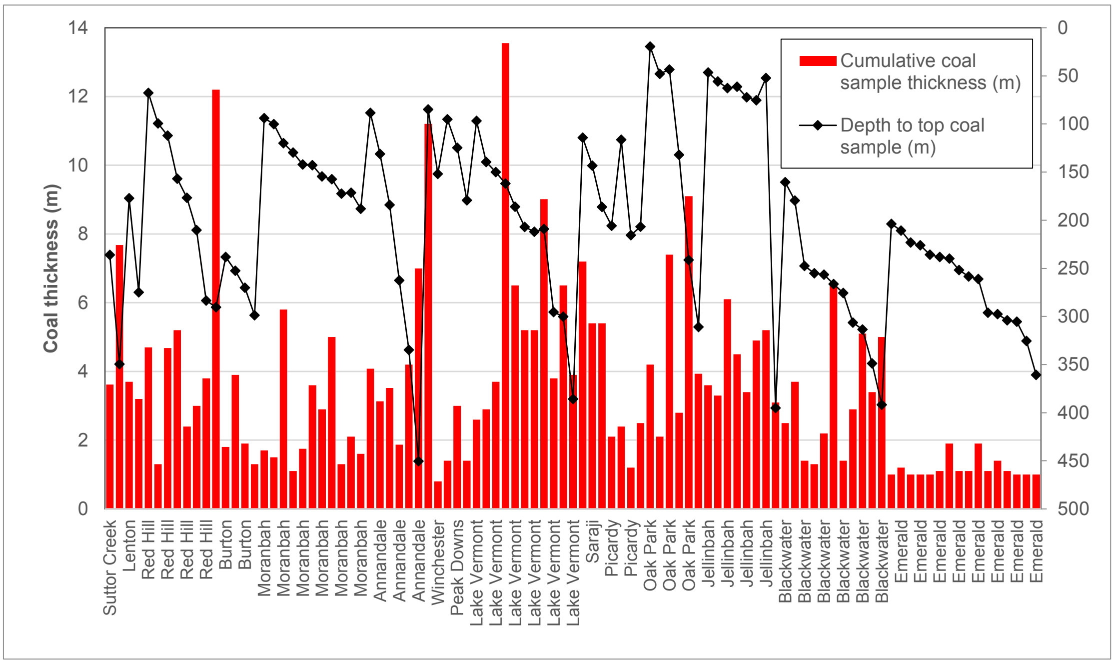

Figure 55. Cumulative coal thickness in relation to depth, from north to south.

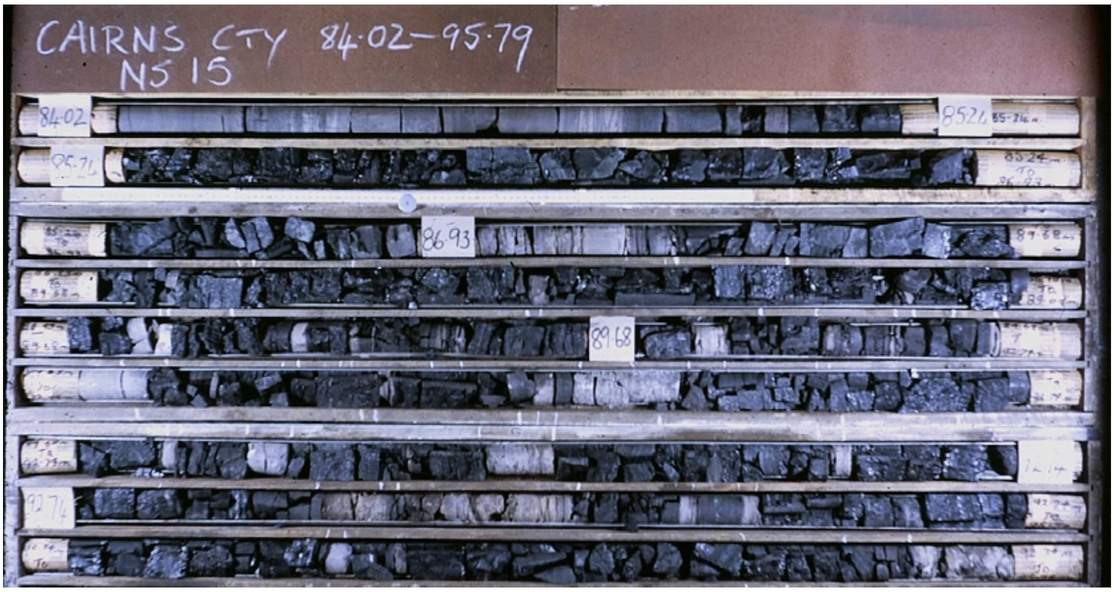

Plate 20. Coal thickness (11.20m) in Cairns County 15 at Winchester.

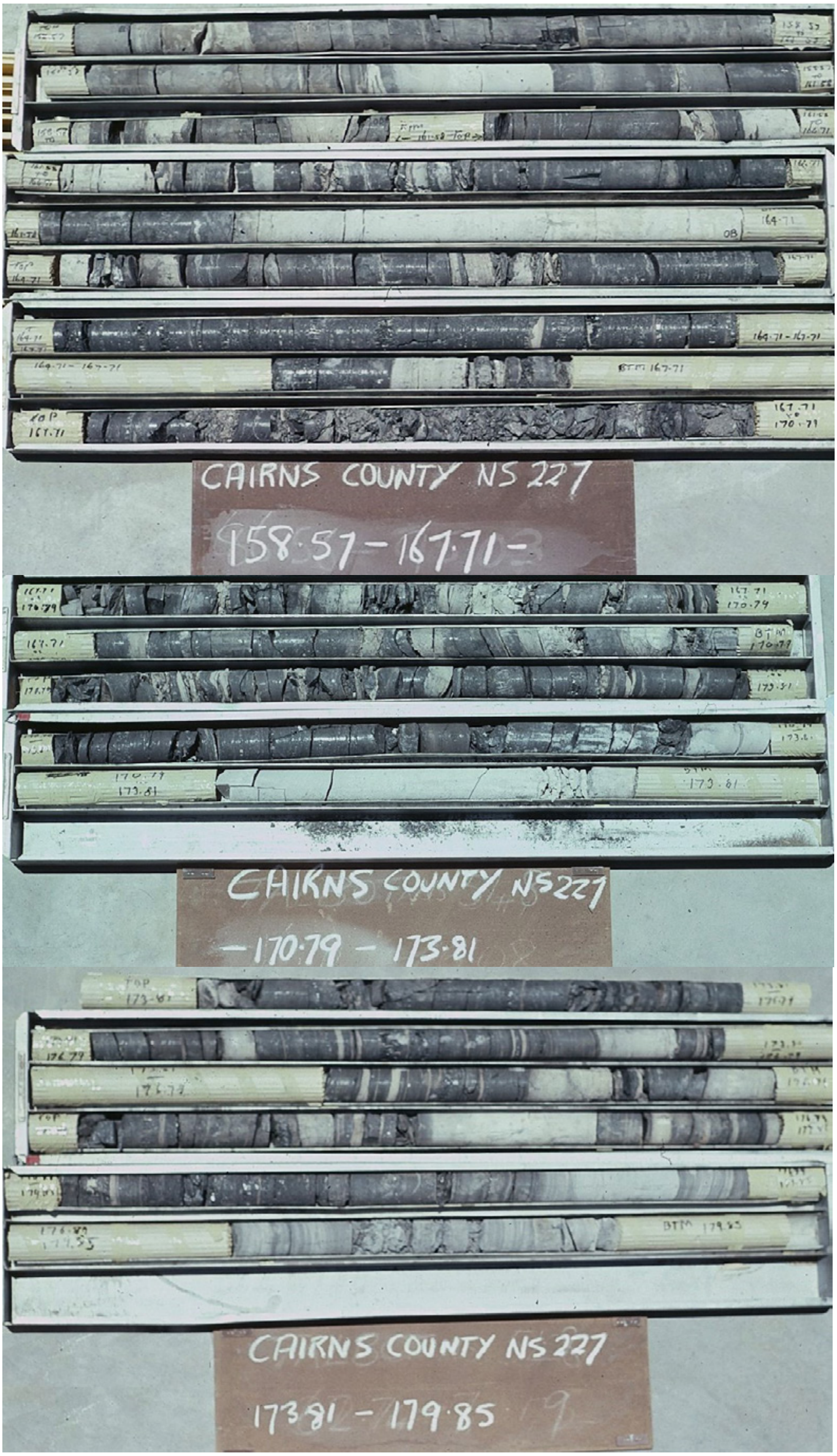

Plate 21. Coal thickness (13.55m) in Cairns County 227 at Lake Vermont.

In these areas of great of coal thickness, the F 1.40 also contains under 10% ash and high CSNs (Figure 56).

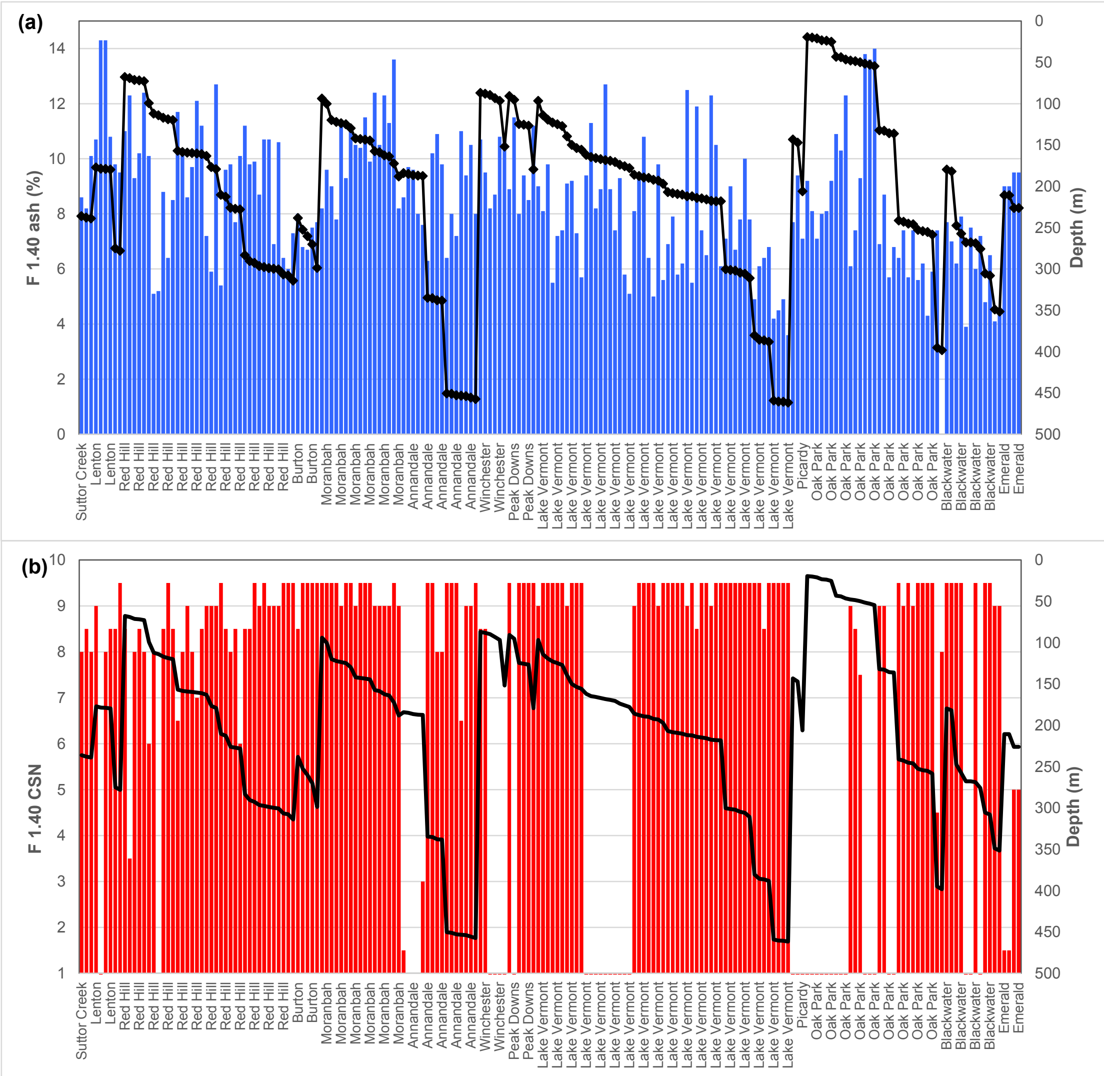

Figure 56. Ash values (a) and CSN (b) variation with depth (black line) to top coal sample, from north to south.

At Red Hill and Winchester, the thick seams encountered are Girrah, Vermont or Vermont-Girrah. At Lake Vermont, the main seam is Girrah and at Oak Park is Virgo.

Overall, the Girrah Seam occurring in the north is thicker than its southern counterpart, the Virgo Seam (Figure 57).

