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A review of the geology and exploration history of the Lopingian (late Permian) coals in the northern Galilee Basin

D. Coffey, M. Grigorescu, J.L. McKellar & A. Isles

Queensland Government

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**D. COFFEY, M. GRIGORESCU,
J.L. McKELLAR & A. ISLES**

Address for correspondence:

Geological Survey of Queensland
Department of Natural Resource and Mines
PO Box 15216 City East QLD 4002
Email: geological_info@dnrm.qld.gov.au

Cover photograph: Thin-bedded, carbonaceous siltstone and mudstone overlain by poorly sorted, coarse- to very coarse-grained, pebbly sandstone, Betts Creek beds. Photograph taken (May 2017) in Porcupine Creek (Galah) Gorge at 20°19'34.93", 144°38'13.8".

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Introduction

Initial work undertaken in the Galilee Basin was restricted to the outcrop regions along the northern basin margin in the district around Hughenden, north of the Townsville to Mount Isa railway line, where the presence of *Glossopteris*-bearing, and thus Permian, sedimentary rock had been first recorded by William (W.H.) Rands in the late 19th century in his report on the Cape River Goldfield. Other occurrences in the region of *Glossopteris*-bearing strata were later described by Edward (E.O.) Marks.

Subsequent mapping of reported coal occurrences in the Hughenden district by Geological Survey of Queensland (GSQ) geologists during the first half of the 20th century included work by John (J.H.) Reid and Cecil (C.C.) Morton. During this period there were also several attempts made by the private sector to evaluate the coal potential of the region—most notably work by Mount Isa Mines Limited which included the sinking of an exploratory drift at a locality known as 'Coal Camp' near the Flinders River.

The name of the depositional system that is now known as 'the Galilee Basin' was first applied informally and incidentally by Dr Fredrick (F.W.) Whitehouse, although its use did not obtain general recognition and acceptance until it was incorporated into the results of regional field mapping commenced by the Bureau of Mineral Resources (BMR) in the mid-1960s.

Exploration drilling in the deeper parts of the basin also commenced in the early 1900s, but largely had a petroleum focus. It was not until 1960 that the wider coal potential of the basin was realised with the intersection of the coal-bearing Permian strata by Magellan Petroleum Corporation. This earlier phase of petroleum exploration largely drew to a close with the repeal of the Commonwealth's Petroleum Search Subsidy Act (PSSA) on 31 December 1973.

By 1970, as large scaled regional coal exploration by multinational companies was being undertaken in the Bowen Basin to the east, there remained very little interest in the coal potential of the Galilee Basin.

Although, at that stage, the GSQ had recognised the considerable potential of the (Galilee) basin to host very large resources of potentially exploitable coal, little was known about the subsurface extent or properties of the Late Permian coal seams present there.

To address this shortcoming and help establish a regional stratigraphic framework for the basin, over a period of almost two decades between the early 1970s and mid-1990, the GSQ undertook a program of stratigraphic drilling within the basin, supplemented in the early to latter part of the 1970s by a regional coal reconnaissance drilling program along the eastern flank of the Koburra Trough—one of the two main depocentres in its northern part.

During this period, work undertaken on the Galilee Basin by geologists and other scientists working for the GSQ includes studies by:

Alan (A.R.G.) Gray and Chris (C.F.J.) Swarbrick—regional geological framework and stratigraphy

Dr Peter (P.J.) Hawkins—basin analysis and hydrocarbon potential

Dr John (J.L.) McKellar—palynology and biostratigraphic relationships

Allan (A.F.) Carr, Stephen (S.G.) Matheson and Steven (S.G.) Scott—coal geology

Dr Allan Davis and Dr James (J.W.) Beeston—coal petrology.

There have been two separate releases of land in the Galilee Basin by the Queensland Government, seeking expressions of interests from the private sector to undertake coal exploration. The first in 1973, around the time of the first global 'Oil Shock', primarily focussed on determining the liquefaction potential of the coals, and the second was in 1978 at the completion of the departmental coal reconnaissance drilling program.

The second land release attracted interest from private enterprise which led to further work over a number of discrete areas comprising the coal deposits of Elimeek and Lauderdale (the Pentland Group), Milray in the north, and the adjoining Kevins Corner and Alpha areas further south.

Over the following decade, exploration resulted in the identification of substantial quantities of relatively shallow coal at these localities, with potential for both open-cut and underground mining.

Distance from potential markets, falling coal prices, and limited infrastructure saw coal exploration levels in the Galilee tail off again from the middle 1980s until mid-2006, when a boom in the demand for coal sparked renewed interest in the basin.

Although there have been no coal mining operations developed in the Galilee Basin as yet, there are now a number of proposals to construct very large-scale coal mining projects in the region, to produce thermal coal for export. Consequently, the Galilee Basin is anticipated to see substantial development in the coming years, as its thermal coal resources gain viability for extraction.

This document aims to provide a referenced review outlining the work done to date on the exploration for, and geological evaluation of, the shallow Lopingian (late Permian) coals that are present along the eastern flank of the Koburra Trough/Aberfoyle Syncline. Summary details of the current mining proposals being considered to extract these coals are also provided.

Since most of the coal exploration data associated with these projects remain confidential at this time, the summary details presented in this report have mainly been sourced from publicly available documents. Most of these are associated with documentation linked to statutory environmental approval processes.

Coal analytical results for all coal samples taken during the departmental 1970s coal reconnaissance drilling program are provided here, including, for the first time, calculated coal analytical results for all seam composites. A statistical review of the analytical dataset is included.

Regional geology

Whitehouse (1955) is attributed with the first usage of the term ‘Galilee Basin’ in his report *The Geology of the Queensland Portion of the Great Australian Artesian Basin*, presumably taking the name (according to Vine *et al.*, 1965) from the large ephemeral Lake Galilee near Aramac. He mentioned the basin only in passing (figure 34), merely referring to it elsewhere in his report as forming one of the geomorphic features present of the beginning of Mesozoic he described as including “*the depression flanking the Drummond ridges on the southern and western sides*” (item 4, page 4) and later as “*another more or less meridional depression*” that “*was formed west of the Drummond Ranges*” (page 15, Structural Geology) in late Permian time.

It was not until mapping of the Great Artesian Basin in the 1960s, that the term “Galilee Basin” was formalised and the first stratigraphic framework of the basin was outlined by Vine *et al.* (1965).

Further work by Mollan *et al*. (1969), Gray & Swarbrick (1975), Gray (1976), and Scott *et al.* (1995) continued to develop the nomenclature in discrete areas—primarily in the northeastern part of the basin, around Jericho and on the Springsure Shelf. Terminology applied by Scott and colleagues borrowed heavily from the stratigraphy of the Bowen Basin (Gray & Swarbrick, 1975; Gray, 1976). More recently, Allen & Fielding (2007a) identified six stratigraphic sequences within the late Permian Betts Creek beds, which they correlated across the basin and into the Denison Trough of the Bowen Basin.

Previous geological reviews of the wider Galilee Basin include those of Vine (1976) and Evans (1980). Hawkins (1976, 1978) assessed the conventional hydrocarbon potential of the basin, while the coal seam gas potential of the basin has been evaluated by Durie *et al.* (1992) and Scott & Hawkins (1992). Reviews of the late Permian/Lopingian coals therein have been undertaken by Wells (1989) and Scott *et al.* (1995). This report embraces these works and is also grounded on the overview of McKellar & Henderson (2013).

A more recent overview of the coal and coal seam gas resources of the Galilee Basin is provided by Lewis *et al.*, (2014) as part of the Australian Government’s bioregional assessment of the ‘Galilee subregion’ within the ‘Lake Eyre Basin bioregion’. The Bioregional Assessment Programme is a collaborative project between the Australian Department of the Environment, the Bureau of Meteorology, the CSIRO and Geoscience Australia (GA). Further information on the program and its products can be found at: http://www.bioregionalassessments.gov.au/

During the early 1960s a surface mapping program of the Galilee Basin and overlying Eromanga Basin was initiated by the BMR in collaboration with the GSQ. This mapping program was completed in the early 1970s.

The 1:250 000 geological series map sheets areas of the Galilee Basin are shown in Figure 1. The accompanying explanatory notes that cover the interpreted subsurface extent of the Galilee Basin are listed in Table 1.

Between April and September 1997, the Queensland Department of Mines and Energy conducted an airborne geophysics survey over the exposed and buried portions of the Drummond Basin, beneath the Galilee and Eromanga basins. The Drummond-Galilee Survey formed part of the department’s ‘AIRDATA’ initiative, a component of the department’s GEOMAP 2005 program. The survey acquired both magnetic and radiometric data, over more than 198 000 line kilometres (Department of Mines and Energy, 1997, 1998). The primary focus was to assist with mapping of the Drummond Basin. The geological mapping of the Drummond Basin that followed has been reported by Blake *et al.* (2012).

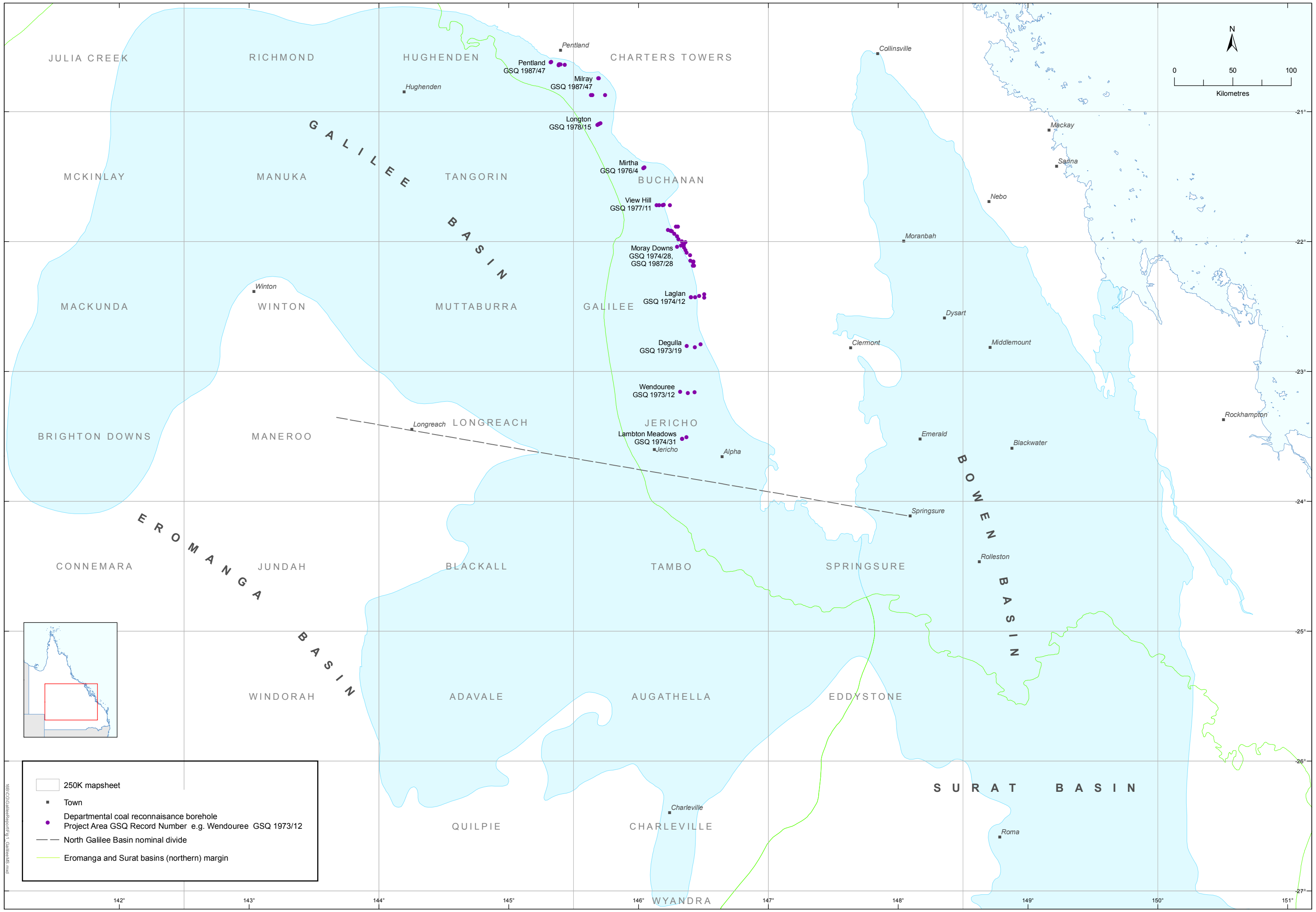


Figure 1. 1:250 000 map sheet index, Galilee Basin. (This page may be printed at A3 for clarity.)

Table 1. 1:250 000 geological series map sheet areas, Galilee Basin.

Sheet name	Map number	Zone	Regional locality	Explanatory notes compiler(s)	Year published	QDEX report number	Other related BMR publication
Brighton Downs	SF54-15	54	northern/southern Galilee	Jauncey	1964	CR40230	
Julia Creek	SF54-3	54	northern Galilee	Vine	1964	CR40219	
Longreach	SF55-13	55	northern/southern Galilee	Vine	1970	CR40236	BMR record 1965/245
Mackunda	SF54-11	54	northern Galilee	Vine	1964	CR40210	
Maneroo	SF54-16	54	northern Galilee (marginal central)	Jauncey	1967	CR40231	BMR record 1965/122
Manuka	SF54-8	54	northern Galilee	Casey	1968	CR40203	BMR record 1965/160
McKinlay	SF54-7	54	northern Galilee	Vine	1963	CR40202	
Muttaburra	SF55-9	55	northern Galilee	Vine	1970	CR40212	BMR Record 1964/39
Richmond	SF54-4	54	northern Galilee	Vine	1970	CR40220	
Winton	SF54-12	54	northern Galilee	Casey	1966	CR40211	BMR record 1965/129; BMR Record 1964/39
Buchanan	SF55-6	55	northern Galilee (eastern flank)	Olgers	1970	CR40205	BMR record 1965/245
Charters Towers	SF55-2	55	northern Galilee (eastern flank)	Clarke & Paine	1970	CR40171	BMR record 1967/104; BMR report 137
Galilee	SF55-10	55	northern Galilee (eastern flank)	Vine & Doutch	1972	CR40213	
Hughenden	SF55-1	55	northern Galilee (eastern flank)	Vine & Paine	1974	CR40173	BMR record 1965/93; BMR report 126; BMR Record 1964/39
Jericho	SF55-14	55	northern/southern Galilee (eastern flank)	Senior	1973	CR40237	BMR record 1965/245
Tangorin	SF55-5	55	northern Galilee (eastern flank)	Casey	1969	CR40204	BMR Record 1964/39
Adavale	SG55-5	55	southern Galilee	Galloway	1970	CR40172	BMR record 1967/16
Augathella	SG55-6	55	southern Galilee	Galloway	1970	CR40276	BMR record 1966/89; BMR report 143
Blackall	SG55-1	55	southern Galilee	Casey & Galloway	1971	CR40245	BMR record 1966/89
Charleville	SG55-10	55	southern Galilee	Senior	1971	CR40275	BMR record 1969/13
Connemara	SG54-3	54	southern Galilee (marginal southwest)	Senior	1969	CR40246	BMR record 1967/16
Eddystone	SG55-7	55	southern Galilee	Exon	1968	CR40281	BMR record 1965/98
Jundah	SG54-4	54	southern Galilee (marginal southwest)	Senior	1969	CR40247	BMR record 1967/16
Quilpie	SG55-9	55	southern Galilee	Senior	1970	CR40294	BMR record 1969/13
Springsure	SG55-3	55	southern Galilee - Springsure Shelf	Mollan	1972	CR40282	BMR record 1964/27; BMR report 123
Tambo	SG55-2	55	southern Galilee	Exon	1970	CR40277	BMR record 1966/89; BMR record 1965/90; BMR report 143
Windorah	SG54-8	54	southern Galilee (marginal southwest)	Gregory & Vine	1969	CR40252	BMR record 1967/16
Wyandra	SG55-14	55	southern Galilee (marginal)	Thomas	1971	CR40274	BMR record 1969/13

Galilee — Northern Galilee Basin (nominal divide taken as the area north of a line drawn from Longreach to Springsure along the approximate trend of the Barcaldine Ridge) denotes map sheets along the eastern flank of the northern Galilee Basin

Scanned copies of 'legacy publications' of the Bureau of Mineral Resources can be downloaded through links available from the following page on the Geoscience Australia website: www.ga.gov.au/data-pubs/library/legacy-publications

Structural setting

The Galilee Basin is an extensive and relatively shallow, intra-cratonic basin which developed over the northern Thomson Orogen, in the mid-Carboniferous [latest Mississippian(?) – early Pennsylvanian] (Figure 2 and Figure 3).

The Galilee Basin covers a total area of approximately 247 000 km^2, with the northern part accounting for roughly two-thirds of this total or some 160 000 km^2. The southern boundary of 'the northern Galilee Basin' is placed along a line drawn from Longreach in the west to Springsure in the east, approximating the trend of the Barcaldine Ridge (Figure 1; Figure 4a,b).

Deposition initially commenced in a limited area within the north-northwest-trending Koburra Trough/ Aberfoyle Syncline (Figure 4a,b), located in the basin's northeast and to the west of the Anakie Inlier during the latest Mississippian(?) – early Pennsylvanian (Figure 3) (Day *et al.*, 1983; van Heeswijck, 2010; McKellar & Henderson, 2013).

This early sedimentation appears to have preceded the active-margin crustal extension that led to the formation of the latest Carboniferous(?) – Permian – Middle Triassic Bowen Basin to the east and was superimposed on the underlying latest Devonian – Mississippian Drummond Basin. This is believed to have resulted from inferred local foreland loading that has been tied to the Hopkins Thrust System and the associated mid-Carboniferous Kanimblan contraction (van Heeswijck, 2010; McKellar & Henderson, 2013, figure 3.109).

The depositional area of the basin became more laterally extensive following the initiation of an apparent Pennsylvanian (late Carboniferous) phase of extension, with sedimentation commencing in the two other principal depocentres:

- the southern Galilee Basin (in its western area embracing the Powell Depression and the underlying Devonian Adavale Basin, and in its eastern area on the western Springsure Shelf); and subsequently,
- the Lovelle Depression, located in the basin's northwest (Figure 4a,b), in the latest Pennsylvanian.

Totterdell (1990) briefly reviewed the structural development of the Bowen and Galilee basins, and van Heeswijck (2010) appraised the northeastern Galilee and underlying Drummond basins. Vine *et al.* (1965) described the Galilee and Bowen basins as complimentary depositional systems which developed respectively on the western and eastern flanks of the Anakie Inlier and the 'Nebine-Nogoa Axis'. Van Heeswijck (2010) agreed that the Galilee and Bowen basins are closely aligned in time and processes, although previously noting (van Heeswijck, 2004) that the initial tectonic development of the former contrasts markedly with that of the latter, where the opening phase of the basin's evolution involved rifting and the formation of horst and graben structures.

In the Galilee Basin, the extensional tectonism commenced of the late Pennsylvanian (late Carboniferous) continued into the Cisuralian (early Permian). In both the Galilee and Bowen basins, this extensional phase was associated with dextral/right-lateral transtensional movements and produced a complex series of grabens and half-grabens. A mid-Permian compression marking the beginning of foreland loading to the east resulted in uplift, erosion and unconformity. This was followed by the resumption of sedimentation in the Galilee Basin in the early Lopingian (early late Permian).

Further compressional episodes, also reflected by hiatuses in sedimentation, occurred near the end of the Permian and toward the end of the Early Triassic.

Foreland loading, in the lead up to the major latest Middle – earliest Late Triassic contractional event, resulted in deposition of the Middle Triassic Moolayember Formation, the thickest and most widespread unit across the entire Galilee Basin.