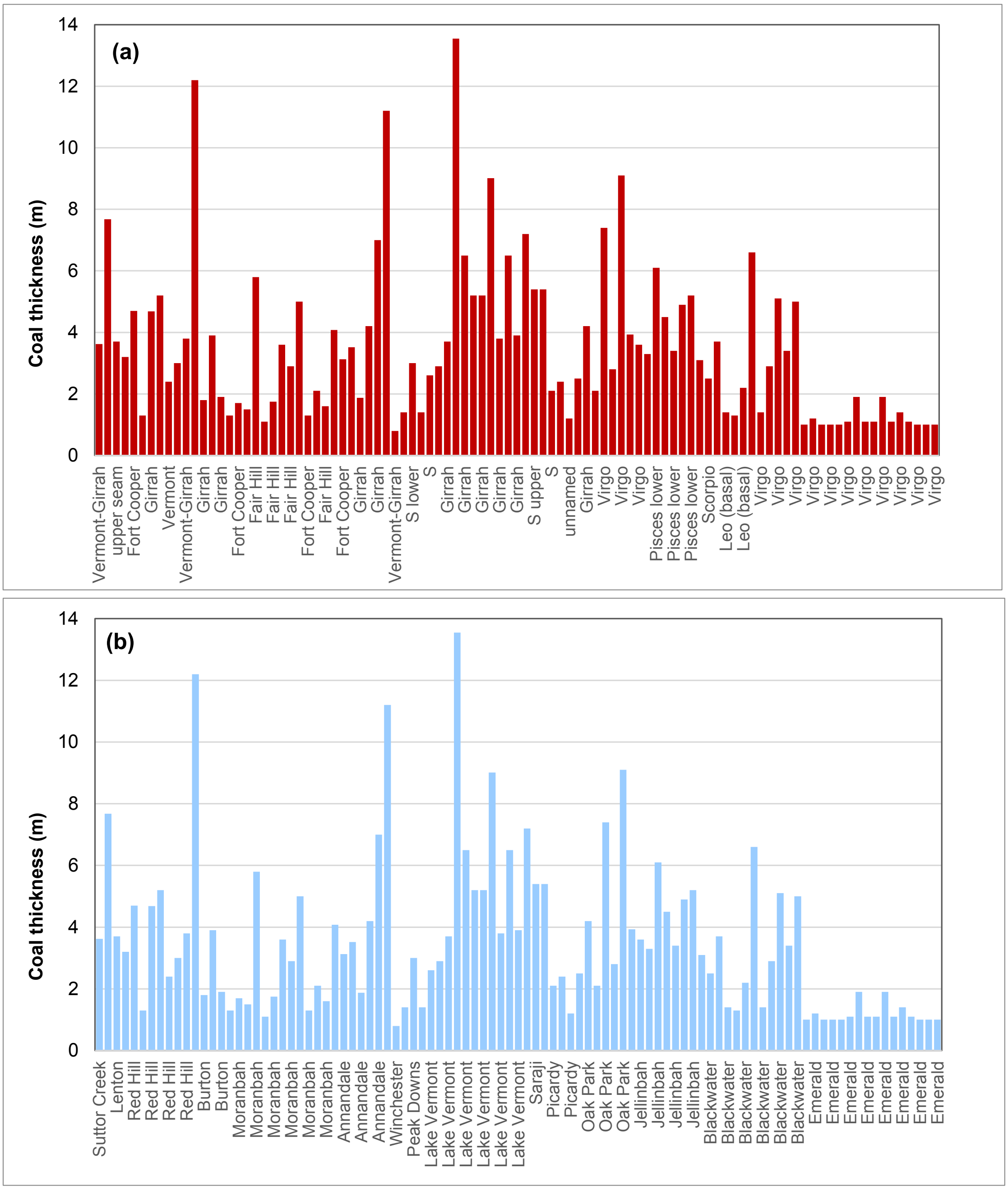

Figure 57. Regional variation of cumulative coal seam thickness, by seam (a) and project areas, from north to south (b).

4.6 Vitrinite reflectance

Isoreflectance mapping was undertaken as part of a comprehensive Bowen Basin study of coal rank (Beeston, 1981), which showed a direct relationship with depth for all the formations sampled, including the Fort Cooper Coal Measures.

Analysis of data available for the Fort Cooper Coal Measures in the northern section of the basin, which were reviewed as part of this study, revealed the existence of three data populations:

1. centred around 1% vitrinite reflectance (Rv,max) and ranging from 0.8–1.3%
2. intermediate, 1.3–1.6%
3. centred on 2% vitrinite reflectance and ranging from 1.6–2.5% (graph in Figure 58).

Based on the company data compiled by Mutton (2003), the typical vitrinite reflectance ranges for coals in the Bowen Basin are as follows:

- Thermal: Rv,max = 0.4–3.1%
- PCI (pulverised coal injection): Rv,max = 1.2–2.2%
- Coking coal: Rv,max = 0.8–1.7%.

These ranges confirm the coking potential of the Fort Cooper coal with a few exceptions where local conditions caused the formation of higher rank coal.

Within the Nebo Synclinorium, in terms of the depth-rank relationship (as measured by the mean maximum reflectance of vitrinite), quite a number of the vitrinite reflectance results obtained from coal in seams of the Fort Cooper Coal Measures appear to be anomalous, probably due to effects of igneous activity on the coal seams in this region, although the degree to which samples at different sites were affected varies. In CC 10 and 11 for instance (Figure 58), which are only a few kilometres apart and presumably influenced by the same sill emplacement (Holmes, 1980), CC 10 appears to be of higher rank (more altered) than samples taken of coal in CC 11. Similarly, HL 2 appears to have been thermally affected to a depth of around 330 m depth (Koppe, 1973), while WO 2 was completely altered to a depth of almost 700 m (Koppe, 1976a). The high vitrinite reflectance in GR 8 is explained by its location, being only 10 km west of the Bundarra Granodiorite (Figure 58).

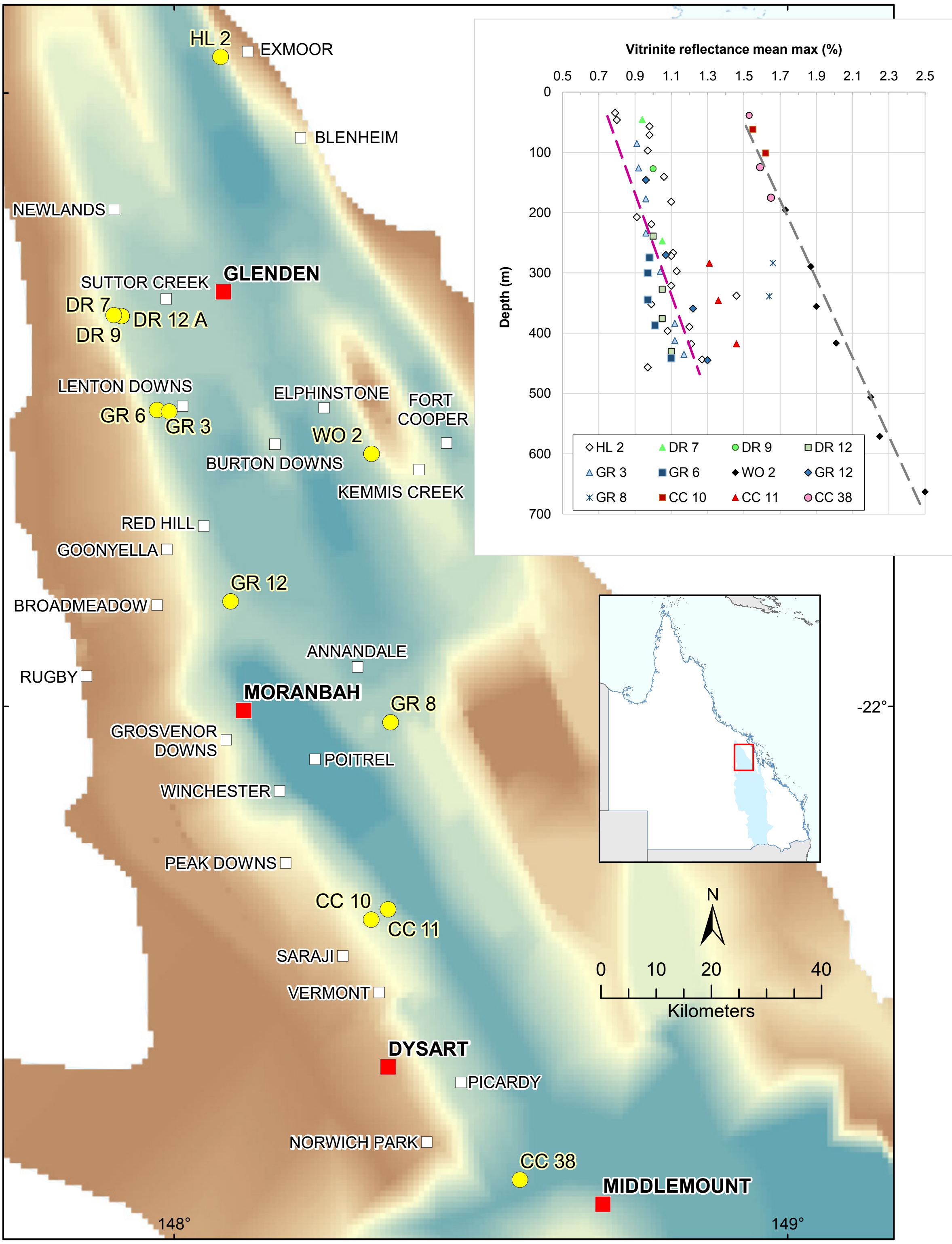

Figure 58. Horizontal and vertical (versus sample depth - inset) distribution of vitrinite reflectance analyses in the northern Bowen Basin. Legend in Figure 7.

Beeston (1981) found that the Collinsville Shelf and the Nebo Synclinorium had different reflectance gradients which he attributed to their different subsidence evolutions. For coal seams in the Fort Cooper Coal Measures, however, this relationship could not be tested, as this formation does not extend over the Collinsville Shelf, only over its eastern slopes.

Previously unpublished departmental vitrinite data and open file CSG data were spatially analysed and mapped by McKillop (2016), who expanded on work by Beeston (1986). The study confirmed that the rank of the Fort Cooper Coal Measures and their correlatives increased with depth; however, the vitrinite reflectance profile changed, having a steeper slope at depths greater than 500 m (graph in Figure 59). Data variability appeared to have increased at depth as well, although those analyses were from only one well, Foxleigh 4, near Middlemount (Figure 59).

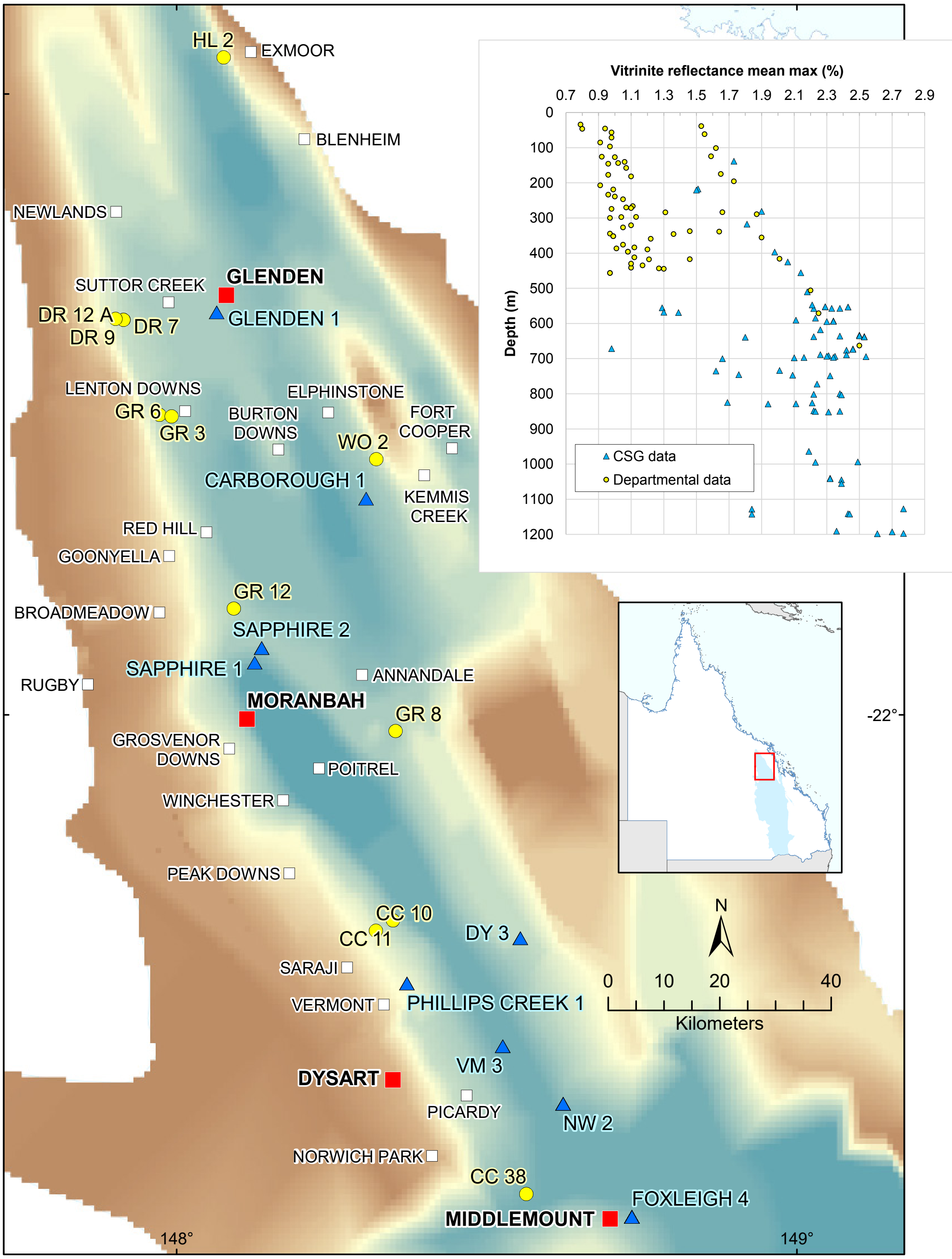

Figure 59. CSG vitrinite reflectance analyses (after McKillop, 2016) and comparison with departmental data. Legend in Figure 7.

The direct relationship between rank and depth (graphs in Figure 58 and Figure 59) was often upset by localised processes. The eastern flank (Exmoor to Annandale), for instance, had high vitrinite reflectance values due to igneous activity. The western flank (Suttor Creek to Dysart) had lower rank coal and values outside the coking coal window were rare, as igneous influence appeared to be localised and less intense than in the east. Over the central Taroom Trough, near Middlemount, the Fort Cooper Coal Measures occurred at depths greater than 550 m and most samples fell outside the PCI window (Rv,max > 1.7%), presumably due to the depth of burial rather than other causes.

Isoreflectance mapping on the Comet Ridge was limited (Figure 60). The data, primarily from Beeston (1981) and reinterpreted by McKillop (2016), revealed the existence of three data populations (Figure 61):

1. a low rank population with vitrinite reflectance <0.8%, which occurs on the western flack (based only on EM 7)

2. largest population = 1.1–1.7%

3. small population with vitrinite reflectance > 1.7%, with a few high rank values occurring in boreholes BL 168, BL 173, TA 300, TA 301, TA 852, TA 854 (Figure 62; Plate 22), in the Jellinbah area, and along a fault, apparently related to the Jellinbah Fault system.

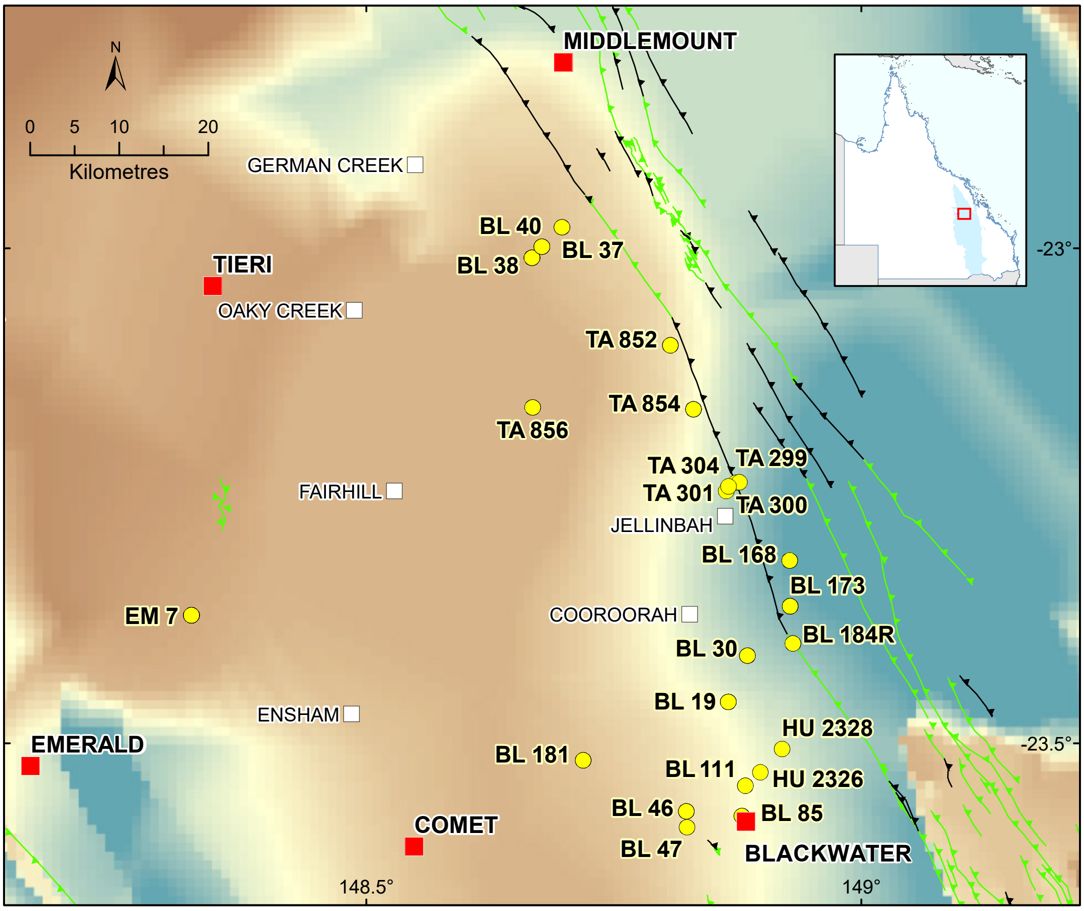

Figure 60. Vitrinite reflectance data on the Comet Ridge. Legend in Figure 7

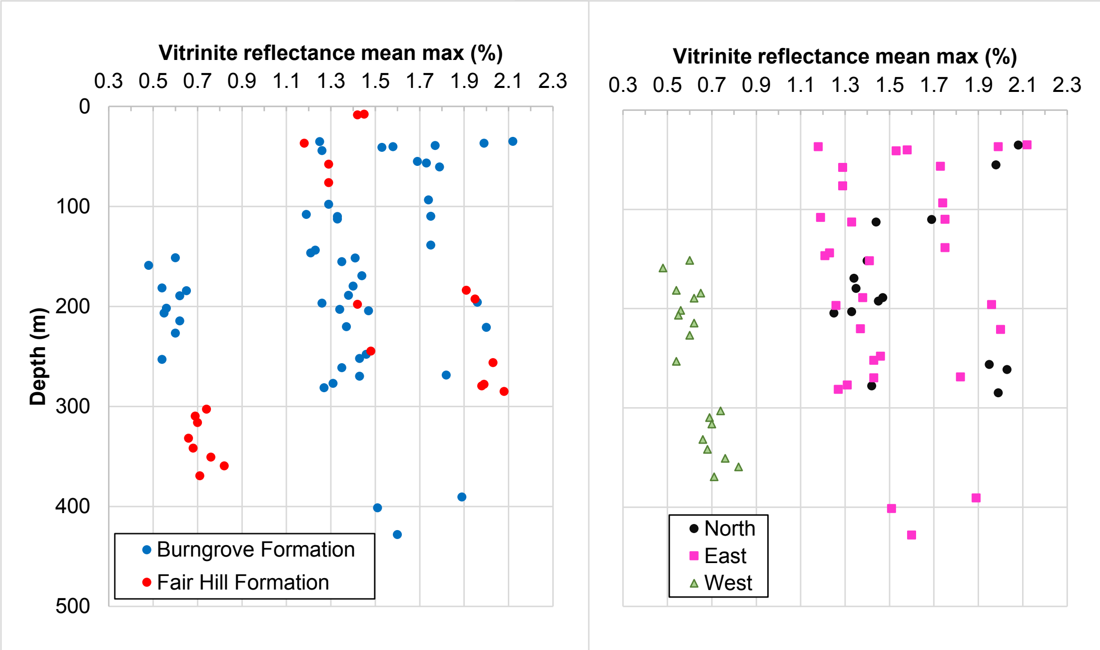

Figure 61. Vitrinite reflectance data in relation to sample depths.

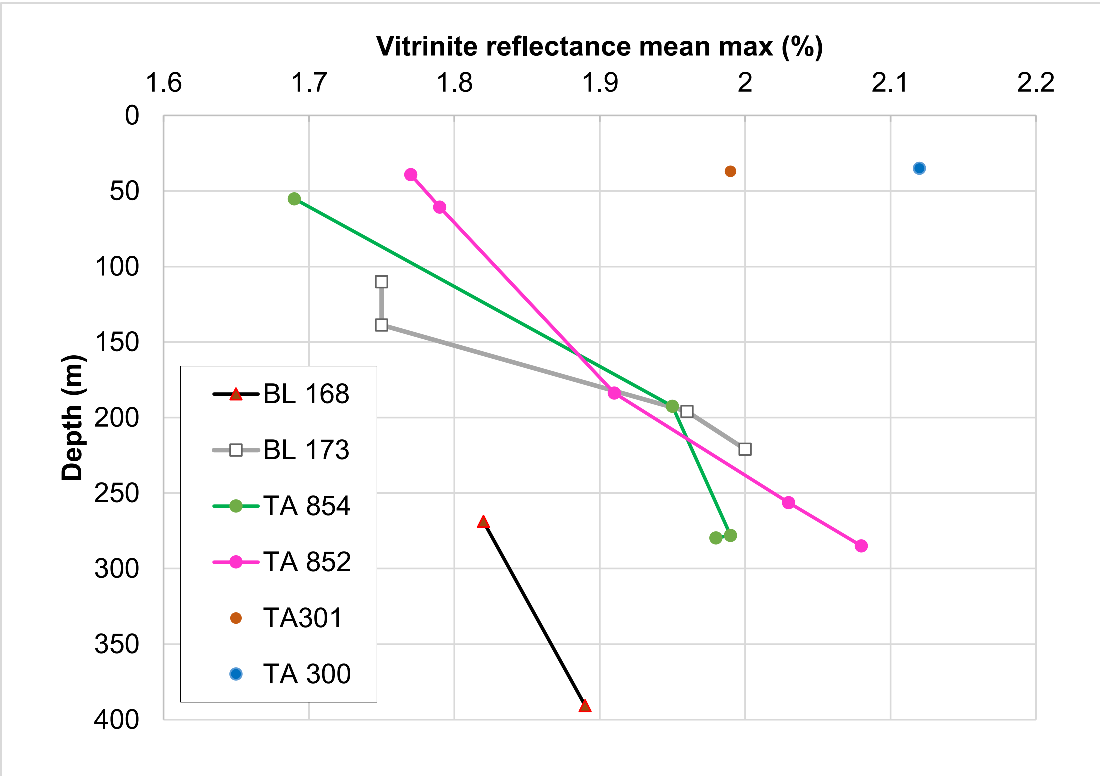

Figure 62. High vitrinite reflectance along a fault line. Borehole locations in Figure 60.

Plate 22. Relatively bright-banded high vitrinite reflectance coal in Talbot 854 (see Figure 62 for vitrinite reflectance profile and Figure 60 for borehole location proximal to a fault).

4.7 Fort Cooper Coal Measures sequences

The comprehensive study of the Rangal Coal Measures by Matheson (1990a) was restricted to the north Bowen Basin and included a summary of departmental boreholes which intersected the sequence. His review also included the stratigraphic boundary information concerning the Yarrabee Tuff and the seams in the underlying Fort Cooper Coal Measures. Matheson's (1990a) dataset (Figure 63), augmented by borehole data extracted as part of this review (Table 44), is presented in Appendix 5.

As seen in Figure 63, departmental boreholes with boundary information are sparse. Furthermore, the data compiled in Appendix 5 show that either the top or the lower boundary is uncertain due to data not being collected or boreholes being stopped before reaching the lower boundary. Consequently, only 13 boreholes (GR 3, GR 12, GR 19, GR 45, GR 39, GR 28, GR 23, CC 13, CC 62, CC 10, CC 499 and CC 583; Figure 64) have been selected to construct a cross section along strike on the western flank of the northern part of the basin (Figure 65). The section extends from Lenton Downs in the north to west of Dysart in the south. Of note is the structural disturbance in the cores taken from boreholes CC 499 and CC 583 (Figure 64) due to proximity to the Isaac Fault.

Insufficient stratigraphic and boundary information on the Burngrove and Fair Hill formations is available in the southern section of the basin to allow the construction of a cross section over the Comet Ridge.