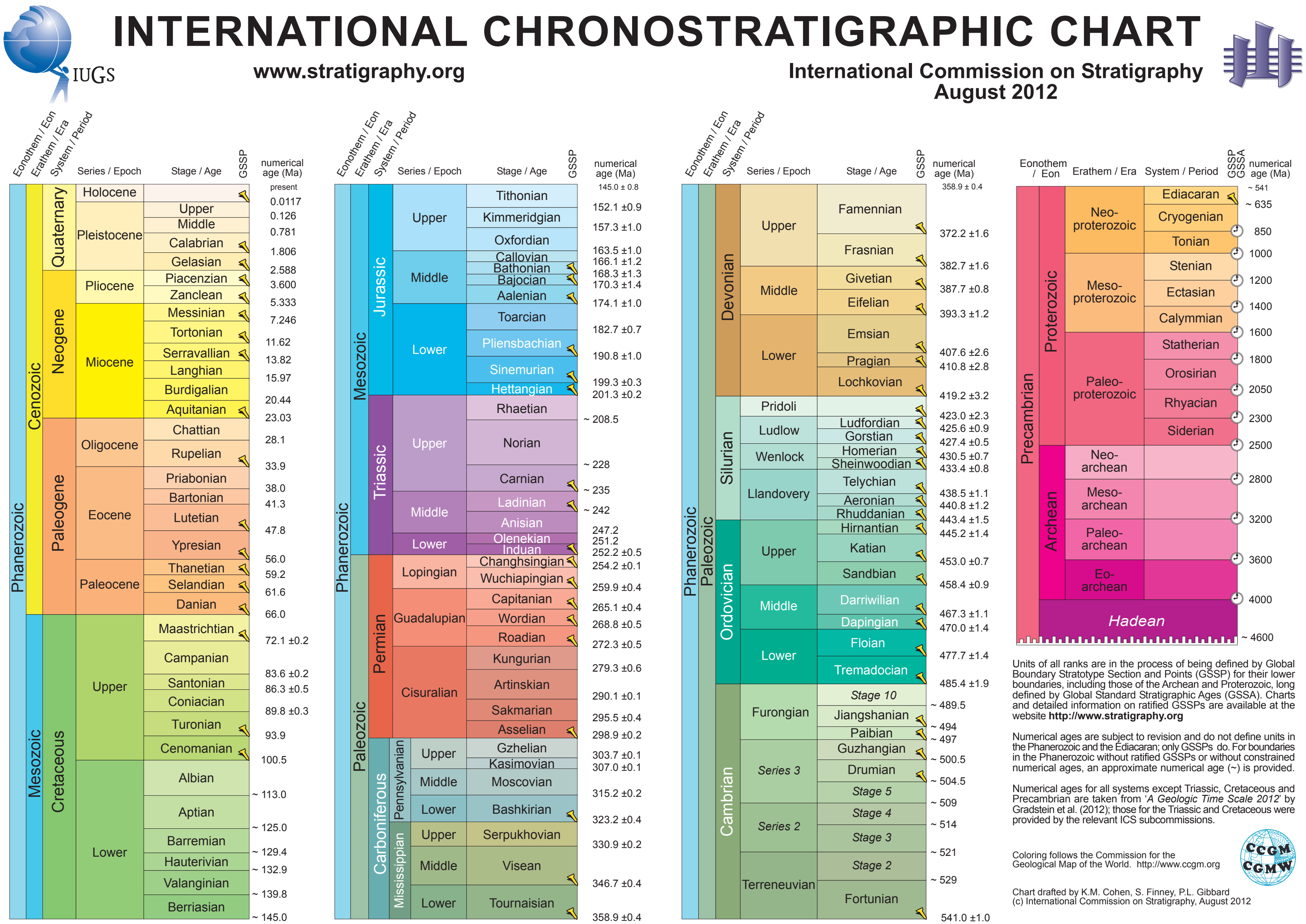
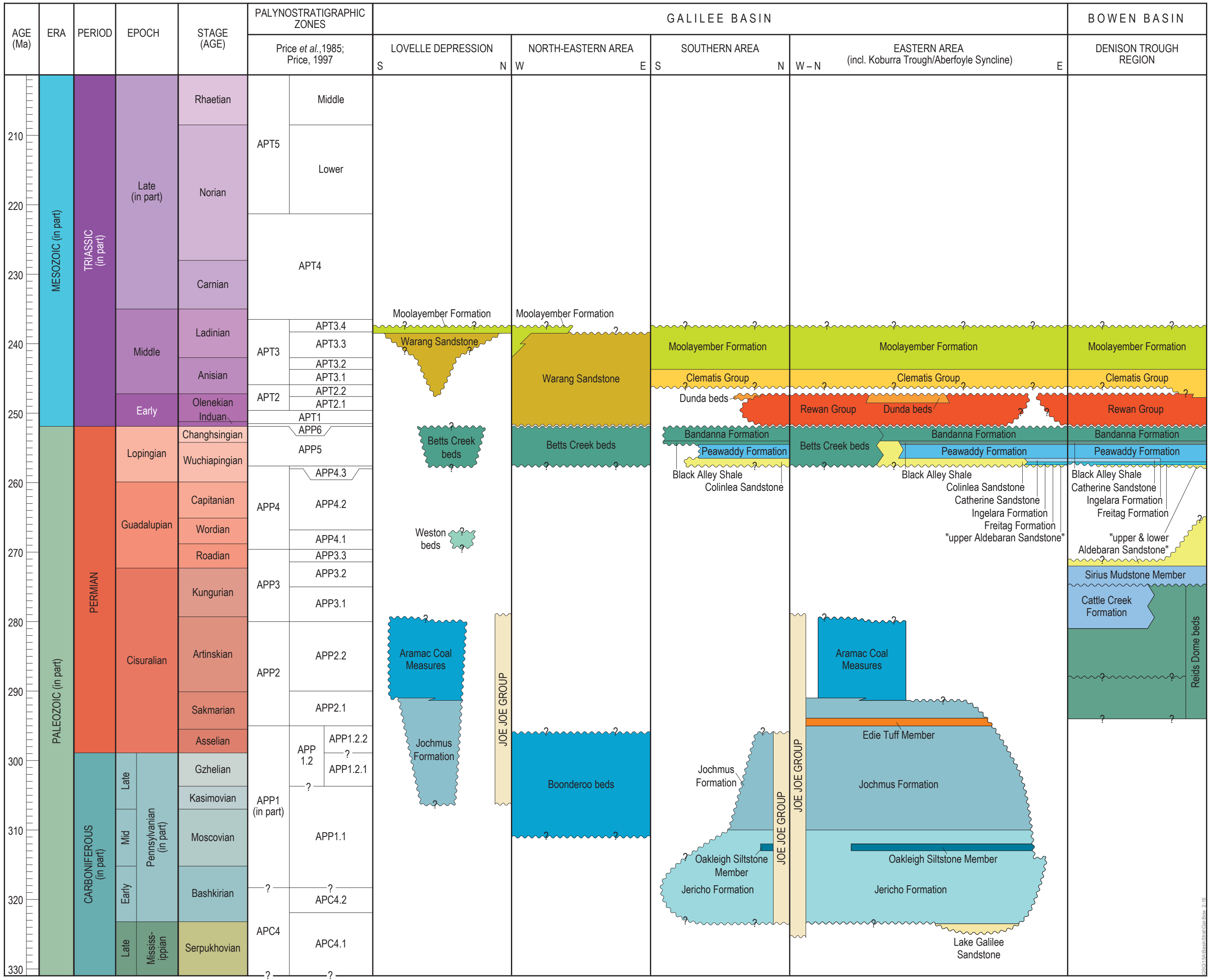


Figure 2. The ICS International Chronostratigraphic Chart (Gradstein et al., 2012). (This page may be printed at A3 for clarity.)



Timescale after Gradstein *et al.* (2012). Compiled by JL McKellar (Feb 2016).

Figure 3. Stratigraphic correlations, Galilee Basin and western flank of the Bowen Basin. (This page may be printed at A3 for clarity.)

The latest Middle Triassic – earliest Late Triassic contraction uplifted the Galilee Basin and terminated deposition. Sedimentation in the region generally did not resume until the onset of the overlying latest Triassic – mid-Cretaceous Eromanga Basin.

The Galilee Basin contains a maximum measured stratigraphic thickness of about 2800 m comprising strata derived from largely non-marine sediments (Evans, 1980). This section of strata was penetrated in ENL Lake Galilee 1 in the Koburra Trough (Scott *et al.*, 1995). The location is shown in Figure 4a,b.

Except for the Galilee's eastern margin, where late Carboniferous/early Permian to Middle(?) Triassic rocks are exposed in a long, narrow, predominantly north–south-orientated, gently-curved belt, the basin is almost entirely concealed beneath the unconformably overlying Jurassic–Cretaceous strata of the Eromanga Basin.

Along the basin's eastern margin, stretching from between the Capricorn Highway in the south to Pentland on the Flinders Highway in the north, where the late Permian coals rise to subcrop, and in a few places occur in outcrop, is where virtually all of the coal exploration activity in the Galilee Basin has occurred.

In the northwest, the Lovelle Depression measures approximately 300 km in length and over 100 km in width, and contains in excess of 730 m of latest Pennsylvanian to Middle Triassic strata (Hawkins & Harrison, 1978; McKellar & Henderson, 2013). As previously stated, in the basin's northeast, the Koburra Trough contains over 2800 m of mid-Carboniferous to Middle Triassic strata (Benstead, 1973; Allen, 1974; McKellar & Henderson, 2013).

The northern Galilee Basin is bounded by outcrop and subcrop of a range of older rocks including:

- to the east, latest Devonian to mid-Carboniferous Drummond Basin strata
- to the north, by outcropping and sub-cropping unconformable contacts with rock units within Charters Towers Province (Fergusson *et al.*, 2013). These units incorporate Neoproterozoic to early Paleozoic sedimentary rocks, volcanics, and meta-sedimentary rocks of the Cape River Metamorphics (formerly the Cape River beds) and granites of the Lolworth and Ravenswood batholiths
- to the northwest and west, by sub-cropping, high-grade metamorphics and granitic rocks of the Mesoproterozoic Mount Isa Inlier
- in the central-south, partially by sub-cropping meta-sedimentary rocks and granites of the Maneroo Platform, of probable early Paleozoic age.

The northern Galilee Basin is also underlain by a variety of older rocks that include:

- latest Devonian to mid-Carboniferous volcanoclastic rocks of the Drummond Basin in the east (Olgers, 1972; Vine, 1972; Nelson, 1977, 1981; Evans, 1980; Pinchin, 1978)
- metamorphosed, probable early Paleozoic sedimentary rocks and intrusives (of unconfirmed age) of the Thomson Orogen in the central region (Kirkegaard, 1974; Murray & Kirkegaard, 1978; Evans, 1980)
- Proterozoic and probable early Paleozoic rocks in the southwest of the Lovelle Depression (Hawkins & Harrison, 1978).

Figure 5 shows the generalised surface geology for the Hughenden, Pentland and Milray areas around the northeastern margin of the Galilee Basin where the Betts Creek beds outcrop and most of the initial coal exploration was undertaken.

Significant structural features within the northern Galilee Basin evolved due to faulting along north-northeasterly, northeasterly and northwesterly directions. The prominent faults and fault-related

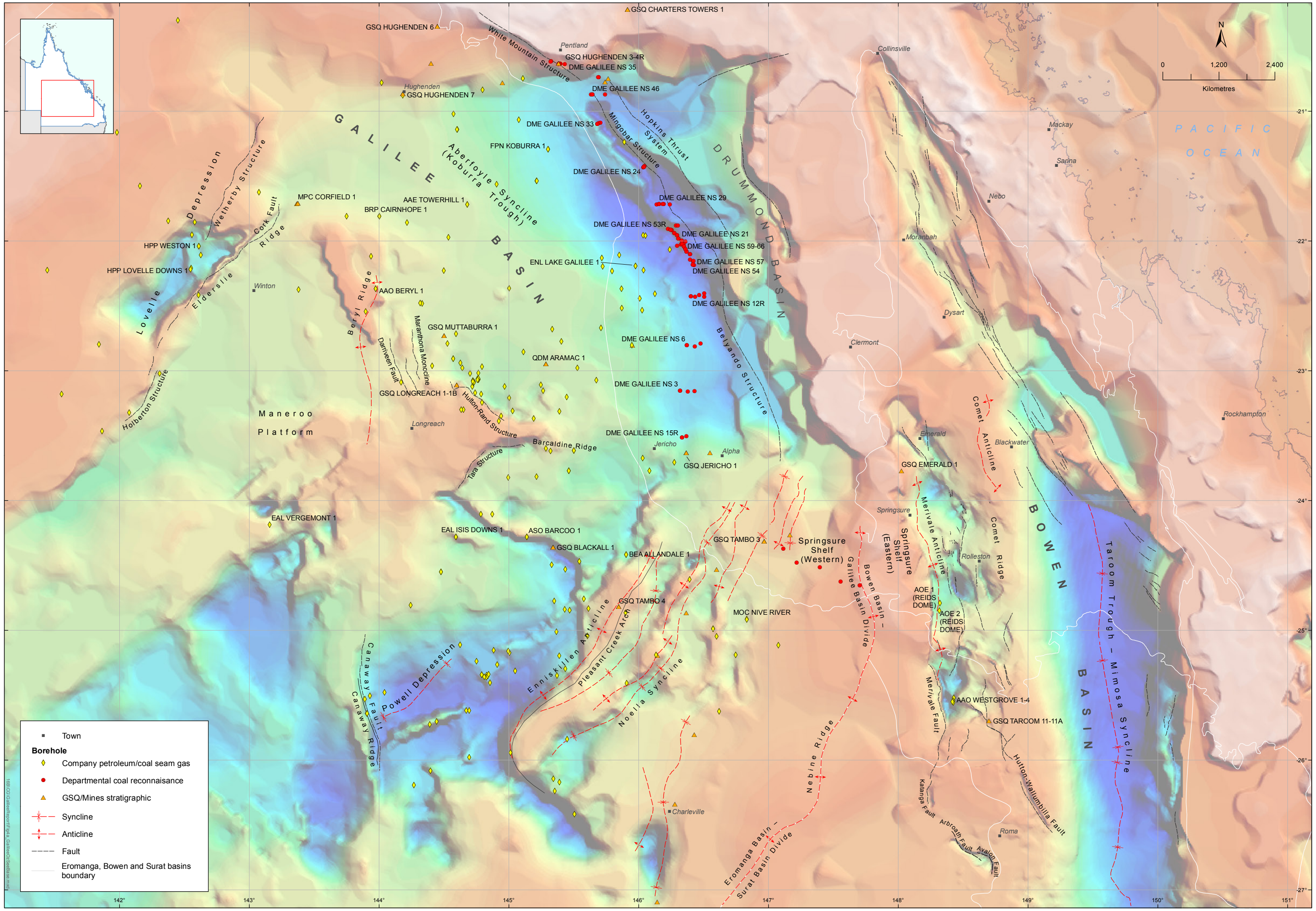


Figure 4a. Structural elements and setting, Galilee and Bowen basins, plotted over Australian Phanerozoic OZ SEEBASE (2005). Note: The colours in the SEEBASE background are blue for deep basement graduating to brown-orange for shallow basement. (This page may be printed at A3 for clarity.)

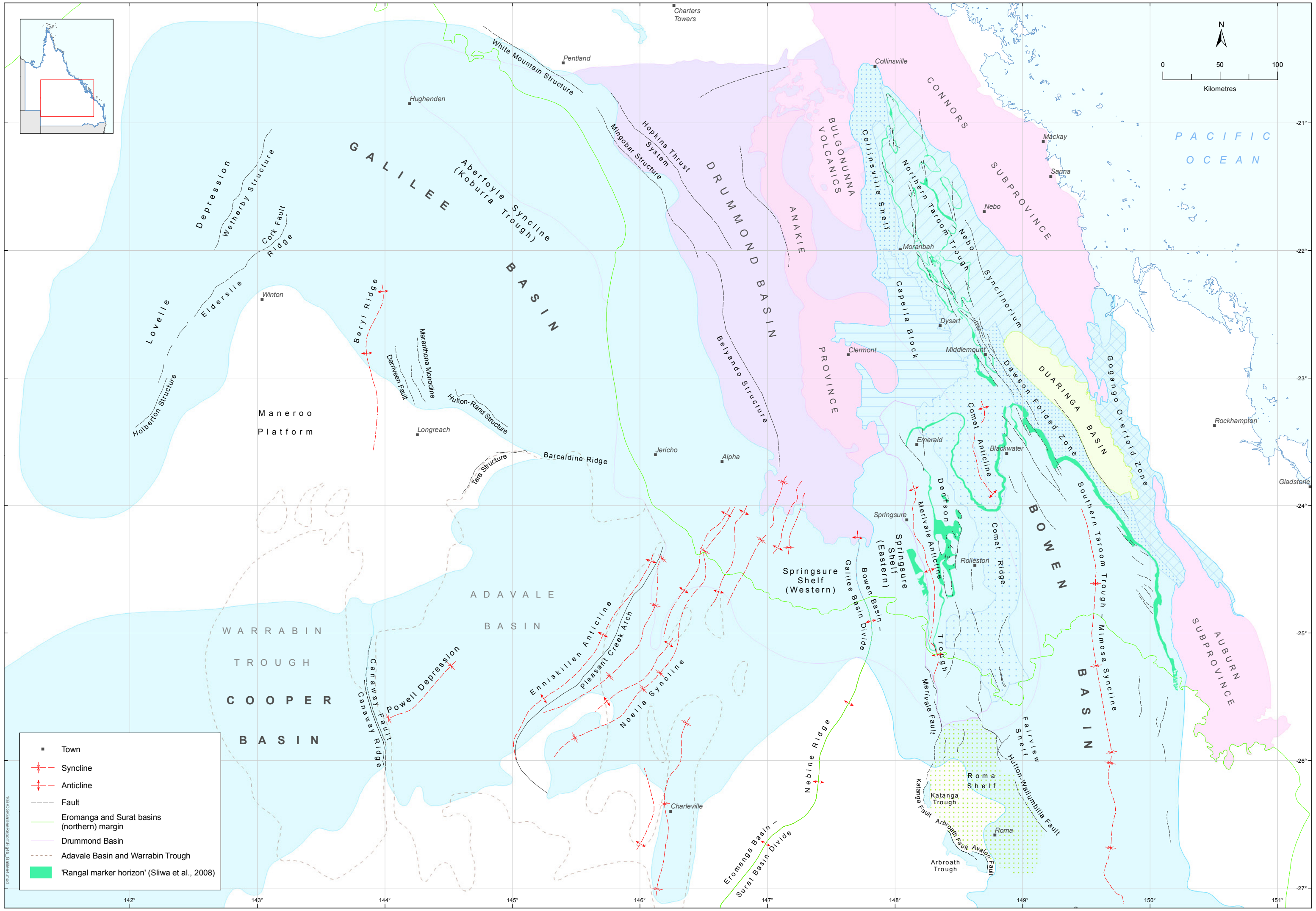


Figure 4b. Structural elements and setting, Galilee and Bowen basins. (This page may be printed at A3 for clarity.)

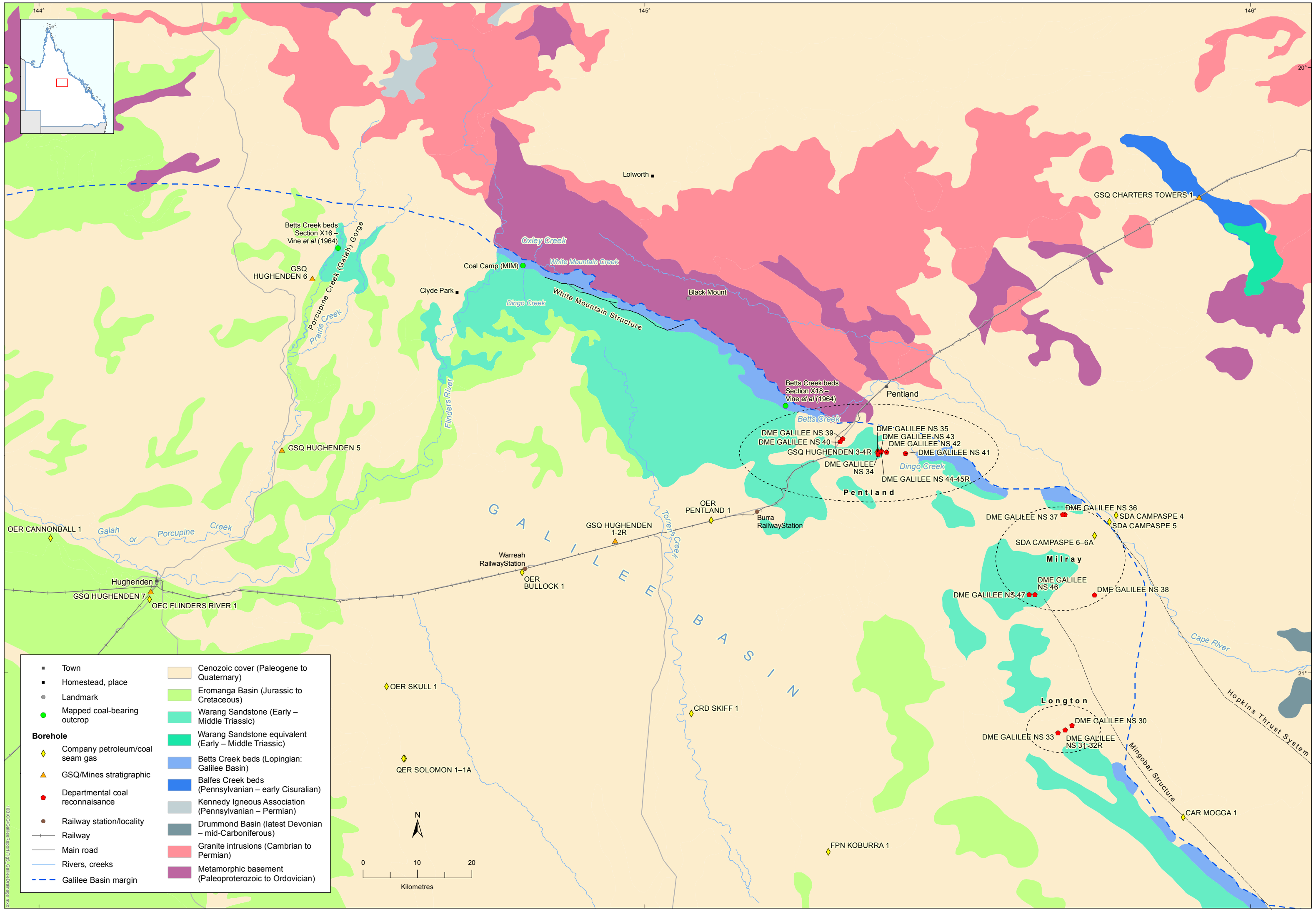


Figure 5. Generalised surface geology, Hughenden-Pentland region, northern Galilee Basin. (This page may be printed at A3 for clarity.)

structures are the Cork Fault, Holberton Structure, Wetherby Structure, Elderslie Ridge, Beryl Ridge and Tara Structure (Figure 4a,b; Vine, 1976; Jackson *et al.*, 1981).

Important northwesterly and north-northwesterly trending structures include the White Mountain Structure, Mingobar Structure, Hulton-Rand Structure and Dariveen Fault (Jackson *et al.*, 1981). Vine *et al*. (1965) assigned the name Belyando Feature to a lineament that included the White Mountain Structure and Mingobar Monocline (Mingobar Structure) along the eastern margin of the Koburra Trough (Figure 4).

The northeasterly trending Cork Fault in the Lovelle Depression constitutes an important structural boundary. This boundary coincides with a pronounced change in total-magnetic-intensity trends from the north to north-northwest-directed anomalies of the Mesoproterozoic Mount Isa Inlier to the generally northeast-trending anomalies of the early Paleozoic Thomson Orogen (Murray & Kirkegaard, 1978; Jackson *et al.*, 1981).

Figure 6 shows the locations of a number of diagrammatic cross sections superimposed against structural features and interpreted depth to basement.

Diagrammatic cross sections over selected parts of the northern Galilee Basin are presented as:

- Figure 7. Section A-A', based on seismic lines CAR82-9 and CS86-3 and modified from van Heeswijck (2006) and Bradshaw *et al.* (2009)
- Figure 8. Section B-B', based on seismic line CAR82-25 and modified from van Heeswijck (2010)
- Figure 9. Section C-C', based on seismic lines Y81A, Y80A and extension, D81D and Y81B-1211 and modified from Bradshaw *et al.* (2009)
- Figure 10. Section D-D', a longitudinal section along the eastern flank of the northern Galilee Basin showing the generalised coal-seam architecture based upon coal-seam intersections in departmental, coal-reconnaissance boreholes.

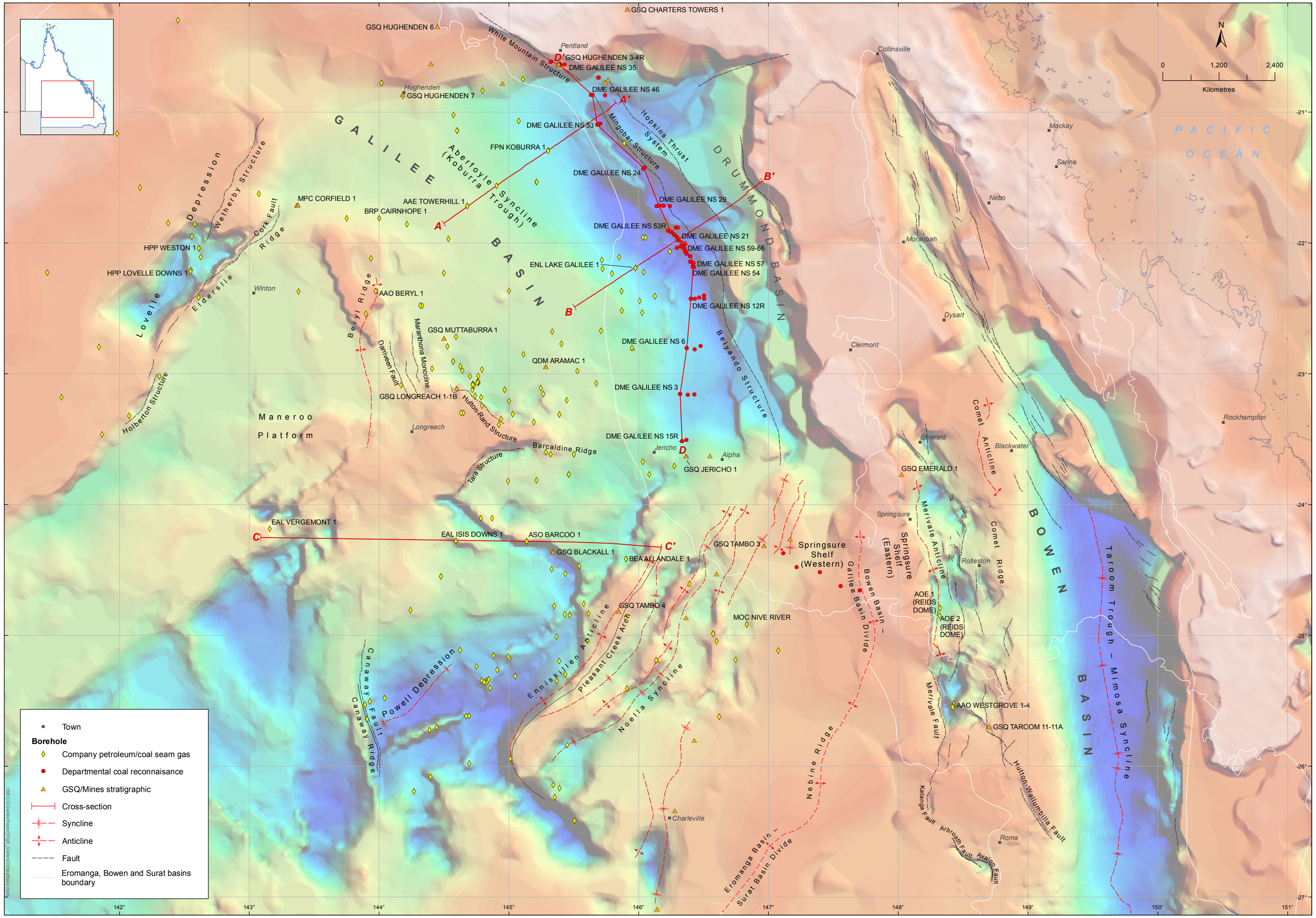


Figure 6. Cross section locations. (This page may be printed at A3 for clarity.)