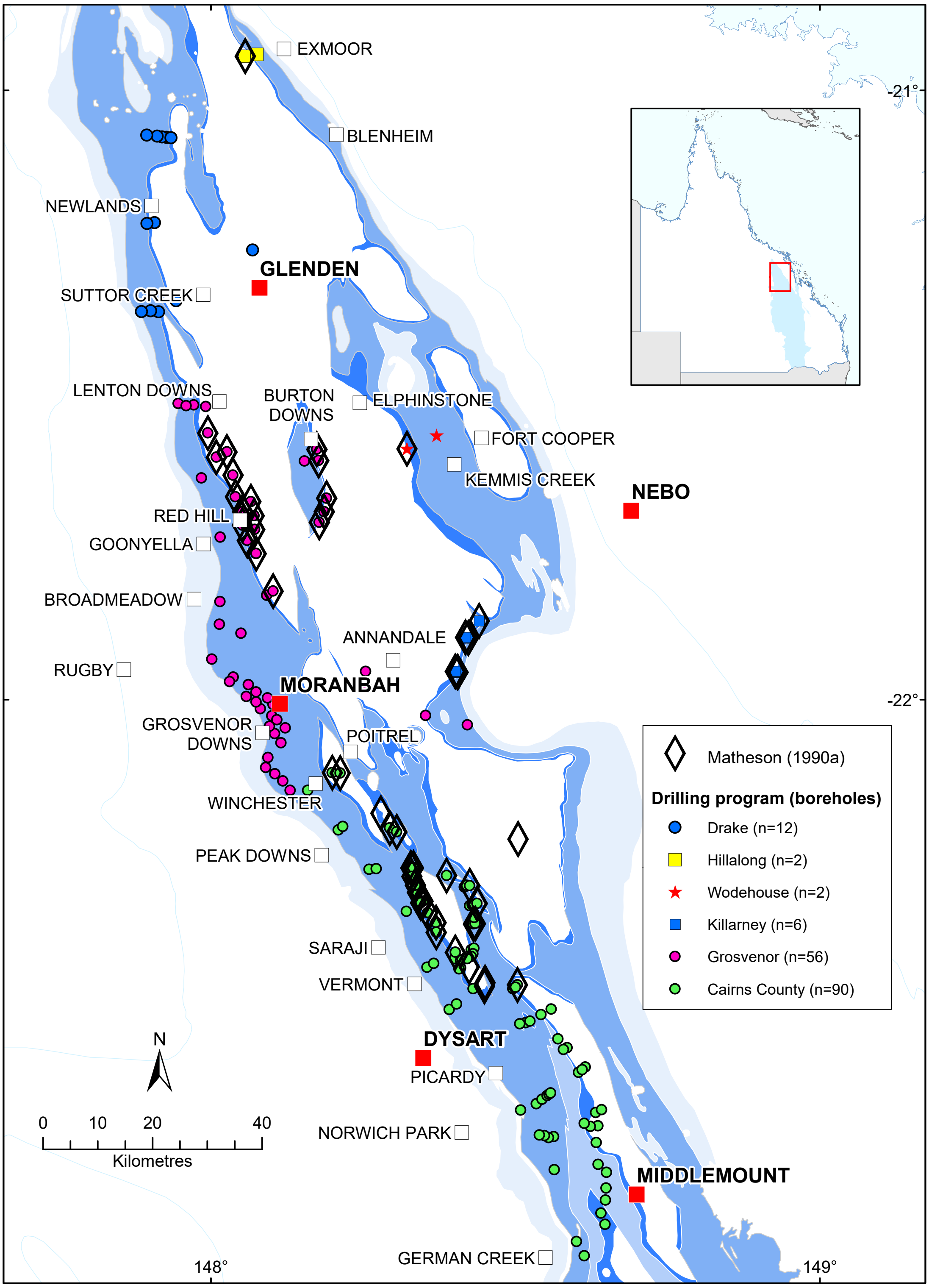

Figure 63. Departmental boreholes (n=168) with boundary information in relation to boreholes described by Matheson (1990a); details in Appendix 5. Legend in Figure 7.

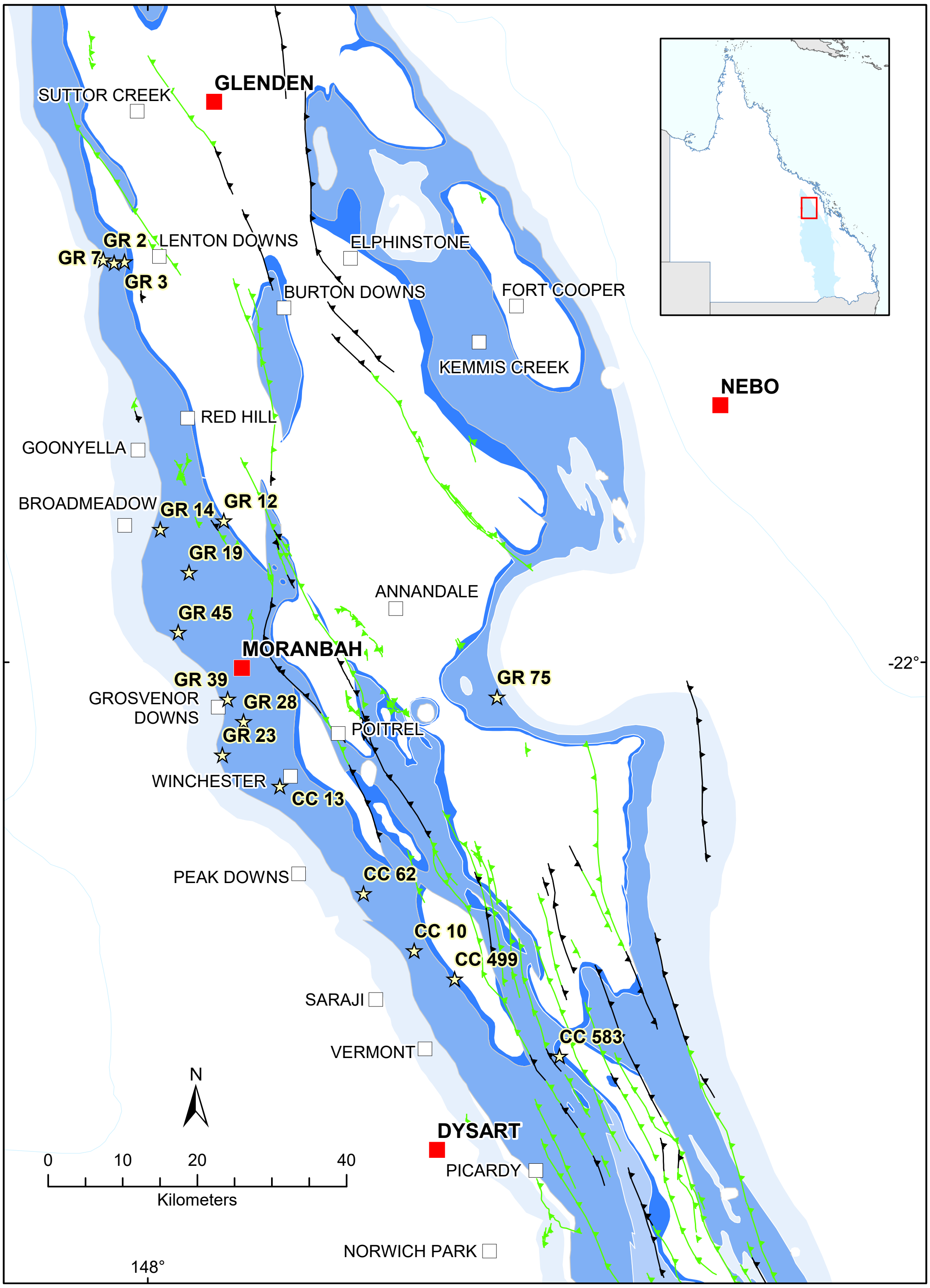

Figure 64. Departmental boreholes with complete cored sections of the Fort Cooper Coal Measures, north Bowen Basin. Legend in Figure 7.

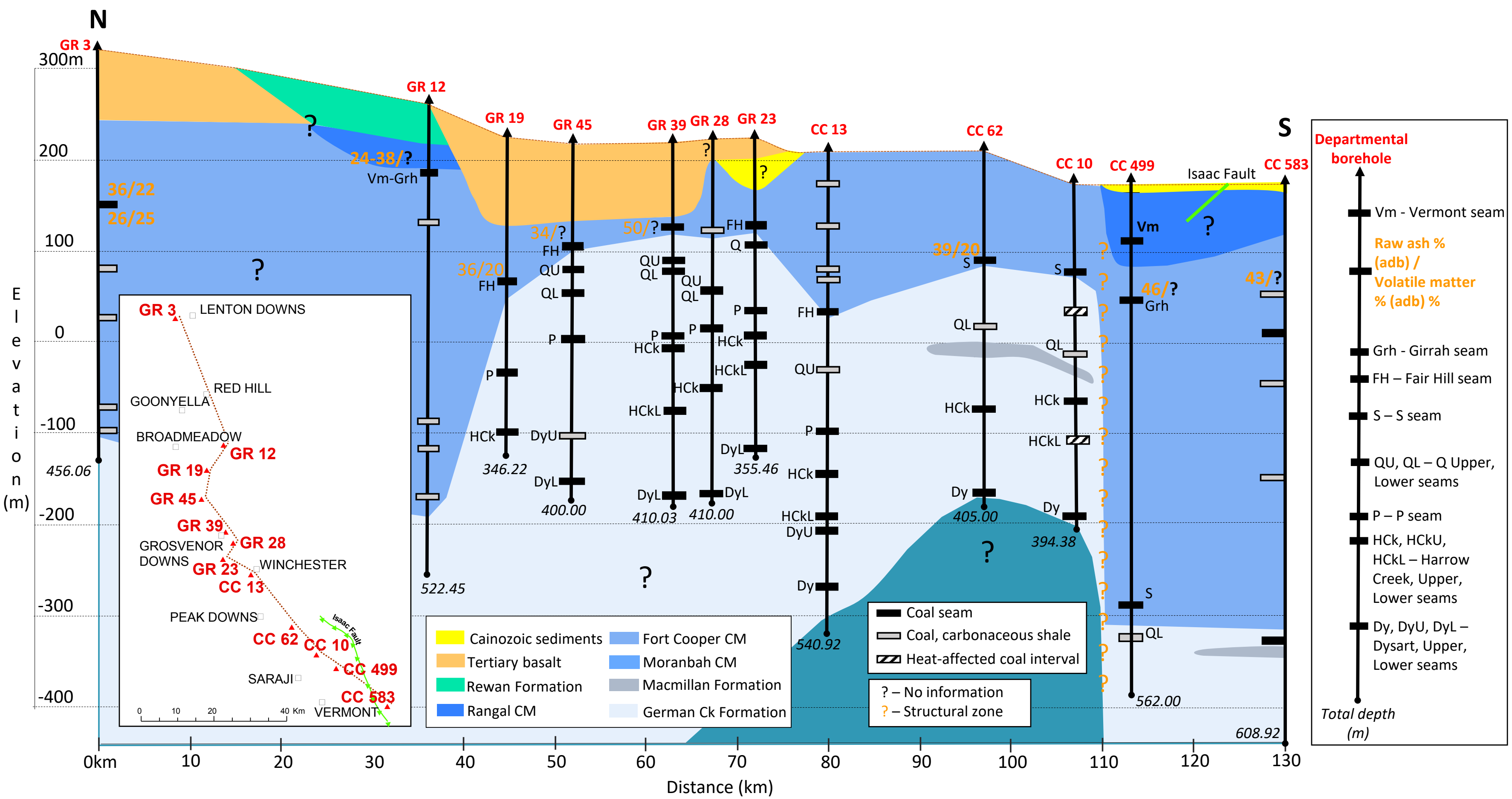

Figure 65. North–south section along strike of the Fort Cooper Coal Measures (seam thickness not to scale)

4.8 Potential exploration targets

4.8.1 North

The overall lack of interest in the Group 4 coals has been based on the opinion that their seams have no commercial potential. This view formed in the early 1970s, when work by Koppe (1972, 1973, 1974, 1976a, 1976b) revealed the tuffaceous nature of the Fort Cooper Coal Measures. However, recognition of their coking coal properties meant exploration and sampling undertaken over the following decades have identified areas where further investigation is warranted (Figure 66).

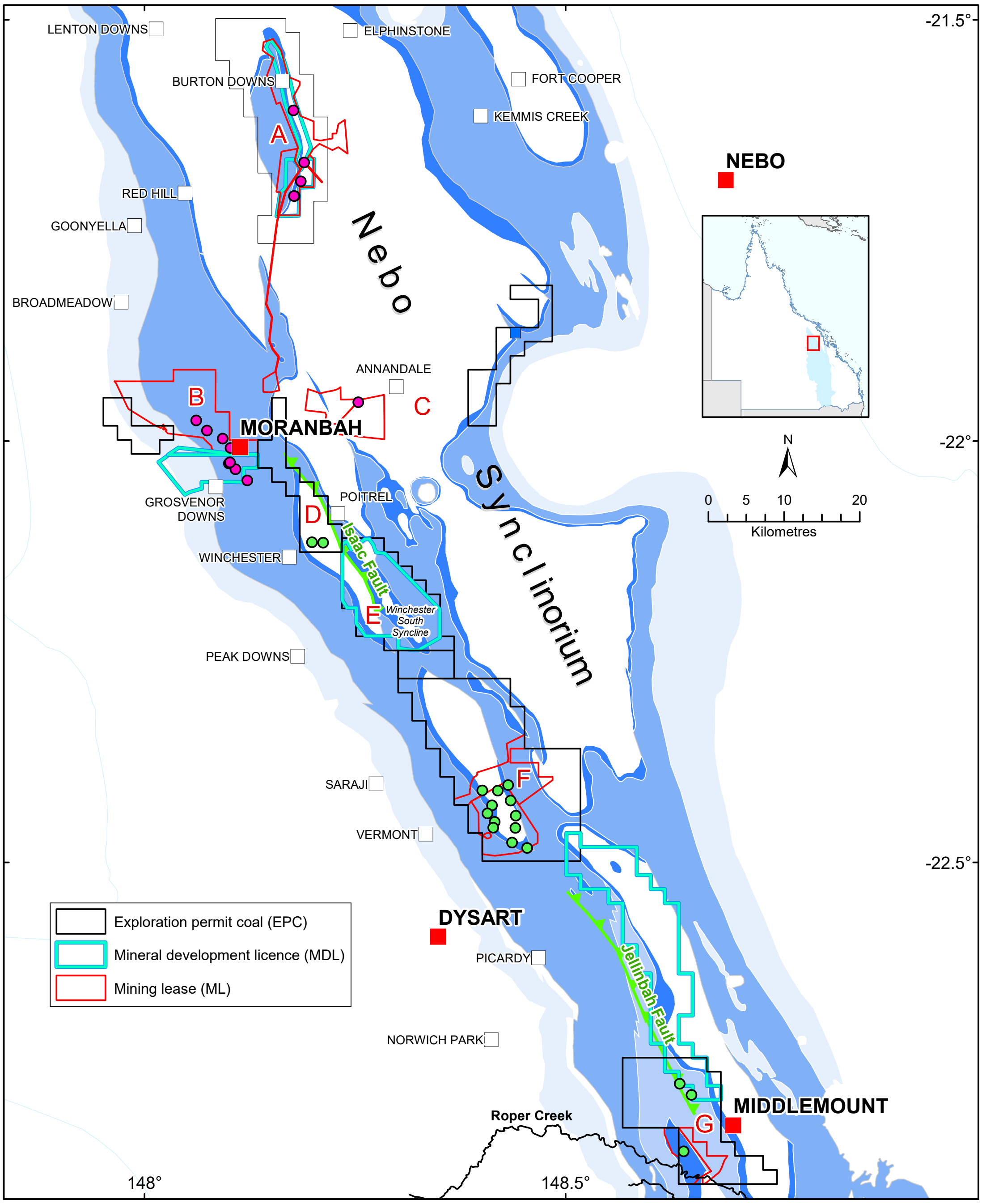

Figure 66. Potential exploration targets (A to G) in relation to subcrop and current tenure. Legend in Figure 7.

A. A potential area is **Burton Downs** (boreholes GR 183 to 187) where the Girrah Seam is 32 m thick, according to Matheson & Jameson (1988). Dash (1985a) found good swelling properties and reasonable yields in the 1.40, 1.50 and 1.80 fractions (Table 17). The area is currently included in ML 70109 (Burton), ML 70258, ML 70259 and ML 70260 (Plumtree), and two non-current MDLs: MDL 129 and MDL 245. However, some information is available from boreholes drilled in parts of EPC 497 (Figure 67), which have now been relinquished. The Fort Cooper Coal Measures are 20–60 m thick and consist of fine-grained lithic sandstone with interbeds of tuffaceous siltstone, mudstone and coal. The sandstone is moderately strong and well-cemented, while the minor mudstone interbeds are occasionally fissile. The Girrah Seam can be more than 20 m thick in places and includes predominantly dull (~95%) banded coal. At the southern edge of the subcrop, where the Fort Cooper Coal Measures occur at depth, a basic intrusion has been reported at 165 m (McElroy Bryan Geological Services Pty Ltd, 1995).

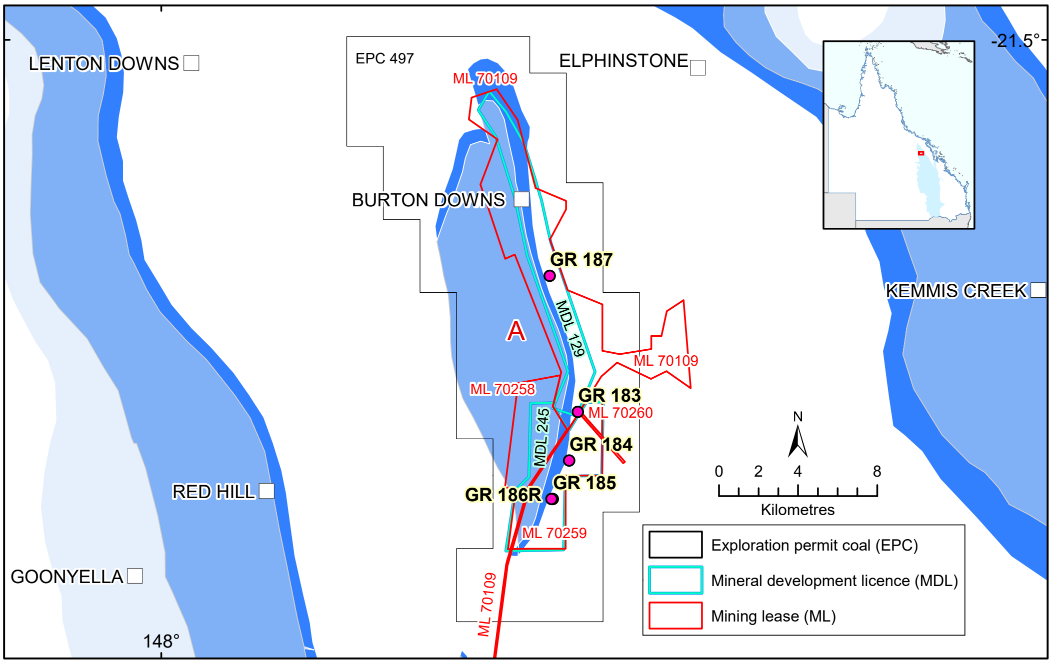

Figure 67. Area A, Burton Downs. Legend in Figure 7.

B. A promising area found through the Grosvenor drilling program (boreholes GR 54 to GR 70) was **Moranbah**, where Scott (1987b) assessed the Fairhill Seam to be economic due to high CSNs and yields, and under 30% ash in the F 1.60 fraction (Table 21). Currently this area is under tenure (ML 70378—Grosvenor, MDL 273 and MDL 377, Figure 68), but some limited information is publicly available in a relinquishment report for parts of EPC 552; the Fairhill Seam is more than 20 m thick but highly tuffaceous and therefore, considered uneconomic by Anglo Coal (2014). No coal quality analysis has been reported.

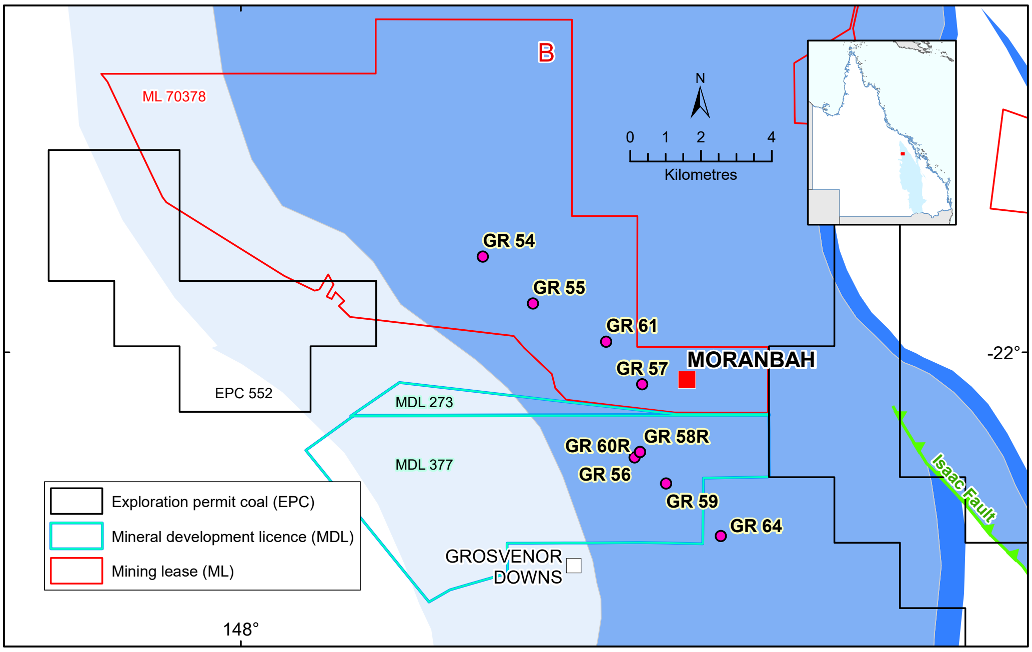

Figure 68. Area B, Moranbah. Legend in Figure 7.

C. Although the eastern flank of the basin has limited prospectivity due to structural deformation and thermal alteration of seams, Koppe (1974) found that the top Fort Cooper Seam near **Annandale** (in Killarney 2, Table 12 and Grosvenor 9, Table 22) is reasonably thick and contains *"coal suitable for non-coking purposes"* (page 1). Grosvenor 9 is currently located on the boundary between ML 70340 (Annandale) and ML 70339 (Carborough Downs) and no additional information is publicly available. Although Killarney 2 is open domain, it is within EPC 646 (Figure 69), which remains confidential as part of the Coppabella coal projects.

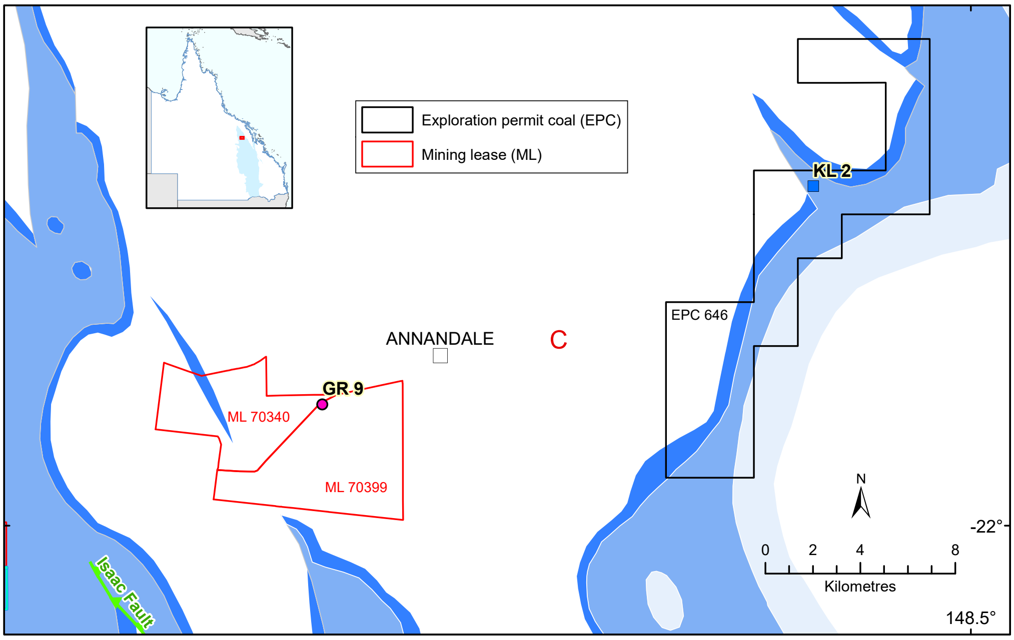

Figure 69. Area C, Annandale. Legend in Figure 7.

D. Exploring the **Winchester** area (boreholes CC15 and CC16; Table 23), Koppe & Scott (1981) concluded that "*Despite the low yield which would result from washing the Vermont-Girrah seam to an ash content of approximately 15 per cent, the seam, by virtue of its thickness of 14m, has some economic potential. Even with a yield as low as 30 per cent, the reserves of open-cut product coal may be substantial. Since most of the raw coal ash is present as discrete bands, significant ash reduction may be possible by mechanical segregation of coal and dirt"* (page 12). The area Koppe & Scott (1981) referred to was subsequently part of several relinquished sub-blocks of EPC 755 (Isaac Plains Coal Management Pty Ltd, 2008), which were never thoroughly explored. Currently, no MLs or MDLs cover this area (Figure 70).

E. A few years later, Anderson (1985) reported on the Fort Cooper seams at **Winchester South** (no boreholes specified): *"The Fort Cooper Coal Measures contain numerous tuffaceous seams, some up to 30m thick, which comprise as much as 20% of the stratigraphic section. Coal plies, however, make up generally less than 50% of the gross coal seams, and themselves usually contain high proportions of mineral matter. The better quality seams occur towards the top of the unit and have been investigated to a limited extent. Raw ash content of the Girrah seam, a thick seam commonly found at or near the top of the Fort Cooper Coal Measures – Burngrove Formation, ranges between about 30 to 40%. A washed product yielding about 60 to 70% with an ash level of less than 20% and variable swelling properties is achievable. This type of coal could be blended in with other better-quality coals, either coking or steaming"* (page 90).

"The uppermost Fort Cooper seam at Winchester South, the Vermont Lower, was investigated in detail. It is some 4m thick, has an average raw ash content of 40%. Washability testing yielded an average cumulative float fraction of (for example) 55% for an ash content of 27%. A better quality ply, the Vermont Upper, overlies the Vermont Lower, separated by the Yarrabee Tuff Bed" (page 90). Anderson (1985) also warned that *"mining conditions in the Fort Cooper seams would present geotechnical problems. The tuffs are weak, hydrate easily, and would cause floor and slope instabilities, and problems in a wash plant"* (page 90).