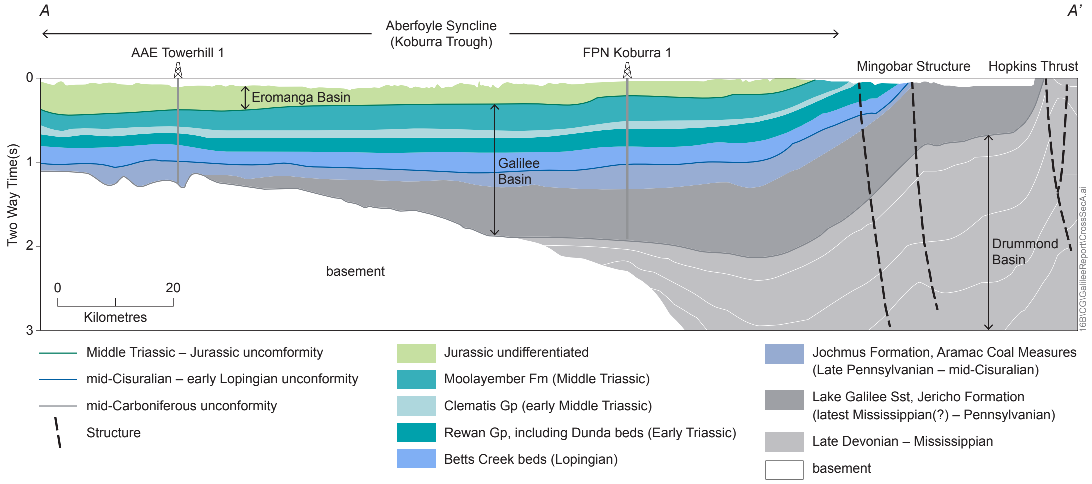


Figure 7. Section A-A'—weakly folded strata in the Aberfoyle Syncline, northeastern margin.

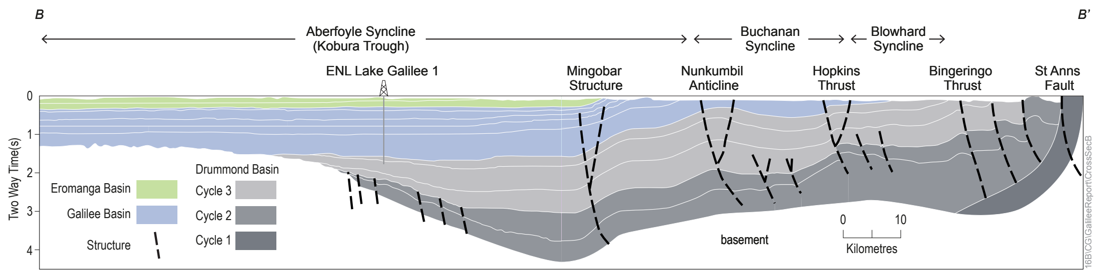


Figure 8. Section B-B'—weakly folded strata in several synclines of the northeastern margin and upright structures in the underlying Drummond Basin.

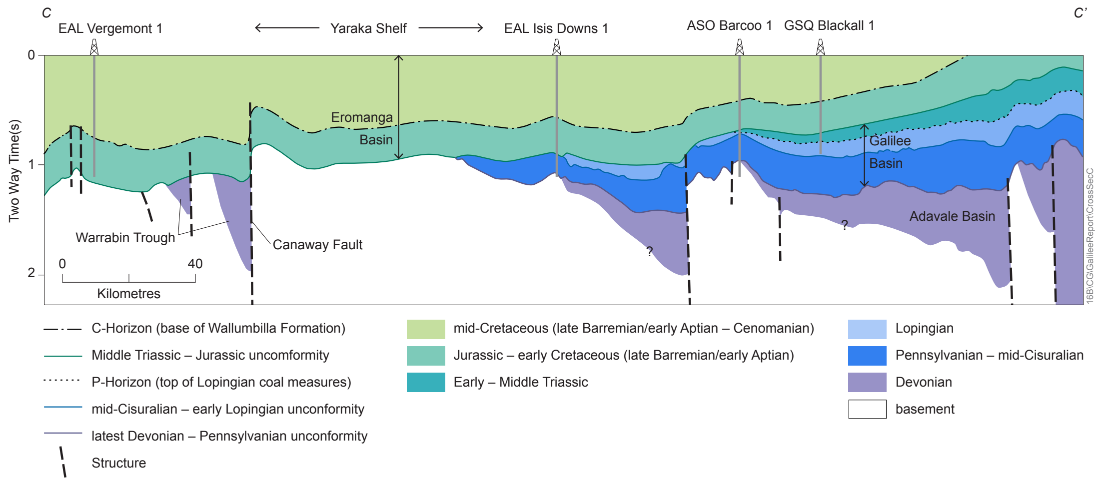


Figure 9. Section C-C'—east–west section showing the absence of the Permian-Triassic Cooper Basin strata.

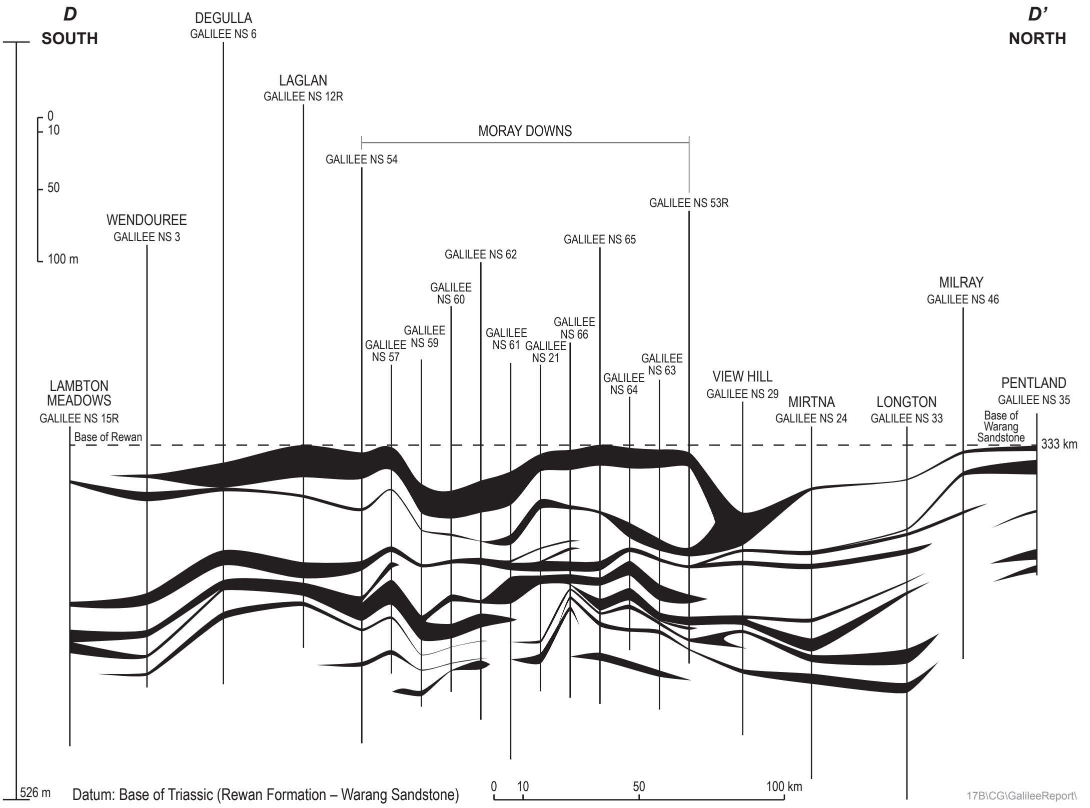


Figure 10. Section D-D'—generalised seam architecture.

Stratigraphy

Nomenclature

The stratigraphic nomenclature of the Galilee Basin is still evolving, with the most recent reviews of the basin's Lopingian (late Permian) stratigraphy being undertaken by Phillips *et al*. (2016a,b, 2017, in review). A combination of complex outcrop and subsurface relationships exist over large distances between the basin's three major depocentres and across the Springsure Shelf into the southwestern Bowen Basin (Denison Trough). This has led to different lithostratigraphic nomenclature being applied locally to the various parts of the Galilee Basin succession. Currently recognised units and their general regional distribution are shown in Figure 3.

Setting aside identification of discrete facies in the basin, basic problems associated with lateral lithostratigraphic relationships and appropriate rock-unit nomenclature presently remain to be overcome.

The coal-bearing formations of the Galilee Basin encompass the mid- to late Cisuralian (middle–late early Permian) Aramac Coal Measures, the Lopingian (late Permian) Betts Creek beds and Colinlea Sandstone, as well as the late Lopingian (Changhsingian) Bandanna Formation (Figure 3). A laterally and vertically extensive mid-Permian unconformity generally divides the Galilee Basin succession into fluvial, lacustrine and restricted paludal strata below the unconformity and widespread fluvial and paludal strata above it. Erosion associated with this hiatus has restricted the present-day geographic distribution of the Aramac Coal Measures to the Lovelle Depression and the area bordering the Maneroo Platform in the northeastern Galilee Basin (Scott *et al.*, 1995, figure 9).

Other unconformities associated with the Hunter–Bowen Orogeny mark the boundary between the Bandanna Formation and the Early Triassic Rewan Group and between the Rewan Group and the early

Middle Triassic Clematis Group. A major unconformity defines the top of the ensuing Middle Triassic Moolayember Formation at the upper limit of the succession in the Galilee Basin.

Mid-Carboniferous–Cisuralian (early Permian)

Joe Joe Group

The mid-Carboniferous to Cisuralian (early Permian) Joe Joe Group (Figure 3) comprises glaciogenic and fluvial sediments and consists of tillitic conglomerate, lithic sandstone, siltstone, minor mudstone and coal (Gray & Swarbrick, 1975; Hawkins & Carmichael, 1987; McKellar & Henderson, 2013). The group, in ascending stratigraphic order, consists of the Lake Galilee Sandstone, Jericho Formation, Jochmus Formation and the Aramac Coal Measures.

Lake Galilee Sandstone

The latest Mississippian(?) – early Pennsylvanian (mid-Carboniferous) Lake Galilee Sandstone is restricted to the Koburra Trough and represents initiation of sedimentation in the Galilee Basin (Figure 3; McKellar & Henderson, 2013). It was deposited by braided streams and comprises quartzose sandstone with minor amounts of conglomerate, mudstone and siltstone (Gray & Swarbrick, 1975). The formation unconformably overlies Devonian clastics of the Drummond Basin and is conformably overlain by the Jericho Formation (Gray & Swarbrick, 1975; Hawkins *et al.*, unpublished).

Jericho Formation

The Pennsylvanian (late Carboniferous) Jericho Formation is present throughout much of the northeastern and southern Galilee Basin (Figure 2; McKellar & Henderson, 2013). In the latter depocentre, the unit represents the majority of the extant Joe Joe Group as erosion associated with the mid-Permian unconformity has removed much of upper part of the sequence. The formation consists of mudstone, siltstone and volcaniclastic sandstone deposited in a fluvio-lacustrine environment. Locally, dropstones and pebbly mudstones have been recorded in outcrop, indicating a glacial influence (Gray & Swarbrick, 1975; Jones & Fielding, 2008; Hawkins *et al.*, unpublished).

The Oakleigh Siltstone Member (Gray & Swarbrick, 1975), comprising banded and varved siltstone, mudstone and shale, occurs in the Jericho Formation in the Koburra Trough, and in the northern area of the southern Galilee Basin (Hawkins & Green, 1993). The upper part of the Jericho Formation, above the Oakleigh Siltstone Member, contains a higher proportion of mudstone than below it. Tuff bands within a lacustrine facies near the top of the formation indicate the onset of proximal volcanism (Hawkins *et al.*, unpublished).

Jochmus Formation

The Late Pennsylvanian – early Cisuralian (latest Carboniferous – early Permian) Jochmus Formation was deposited in a fluvio-lacustrine environment, also under a glacial influence. The formation features sandstone, siltstone, varved mudstone and some tuff. The tuffaceous interval is located toward the middle of the unit and is referred to as the Edie Tuff Member. This interval also features less sandstone than is present in the remainder of the Jochmus Formation below and above it, which are referred to respectively as the lower and upper parts of the formation (Gray & Swarbrick, 1975).

The Jochmus Formation occurs extensively in the northeastern Galilee Basin, including the Koburra Trough, and heralds the onset of sediment accumulation in the Lovelle Depression. Progressing south, only parts of the lower Jochmus Formation are represented while in the Powell Depression (*viz*., over the Adavale Basin), the formation is totally absent (Scott *et al.*, 1995, figure 7; McKellar & Henderson, 2013).

The Jochmus Formation is conformably overlain by the Aramac Coal Measures in the western area of the northeastern Galilee Basin, and also in the Lovelle Depression. In the eastern area of the northeastern Galilee Basin and in the southern area of the basin (where the Aramac Coal Measures are absent), the Jochmus Formation is unconformably overlain by the Colinlea Sandstone (Figure 3; Scott *et al.*, 1995; McKellar & Henderson, 2013).

Aramac Coal Measures

The mid- to late Cisuralian (middle–late early Permian) Aramac Coal Measures are composed of sandstone, siltstone, shale, mudstone and minor coal (Gray & Swarbrick, 1975; Swarbrick & Wallin, 1976; Scott & Hawkins, 1992; McKellar & Henderson, 2013). The formation has been identified in the northern Galilee Basin (in the Lovelle Depression and in parts of the northeastern Galilee Basin), but is absent from the southern regions of the basin. The coal measures were deposited conformably over the Jochmus Formation in a deltaic to paludal setting. A major regional unconformity at the eroded top of the Aramac Coal Measures extends from the late Cisuralian (late early Permian) to the early Lopingian (early late Permian), highlighting the distal effects of the Hunter–Bowen Orogeny.

Boonderoo beds

The Late Pennsylvanian – early Cisuralian (late Carboniferous – early Permian) Boonderoo beds, described by Vine *et al.* (1964), crop out in Porcupine Creek (Galah) Gorge, at the northern end of the Koburra Trough, on the northeastern margin of the Galilee Basin. They are equivalent in age to the upper Jericho – Jochmus Formation succession further to the south (McKellar, 1977a,b). Comprising mainly interbedded sandstone, shale (varved in part), siltstone, mudstone, conglomerate, tuff and minor coal, these strata also contain striated and faceted pebbles and cobbles which point to a glacial influence in their depositional environment (Vine *et al.*, 1964; Vine & Paine, 1974; Gray, 1977).

Lopingian (late Permian)

Betts Creek beds and equivalents

Following the mid-Permian tectonism and associated hiatus, sediment accumulation resumed with deposition of the Betts Creek beds (as they are presently recognised and mapped) in the Lovelle Depression and in the northeastern Galilee Basin (Figure 4a,b).

The Betts Creek beds were initially described from outcrop on the basin's northeastern margin (Vine *et al.*, 1964) and in the sub-surface in the northeastern Galilee Basin, although not where the Galilee Basin overlies the Drummond Basin (Gray, 1977; Balfe, 1979; Scott *et al.*, 1995). The unit has been recognised as extending from outcrop in Porcupine Creek (Galah) Gorge (Plate 1) and its type locality in the Pentland area (Vine *et al.*, 1964) to the southwest and south-southwest in the sub-surface along the eastern margin of the Maneroo Platform, almost to the Barcaldine Ridge (Scott *et al.*, 1995, figure 14). In the Lovelle Depression, in the northwestern Galilee Basin, the Betts Creek beds nomenclature was applied to the sequence by Hawkins & Green (1993) and Scott *et al*. (1995) that previously had been considered to be correlatives of the Colinlea Sandstone and Bandanna Formation (e.g., Hawkins & Harrison, 1978).

The Betts Creek beds contain white to light grey sandstone, siltstone, shale, claystone, coal, carbonaceous shale, conglomerate and minor tuff (Vine & Paine, 1974; Gray, 1977; Hawkins *et al.*, unpublished). The unit represents a succession of coal-bearing, alluvial plain and braided channel deposits and rests unconformably on early Permian strata of the Boonderoo beds, Jochmus Formation and the Aramac Coal Measures (Figure 3). Exposures of the unit in Porcupine Creek (Galah) Gorge are shown in Plates 2 and 3.

Plate 1. Porcupine Creek (Galah) Gorge, viewed from location 20° 19' 31.03", 144° 27' 57.25" approximately 2.4 km north of the Pyramid Camping ground, Porcupine Gorge National Park, Hughenden District.

Plate 2. Thin-bedded, carbonaceous siltstone and mudstone overlain by poorly sorted, coarse- to very coarse-grained, pebbly sandstone, Betts Creek beds. Tape measure is extended 1 m. Photo taken at 20° 19' 34.93", 144° 28' 13.8".

Plate 3. Thinly interbedded very fine to fine-grained sandstone and siltstone overlain by carbonaceous siltstone and mudstone which is overlain by coarse- to very coarse-grained, poorly sorted, pebbly sandstone, Betts Creek beds. Photo taken at 20° 19' 32.41", 144° 28' 3.72".

In the Lovelle Depression, however, the Betts Creek beds are also reported as unconformably overlying the ill-defined Guadalupian/middle Permian Weston beds. The Weston beds have only been recognised in one well, HPP Weston 1 (Price 1974, 1997; Price *et al.*, 1985) and have no other known equivalents in the Galilee Basin (McKellar & Henderson, 2013).

According to sequence-stratigraphic studies by Allen & Fielding (2007a), the Betts Creek beds embrace six sequences that can be traced throughout the Galilee Basin and across the Springsure Shelf into the Denison Trough (southwestern Bowen Basin). These sequences have been related to the entire section in the Denison Trough upwards from the upper Aldebaran Sandstone, through the Freitag Formation, Ingelara Formation, Catherine Sandstone and Peawaddy Formation, up to and including the Bandanna Formation.

From a lithostratigraphic perspective, lateral relationships between this Denison Trough succession and the succession at and around Porcupine Creek (Galah) Gorge (Hughenden area) are problematic and remain poorly delineated because of seemingly changing facies. This has lead to contrasting interpretations between the lithostratigraphic and sequence-stratigraphic approaches.

The thin arenaceous unit defined by Mollan *et al.* (1969) as the Colinlea Sandstone, was recognised by Gray (1976) on the Springsure Shelf's eastern margin to represent equivalents of the upper Aldebaran Sandstone, Freitag Formation, Ingelara Formation and Catherine Sandstone in the Denison Trough. In the subsurface, on the eastern margin of the Springsure Shelf, Gray (1976) recognised, in the Colinlea Sandstone, correlatives of the above-cited Denison Trough units; although he was unable to identify such a four-fold subdivision of the formation on the shelf's western margin. There, in GSQ Tambo 3, the Colinlea Sandstone was regarded as largely being a possible correlative of the Catherine Sandstone, as it was found to be thinned and to consist mainly of sandstone.

The succeeding Peawaddy Formation, Black Alley Shale and Bandanna Formation were correlated by Gray (1976) westward, from the Denison Trough, across the Springsure Shelf and into the Galilee Basin. This is where Swarbrick (1974) had previously recognised a four-fold subdivision of the late

Permian succession in GSQ Jericho 1, including correlatives of these three Denison Trough units (Peawaddy Formation, Black Alley Shale, Bandanna Formation), together with the underlying Colinlea Sandstone of the eastern Springsure Shelf.

In the Galilee Basin, the Peawaddy Formation comprises mainly sandstone, with lesser siltstone, mudstone and coal deposited under marine to deltaic to lacustrine conditions (Swarbrick, 1974; Gray, 1976; Allen & Fielding, 2007b). The Black Alley Shale comprises dark grey to black shale and siltstone with interbedded tuff and sandstone, representing a transitional period of sedimentation (Swarbrick, 1974; Gray, 1976). The Bandanna Formation comprises interbedded sandstone, siltstone, mudstone and coal, deposited under paludal, lacustrine and fluviatile conditions (Swarbrick, 1974; Gray, 1976; Scott *et al.*, 1995; Hawkins *et al*, unpublished).

A recent mineralogical study (Grigorescu, 2012) of late Permian formations (Peawaddy Formation, Black Alley Shale, Bandanna Formation, Betts Creek beds) in the southeastern section of the basin, revealed that the local sediments are largely fine grained and moderately to poorly sorted with sub-angular to sub-rounded grains consistent with fluvial sedimentation. No coal seams were observed in the Permian formations analysed, which were intersected at depths ranging between 750 and 1400 m.

The main mineral components of samples taken include quartz and feldspar. Polycrystalline quartz grains are more frequent than quartz with undulatory extinction, and plagioclase is dominant over K-feldspar. In many clay-rich samples, the feldspar concentrations exceed the quartz concentration, indicating the high immaturity of the sediment and its proximity to source. Generally, the feldspars have pitted and altered surfaces and fresh grains are rare. Kaolinite is always present, although in some clay-rich units, smectite-illite mixed layer clays become pre-eminent, which suggests localised low-energy environments of deposition. A clay-rich unit in the Bandana Formation also contains minor zeolites, which are likely to be of volcanic origin. Muscovite and biotite occur as flakes or fibres and these are often deformed or exfoliated. However, the vast majority of micas (often amounting to a third of a sample) are intertwined with clay particles and form a very fine grained matrix which is typical of all the late Permian formations analysed, but particularly notable in fine-grained units like the Black Alley Shale. Calcite veins and haematitic alterations are rare. Pyrite is present in the Peawaddy Formation, confirming a marine influence during its sedimentation (Grigorescu, 2012).