Although Winchester South is presently covered by MDL 183, some information is available in a relinquishment report of several sub-blocks of EPC 352, which fall immediately outside the MDL perimeter (Figure 70). The Fort Cooper Coal Measures occur east of the Winchester South Syncline and contain poor quality banded coal seams. The formation includes abundant carbonaceous shales, moderately hard coal and heat-affected intervals (Anderson, 1989). Early explorers (*e.g.,* Koppe, 1979 and Carr, 1980) also considered Winchester South of no commercial interest.

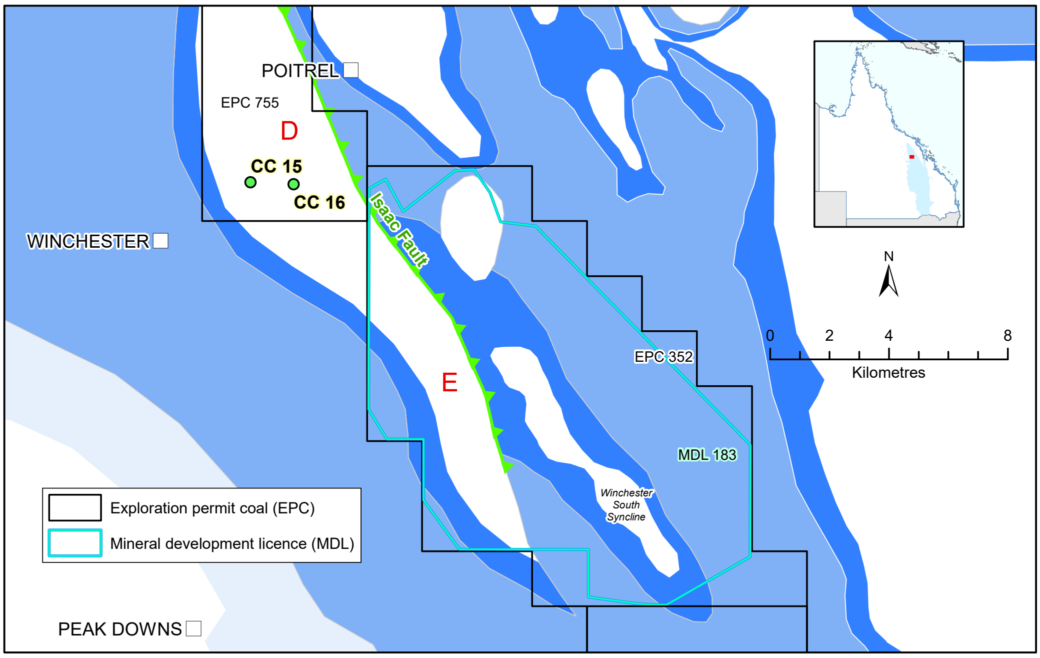

Figure 70. Areas D and E, Winchester. Legend in Figure 7.

F. In the **Lake Vermont** area (boreholes CC 174 to CC 227, Figure 71), Sorby (1981) identified a ply towards the top of the Fort Cooper Coal Measures (Table 25) that may be a source of thermal coal and recommended further examination. No additional departmental exploration was carried out in that area, which today is part of ML 70331 (Vermont Mine) and ML 70528 (Lake Vermont North). Drilling undertaken in relinquished areas of EPC 549 (which were along the perimeter of the tenement) encountered thin poor-quality Leichardt, Vermont and Girrah seams. In addition, the depth of weathering extends to more than 75 m in places according to Bowen Basin Coal Pty Ltd (2003).

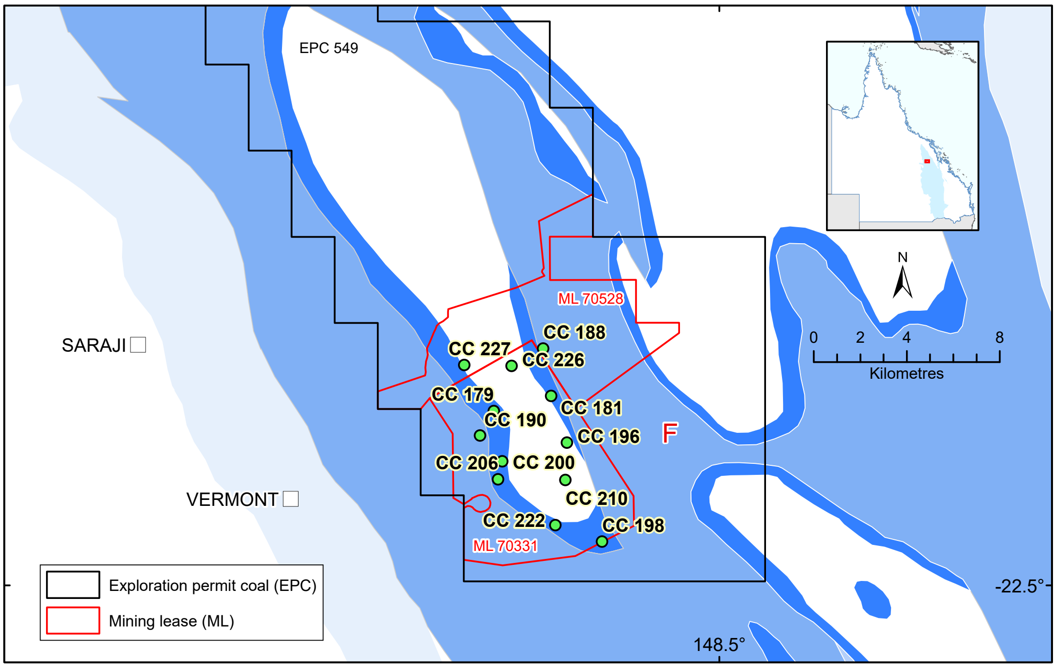

Figure 71. Area F, Lake Vermont. Legend in Figure 7.

G. At **Roper Creek**, Anderson (1974) reported lenticular clean coal intervals with high swelling properties in the Girrah Seam (boreholes CC 6, 8 and 12, Figure 72); analytical results were reported only for CC 8 (Table 29). A decade later however, Anderson & Jameson (1982) considered the local Burngrove seams (in boreholes proximal to Middlemount) of no commercial value despite their considerable thickness. The area referred to by Anderson (1974) is now covered by the Middlemount Mine (ML 70379 and ML 70417), a few kilometres southwest of Middlemount, and MDL 454 to the north of the town. Thin coaly layers of no economic interest are reported in the Burngrove Formation in relinquished parts of EPC 315 (McElroy Bryan & Associates, 1983), which are located on the western side of the tenement and about 5 km away from the boreholes drilled by Anderson (1974). Faulting, steeply dipping coal seams and igneous intrusions are also recorded proximal to the Jellinbah Fault (McElroy Bryan & Associates, 1988).

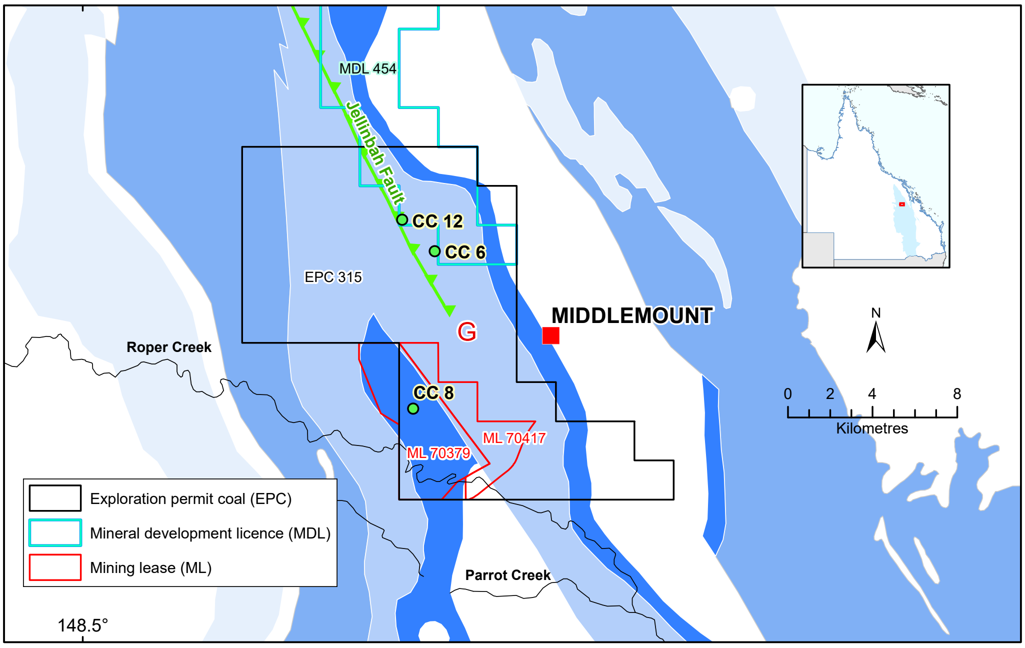

Figure 72. Area G, Middlemount. Legend in Figure 7.

4.8.2 South

Two areas where the Burngrove Formation coal presented coking properties have been identified on the Comet Ridge:

- Oak Park – Girrah
- Caledonia–Curragh–Blackwater (Figure 73).

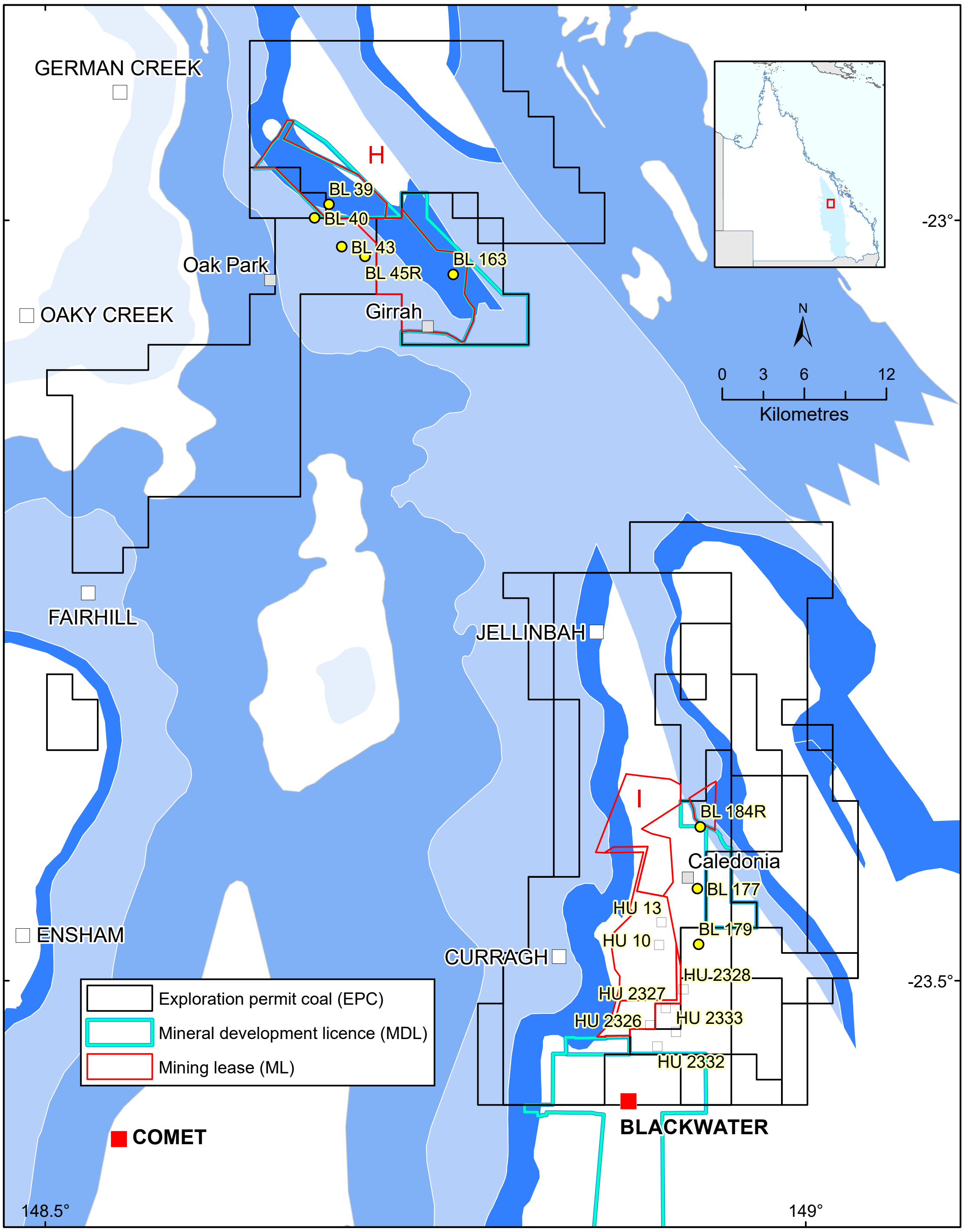

Figure 73. Potential exploration targets (H and I) in relation to subcrop and current tenure. Legend in Figure 7.

H. In the area immediately north of **Oak Park** and **Girrah**, Carr (1973) and Staines (1973) reported coal with coking properties in the boreholes BL 39, 40, 43, 45R and 163 (Figure 74, Table 32 and Table 34). The area is currently part of ML 70311 and ML 70336 (Figure 74). In relinquished sub-blocks of EPC 713, located between Oak Park and Girrah, a 5 m banded and tuffaceous Fair Hill Formation coal seam was reported between 23 and 28 m depth (Glencore Coal Queensland Pty Limited, 2017). Proximal to MDL 331, in relinquished parts of EPC 414, a 10 m thick tuffaceous Girrah Seam was reported at depths of under 80 m (Johnson, 1996). Coal quality was not tested. Further to the east, in EPC 472, exploration boreholes terminated around 160 m depth, without intersecting the Girrah Seam (Derrington, 1996), which suggests eastward dipping of the formation. Information related to the MDLs in this area is currently confidential.

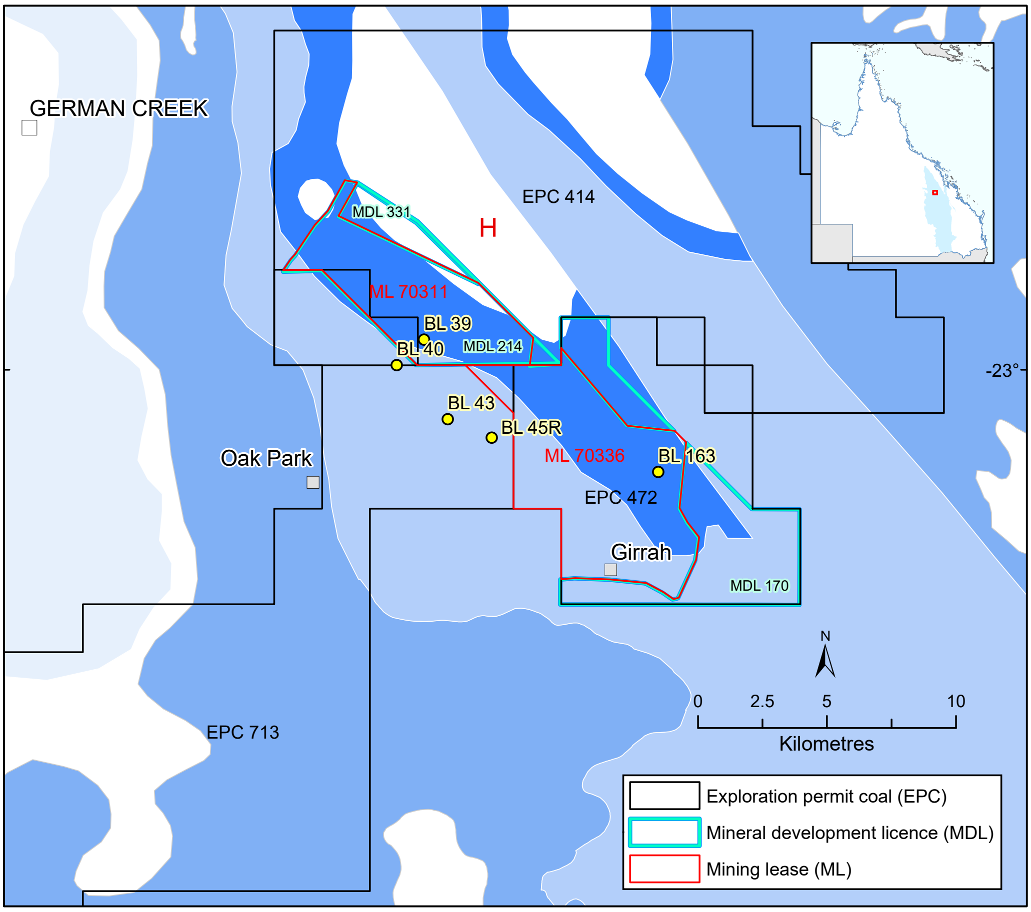

Figure 74. Area H, Oak Park – Girrah. Legend in Figure 7.

I. In the area **Caledonia–Curragh**, immediately north of Blackwater, Galligan (1978) reported the greatest thickness of the Virgo Seam (40 m), although he did not provide details on location or coal quality. At Caledonia, Park (1973a) analysed coal samples in boreholes BL 177, 179 and 184R (Figure 75; Table 35) and found that the F 1.45 presented coking properties, although the yields varied largely between 20 and 90%.

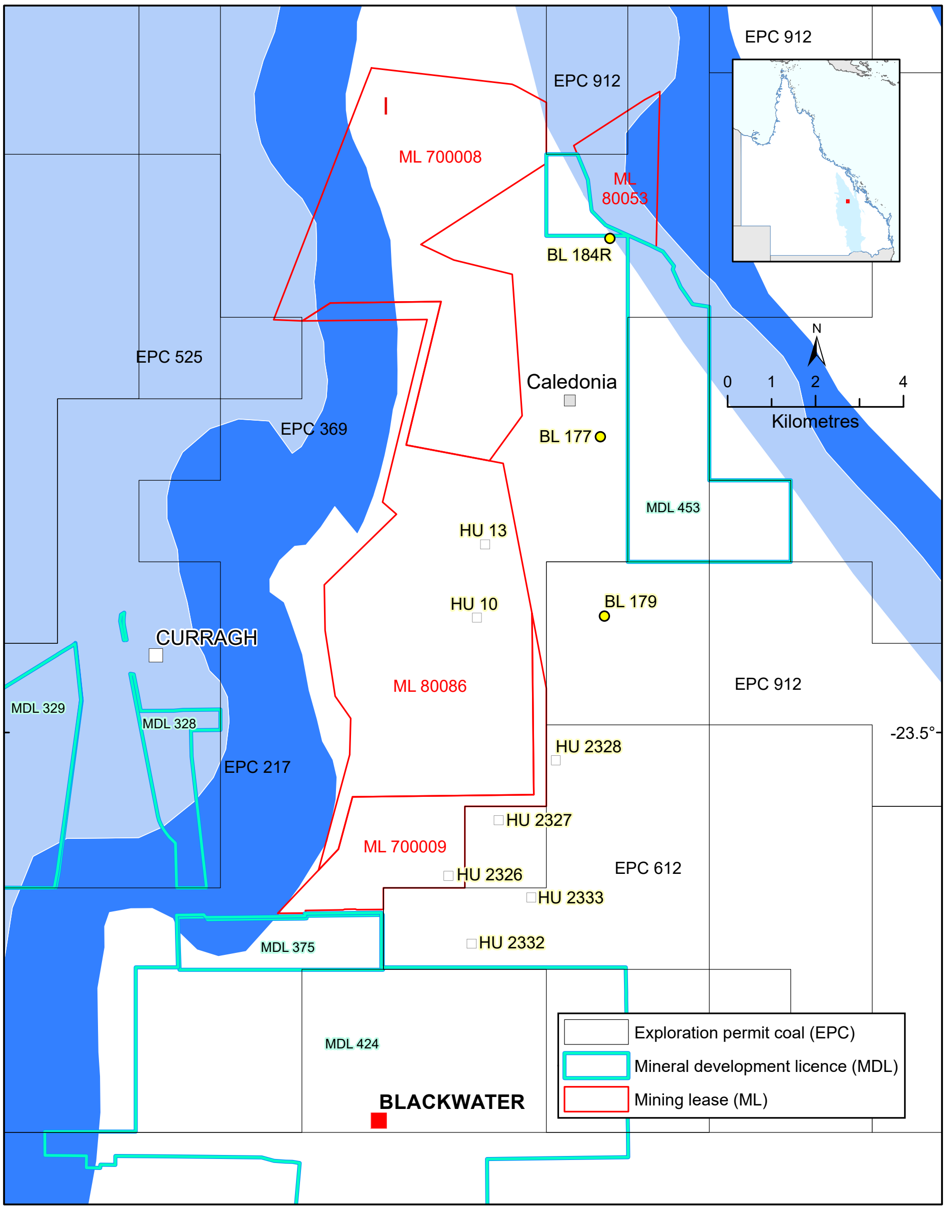

Figure 75. Area I, Caledonia–Curragh–Blackwater. Legend in Figure 7.

Similar results were presented by Staines (1978), immediately west of the Blackwater boreholes, in HU 10 and HU 13. Further south, D'Arcy (1985) analysed coal in several Humboldt boreholes (Table 39) and reported CSNs of 9 or higher in the Leo Seam (F 1.40), but low yields (<25%). Currently, the boreholes mentioned in this area are adjacent or included in several MLs held by Wesfarmers Curragh Pty Ltd. In relinquished parts of EPC 369, it was reported that the Pisces Seam was separated by the Yarrabee Tuff in the Pisces 'working section' (Rangal Coal Measures) and the Pisces Lower Seam (Burngrove Formation). The latter was intersected in 26 boreholes and ranged in thickness between

0.2 and 2.7 m. The seam was interbedded with carbonaceous mudstone and considered uneconomic (Avenell, 2001). Exploration within EPC 612 aimed to locate an upthrown block of Rangal Coal Measures and to assess its suitability for open cut mining. The drilling was shallower than 100 m and did not intersect the Burngrove Formation (Carr, 2001). The most recent exploration was undertaken within EPC 912. The top of the Burngrove Formation was defined by the Yarrabee Tuff, which was found to be thin and interbedded with carbonaceous mudstone and fine-grained sandstone in the area. Banded coal seams of variable thickness and quality were reported but considered sub-economic (Wallin, 2008).

4.8.3 Curragh West

Although Curragh West was never targeted for drilling by the department, considerable company exploration was undertaken in the area during the 1990s for its potential to support operations at Curragh.

During the mid-1990s, Arco Coal Australia (a wholly owned subsidiary of the Atlantic Richfield Company based in the United States) undertook regional coal exploration within EPC 525, over the northern part of the Comet Ridge to the west of the Curragh open-cut mine (location in Figure 75). In joint venture with three other Australian and overseas companies, following a competitive tender process, the company had won the right to develop the coal resources at Curragh, on behalf of the State Electricity Commission of Queensland (SEC) in early 1981. The SEC subsequently became the Queensland Electricity Commission, with the Curragh Mine and associated coal assets eventually coming under the control of Stanwell Corporation, as one of the corporate entities created as the electricity industry in Queensland began to be progressively corporatised.

The mine commenced operation in October 1983 and, in addition to producing metallurgical coal for export, was also contracted (through the 1981 Curragh Coal Supply Agreement) to supply coal to the Queensland electricity industry under a long-term, 20-year contract with the SEC.

Between 1993 and 1997, Arco and its joint venture partners (at that time R.W. Miller and Company Pty Ltd and Mitsui Coal Development (Australia) Pty Ltd) undertook exploration within EPC 525 (Figure 75), eventually identifying a relatively shallow (< 130 m depth of cover) thermal coal resource of moderate size (~70 million tonnes of raw coal *in situ*, measured and indicated status) in a seam within the Burngrove Formation, which the company correlated as the Scorpio Seam.

The suite of coal analyses undertaken on the Burngrove Formation coal seams intersected indicated that the coal resource identified at Curragh West had been evaluated for its potential use as a thermal coal, potentially to fulfil the joint venturer's contractual commitment to supply thermal coal for use by the State for the generation of electricity. MDLs 328 and 329 (locations in Figure 75) were subsequently granted (August 2001) to the Curragh Joint Venture over the Curragh West coal resource. The resource remains unmined at this time.

4.8.4 Summary

Although the information provided by relinquishment reports is biased towards negative potential, these types of results are valuable as they demonstrate the high heterogeneity of the Fort Cooper fluvial system in terms of seam thickness, composition and rank, and the impact of localised post-depositional processes such as weathering, faulting, basalt flows and heat-caused alteration by intrusions.

Based only on this comparative examination of departmental and open file company findings, and in the absence of a drilling and testing program directed specifically to the assessment of the Fort Cooper Coal Measures and correlatives in these areas, it remains problematic to ascertain the real prospectivity of the Girrah, Fairhill, Virgo and Leo seams in the Bowen Basin.

5. Conclusions

The Fort Cooper Coal Measures and their southern correlatives are Lopingian coal-bearing formations, which consist of green-grey, highly tuffaceous, thinly interbedded sandstones, siltstones and mudstones. They are primarily fluvial with localised lacustrine episodes or marine incursions.

Although inconsistently mapped, the Yarrabee Tuff is widely accepted as a sequence boundary, presumably marking the last significant volcanic ash-fall in the Lopingian. It is taken as the top boundary of the Fort Cooper Coal Measures in the northern Bowen Basin and as the top of the Burngrove Formation further south, around the Comet Ridge. Where absent, the top boundary of these two units has been placed at the top of the uppermost/stratigraphically highest coal seam containing tuffaceous bands. Locally, the Yarrabee Tuff has been described as an intraseam marker separating the Vermont seams in the north and the Pisces seams in the south.

As part of this review, the type section tops and bottoms of both the Fort Cooper Coal Measures in the northern part of the basin and the Burngrove and Fair Hill Formations on the Comet Ridge near Blackwater, were converted from the original 20,000 yard grid to GDA94. The conversion process has revealed a number of discrepancies between the location of the sections as originally described and the new locations, which can only be resolved with field reconnaissance.