Early–Middle Triassic

The Triassic succession in the Galilee Basin essentially comprises, in ascending stratigraphic order, the Rewan Group, the Clematis Group and the Moolayember Formation. They form a lateral extension of the time-equivalent stratigraphy across the Springsure Shelf from the Denison Tough in the southwestern Bowen Basin (Figure 4a,b). Conformably overlying the Rewan Group is a sandy unit referred to by Vine *et al.* (1965), Olgers (1970) and Vine & Doutch (1972) as the Dunda beds (McKellar & Henderson, 2013). A lateral equivalent of these Triassic units in the northern Galilee Basin is a distinct sandstone unit termed the Warang Sandstone (Vine *et al.*, 1964; Vine & Paine, 1974; McKellar & Henderson, 2013).

Rewan Group

The Early Triassic Rewan Group consists of quartzose sandstone, siltstone and mudstone (Scott *et al.*, 1995; McKellar & Henderson, 2013, Hawkins *et al.*, unpublished). A brief time break is inferred in Figure 3 between the Betts Creek beds and the Rewan Group where these units are present. It is generally widespread in eastern Australia (e.g., Price, 1997) and observed as an unconformity (of varying magnitude) between Lopingian (late Permian) and Early Triassic strata. A similar unconformity exists between the Betts Creek beds and the lower part of the Warang Sandstone (inferred as the lateral equivalent of the Rewan Group) in the northern Galilee Basin (McKellar, 1977a,b, 1979; McKellar & Henderson, 2013).

The Rewan Group sediments analysed in the southeast of the basin are generally fine-grained with medium-grained layers and are well- to moderately sorted. The main components are quartz and feldspar, although the concentration of feldspar is significantly diminished in comparison with the underlying Permian sediments. Also of note is a shift in feldspar speciation. The K-feldspars increase in concentration in Triassic sediments and they equal or exceed the plagioclase grains which were noted as being dominant in Permian sediments. The red colour of some layers is due to high concentrations of haematite. Muscovite-rich clayey matrices, typical of all the fine-grained Permian sediments, persist in the Rewan Group, with frequent exfoliated or deformed muscovite and biotite flakes. Mixed layer clays were not detected, indicating deposition in a consistently high-energy fluvial system (Grigorescu, 2012).

Dunda beds

Overlying the Rewan Group in the northeastern Galilee Basin are the late Early Triassic Dunda beds (Figure 3), which crop out along the basin margin. In the sub-surface, they have been reported as being restricted to the central and southern Koburra Trough area (Scott *et al.*, 1995; Hawkins *et al.*, unpublished), although their true extent is unknown. The unit has also been recorded in two drill holes in the southern Galilee Basin on the western extremity of the Springsure Shelf in GSQ Tambo 4 (Noon & Coote, 1986) and SPP Birkhead 1 (South Pacific Pty Ltd, 1957). They are represented here by a succession of poorly sorted sandstones with a kaolinitic matrix (Exon *et al.*, 1972; Scott *et al.*, 1995; Hawkins *et al*., unpublished). Siltstones may contain up to 35% micas (mainly muscovite) which intertwine with kaolinite to form a tight very fine grained matrix (Grigorescu, 2012).

According to Vine *et al.* (1965), the Dunda beds rest conformably on the Rewan 'Formation' (Rewan Group) and are probably a facies variant of the upper part of the Rewan 'Formation' (i.e. the Arcadia Formation of the Rewan Group in the Denison Trough). They are mainly fluviatile, with some possible lacustrine intervals (Exon *et al.*, 1972).

Clematis Group

The Anisian (early Middle Triassic) Clematis Group (Figure 3) has a comparable distribution to the Rewan Group in the Galilee Basin, but is more extensively developed in the sub-surface in the south. It consists mainly of sandstone with a kaolinitic matrix and lesser amounts of siltstone and mudstone (Swarbrick & Wallin, 1976; Scott *et al.*, 1995; Hawkins *et al.*, unpublished). Deposition was from braided rivers (Hawkins & Green, 1993).

An erosional unconformity between the Clematis Sandstone and the underlying Dunda beds has been suggested by Exon (1970) in the Tambo 1:250 000 and the Jericho 1:250 000 Sheet areas. Senior (1973) has indicated a disconformable relationship and indicated that the unit unconformably overlies the Rewan 'Formation' further to the north. According to Casey (1970), the top of the Dunda beds represents a disconformity and possibly a regional unconformity. Swarbrick & Wallin (1976) also maintained that an unconformity occurs between the Clematis Sandstone and the underlying Rewan 'Formation' in both QDM Aramac 1 and QDM Hexham 1 (where the Dunda beds are absent). In contrast, Hawkins *et al.* (unpublished) suggested that the Clematis Sandstone rests conformably on the Dunda beds in the subsurface and, on the Rewan Formation where the Dunda beds are absent, (also see Casey, 1970). Nonetheless, an unconformity is shown at this level in Figure 3 and this hiatus is taken to reflect the compressional pulse associated with the Hunter–Bowen Orogeny, at about the end of the Early Triassic.

The medium-grained sandstones of the Clematis Group are well to moderately sorted, although there are layers which are poorly sorted with high-angularity particles. Mineralogically, the sandstones preserve the character of the Triassic sediments in the area as they are similar in composition to the Rewan Group. Microcrystalline quartz and lithic fragments are ubiquitous in the medium-grained material and K-feldspar usually dominates over the plagioclase. The siltstones have a kaolinitic matrix rich in mica-type minerals (Grigorescu, 2012).

Moolayember Formation

The late Anisian–Ladinian (Middle Triassic) Moolayember Formation is the most extensively developed unit in the Galilee Basin. It consists of green, grey, brown, purple and red mudstone, with minor siltstone and some pebbly sandstone (Scott *et al.*, 1995; Hawkins *et al.*, unpublished). Deposition occurred in a fluvio-lacustrine environment.

In the Koburra Trough (and elsewhere), the Moolayember Formation conformably overlies the Clematis Group. It is also conformable on the Warang Sandstone in the north and west of the trough (Hawkins *et al.*, unpublished), as well as being a lateral equivalent of the Warang Sandstone in part.

The Moolayember Formation, represents the uppermost preserved sequence in the Galilee and Bowen basins. Uplift from the final compressional pulse of the Hunter–Bowen Orogeny is believed to account for the termination of sedimentation in both basins (Korsch *et al*., 2009; McKellar & Henderson, 2013).

The Moolayember Formation is compositionally very similar to the Clematis Group, although it is generally much finer grained, moderately to poorly sorted and with numerous sub-angular grains. Quartz occurs as individual grains or as microcrystalline particles. The feldspars are difficult to distinguish due to coatings and alteration, although fresh microcline particles have been identified. Muscovite and kaolinite-rich matrices are characteristic of most fine-grained units. Other features of this formation include calcite and siderite veins, haematitic alterations and abundant lithic fragments in places. Some layers contain mud clasts and apatite. In others, calcite cementation has been identified. Occasional high concentration of smectite-illite mixed layers attest to low-energy sedimentation (Grigorescu, 2012).

Warang Sandstone

The Early–Middle Triassic Warang Sandstone (Figure 3) was defined in outcrop by Vine *et al.* (1964) near the northeastern margin of the Galilee Basin where the formation lies unconformably on the Betts Creek beds (Vine & Paine, 1974; Scott *et al.*, 1995; Gray, 1977; Balfe, 1979; Hawkins *et al.*, unpublished) (Plate 4). From this outcrop area, the formation extends from the Koburra Trough westwards and southwestwards in the sub-surface into the northern half of the Lovelle Depression (Scott *et al.*, 1995; Hawkins *et al.*, unpublished). This unit is well exposed in the Porcupine Creek (Galah) Gorge (Plate 5 and Plate 6).

In the sub-surface, the Warang Sandstone consists of pebbly, poorly sorted, kaolinitic, quartzose to sub-labile sandstone with inter-beds of argillaceous rocks. Minor conglomerate bands are present and a few thin seams of dull, pyritic coal occur near the top of the formation (Gray, 1977; Balfe, 1979). The formation represents a basin-margin facies deposited by southerly flowing rivers draining the Lolworth-Ravenswood Block (Hawkins & Green, 1993).

Plate 4. A lower interval of Betts Creek beds which are a sequence of grey, poorly sorted, coarse- to very coarse-grained sandstone with minor intervals of very fine sandstone and siltstone overlain by the Warang Sandstone which is a sequence of yellowish brown, medium- to very coarse-grained, moderately to poorly sorted sandstone. Photo taken at 20° 19' 32.41", 144° 28' 3.72".

Plate 5. Pavement outcrop of the Warang Sandstone, near The Pyramid. The Pyramid is mostly composed of Blantyre Sandstone with a small amount of Gilbert River Formation at the top. Photo taken at location 20°21'10.48", 144°27'59.76". Photo courtesy of Mrs L. Bullen (image taken August 2016).

Plate 6. Medium- to thick-bedded, moderately sorted medium- to coarse-grained, cross-bedded sandstone, Warang Sandstone. Photo taken at location 20°21'10.48", 144°27'59.76".

Exploration history

Coal exploration

Late 19th Century to 1950

Late 19th and Early 20th Century reports of occurrences of Permian coals and Glossopteris bearing strata in the region around Hughenden and Pentland were made by Rands (1891), Marks (1909; 1911a,b) and Reid (1916, 1918).

Previously, along the Flinders River northwest of Coalbrook Station in the Hughenden district, Jack (1888) had also reported thin coal seams associated with strata he referred to as the 'Rolling Downs Formation'. However, surface mapping in the 1960s by the Bureau of Mineral Resources (Vine *et al.*, 1964; Vine & Paine, 1974) related this occurrence with the strata of the overlying Eromanga Basin (also see Gray, 1977).

Initial coal exploration activity in the northern Galilee Basin was triggered by the extension of the 'Great Northern Railroad' westward from Townsville to Hughenden in 1887. This activity was aimed at sourcing a local supply of coal for the railway, which at the time had to haul coal all the way from Bowen for use on this line. This exploration was largely unsuccessful at the time, failing to intersect any payable prospects, but did confirm the presence of Permian coal in the region (Marks, 1909, 1911a,b).

Reid's report in 1918 was on an occurrence of coal at Oxley Creek, located about 52 miles (84 km) to the northeast of Hughenden and 42 miles (8 km) northwest of Pentland (Figure 5), which he described as occurring in a tributary of the creek above its confluence with White Mountain Creek. Although he attributed 'the discovery' of this occurrence to two gold miners exploring in the region sometime around August 1915, he noted that other coal outcrops had reportedly been observed by local inhabitants of the area some years prior. Reid's report gives a detailed description of the coal, associated strata and other rocks exposed along Oxley Creek as well as observations he made in nearby Dingo Creek of coal seams present in outcrop and intersected in shallow shafts.

MIM subsequently followed up on some of these reported coal occurrences when the company commenced exploration in the Oxley Creek area in late 1939, having made prior application for a licence to occupy a prospecting area for coal. The report on this work by Hall (1939) provides summary details of known coal occurrences in the district prior to 1940.

Shortly after the end of the Second World War, between March 1946 and June 1948, the company undertook further exploratory drilling in the Oxley Creek – Torrens Creek area north of the 'Great Northern Railway', within two coal prospecting areas the company had been granted.

Figure 5 shows the generalised surface geology for the Hughenden, Pentland and Milray areas around the northeastern margin of the Galilee Basin where the Betts Creek beds outcrop and most of the initial coal exploration was undertaken.

Morton (1946) (Appendix 1) provides an insight into the rationale for this work by MIM commenting in an internal GSQ memorandum that the company was searching for "*a dependable source of coal of suitable quality capable of providing up to 100 000 tons per year – the estimated amount, including coke requirements, when simultaneous production of lead and copper is brought into effect*".

Morton's memorandum, entitled '*Coal Search – Great Northern Railway*', written while he was Acting Chief Government Geologist of the GSQ, provides an account of the initial assistance he provided to MIM geologists at the time when he was the District Geologist at the Charters Towers office. The coal prospecting area held by MIM was described as covering "*about 760 square miles lying north of the Great Northern Railway between Flinders River on the west and Torrens Creek on the east*", and located between Warreah and Burra railway stations on that line (Hall, 1946, appendix A, page 1; Morton, 1946).

While consulting as a geologist to MIM at this time, Reid (1948) also undertook an assessment of the coal potential of another area held by MIM. This covered an area of some 1900 square miles (4900 km^2) to the south of the Great Northern Railway near Pentland, extending down to Yarrowmere Station.

Reid's report was based on observations from his own reconnaissance undertaken in the region during mid-1948 and other information available at that time regarding known coal occurrences. He concluded that the coal potential of the area reviewed was not favourable favourable (Reid, 1948, page 14).

Apart from the regional reconnaissance work undertaken by Reid (1948, more detailed exploratory activities were also undertaken in the Hughenden district by MIM during this period. This work, reported by Carter (1948), included sinking an inclined drift (tunnel) at the site of the Oxley Creek coal outcrops.

Before abandoning the site, the company completed an in-seam drive from the base of the drift and took a number of coal samples for analysis. A diagrammatic section of the inclined drift and in-seam drive and analytical results of the coal samples taken at the site by MIM is presented in Appendix 2.

The approximate location of the site is shown in the report prepared by the then UK-based consultants Powell Duffryn Technical Services Ltd, 1949, Volume III, plate 49. The site is referred to therein as "*the new tunnel, at Coal Camp, being driven by Mount Isa Mines Limited*".

The Powell Duffryn Report, commissioned by the Queensland Government two years earlier, in 1947, remains the most comprehensive reference on the state of the Queensland coal industry as it existed at the end of the Second World War. This report contains summaries of the geology of all the known coal-bearing regions of Queensland at that time, and includes a commentary on (Volume I, pages 262–264) and a map (Volume III, plate 49) of the various coal related occurrences in the Hughenden District (Powell Duffryn Technical Services Ltd, 1949). These sections of the report are included in Appendix 3.

Further, government geologist J.E. Ridgway (1947), reported on his examination of carbonaceous and coaly shales outcropping some distance to the southeast of MIM's Oxley Creek prospect. These outcropping strata occurred in a Prospecting Area for Coal (Licence No 13), held by a Townsville-based mining syndicate. This site, referred to as the 'Sladden area', was described as being located at the head of Torrens Creek, northwest of Pentland. While Ridgway reported that there were no coal outcrops sighted in the area investigated, he concluded that the shales observed were "*considered to be the horizon of the Oxley Creek coal seams*" (Ridgeway, 1947, page 198).

1950 to mid-1980s

Between 1950 and the mid-1980s, coal exploration along the eastern margin of the northern Galilee Basin by private enterprise was limited to work by only a few companies (Appendix 4).

In November 1968, Thiess Brothers Pty Ltd were granted two coal Authorities to Prospect (AtP) in the Oxley Creek – Dingo Creek area northwest of Pentland, following up on coal exploration previously undertaken during the 1940s by MIM. These were AtP 56C, located southwest of Pentland and straddling the Great Northern Railway connecting Townsville to Mount Isa, and AtP 58C which covered the area of known coal outcrop in the Oxley Creek – Dingo Creek area, northwest of Pentland (Svenson, 1969).

The company drilled three relatively shallow (< 120 m deep) non-cored boreholes in AtP 56C along the alignment of the railway but undertook no exploration in AtP 58C. None of the boreholes drilled in AtP 56C intersected coal and both tenures were surrendered in late 1969.

During early petroleum exploration undertaken in the northern Galilee Basin in the 1960s, a number of intersections of coal seams of late Permian age were recorded. Hawthorne (1970) emphasised the significance of these intersections and referred to large 'reserves' (page 1) of coal thought to exist in the basin.

It was not until mid-1971, however, that systematic regional coal reconnaissance drilling along the eastern flank of the northern part of the Galilee Basin began, with the commencement of drilling by the GSQ of Galilee NS 1 on Wendouree property, located about 60 km (35 miles) north-northwest of the township of Alpha.

This program of drilling was undertaken between July 1971 and June 1978 and comprised some 66 partly cored boreholes (including six redrills) drilled at 60 sites. This drilling investigated 10 localities along the inferred strike of the late Permian coal-bearing strata on the eastern flank of the northern Galilee Basin, covering a strike length of more than 300 km. These localities were (in south to north order): Lambton Meadows, Wendouree, Degulla, Laglan, Moray Downs, View Hill, Mirtna, Longton, Milray and Pentland. The results of this drilling were reported by Carr (1973a,b, 1974a,b,c, 1976, 1977, 1978) and Matheson (1987a,b).

The depths of the departmental boreholes drilled ranged from about 100 m to 600 m, and averaged around 300 m. Boreholes drilled at three sites (Galilee NS 2, Galilee NS 13 and Galilee NS 14/15R; Figure 5, Figure 6) were interpreted as having penetrated the complete section of potential coal-bearing strata in the late Permian section, as these boreholes terminated in the underlying Joe Joe Group (Carr, 1974c).

Of the 60 sites drilled by the department, coal intersections from 41 sites were sampled and sent for analysis. Coal was not intersected at 15 of the sites drilled, with only thin coals intersected (not sampled) at another four sites. Further details of the coal analytical program and a review of the results obtained is provided in section "Coal quality" on page 47.

A more detailed account of this drilling program is provided by William (Bill) Hawthorne (2011), who was Assistant Chief Government Geologist at the time and among the first geologists employed by the GSQ when the Coal Section was formed, under the direction of Chief Government Geologist, Allan (A.K.) Denmead.

Between the mid-1960s and late 1970s anticipated shortages of oil in Australia led to a number of initiatives being implemented by the Queensland Government. These initiatives included the commencement of stratigraphic drilling in the State by the GSQ in 1965, and the release of land for coal exploration in the northern Galilee Basin in August 1973. This land release was partly aimed at evaluating the liquefaction potential of the late Permian coals known to occur in this area of the basin, when interest was increasing in coal to liquids technology, around the time of the first 'Oil Shock' (Middle East oil crisis) which threatened global access to oil.

The land released by the Queensland Government along parts of the eastern flank of the northern Galilee Basin comprised two Reserved Areas, known as Group 12 and Group 13. Each area comprised 240 sub-blocks (about 770 km^2) that were situated about 48 km and 96 km respectively to the north of Alpha. The areas made available broadly corresponded with the Wendouree (Carr, 1973a) and Degulla areas (Carr, 1973b) drilled by the GSQ at that time.

The area released as Reserved Area – Group 12 (Wendouree) covered a substantial part of what now comprises the Alpha and Kevins Corner coal deposits.

The terms of this land release stated that preference would be given to the applicant company or person proposing to use any of the coal discovered for the manufacture of synthetic fuels and petrochemicals in Queensland (Department of Mines, 1973).

Subsequently, AtP 136C (Wendouree) and AtP 137C (Degulla) were granted in February 1974, respectively to Dampier Mining Company Limited (a wholly owned subsidiary of The Broken Hill Propriety Co. Ltd) and to a joint venture between Shell Development (Australia) Pty Ltd and Western Mining Corporation.

Over the following two years, considerable exploratory drilling was undertaken to evaluate the geology and conversion potential of the coal seams in each area. About 150 boreholes were drilled in AtP 136C between 1974 and 1976, with about 50 boreholes, including five large diameter (200 mm) cored boreholes, drilled in AtP 137C (Degulla) over a similar timeframe.

Much of the laboratory work undertaken on the conversion potential of coals sampled from AtP 136C was performed at BHP's Central Research Laboratories. Testing evaluated the potential of these coals as feedstock for a variety of the known conversion processes that included: pyrolysis, hydrogenation, gasification, solvent refining, and Fischer Tropsch synthesis. Test results were reported by Keith & Smith (1976) and Keith (1976).

The company relinquished title to the area upon the expiry of AtP 136C in February 1977.

In AtP 137C, the conclusions reached at the completion of the second drilling program in 1975, were that there was "*a definite lack of shallow coal within the AtP*" and that the coal quality and washability characteristics were such that, at best, a yield of only about 55 per cent could be achieved to produce a 15 per cent ash product coal [Shell Development (Australia), 1976, page 13]. The tenure was surrendered at the end of the second year in February 1976.

Soon after the completion of the department's Galilee Basin coal reconnaissance drilling program in mid-1978, the Queensland Government advertised a second release of land in the Galilee Basin, seeking expressions of interest to undertake exploration for coal in the region (Department of Mines, 1978). The areas advertised at this time covered some of the same ground that had previously been released in 1974, and comprised three groups of sub-blocks. These areas were:

- Group 16 (300 sub-blocks) – awarded to the Shell Development Company of Australia Limited (Shell) as AtP 249C* in January 1979
- Group 17 (230 sub-blocks) – awarded to Hancock and Wright Prospecting Pty Ltd as AtP 244C* in December 1978
- Group 18 (230 sub-blocks) – awarded to Bridge Oil N.L. as AtP 245C* in December 1978.

*Note: Initially granted as AtPs for coal under the *Mining Act 1968–1976*, these coal exploration tenures later became, in some cases, Retention coal Authorities to Prospect (e.g., AtP 249C became AtP1CR and AtP 245C became AtP17CR). These retention AtPs were subsequently transitioned across to Exploration Permits for Coal (EPCs) following the introduction of the *Mineral Resources Act 1989* which came into effect on 1st September 1990.

The coverage of Authorities to Prospect for Coal in central Queensland, just prior to, at the commencement of, and just following, the completion of the Departmental coal reconnaissance drilling program, is presented in Appendix 5. These areas are presented as scanned images of three Department of Mines', coal 'Exploration Series' maps.

Over the following decade, exploration in each of these permit areas resulted in the identification of substantial quantities of coal at relatively shallow depths, potentially amenable to either open-cut and/or shallow underground mining methods. These permit areas comprise the coal deposits that subsequently became known (respectively) as Ellimeek and Lauderdale (the Pentland Group) and Milray (AtP 249C), Kevins Corner (AtP 244C) and Alpha (AtP 245C).

Low thermal coal prices coupled with the lack of local infrastructure and market access in the region saw exploration activity decline in these tenures from the mid-1980s. Having identified significant resources of coal in each of these areas at that stage, most were transferred over to retention forms of tenure awaiting a time when market conditions might present opportunities for development.

For a brief period between 1980 and 1982, Carpentaria Exploration Company Pty Ltd (Carpentaria Exploration) undertook coal exploration in AtP 289C, in the region between Porcupine (Galah) Creek (incorporating part of the gorge) and Torrens Creek. This exploration targeted exposures of late Permian coals known to be present in the vicinity of the White Mountains area northwest of Pentland and included the site previously investigated by MIM at Oxley Creek (Robertson, 1981a).

A number of widely spaced boreholes were drilled, with a number of thin coal seams intersected in a few of the holes. These coal seams were described as being of 'relatively low energy' and 'high in ash' (Robertson, 1981b, page 1). A maceral analysis of coal sampled from core taken from borehole FC 02A showed the coal to be very low in vitrinite (~15%) and high in inertinite (~78%) (Robertson, 1981b, page 5). Upon relinquishment of the area, Robertson (1983, pages 4–5) reported that 'significant thicknesses' of coal at depths less than 150 m were located only in two areas, both east of the Flinders River, describing the coal quality at both sites as 'poor to inferior'.

BP Australia Limited (BP) also briefly undertook coal exploration between October 1981 and December 1982 in the White Mountains region in AtP 373C, which was an area adjoining and predominately down-dip of the held by Carpentaria Exploration. BP was principally targeting seams within the Betts Creek beds, although the company postulated that coal occurrences within the Jurassic Blantyre Sandstone in the overlying Eromanga Basin, also offered a potential, albeit 'dubious', exploration target (Veitch & McCaw, 1982).

The company drilled 10 predominantly non-cored boreholes at eight sites, to depths ranging from about 40 m to around 350 m. Drilling conditions were reportedly difficult, with seven of the 10 holes prematurely abandoned due mainly to problems encountered with borehole cave-in and circulation loss within the overlying (Triassic/Jurassic) sandstone units (Veitch & Macmillan, 1982).

No significant shallow occurrences of coal were reported, although what was described as a 'thin, high-ash' coal interval was encountered at about 280 m depth in one borehole, which was cored and sent for analysis. A maceral group analysis of this coal sample determined a vitrinite content of 22% (vol.) and an inertinite content of 53% (vol.), with a mean maximum vitrinite reflectance of 0.59% (Veitch & Macmillan, 1982, appendix 4).

In two boreholes completed during the program, the Warang Sandstone was shown to overlap the Betts Creek beds, with the former unit also directly overlying basement rocks of the Lolworth Ravenswood Block.

The company relinquished the area in late 1982 after it was concluded that "*the White Mountains area does not have any recognisable potential for containing economic coal*" (Veitch & Macmillan, 1982, page 7).

Other AtPs for coal granted in the region during this period were targeting Jurassic coal seams in the overlying Eromanga Basin. These prospects included: AtP 211C (Otter Exploration N.L.); AtP 214C and AtP 228C (Houston Oil and Minerals Australia Ltd); AtP 365C and AtP 366C (Drayton Investments Pty Ltd); AtP 378C (Eastern Copper Mines N.L. and Gulf & Western Exploration Pty Ltd) and AtP 395C (Total Energy Development Australia Pty Ltd and CdF Minerals Pty Ltd).

Mid-1980s to 2014

During the period spanning the mid-1980s until mid-2006, coal exploration along the eastern flank of the northern Galilee Basin remained limited and sporadic. It was largely restricted to periodic activity by Shell and MIM in the north around Pentland in the Lauderdale, Elimeek and Milray deposits (AtP 249C), by Bridge Oil Limited over the Alpha deposit (AtP 245C) and by Hancock Wright Prospecting Pty Limited over the Kevins Corner deposit (AtP 244C) further to the south.

From about mid-2006, however, coal-exploration activity along the eastern margin began to increase rapidly, with much of the initial interest shown by small to medium sized junior exploration companies.

This rapid and significant increase in coal-exploration activity at this time, was in response to anticipated demand growth for thermal coal in south and east Asia, particularly for power generation. In late 2007 Hancock Prospecting began to promote their Kevins Corner / Alpha project, and the likelihood of the extension of infrastructure to the northeastern Galilee Basin to support these project areas, attracted other players to the region.

The massive spike in coal prices (based on Queensland Coal Board Annual Reports and Annual Queensland Coal Industry Reviews) that followed flooding in central Queensland in January 2008 attracted even further interest (Figure 11). This flood event disrupted a significant proportion of internationally traded coals sending many users scrambling to find alternate sources of supply, at whatever price, and more than countered the impacts of the global financial crisis (GFC) following the collapse of Lehman Brothers in September 2008.

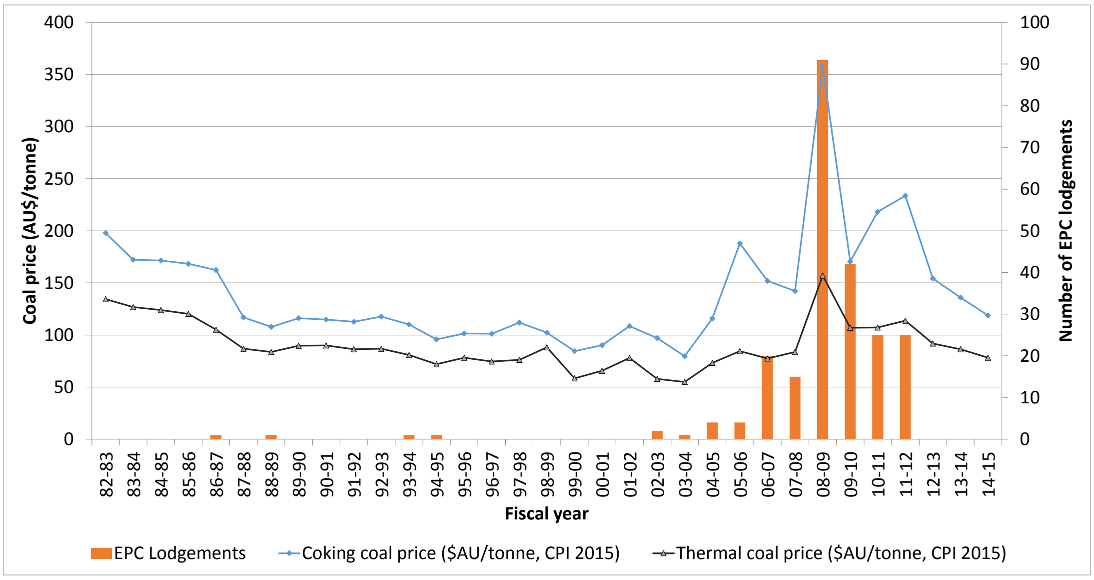


Figure 11. Average price/tonne (free-on-board A$, as reported adjusted for CPI) – Traded Queensland thermal coal vs EPC lodgements, eastern flank, northern Galilee Basin.

While the impacts of the GFC muted demand in a number of markets such as Japan, this was largely offset by double digit growth in the Chinese economy and continued robust growth in India. Another flood event in 2010 further encouraged the search for alternate sources of supply.

Coupled with this commercial incentive was the unavailability of land for coal exploration elsewhere in Queensland at that time. Figure 12 shows the spatial coverage of Exploration Permits for Coal in Queensland as at mid-2005 (Figure 12a), 2011 (Figure 12b) and 2016 (Figure 12c).

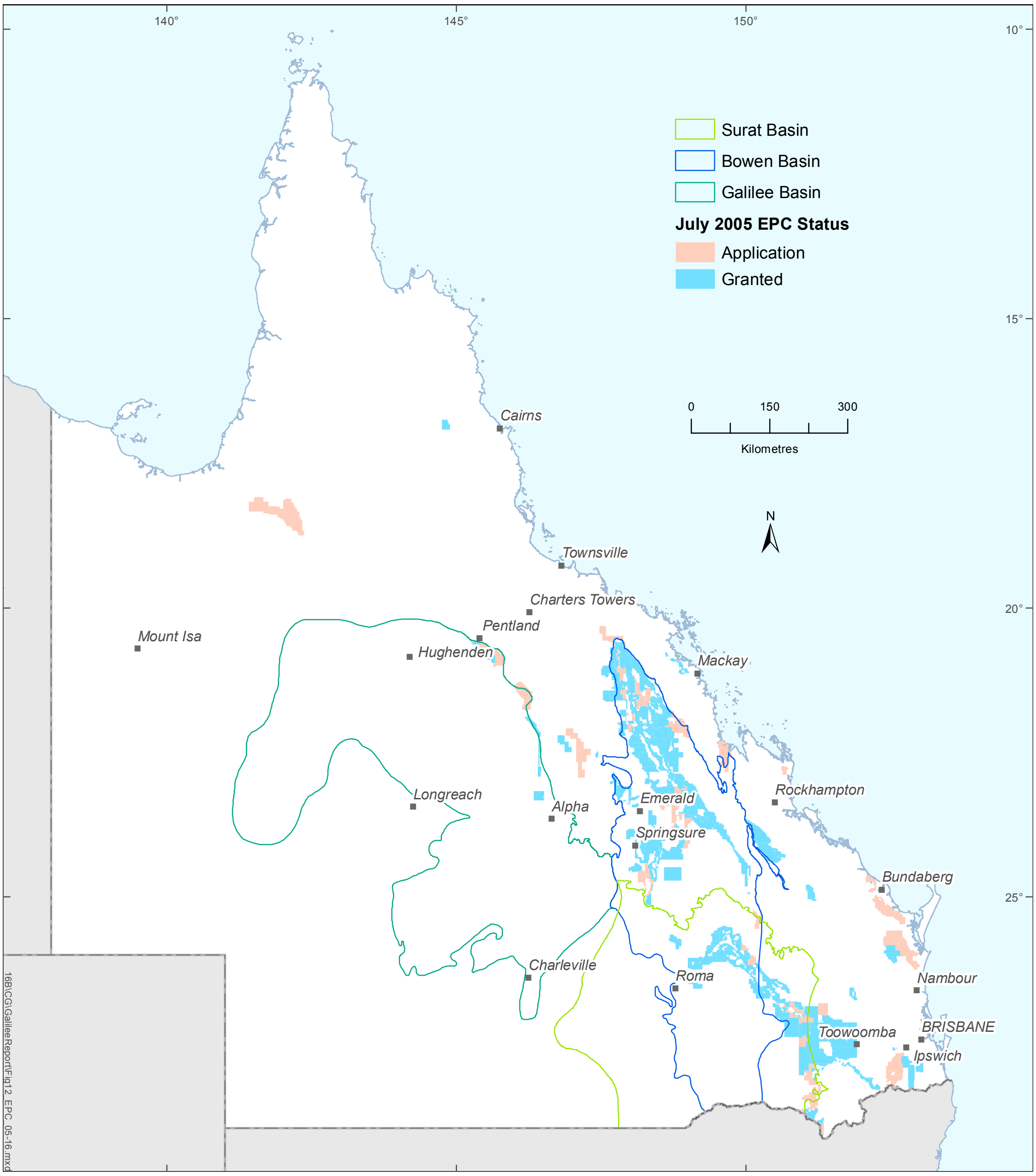


Figure 12a. Queensland EPC Coverage—as at July 2005.

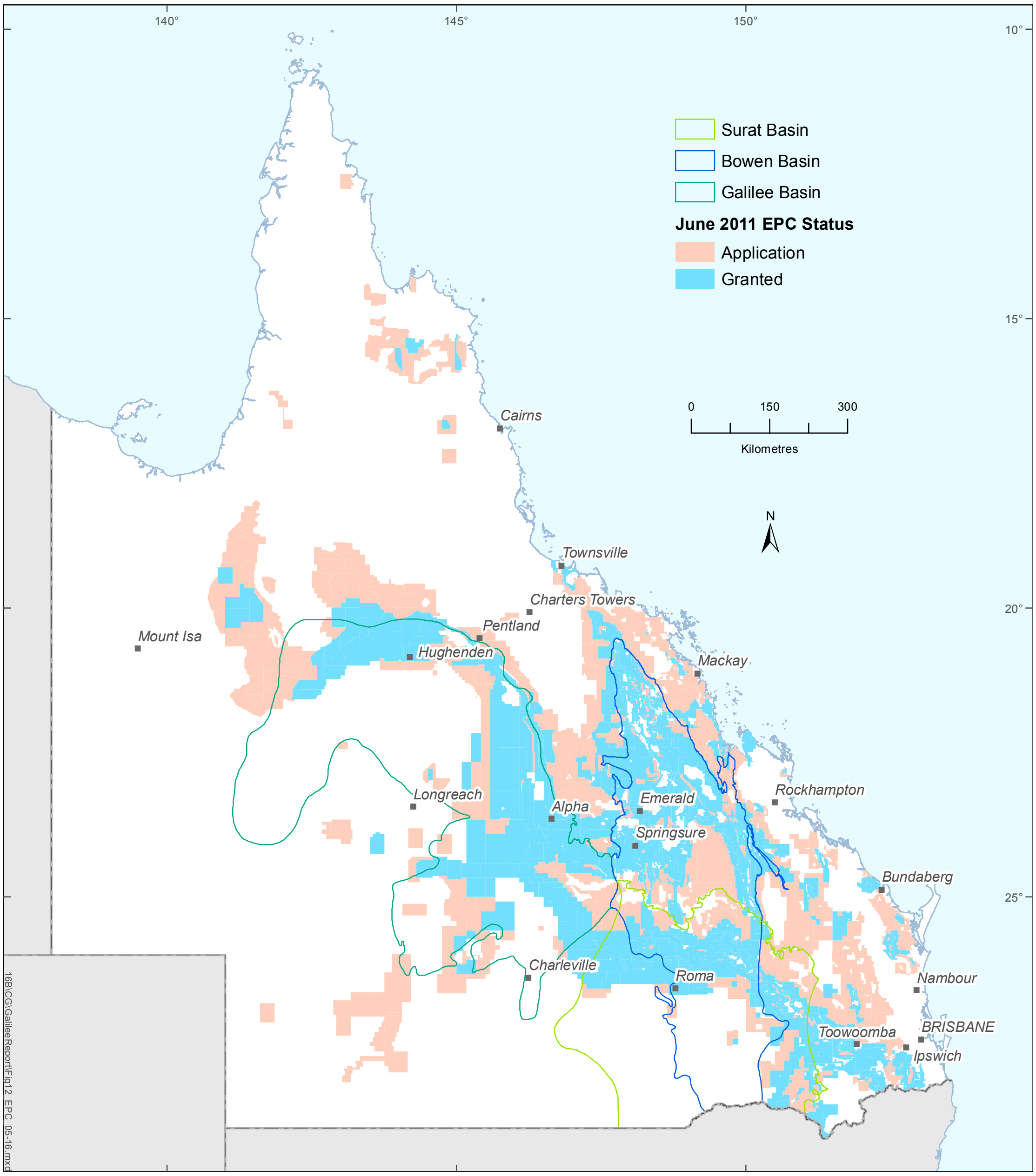


Figure 12b. Queensland EPC Coverage—as at June 2011.

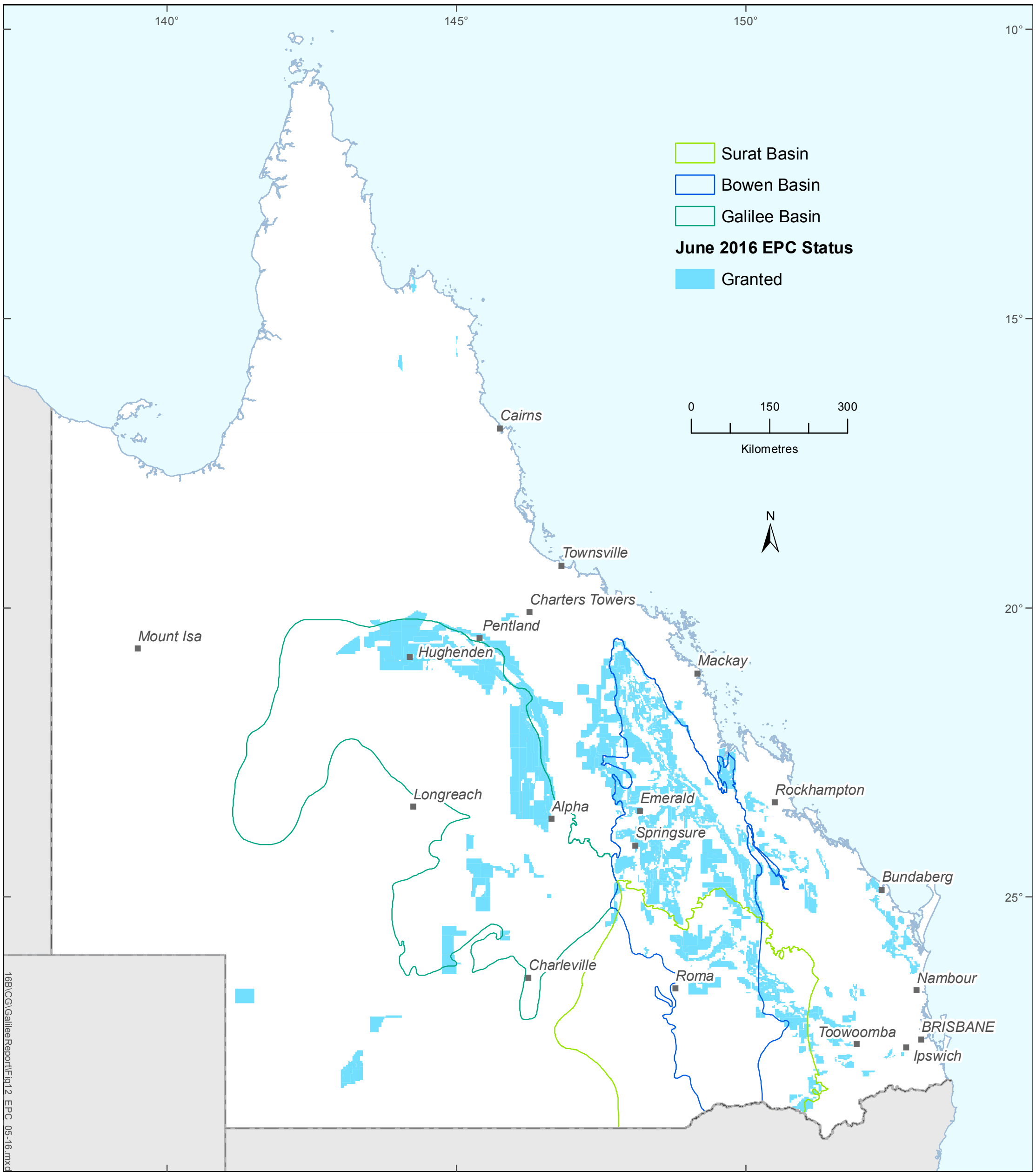


Figure 12c. Queensland EPC Coverage—as at June 2016.

Appendix 6a provides an overview of Queensland government controls over land available for coal exploration within the Bowen and Galilee basins between 1970 and January 2012, when RA 394 was gazetted, which effectively prohibited ‘over-the-counter’ lodgements of applications for coal-exploration permits in Queensland.

Since the implementation of this restriction, there has been no land in the Galilee Basin made available for coal exploration, with a considerable amount of the land previously held under coal exploration tenure at the time of gazettal, being either surrendered or relinquished (Figure 12c).

Company coal-exploration activity undertaken along the eastern flank of the northern Galilee Basin between 1969 and 2014 (as measured by the number of boreholes and approximate meterage drilled) is shown in Figure 13.

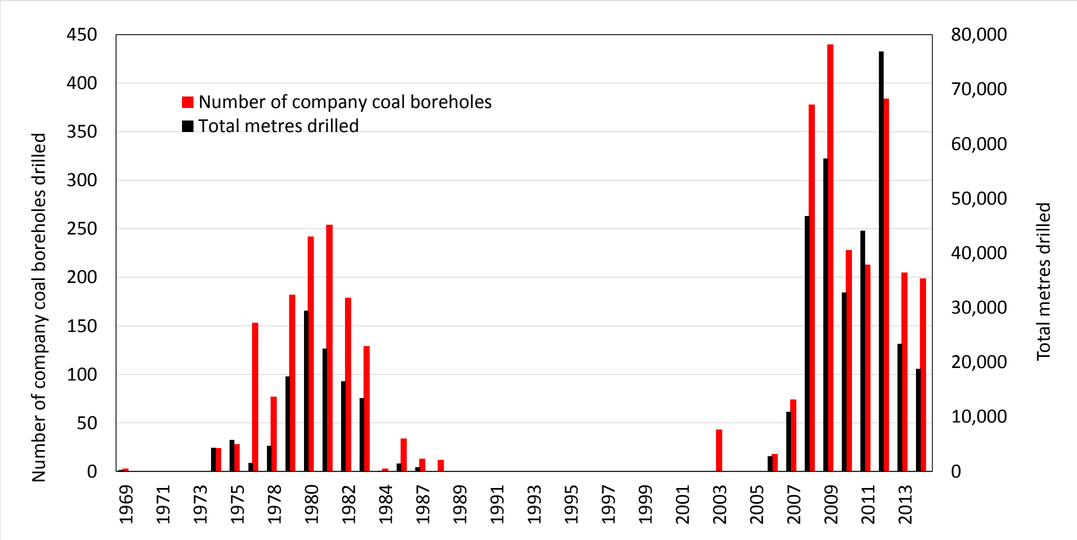


Figure 13. Company coal exploration drilling, eastern flank, northern Galilee Basin—1969 to 2014.

Oil shale exploration

During the Second World War, the GSQ undertook a drilling program at a site located about 50 km south-southeast of Alpha to investigate an occurrence of torbanite associated with Permian coal. Driven by the war-time need for domestic supplies of oil at that time, this involved drilling 15 bore holes between October 1942 and mid-1944. Connah (1964) later detailed the results of this exploration which previously, had only been presented in summary by Ball (1941, 1945). The area investigated is currently held under tenure by Alpha Resources Pty Ltd, as Mineral Development Licence (MDL) No 330 which is 55 km south-southeast of the township of Alpha.

During the early to mid-1980s, exploration was undertaken in the region around Alpha along the western margin of the Springsure Shelf and into the southern part of the eastern margin of the northern Galilee Basin by a number of companies attempting to locate oil shales similar to the coal-associated torbanite occurrence that had been drilled and reported on by the Department of Mines (Ball, 1941, 1945; Connah, 1964). These companies included BHP Minerals (AtP 3170M), International Mining Corporation (AtP 2204M), Pan Pacific and Otter Exploration (AtP 2265M), and Bridge Oil (AtP 2898M). For more detail, see Noon (1984, table 5 and pages 17–19).

While some further resolution of the previously identified torbanite resource at Alpha was achieved, falling oil prices and the remoteness of the resource from existing infrastructure and markets ensured that this interest was fairly short-lived, with most tenure dropped by the end of the 1980s.

Further details of the high-yielding torbanite and cannel coal from the Alpha oil shale deposit are provided by Madre (1987) and Hutton *et al.* (1996).

Petroleum and coal seam gas exploration

While initial petroleum-exploration drilling commenced in the Galilee Basin in 1922, significant petroleum exploration did not commence in the area until the 1960s. This was predominantly in response to the Commonwealth Government's Petroleum Search Subsidy Act (PSSA) when more than 55 wells were drilled between 1958 and 1974. Prior to that time, only about seven petroleum exploration wells had been drilled in the basin (Appendix 7). The first intersection of Permian strata in the northern Galilee Basin was in MPC Corfield 1, drilled in 1960 by Magellan Petroleum Corporation (MPC) (Hawkins *et al.*, unpublished; Figure 6).

The results of exploration efforts over the next decade and a half proved to be disappointing with no commercial oil or gas discoveries being made and with only minor shows of oil and/or gas recorded in two wells: ENL Lake Galilee 1 and FPN Koburra 1 (Evans, 1980; Randal, 1984; Hawkins *et al.*, unpublished).

The lack of any substantial discoveries resulted in a gradual decline in petroleum-exploration drilling in the Galilee Basin during the 1970s. The number of petroleum and gas exploration wells drilled increased slightly in the 1980s, following which there was a continual decline in exploration activity until around the year 2000, with a period of no activity at all between 2000 and mid-2007.

Since mid-2007, there have been more than 50 petroleum wells drilled in the basin, primarily to investigate the coal seam gas potential of the region. This compares with over 2100 boreholes drilled during the same period, along the basin's eastern flank, for the purposes of coal exploration.

Figure 14 shows drilling activity undertaken in the Galilee Basin by decade and category, exclusive of coal exploration undertaken by private enterprise.