The limited coal analytical testing that has been undertaken (880 analyses in 100 boreholes) on Group 4 coals intersected in departmental drilling over the years shows that the raw coal (34% of samples) contains high ash values, commonly ranging between 30 to 50% (adb) which, when washed at a specific gravity of 1.40 g/cm^3, may be reduced in places, to as little as 10% (adb), although at a low yield (mostly < 35%) (Figure 76). The available data indicate that at separation densities of between 1.40 and 1.60, high swells may be achieved (CSN=7–9), with variable yields but generally < 30% (by mass).

Sampled coal thicknesses across all of the departmental boreholes drilled ranges from between 0.8 metres to approximately 14 m in some areas. There is an overall trend of decreased (sampled) coal thickness towards the south, which is consistent with the dataset reviewed in that the Virgo Seam in the area around the Comet Ridge is statistically thinner than the Girrah Seam further to the north. However, a localised exception has been noted at Curragh, where the Virgo Seam was reported to reach 40 m in thickness, presumably for structural reasons.

Vitrinite reflectance values for samples of Group 4 coal range from 0.5 to 2.5%, indicating high regional rank variations throughout the basin; however, most values are within the coking coal range. The higher values have been associated with intrusive emplacement or faulting.

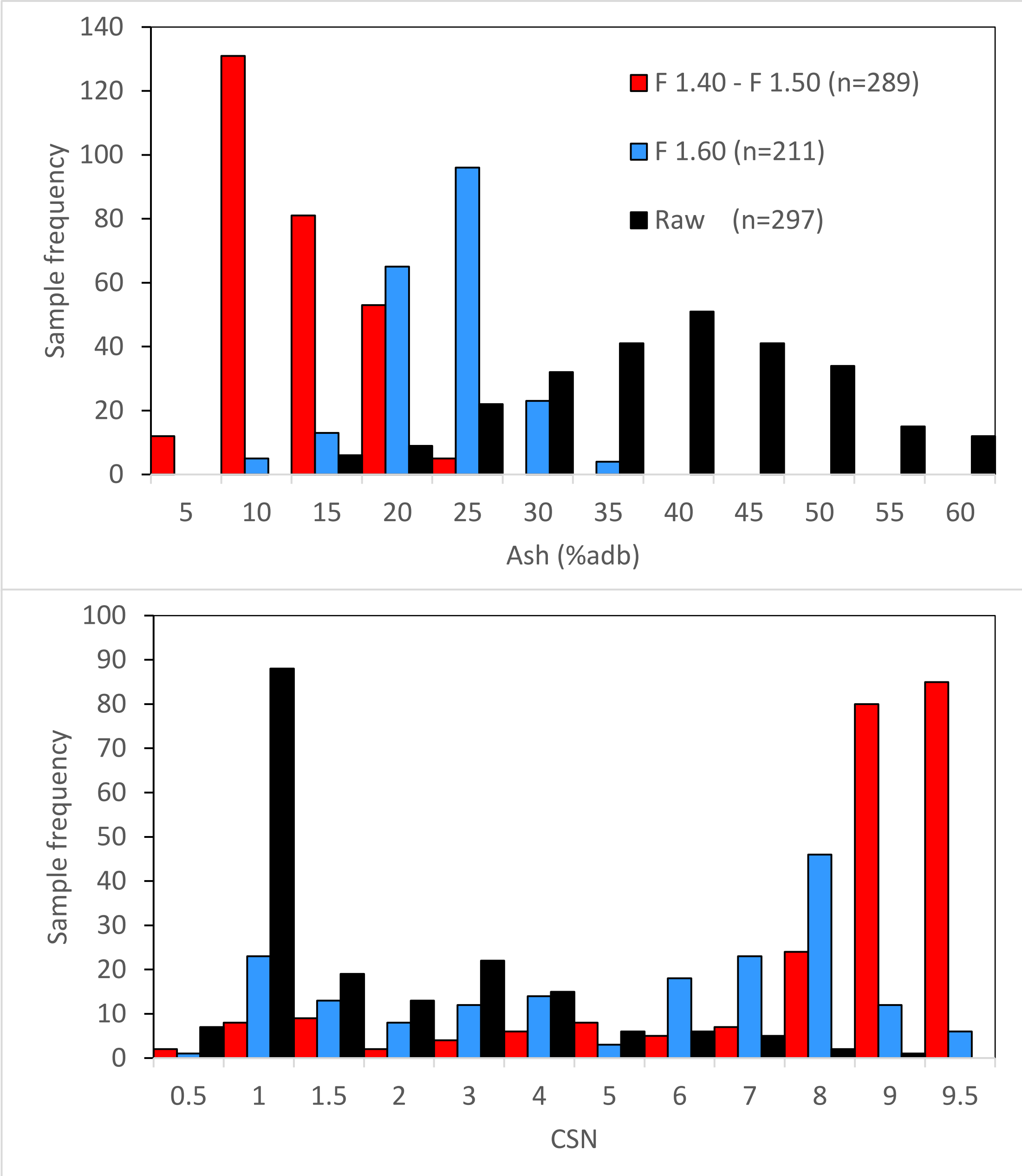

Figure 76. Frequency of ash and CSN values in F 1.40, F 1.60 and raw coal (see Figures 53 and 54).

In the northern Bowen Basin, at Wollombi, Eastern Creek (both part of the Newlands mining complex) and at Hail Creek Mine, there have been recent attempts to trial mine sections of Group 4 coal seams that occur in close proximity to other seams being mined at these open-cut operations. Despite this, however, the prospectivity of Group 4 coals on the eastern flank of the northern part of the basin is regarded as low due to structural disturbance in the region (faulting, steep dips) and the presence of intrusions.

The western flank of the basin is less affected by igneous activity and, although the ash content of the Fort Cooper seams is high, there are a few areas where further consideration may be warranted, particularly for Group 4 coals as a source of coal suitable for blending with metallurgical coal products derived from other coal-bearing sequences. These areas include:

- Burton Downs (Dash, 1985a)
- Moranbah (Scott, 1987b)
- Winchester (Koppe & Scott, 1981)
- Winchester South (Anderson, 1985)
- Lake Vermont (Sorby, 1981)
- Roper Creek (Anderson, 1974).

The marginally higher potential prospectivity of Group 4 coals apparent in areas such as Burton Downs, Moranbah, Lake Vermont and Winchester is supported by the departmental coal quality data reviewed, although the notion is not generally reinforced by comments and other information presented in geological reports submitted to the department by coal exploration companies in these areas.

Two factors may contribute to this disparity relating to potential prospectivity of these coals in parts of the basin. The first seems likely to be the overall negativity of opinions expressed in company relinquishment reports regarding the prospectivity of these coals. The second reason quite possibly relates to the fact that these coals have not been the primary target of the exploration in the first place.

The high degree of variability observed in the proportions and quality of coal developed within Group 4 coal seams can be explained by fluctuating conditions of deposition, subsequent erosion and sediment redistribution within the Fort Cooper fluvial system. This relatively dynamic sedimentary system is interpreted as comprising relatively short-lived episodes of peat formation followed by peat flooding, channel migration and continuous 'contamination' with volcanic ash. This level of complexity suggests that areas where commercially viable Group 4 coals may exist are likely to be relatively localised, of variable thickness, rank and quality.

Broad-scale regional assessments would fail to identify localised areas of potentially prospective coal of this nature. At Eastern Creek on the Newlands mining leases for example, detailed exploration undertaken by the company indicates that the Girrah Seam thins out and the coal is absent within 10 km of the area that has been mined.

Other zones for consideration are the well-established resource areas, like the Hail Creek Syncline, where deeper Fort Cooper coal seams may have some potential for mining.

In the south, coking coal properties have been reported in certain areas on the Comet Ridge, although no further exploration of the Burngrove Formation has been recommended. These are:

- Oak Park – Girrah (Carr, 1973; Staines, 1973)
- Caledonia–Curragh–Blackwater (Park, 1973a; Galligan, 1977; D'Arcy, 1985).

The anomalously high thickness of the Virgo Seam at Curragh (Galligan, 1978) would also warrant further investigation.

Of the areas where Group 4 coals have either been extracted for blending or explored for potential 'stand-alone' mine development, two factors have seemingly been of influence. These are stratigraphic proximity to coals seams in other confining coal-bearing sequences (either Group 3 or Group 5 coals) or proximity to existing rail infrastructure (such as at Washpool and Comet Ridge projects).

The negative view of the prospects of the Fort Cooper Coal Measures and correlatives was understandable in the past, as much lower ash alternatives were widely available in the Rangal, German Creek and Moranbah coal measures. With time, depletion of metallurgical coals resources from seams traditionally mined in the Bowen Basin may become an influential factor in the viability of any future commercial development of Group 4 coals.

In this context, the conclusive remarks by Matheson (1990a, page 1) are still valid today, almost 30 years later: *"The basic data gathering and descriptive geology undertaken by early pioneering Government geologists provided much information for later exploration and coal delineation* [Figure 77]*. There is a need to continue to investigate coal resources in areas where information is scarce, particularly in relation to coal types that are in demand… exploration programs should be tailored to suit the deposit or area under investigation using a flexible multi-disciplinary approach to produce the required results with the greatest efficiency"*.

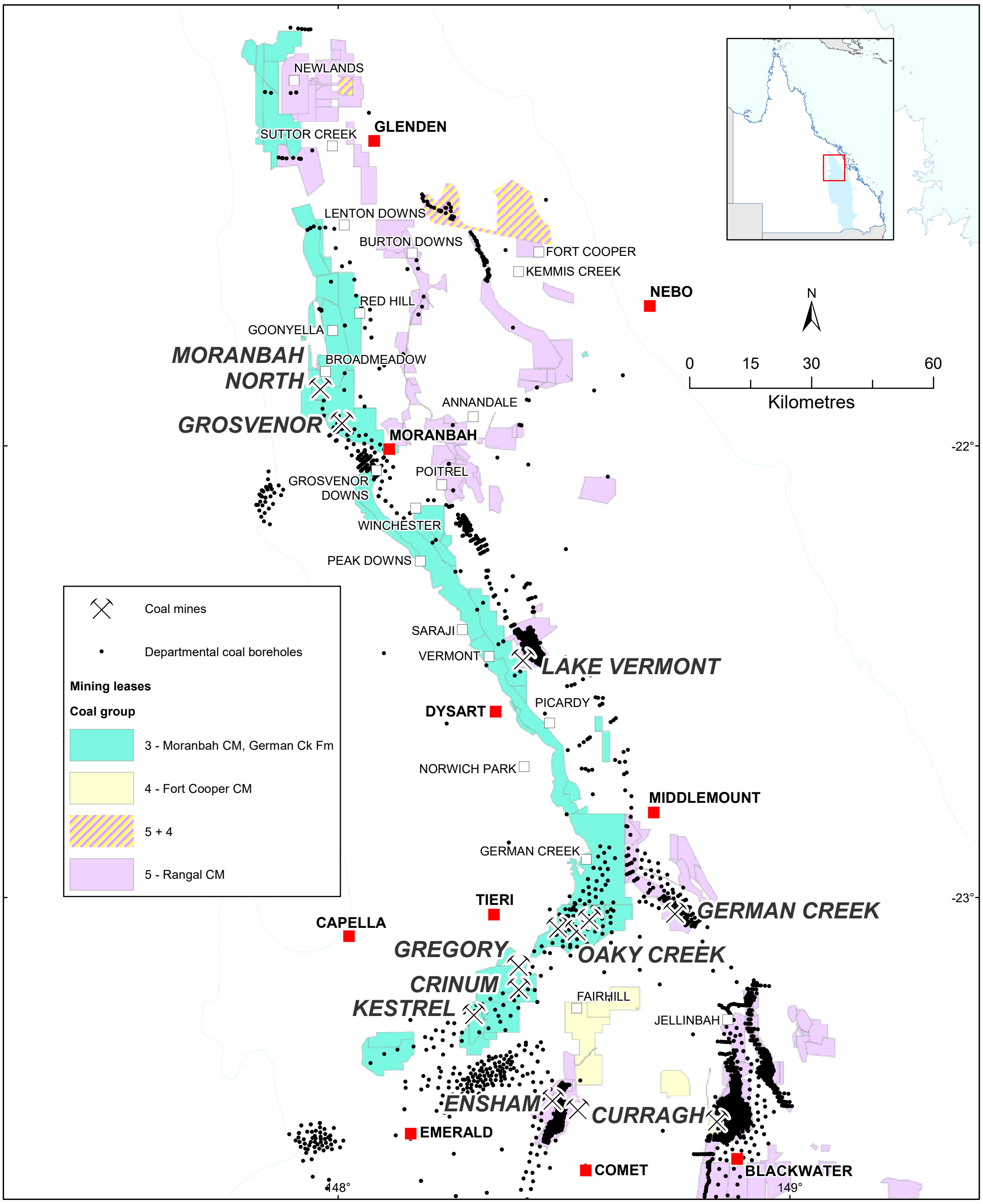

Figure 77. Coal mines owing the discovery of their resources to departmental exploration, in relation to current mining leases.

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