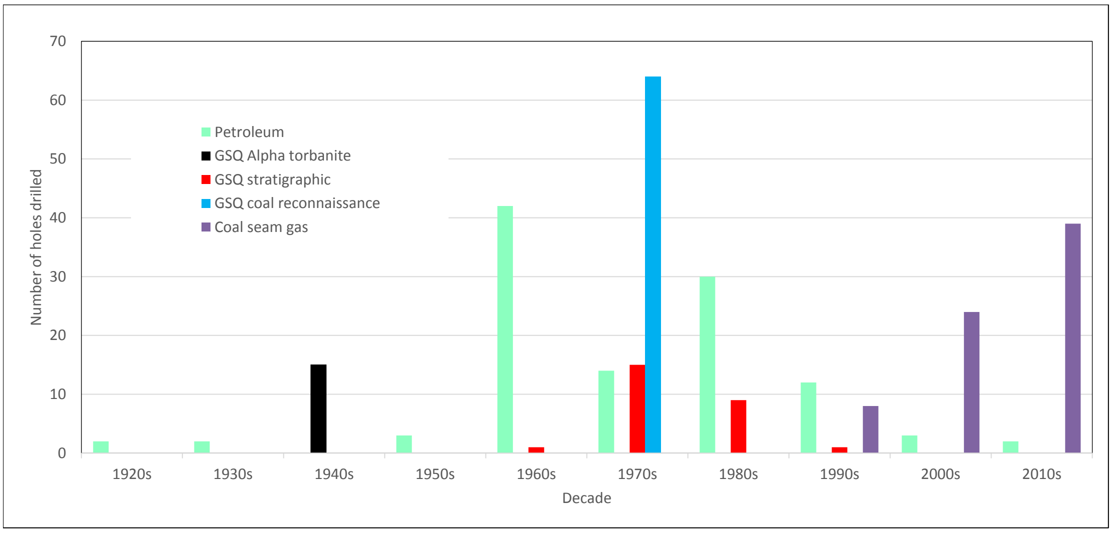


Figure 14. Drilling activity by decade.

Appendix 7 presents a tabulation of all of the conventional petroleum-exploration wells, more recent coal seam gas exploration wells, as well as the stratigraphic and coal reconnaissance boreholes drilled by the Geological Survey of Queensland in the Galilee Basin. Also included are the boreholes drilled by the Department of Mines during the 1940s over the torbanite occurrence near Alpha.

The tabulation excludes holes that are considered to have only intersected strata in the overlying Eromanga Basin, as well as all coal- and mineral-exploration boreholes drilled in the basin by private enterprise. Also excluded are the 'scout' boreholes drilled by BMR in the 1960s, to augment the surface mapping undertaken in the Galilee and overlying Eromanga basins. These BMR boreholes were drilled primarily to confirm near surface geology and not for exploration of any particular commodity.

Departmental stratigraphic drilling

In 1965, the GSQ commenced a series of regional stratigraphic drilling programs within the State to assist with the search for hydrocarbons in Queensland.

From late 1972, efforts were concentrated on stratigraphic drilling of the Upper Paleozoic strata of the western Bowen Basin and the eastern Galilee Basin (Allen, 1974). This work was initiated to help resolve problems being experienced by geologists working on the stratigraphy in these parts of the Bowen and Galilee basins. These issues arose from trying to apply stratigraphic-unit names that had been assigned to outcrop sections, to sequences being intersected in the sub-surface in exploration wells, and from extending Bowen Basin nomenclature across the Springsure Shelf in the Galilee Basin. Drilling undertaken as part of this program commenced in the south on the Springsure Shelf and gradually extended northwards along the eastern margin of the Galilee Basin into the area around Hughenden (Hawkins *et al.*, unpublished).

Over 18 years, a total of 26 boreholes (including redrills) were drilled at 23 sites by the GSQ within the Galilee Basin. Drilling commenced in November 1972 with GSQ Tambo 1-1A and ended with the drilling of GSQ Muttaburra 1 in July 1990. Of this total, 10 sites were drilled in the northern Galilee Basin commencing with GSQ Jericho 1 in September 1973 (Swarbrick, 1974). Further details on these boreholes are provided in Appendix 7.

Coal geology

Local geology—eastern margin

Towards the northern limit of the eastern flank of the northern Galilee Basin, the Betts Creek beds have been described by Vine *et al.* (1964) in what they nominated as the 'type locality' of the unit (Vine's Section X18). The site is located at the junction of two main branches of Betts Creek at about latitude 20°34'S and longitude 145°15'E. Vine *et al.* (1964) described the unit at this locality as comprising a lower part of conglomerate, typically overlain by an upper part of *Glossopterid*-bearing mudstone and sandstone. They noted also that the lower conglomerate beds were common, but provided no further details about the character of the conglomerate. Their general observations were that the lithology and thickness of the Betts Creek beds varied considerably (measured thickness ranging from about 150 feet (45 m) in 'Galah Gorge' (Vine *et al*., 1964, page 9) in the west to over 1200 feet (365 m) near Oxley Creek further to the east, noting that the coal and carbonaceous shale appeared to be restricted either to where the beds are thin or to the upper part of the unit where the beds are thick. Tuffs were recorded at two localities.

Elsewhere in the Hughenden district, another section is present in outcrop in Porcupine Creek (Galah) Gorge (Vine *et al.*, 1964; Section X16). A sequence-stratigraphic study by Allen & Fielding (2007a) of a section of the Betts Creek beds exposed in Porcupine Creek (Galah) Gorge, indicated that this outcrop features six condensed sequences which they maintained can be correlated throughout the Galilee Basin and across the Springsure Shelf into the Denison Trough (southwestern Bowen Basin). They submitted that these sequences comprise the section in the Denison Trough from the upper Aldebaran Sandstone to top of the Bandanna Formation.

Although the stratigraphy of the Denison Trough and the Springsure Shelf are comparable (Allen & Fielding, 2007a), Mollan *et al.* (1969), on the Springsure Shelf, applied the name Colinlea Sandstone to the predominantly fluvial section that is collectively equivalent to the Denison Trough section embracing the upper Aldebaran Sandstone, Freitag Formation, Ingelara Formation and the Catherine Sandstone. However, as the Colinlea Sandstone thins westerly across the Springsure Shelf, this unit was taken by Gray (1976) in GSQ Tambo 3, to be a correlative of only the Catherine Sandstone succession in the Denison Trough. The name 'Colinlea Formation' was introduced by geologists from Shell (Queensland) Development Pty Ltd in the 1950s (Hill, 1957).

Gray (1976) also correlated the Peawaddy Formation, Black Alley Shale and Bandanna Formation across the Springsure Shelf and extended these units as far as the Jericho area along with the underlying Colinlea Sandstone. North of Jericho, this subdivision was not recognised, and only the Colinlea Sandstone correlative and the Bandanna Formation correlative were identified in drill holes along the eastern margin of the Galilee Basin (Gray & Swarbrick, 1975; Gray, 1976).

An equivalent of the Peawaddy Formation, represented by a bioturbated paralic facies, was subsequently identified in drill holes north of Jericho (Scott & Hawkins, 1992; Hawkins & Green, 1993), extending the marine influence of the unit further northwards. Scott & Hawkins recognised the extent of the Black Alley Shale to about 23.5°S, and the Peawaddy Formation further north to about 22°S, from which points these units were considered to pinch out. However, Allen & Fielding (2007b) submitted that the marine influence that resulted in the deposition of the Peawaddy Formation reached the northeastern-most, present-day margin of the Galilee Basin, where they identified it in the outcrop of the Betts Creek beds.

Thus, the view that the Betts Creek beds are a lateral equivalent of both the Colinlea Sandstone and the Bandanna Formation (e.g., Scott *et al.*, 1995) cannot be fully maintained, as equivalents of the Peawaddy Formation and Black Alley Shale are overlooked in this interpretation. The same applies to correlation of the 'Bandanna Formation equivalent' to "*include sequences with both Bandanna*

Formation (sensu stricto) as well as correlatives of the Colinlea Sandstone" as proposed by Wells (1989, page 134).

While correlation of the Colinlea Sandstone with the lower Betts Creek beds has some validity, correlation of the upper Betts Creek beds with the Bandanna Formation is much less certain, due to the uncertainty caused by the inability to recognise an equivalent of the Black Alley Shale.

In Galilee NS2 drilled on Wendouree Station, in the southern part of the Koburra Trough, Carr (1973a) did not recognise strata possibly correlative with either the Peawaddy Formation or the Black Alley Shale. In this borehole, Carr tentatively placed the boundary between what he regarded as the Colinlea Sandstone and the overlying Bandanna Formation "*at the apparently disconformable base a prominent conglomerate bed*" (page 4). All five of the coal seams intersected in this borehole, were placed in what was interpreted as the Bandanna Formation. Micas were noted as occurring throughout the formation and the sandstones therein were described as being quartzose and very porous towards in the lower part of the formation and sub-labile to labile in the upper part.

A number of reports by Carr (1973b, 1974a,b, 1976) and geological logs of core compiled during the departmental drilling program also make reference to the 'light fawn to fawn' colouration of the mudstones associated with the intersected coal seams, which may suggest a possibly tuffaceous nature of some of these strata. At Moray Downs for example, Carr (1974b) notes that "*Light fawn, fawn and brown mudstone are associated with the coal seams, and are most common in the C Seam*" (page 4).

In the Bowen Basin, the presence of interbedded tuffs, used in conjunction with simple lithostratigraphic correlation and more recently, attendant isotopic dating, has significantly assisted establishment of the current stratigraphic framework and subdivision of coal-facies groups; this has been well documented (Koppe, 1978; Staines & Koppe, 1980; Mallett *et al*., 1995; Draper, 2013; Ayaz, 2016). In the northeastern Galilee Basin, however, it has only been recently that correlation and U-Pb CA-IDTIMS (Chemical Abrasion – Isotope Dilution Thermal Mass Spectrometry) dating of tuffs has led to a more definitive lithostratigraphic subdivision of the Lopingian (late Permian) section there and correlation with tuffs in the Bowen Basin (Phillips, 2016b, 2017, in review).

Coal seam development

Mollan *et al.*'s (1969, pages 32–33, figure 8) description of the type section of the Colinlea Sandstone in the northern part of the Springsure 1:250 000 Sheet area, east of the Nogoa Anticline, made no mention of coal. The formation was described as comprising "*fine to medium-grained quartz sandstone and granule-pebble-cobble conglomerate, grading to pebbly sandstone*".

Anderson (1974, 1976) reported on reconnaissance coal-exploration drilling undertaken by the Department of Mines on the Springsure Shelf in the latter part of 1973 (Buckland NS and Claude NS series boreholes). He noted that while insufficient drilling had been undertaken across the Springsure Shelf at that stage to evaluate the coal potential of the Colinlea Sandstone in the region, only thin coal seams had been intersected in boreholes drilled through the unit. Anderson (1974) also noted, however, that these boreholes either did not reach the top of the Colinlea Sandstone or were drilled only into the very top of the unit. Further to the west in the Galilee Basin, what were regarded as correlatives of the Colinlea Sandstone were interpreted as containing "*good quality coal seams*" (page 3) near the top.

The basin-wide review by Hawkins (1976), based predominantly on petroleum exploration wells and GSQ stratigraphic boreholes drilled at that time, and the later review by Scott & Hawkins (1992), both showed that the greatest thickness of coal development in the Lopingian (late Permian) sequence was along the central part of the eastern flank of the northern Galilee Basin, in the vicinity of ENL Lake Galilee 1. This well is located down-dip of the Moray Downs area drilled by the Department (Figure 6, Figure 10).

In GSQ Jericho 1 (Figure 6), Swarbrick (1974) reported two seams of coal (1.63 m at 224 m, 1.69 m at 243 m) in what he interpreted as the Colinlea Sandstone. Thin intervening units between the top of this formation and the base of the Bandanna Formation were recognised as correlatives of the Black Alley Shale (~20 m thick at 172 m) and the Peawaddy Formation (~24 m thick at 192 m).

In reporting on the departmental drilling at Lambton Meadows, Carr (1974c), used the stratigraphy interpreted by Swarbrick (1974) in GSQ Jericho 1 and also tentatively assigned some of the lowermost coal seams intersected in Galilee NS 13 and NS 15R, to what he regarded as the Colinlea Sandstone—present in these two boreholes as a sandstone-dominated unit below the Bandanna Formation. In contrast however, at the commencement of the departmental coal drilling program, the stratigraphic interpretation in two of the boreholes drilled further north on Wendouree Station (Galilee NS 1 and NS 2), had Bandanna Formation strata directly overlying the Colinlea Sandstone, with all of the coal seams intersected in both boreholes assigned to the Bandanna Formation (Carr,1973a).

It is widely regarded that there is a continuous development of coal seams in the Lopingian (late Permian) succession (Colinlea Sandstone to Bandanna / Betts Creek beds succession) along the eastern margin of the northern Galilee Basin, both along strike and down-dip, (Scott & Hawkins, 1992, figure 8; Scott *et al.*, 1995, figure 20; Allen & Fielding, 2007a), although the relative proportion of coal is variable.

There is, however, relatively poor development of the coal facies south of the Barcaldine Ridge (Scott *et al.*, 1995, pages 349–350) and in the southern part of the northern Galilee, where coal in the Colinlea Sandstone is either present in very small proportions or is largely non-existent.

Coal development in the Bandanna Formation is also variable, with the proportion of coal being substantially less in the south near the western edge of the Springsure Shelf, than in the central part of the basin's eastern flank near Moray Downs, where the net coal is greatest in both this unit and the underlying Colinlea Sandstone (Scott *et al.*, 1995; Figure 10). The Bandanna Formation was named in the early 1950s, by geologists working for Shell, after Bandanna Homestead in the Arcadia Valley, south of Rolleston. The 'type area' is on the Springsure Shelf at "*the headwater of Rewan Home Creek, 3 miles south of Rewan Station*" Hill (1957, page 11).

The most recent coal exploration undertaken along the eastern margin of the northern Galilee Basin has also helped to provide more detail regarding the basin margins where the late Permian coal-bearing strata on-lap the rocks of the Famennian – Visean/Middle Mississippian (latest Devonian – early Carboniferous) Drummond Basin to the east.

The report by Saul *et al.* (2015), for example, on the results of recent coal exploration undertaken in the Hyde Park project area (EPCs 1754, 2050 and 2166) due east of Lake Buchanan, has shown that the eastern margin of the northern Galilee Basin is still relatively poorly defined in places. The associated drilling in the region east of the areas investigated by the GSQ as Mirtna (Galilee NS 22, NS 23, and NS 24) and View Hill (Galilee NS 25 to NS 29 inclusive), intersected the full sequence of late Permian coal seams, beyond what had previously been considered as the eastern subcrop limit (see section "Structure" on page 44 and Figure 15 for further detail). Their interpretation of the stratigraphy at this site embraced the Betts Creek beds overlying the Colinlea Sandstone, the boundary being placed at the base of the coal interval they have interpreted as the "D2 Seam". This assessment seemed to be based upon the composition and grain size of the sandstones present in each unit. Saul *et al*. (2015, page 240) described the sandstones in the Betts Creek beds as coarsening and becoming "*increasingly quartzose towards the base of the sequence*". The Colinlea Sandstone was identified on the basis of composition (described as quartz to quartz lithic), an increase in grain size (to medium-grained) and the presence of what they described as "*sporadic micaceous intervals, with common fine to medium quartz to quartz lithic conglomerates*" (page 240).

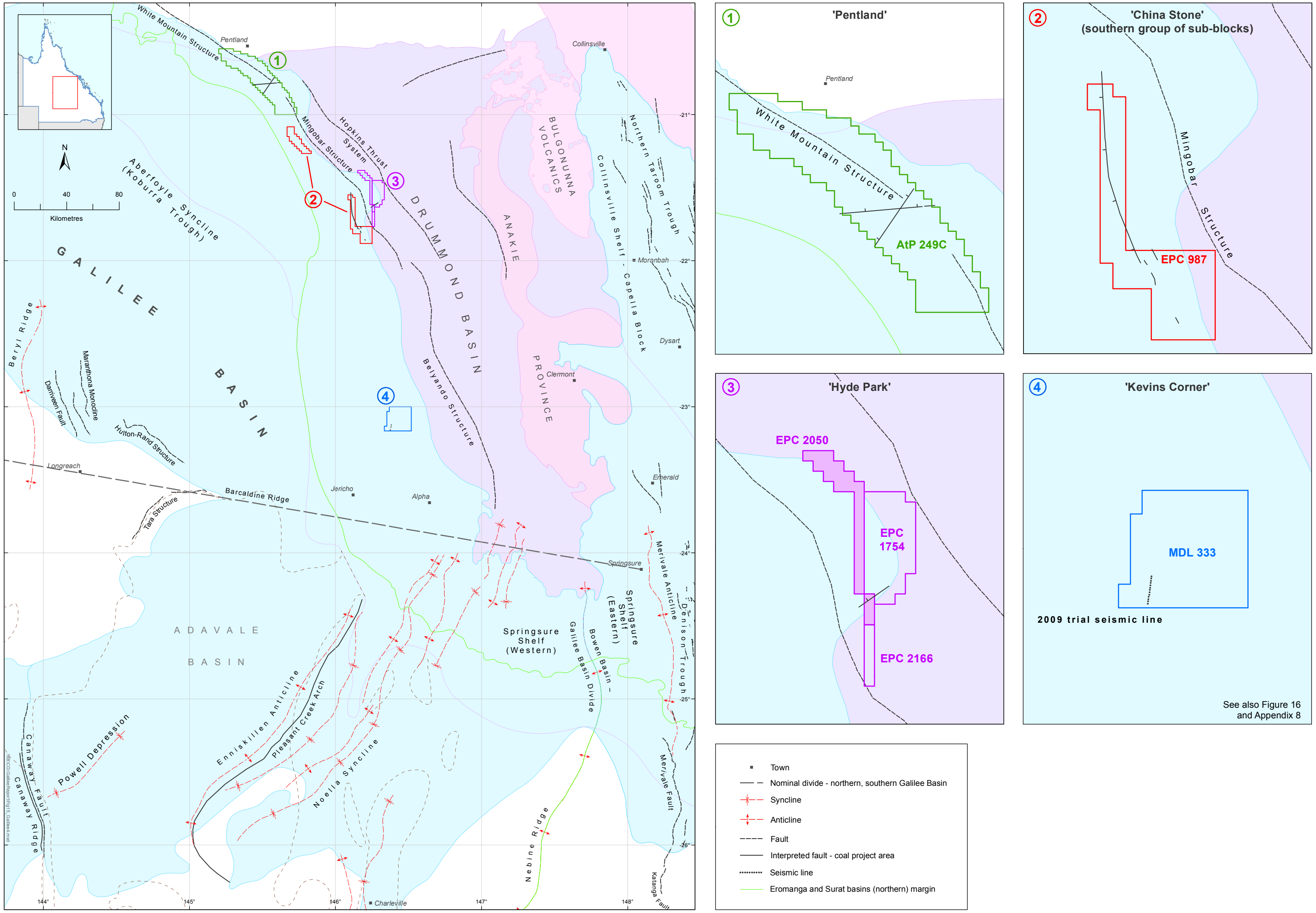


Figure 15. Local structure—eastern margin. (This page may be printed at A3 for clarity.)

Coal seam nomenclature and correlations

At the conclusion of the departmental coal reconnaissance drilling program, six main coal intervals had been recognised and tentatively correlated in places. These were designated, in descending stratigraphic order, as the A, B, C, D, E and F seams (Carr, 1973a,b, 1974a,b,c, 1976, 1977, 1978; Matheson, 1987a).

Scott & Hawkins (1992), based upon their examination of down-hole geophysical logs of both coal-exploration boreholes and petroleum-exploration wells, considered that the coal seams present along the eastern flank of the basin were "*sufficiently uniform*" (page 89) to enable broad correlations to be made further down-dip with coal seams intersected in the deeper parts of the Koburra Trough.

Figure 10 presents a longitudinal section depicting the generalised coal-seam architecture in the Lopingian (late Permian) Colinlea Sandstone – Bandanna Formation/Betts Creek beds succession along the eastern flank of the northern part of the basin based on the departmental coal-reconnaissance drilling.

Shell Development (1976) reported on the coal exploration undertaken within the Degulla area under AtP 137C. Geologists working for the compnay adopted a modified alpha numeric version of the coal-seam nomenclature used by Carr and described the coal seams and seam groups encountered (in descending stratigraphic order) as:

- a largely-coalesced A and B seam (subdivided into the A1, A2, B1 and B2 seams)
- a banded, high-ash, C seam
- a relatively thin but '*clean*' D seam (page 10 - subdivided into the D1 and D2 seams)
- a thin E seam, considered to be of "*little economic significance, but rich in vitrinite and exinite*" (page 12); it was subdivided into three intervals as the E1, E2 and E3 seams.

Ongoing coal exploration in the early 1980s over the Wendouree area by Hancock Prospecting Pty Ltd and Wright Prospecting Pty Ltd in AtP 244C (Salomon, 1983; Broughton, 1987) and by Bridge Oil Limited in the adjoining AtP 245C (Bridge Oil Limited, 1982) continued to adopt the seam nomenclature that had been used by Carr.

The application of Carr's seam-nomenclature has been continued by companies in more recent coal exploration in the northern Galilee Basin at times, with specific modifications to account for localised (project area) coalescence, splitting, or deterioration of particular coal seams.

In the South Galilee Project area (EPC 1049), of the seams intersected, it is only what was correlated as a split D Seam (D1 and D2 Seams) that is considered to be of commercial interest at the present time (Echelon Mining Services, 2012).

Further to the north, in the area currently covered by the Alpha Coal Project (MDL 285 and MDL 333), Hancock Prospecting Pty Ltd (2010i,k,m) considered that only the C and D Seams (subdivided into upper (DU), middle (DLM) and lower (DLL) sections) were economically recoverable at the time of preparing the project EIS. The B Seam, which was not considered viable for mining, was subdivided into three plies (B1,B2 and B3).

In the late 1970s in the region around Pentland in AtP 249C near the Betts Creek beds type locality, Shell opted for a different seam-nomenclature system to that used further south by Carr. The company's coal exploration in this region focussed on two areas, Elimeek and Lauderdale in the north (which are separated by the Flinders Highway) comprising the Pentland group of deposits, and Milray in the south.

Basing correlations of 'coal/shale packages' in AtP 249C on a considerable amount of drilling and extensive use of downhole geophysical logging, the company's geologists (Codd, 1982; Murphy

1984a,b) established a four-fold subdivision of the Betts Creek beds in the area explored. These comprised (Murphy, 1984a):

- the Betts Creek Upper section, containing up to two discontinuous ('sporadic') coal seams
- the Pentland Upper section, generally described as consisting of "*carbonaceous claystone interbedded with inferior coal*" with up to nine coal and/or coaly lithostratigraphic intervals of varying coal/shale proportions (page 8 and figure 3)
- the Pentland Lower section, comprising arenaceous sediments and 'cleaner coal' with up to eight coal and/or coaly lithostratigraphic intervals of varying coal/shale proportions
- the Betts Creek Lower section, described as "*predominantly arenaceous sediments without coal seams developed*" (page 4).

Matheson (1987b) reported on the drilling undertaken in the mid-1970s by the GSQ under the supervision of Carr in the region around Pentland. Only tentative correlations were made between boreholes, without assigning names to seams or attempting to correlate them with those intersected in the other areas drilled further south and reported by Carr some years prior.

The reviews by Wells (1989), Scott & Hawkins (1992) and Scott *et al.* (1995) of the coal present in the Galilee Basin all use the coal-seam nomenclature adopted by Carr as the basis for their respective discussions.

Scott & Hawkins (1992) also commented (page 89) that, while they could find no identifiable wireline-log marker in either the Bandanna Formation or the Colinlea Sandstone, the 'C Seam', placed by them at the top of the Colinlea Sandstone, offered some assistance as a "*marker horizon*". This was due to a very distinctive wireline-log response, reflecting a banded top portion and cleaner basal section in that seam. This comment aligns closely with the observation of subsequent workers (Phillips *et al.*, 2015, 2017; Saul *et al.*, 2015) who have described the association of a tuff bed with this coal seam interval.

Recent coal-seam correlations proposed by Phillips *et al.* (2015, 2017) within the Lopingian (late Permian) Colinlea Sandstone – Bandanna Formation/Betts Creek beds succession in the northern Galilee Basin, have been based on downhole geophysics gathered from open-file exploration reports supplemented by the examination of core taken from boreholes drilled in the region. The coal seam nomenclature scheme used broadly follows that proposed by Carr (1973a,b, 1974a,b,c, 1976, 1977, 1978). Their correlations placed what they regarded as the C Seam at the top of the unit correlated as the Colinlea Sandstone.

Further studies by Phillips *et al*. (2016b, in review) have since proposed a revised stratigraphic framework of these coal-bearing strata, supported by CA-IDTMS dating of zircons derived from interbedded tuff. A numerical age of 252.81 ± 0.07 Ma, similar to that reported for the Yarrabee Tuff in the Bowen Basin (Ayaz, 2016), was obtained by them for a tuff sampled from what they correlated as the 'B Seam'. Additionally, an age range of 254.32 ± 0.10 to 255.13 ± 0.9 Ma was determined for tuff samples taken from a coal seam that they correlated as the 'C Seam'. This age range embraces dates that are similar to those obtained from tuff samples from the Fair Hill Formation in the Bowen Basin (Ayaz, 2016; Phillips, 2016b, in review).

Coal-seam correlations by Saul *et al.* (2015) in the Hyde Park project area (EPCs 1754, 2050, 2166) (Figure 15) recognised a group of six coal seams (A to F), all of which split and coalesce to varying degrees. They also made reference to the G Seam, which "*occurs rarely*" (page 243) below the F Seam in the eastern parts of the project area.

As mentioned in section "Coal seam development" on page 39, Saul *et al.* (2015) opted to place the top of the unit they regarded as the Colinlea Sandstone at the floor of what they referred to as the D2 Seam. They placed the D2 Seam, upper splits of the D Seam, together with the stratigraphically higher C, B, A and AU seams, in the overlying Betts Creek Beds. The C Seam is described as having a sharp basal contact with a thin (20 to 35 cm) tuffaceous unit they referred to as the "CD Tuff" (Saul *et al*., 2015, page 240). In the project area, they regarded the AU Seam as the upper boundary of the Betts Creek beds. The underlying Colinlea Sandstone also contains the E and F Seams and, in places, the G Seam.

Structure

Although regional mapping has been an important contributing factor to developing the current structural and stratigraphic framework of the northern Galilee Basin (Figure 4a,b), much of the current understanding of the structural framework of the basin has been derived from interpretations based on seismic surveys and drilling that have been undertaken for petroleum and gas exploration (Figure 6 to Figure 9).

Having primarily targeted the deeper parts of the basin, this exploration provided very little detail about the eastern margin of the basin where the Lopingian (late Permian) coals rise to subcrop. The stratigraphic and coal-exploration drilling undertaken by the GSQ in the 1970s also offers little insight into the structural fabric of the coal seams present along the eastern margin of the northern Galilee, given the regional scale and focus of these programs.

Virtually all of the structural features represented in Figure 4a,b are only present in the sub-surface, having been mostly interpreted from a combination of borehole and seismic data. There are, however, some exceptions which have been recorded by field mapping in the region.

One such feature is the White Mountains Structure at the far northern edge of the basin (Figure 4a,b). This has been mapped at surface and is shown on the White Mountains 1:100 000 Geological Series map (Withnall *et al*., 1998). Olgers (1970) described this feature as one "s*eparating Permian and Triassic sediments from crystalline basement rocks*" (page 13). Another feature, along the northeastern margin of the basin, on the Buchanan 1:250 000 Geological Map Sheet, is the Mingobar 'Monocline' (also referred to as the Mingobar Structure; Figure 4a,b). Olgers (1970) considered the Mingobar Structure to be a surface manifestation of the Belyando 'Feature' (Structure) further to the south—a feature that he described as being the largest structure in the basin, which in the Buchanan Sheet area, he regarded as probably being represented by "*a large basement fault detected in the south by seismic*" (page 13), making reference to an unpublished report by Austral Geo Prospectors Pty Ltd (1962) for a seismic survey conducted within AtP 76P.

Pinchin (1978), who reported on four seismic-reflection surveys undertaken by the BMR in 1976 across, and close to, the eastern margin of the northern Galilee Basin, noted that the results for his Traverse 1 indicated a steep and faulted basin margin to the northeast of Hughenden, adjacent to meta-sedimentary rocks and granite of the Lolworth-Ravenswood Block. However, about 30 km further south along Traverse 2, he noted the strata were undisturbed and displayed with very shallow dips (estimated at about 0.5°) to the south.

In a review of seismic data in the northeastern Galilee Basin, Nelson (1981) noted that the late Permian 'P' Horizon, showed only minor structural relief with little evidence of faulting. The 'P' Horizon is a well-known seismic reflector and has been identified as being at the top of the (Lopingian) late Permian coal measures.

More recent work by van Heeswijck (2010), adding to his earlier analysis of seismic data in the region (van Heeswijck, 2004), described newly-interpreted structural and depositional features in the northern Galilee Basin, using seismic facies analysis undertaken on approximately 750 line kilometres of seismic surveys.

The field mapping by Reid (1918) showed, at Oxley Creek, a faulted contact of the strata associated with the "*Coal Measures*" with the underlying mica schists of the Cape River beds ("*Cape River*

Series"), although away from this contact, he noted that the dips flatten to the south where these strata "*lie quite flat before assuming a gentle dip again which carries them under the White Mountains sandstone cliffs*" (page 6). Reid (1948) later reported on reconnaissance field mapping he undertook for Mount Isa Mines Limited in the region to the west and south of Pentland. He regarded the geological structure in the area as "*simple*" and considered that "*there are not likely to be other than minor fault displacements*" (page 4). However, he noted that the dips of the strata measured at Milray, to the southeast of Pentland, were in the range from 10 to 15 degrees.

Initial observations by Carr were that regional dips of the Lopingian (late Permian) strata were "*very low*" and that "*major structural problems should pose no difficulties*". (Carr, 1973a, page 9; 1974c, page 9). Bedding-plane dips measured in core taken during the course of the departmental drilling program largely supported this observation, although steep dips and evidence of faulting were recorded in a few boreholes [e.g., >40° commencing at ~90m depth to bottom of hole in Galilee NS 39 at Pentland (Matheson, 1987b); ~20° at 330m depth in Galilee NS 54 at Moray Downs (Matheson, 1987a)].

Codd (1982), in his report on coal exploration undertaken by Shell in the region around Pentland, remarked that the Permo-Triassic strata in AtP249C were both very shallow and dipping at around 2 to 3° to the south-southwest. Local variations were noted, from being "*flat lying*" to around 6°. Codd also indicated that the coal measures dipped at a very shallow angle (< 2° to the southwest) at Milray in the southern part of the tenure.

It is significant to remark here that, of the open-file company reports reviewed for the current report, very few make mention of any significant geological structures having either been directly encountered by, or interpreted from, drilling activities or seismic surveys undertaken.

Taken collectively, this information supports the widely-held view that the Lopingian (late Permian) coals on the eastern margin of the northern Galilee Basin are largely shallow dipping and relatively undisturbed structurally. However, there have been a few significant structures that have been interpreted from coal exploration drilling undertaken in the region. Shell geologists, for example, inferred the existence of an ENE–WSW fault structure with an estimated throw of about 300 m, separating the Pentland group of deposits in the north of the AtP 249C, from the Milray area further to the south. At the time, this structure was interpreted as bounding the Milray deposit to the northwest (Figure 15, Inset 1), with a second, inferred east–west-trending fault structure, thought to intersect the boundary fault (Codd, 1982).

More recently, Hancock Galilee Pty Ltd (2011h) made reference to a trial 2D-seismic line that was run across part of the Kevins Corner project area (MDL 333) in late 2009. This survey of approximately 4.5 km in length was orientated roughly north–south (Figure 15, Figure 16; see Appendix 8 for a higher-resolution image of this seismic profile) and indicated the existence of a number of somewhat widely-spaced faults (~2 to 3 km spacing), with estimated vertical displacements interpreted as being "*up to 3 times the seam height*" (Hancock, 2011h; Figure 16, Appendix 8).

Interpreted results of a 2D seismic survey subsequently conducted over the adjoining Alpha deposit in the latter part of 2011 indicated a similar structural style, in that there was no large/regional scale

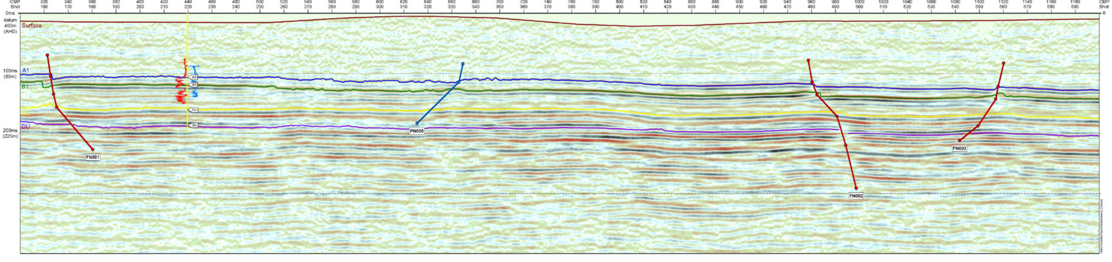


Figure 16. Trial seismic survey (S–N, looking W, southwestern Kevins Corner deposit).
Note: blue = possible fault; red = probable fault; F = probable fault; P = possible fault; N = normal fault; A1, B1, CU, DU = coal seams.

faulting evident, although there was clear evidence of numerous and widespread small-scaled high-angle normal and reverse faults. These faults were interpreted to have vertical displacements between 4 and 10 m, but generally on the lower end of this range. However, correlation of individual faults between seismic lines proved to be difficult, making interpretations of fault orientations problematic (personal communication, A. Restell, Hancock Coal Pty Ltd).

Further north, to the east of Lake Buchanan, a significant fault with an estimated vertical displacement of up to 100 m has been interpreted in the northern part of the China Stone project area (EPC 987). A north-northwest/south-southeast trend, and a normal sense of displacement (downthrown to the east) was inferred, with vertical displacements diminishing significantly at the extremities of the structure (Gordon Geotechniques Pty Ltd, 2014). Its orientation appears to roughly align with that of the Mingobar Structure.

Aramac Coal Measures

The Galilee Basin also hosts the Cisuralian (early Permian) Aramac Coal Measures, which are considered by some to be approximately of the same depositional age as the Reids Dome beds in the Bowen Basin (Wells, 1989; Brakel, 1989; Figure 3).

Scott & Hawkins (1992) indicated that this coal-bearing sequence can only be distinguished from the late Permian coal measures of the basin using palynology and has been subdivided into a lower interval where only minor dull coal seams are developed and an upper interval where coal seam development is more prominent.

Samples taken from petroleum-exploration wells indicate a high volatile bituminous rank for these coals, with mean maximum vitrinite reflectance values ranging from ~0.6% to 0.8%, with values of up to 1.1% being recorded at about 1700 m depth (Smith, 2013). This sequence occurs over a comparatively small area within the central northern part of the basin, being restricted to part of the western Koburra Trough and a portion of the southern Lovelle Depression (Scott *et al.*, 1995).

There appears to be very little potential for mining of these coals because of the considerable depth at which the seams occur (Scott *et al.*, 1995; Smith, 2013).

Coal quality

Coal rank, classification and potential utilisation

Davis (1972) made initial attempts to classify the coals of the Galilee Basin based on vitrinite reflectance values of coal cuttings from company and departmental boreholes. He described the majority of coals as having reflectance values "*below the lower limit of coking coal range, falling mainly in the sub-bituminous and high volatile ranges*" (page 242).

Beeston (1977) subsequently reported on the petrography of coal seams intersected in departmental stratigraphic and coal-reconnaissance boreholes drilled by the GSQ. These intersections were obtained from five sites drilled over a strike length of about 350 km in the Koburra Trough. Based on vitrinite-reflectance values, Beeston (*op.cit.*) classified these coals as sub-bituminous (ASTM classification system) using the relationships established by McCartney & Teichmuller (1972).

Smith (2013) noted the mean maximum vitrinite reflectance (Rv, max) of these coals as generally ranging between 0.4% and 0.6%, which is significantly lower than the coking window (Figure 17). Mean maximum reflectance values increase at depth westward to about 0.7% in the western Koburra Trough and Lovelle Depression (Hawkins *et al.*, unpublished).

Durie *et al.* (1992) have broadly described the characteristics of the Lopingian (late Permian) coal seams present along the eastern flank of the northern Galilee Basin as ranging from being thin and bright in the south to thin and dull in the north. They generally characterised the coals as having a low vitrinite content (decreasing from south to north) and a high inertinite content.

The Queensland Coal Board (1978) described the coals as high volatile, weakly caking and classified them as meta-lignitious and sub-hydrous using Seyler's (1933) classification system.

Table 2 presents the first comprehensive analysis of 'Galilee Basin' coal reported by the Queensland Coal Board (1978, table 2a: "Typical Physical and Chemical Properties of Queensland Coals") although the source of the data and the nature of the sample(s) are unknown.

Dampier Mining and Shell in joint venture with Western Mining Corporation examined the liquefaction potential of these coals during the mid- to late-1970s, as part of coal-exploration activities undertaken in AtPs 136C and 137C, respectively.

Test results on the conversion potential of the Galilee Basin coals were reported in Keith & Smith (1976) and Keith (1976). Keith (1976) concluded that, the coals tested were not particularly well suited for many of the known conversion processes, as a significant proportion of the raw coal (determined at around 40%, presumably by mass), comprised components that would "… *contribute nothing towards the production of hydrocarbons*" (page 2). Furthermore, he considered that a considerable portion of the remaining carbonaceous matter to be "*fusinitic in character, which reduces activity in some conversion processes*" (pages 2–3).

Keith also considered that the coal was "*probably best suited to gasification to either high or low Btu (calorific value) gas or synthesis gas from which methanol or Fischer Tropsch products could be made*" (page 4).

Beeston (1977) also considered that the sub-hydrous nature and moderate to low reactive component of the coals made them "*an unattractive proposition for liquid product conversion*" (page 265) using the techniques that were available at that time.

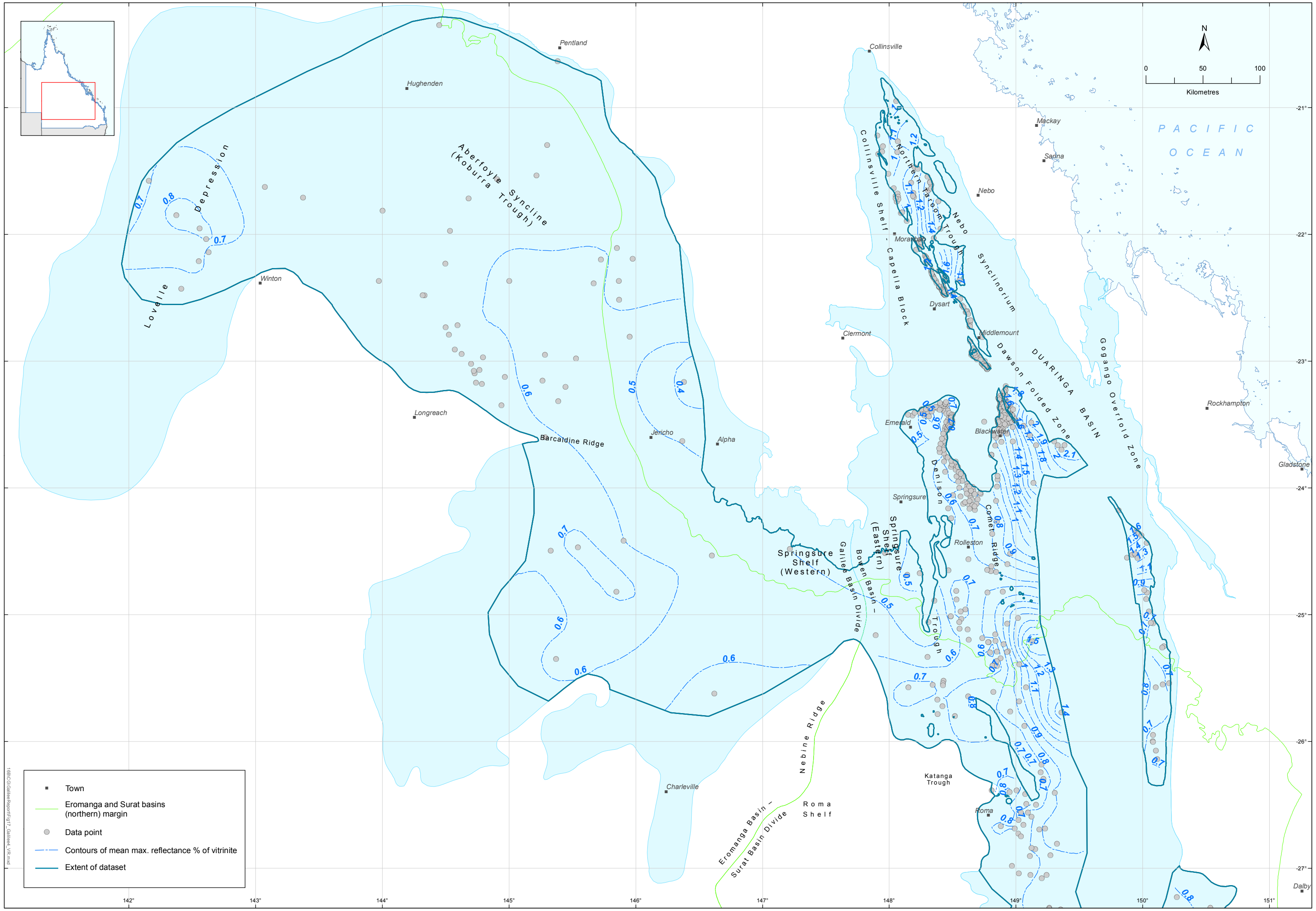


Figure 17. Spatial distribution of vitrinite reflectance of Group V coals based on departmental data (after McKillop, 2016). (This page may be printed at A3 for clarity.)

Table 2. Typical physical and chemical properties, Galilee Basin (Queensland Coal Board, 1978).

PROXIMATE ANALYSIS (% adb)		
Inherent Moisture		14.1
Volatile Matter		28.7
Fixed Carbon		37.9
Ash (average or 'as to be sold')		19.3
TOTAL		**100.0**
VOLATILE MATTER		
% dry ash-free		43.1
% dry mineral-free		41.4
ULTIMATE ANALYSIS (% daf)		
Carbon		76.6
Hydrogen		4.2
Nitrogen		1.5
Sulphur		0.6
Oxygen		17.1
TOTAL		**100.0**
(% dmf)		
Carbon		80.3
Hydrogen		4.1
Nitrogen		1.5
Oxygen		14.1
TOTAL		**100.0**
SPECIFIC ENERGY (Gross Mj/kg)		
Air-dried basis	(adb)	20.94
Dry basis	(db)	24.38
Dry ash-free basis	(daf)	31.44
Dry mineral-free basis	(dmf)	32.38
Crucible ('Coke') Swelling Number		0-1½
SULPHUR (% adb)		
Pyritic		0.03
Sulphate		0.01
Organic		0.46
TOTAL		**0.50**

ASH FUSION TEMPERATURES (°C) (Semi-reducing atmosphere)	
Deformation	1290
Hemisphere	1360
Flow	1390
ANALYSIS OF ASH (%)	
SiO_2	61.5
Al_2O_3	25.1
Fe_2O_3	6.5
TiO_2	0.5
Mn_3O_4	0.1
CaO	1.9
MgO	0.6
Na_2O	0.5
K_2O	0.5
P_2O_5	0.2
SO_3	0.7
Loss on ignition or undetermined	1.9
TOTAL	**100.0**
GRAY-KING CARBONISATION ASSAY AT 600 °C	
Yield per tonne of dry coal (Ash as above)	
Coke (kg)	734.8
Tar and Oils (litres)	76.9
Liquor (litres)	89.7
Gas (m^3)	118.3
% yield by weight	
Coke	73.5
Tar and Oils	7.7
Liquor	9.0
Gas	9.8
TOTAL	**100.0**
FISCHER ASSAY	
Coke %	80.8
Tar %	5.7
Water %	6.1
Gas %	7.4
TOTAL	**100.0**

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Departmental Coal-Reconnaissance Drilling

Overview of coal analyses data set

Over the course of the coal-reconnaissance drilling program undertaken by the Department of Mines between July 1971 and June 1978, about 460 coal samples from more than 190 discrete coal intervals intersected were taken and sent for analysis. The samples were taken from coals intersected in 41 of the 60 sites drilled during the program (Figure 18, Appendix 9, Appendix 10). In the majority of the boreholes, NQ sized core was cut.

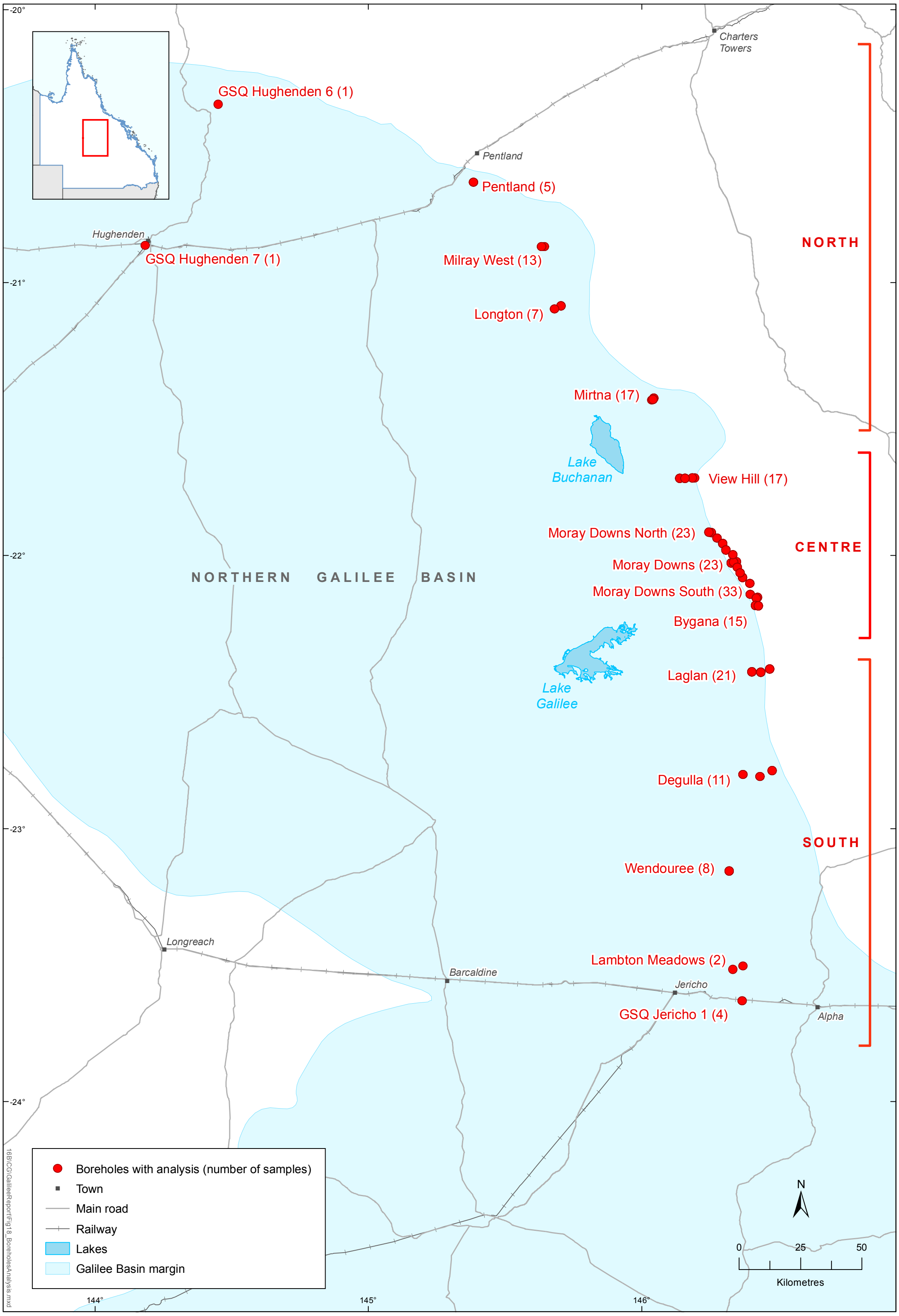

Figure 18. Location of analysed sites with the number of samples per location in brackets.

The breakdown of the sites (in south to north order) from which coal samples were taken for analysis is as follows:

- Lambton Meadows: from the two sites drilled (Galilee NS 13, NS 14-15R)
- Wendouree: from the three sites drilled (Galilee NS 1-1A, NS 2, NS 3)
- Degulla: from the three sites drilled (Galilee NS 4-4A, NS 5, NS 6)
- Laglan: from three of the five sites drilled (Galilee NS 8, NS 10, NS 11-12R)
- Moray Downs: from 18 of the 23 sites drilled (Galilee NS 16, NS 19-20R, NS 21, NS 51, NS 52-53R, NS 54, NS 55, NS 56, NS 57, NS 58R, NS 59, NS 60, NS 61, NS 62, NS 63, NS 64, NS 65, NS 66)
- View Hill: from four of the five sites drilled (Galilee NS 26, NS 27, NS 28, NS 29)
- Mirtna: from the three sites drilled (Galilee NS 22, NS 23, NS 24)
- Longton: from two of the three sites drilled (Galilee NS 30, NS 33)
- Milray: from two of the five sites drilled (Galilee NS 46, NS 47)
- Pentland: from one of the eight sites drilled (Galilee NS 35).

Analytical schedule

The program commenced with the drilling of Galilee NS 1-1A, NS 2 and NS 3 on Wendouree Station. Initially, analysis of the coals sampled comprised a basic suite of tests on the raw coal consisting of Proximate Analysis, Crucible Swelling Number and Specific Energy (calorific value).

Following the completion of testing of the first coal samples taken at the Wendouree sites, in the majority of cases, coal samples were subsequently analysed in two stages as follows:

Stage 1—Raw coal washed at SG 1.90—mass balance/yield and relative densities of the float and sink fractions reported. On the Floats 1.90 fraction, Proximate Analysis, Sulphur, Specific Gravity and Ash Fusion Temperatures were determined.

Stage 2—Specific Energy of the Floats 1.90 fraction. For thicker coal intervals, where multiple contiguous samples were taken, Specific Energy was determined on mass proportioned composites prepared in the laboratory of the Floats 1.90 fractions of the constituent plies. At about 11 sites, the air dry moisture content and ash values were again determined on the analysis sample at the time of determining the Specific Energy. At about 17 sites (seven of the 10 localities drilled), Stage 2 testing also included an Ash Analysis, and Ultimate Analysis of the Floats 1.90 fraction. The Hardgrove Grindability Index (HGI) was determined on the Floats 1.90 fraction of coal sampled at 9 sites with one site at Pentland and eight sites at Moray Downs. For the thicker seams where multiple contiguous samples were taken, no other analyses were undertaken on laboratory prepared composites other than for determining Specific Energy.

Washability tests at multiple density fractions (0.1 increments) were only undertaken on coals sampled from two boreholes—Galilee NS 3 (Wendouree) and Galilee NS 24 (Mirtna).

With only a few exceptions, where analyses were undertaken by the Government Chemical Laboratory, the coal samples were analysed by Australian Coal Industry Research Laboratories (ACIRL) in Sydney, nominally in accordance with the requirements of British Standard (BS) 1016. No specific size fractioning was performed on any of the coal samples analysed.

Coal seam correlations were not attempted in the review of analytical results presented below. The methodology is detailed in Appendix 11.

Coal analyses

A statistical breakdown of key coal quality parameters obtained from the analytical results of the coal sampled during the 1970s' Departmental coal reconnaissance drilling program is presented in Table 3.

Proximate analyses were conducted on the Floats 1.90 fraction of almost all of the samples in the dataset; the results suggest that there is little variation in the values of Inherent Moisture, Ash, Volatile Matter and Fixed Carbon between samples.

Ash (17.5 ± 6.1% adb) and Fixed Carbon (45.5 ± 4.3% adb) display highest variability. The mode of each of these parameters differs from the mean and median values indicating skewness of the population, towards lower values for Ash (Figure 19) and towards higher values for Fixed Carbon (Figure 20).

Moisture (9.5 ± 1.8% adb) and Volatile Matter (27.6 ± 2.6% adb) are quite consistent with very similar mean, median and mode values; this indicates a distribution close to normal. In addition, their low coefficient of variation suggests limited dispersion of values around the mean (Table 3).

Overall, few trends are obvious based on these data, although there appears to be a trend for Volatile Matter content values (on both an air dry and dry, ash-free basis, Floats 1.90 fraction) to decrease slightly from south to north (Figure 21). This may be due to a combination of factors of either coal rank, and/or maceral composition of the coals (coal type).

Generally, the Total Sulphur content of the samples taken from departmental coal boreholes were in almost all cases, low to very low (0.2 to 0.35% adb; Figure 22). However, more recent company exploration by the AMCI/Bandanna Energy Joint Venture at the western edge of the Springsure Shelf in the South Galilee Coal Project area (refer to section on proposed projects), indicates that the principal coal seam being targeted there has a high Total Sulphur content, averaging around 0.9% adb [AMCI (Alpha) Pty Ltd, 2012d; Collective Experience Pty Limited, 2011].

Hardgrove Grindability Indices (Floats 1.90 fraction) are mainly available for the Moray Downs area (Figure 23). Results show quite a variation, ranging from between 40 and 63, but typically are 50 to 60, (mode of 51) comparable to some of the washed product coals being obtained from the lower rank Group V (Rangal) coals (e.g. Ensham, Theodore) in the central and southern part of the Bowen Basin (Mutton, 2003, appendix B).

Specific Energy values of the Floats 1.90 fraction (all samples) averaged around 5500 Kcal/kg (adb) (~7500 Kcal/kg [dmmf]; Figure 24).

Ash Fusion Temperatures (reducing atmosphere) overall are high, with Deformation Temperatures generally >1400°C.

Ultimate Analysis was also performed on a few samples as part of Stage 2 testing—results showed the carbon is highly consistent and around 76%, while carbonates as CO_2 display great variability.

Although the ash composition dataset is limited, it does show the heterogeneity of the ash residue, with oxides of silicon and aluminium consistently high. The minor and trace elements are highly variable (i.e. high coefficients of variation) as they can occur in association with feldspars (Na, K, Ca, Mg) or oxidation products (Fe, Mn, S).

The relationship between various parameters and the spatial variability of these relationships was analysed through scatter diagrams.

Table 3. Descriptive statistics of Departmental coal analytical data—Floats 1.90 Fraction.

Analysis	Parameter	Basis	Unit	Count	Minimum	Maximum	Mean	Median	Mode	Standard deviation	Coefficient of variation
Raw coal	Relative Density		g/cm^3	170	1.40	2.01	1.63	1.62	1.58	0.10	0.06
Cumulative F 1.90	Yield		weight %	191	64.5	99.2	85.4	86.0	84.6	7.8	0.09
	Ash	adb	%	43	5.5	26.4	16.8	16.9	14.5	4.8	0.29
	Relative Density	adb	g/cm^3	189	1.36	1.73	1.52	1.51	1.53	0.06	0.04
Proximate analysis - F 1.90	Moisture	adb	%	192	4.6	15.0	9.5	9.4	9.6	1.8	0.18
	Ash	adb	%	193	5.6	34.5	17.5	16.5	13.3	6.1	0.35
	Volatile Matter	adb	%	192	19.7	36.7	27.5	27.4	26.3	2.6	0.10
	Fixed carbon	adb	%	192	35.7	57.0	45.5	45.9	48.5	4.3	0.09
	Hardgrove Grindability Index			35	40	63	53	52	51	4.8	0.11
Speci ic energy analysis - F 1.90	Specific Energy	adb	MJ/kg	142	17.2	27.2	22.8	23.0	23.9	2.0	0.09
	Specific Energy	adb	kcal/kg	142	4111	6506	5439	5483	5716	472	0.09
	Moisture	adb	%	55	4.8	11.6	8.7	8.7	8.7	1.1	0.13
	Total Sulphur	adb	%	188	0.14	1.30	0.30	0.28	0.29	0.12	0.42
Ash fusion temperatures - F 1.90	Deformation		°C	70	1170	>1600	1467	1480	>1600	117	0.08
	Hemisphere		°C	70	1390	>1600	1564	>1600	>1600	52	0.03
	Flow		°C	70	1460	>1600	1578	>1600	>1600	39	0.02
Ultimate analysis - F 1.90	Carbon	daf	%	69	72.34	81.06	76.43	76.53	76.17	2.06	0.03
	Hydrogen	daf	%	69	3.14	5.63	4.44	4.47	4.47	0.40	0.09
	Nitrogen	daf	%	69	1.30	1.73	1.53	1.54	1.57	0.09	0.06
	Sulphur	daf	%	69	0.21	0.67	0.38	0.37	0.23	0.12	0.31
	Oxygen	daf	%	69	12.60	22.63	17.22	16.94	21.12	2.24	0.13
	Carbonates as CO_2%	daf	%	69	0.07	2.31	0.65	0.58	0.12	0.40	0.61
Ash analysis - F 1.90	SiO_2		%	63	50.5	83.6	66.7	67.9	70.1	9.3	0.14
	Al_2O_3		%	63	10.0	39.5	23.2	22.7	31.4	7.7	0.33
	Fe_2O_3		%	63	0.8	13.9	4.4	3.5	0.8	3.3	0.76
	TiO_2		%	63	0.24	2.32	1.01	0.85	1.08	0.51	0.50
	CaO		%	63	0.43	4.91	1.37	1.26	0.96	0.84	0.61
	MgO		%	63	0.15	2.46	0.62	0.55	0.55	0.39	0.62
	Na_2O		%	63	0.08	0.84	0.27	0.21	0.17	0.17	0.63
	K_2O		%	63	0.07	1.44	0.25	0.18	0.20	0.20	0.80
	P_2O_5		%	63	0.01	0.59	0.14	0.10	0.07	0.12	0.88
	SO_3		%	63	0.07	1.52	0.54	0.50	0.83	0.35	0.64
	Mn_3O_4		%	61	0.01	0.33	0.10	0.06	0.02	0.08	0.83
Calculated parameters - F 1.90	Specific Energy	dmmf	MJ/kg	142	29.2	33.0	31.50	31.6		0.7	0.02
	Specific Energy	dmmf	kcal/kg	142	6977	7885	7531	7542		174	0.02
(Seyler classification)	Specific Energy	dmmf	BTU/lb	142	12559	14194	13556	13575		313	0.02
	Volatile Matter	dmmf	%	192	28.5	45.4	36.4	36.3		2.5	0.07
	Carbon	dmmf	%	68	73.6	82.3	78.1	78.5		2.1	0.03
	Hydrogen	dmmf	%	38	3.3	5.7	4.5	4.5		0.4	0.09
ASTM classification	Fixed carbon	dmmf	%	192	54.6	71.5	63.6	63.7		2.5	0.04

F 1.90—floats at 1.90 g/cm^3; adb – air dried basis; daf – dry ash free; dmmf – dry, mineral-matter free
Count—number of samples; Minimum and Maximum—range of variation; mean—average value; Median—middle value; mode—most frequent value; standard deviation—spread around the mean; coefficient of variation (standard deviation/mean)—dispersion of values (the higher the value, the greater the level of dispersion around the mean)

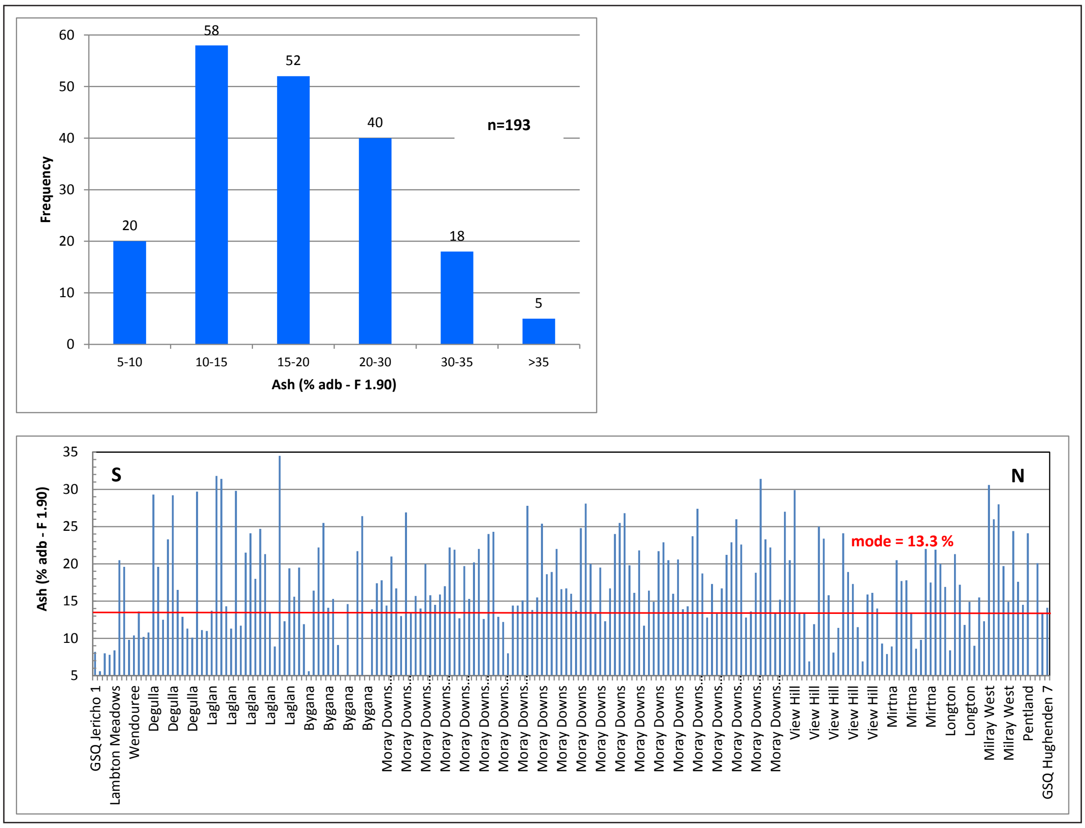

Figure 19. (a) Range of Ash values and mode value based on 193 samples; (b) south–north spatial distribution. Locations shown in Figure 18.

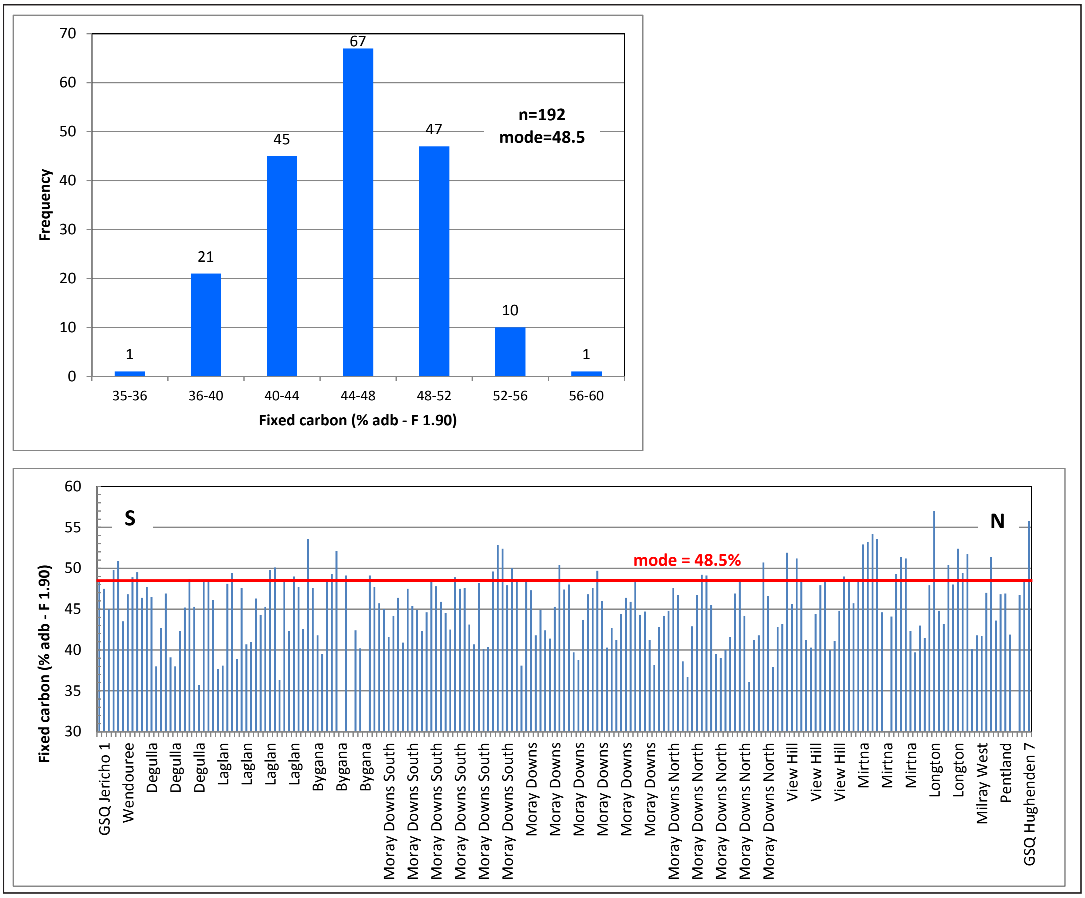

Figure 20. (a) Range of Fixed Carbon content and mode value based on 192 samples; (b) south–north spatial distribution. Locations shown in Figure 18.

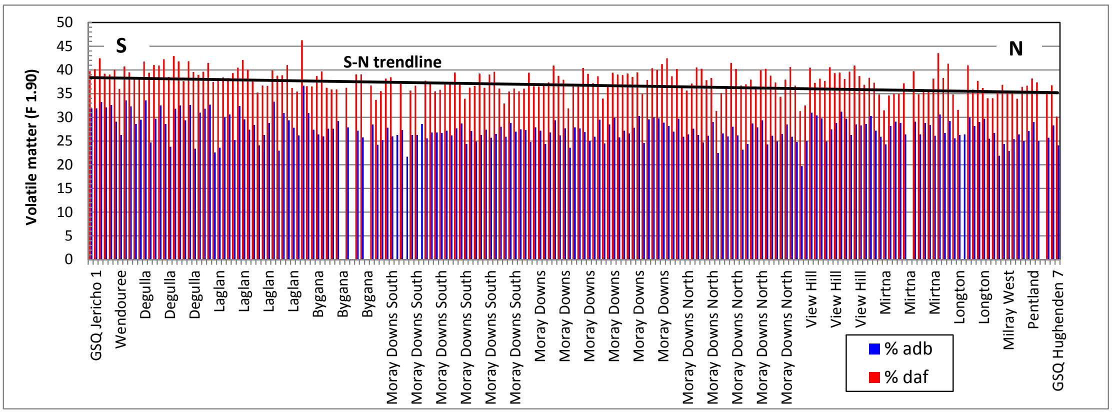

Figure 21. South–north spatial distribution and trend in Volatile Matter content (n=192).

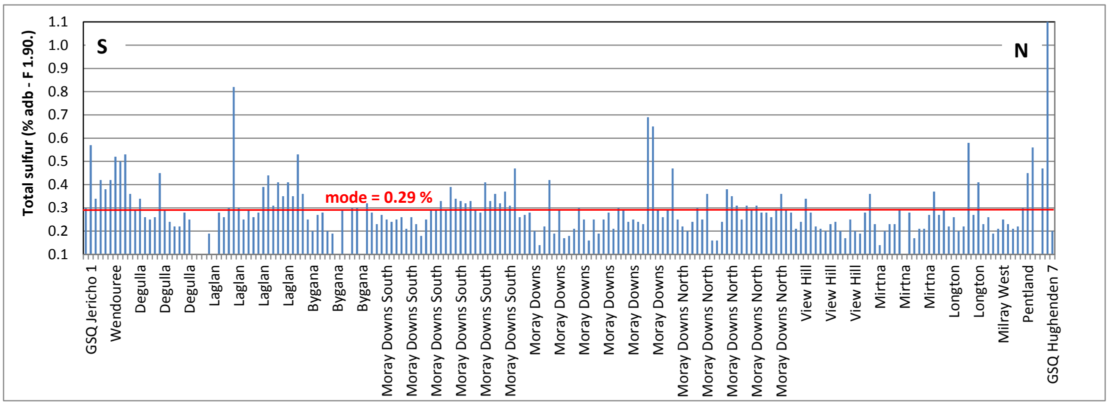

Figure 22. South–north spatial distribution of Total Sulphur (n=188).

Ash concentration is directly proportional with the Relative Density of raw coal ($R^2 = 0.68$, Figure 25a). The northern (Figure 25b) and the southern values (Figure 25d) are distributed quite similarly, although the Laglan and Wendouree sample sets (Figure 25d) include several outliers containing more ash, relative to their density and compared to other sites. In the central area (Figure 25c), Moray Downs exhibits higher densities relative to their ash composition when compared with Moray Downs North and Moray Downs South.

Ash concentration is inversely proportional to Specific Energy ($R^2 = 0.89$, Figure 26a). The sample from GSQ Hughenden 7 has high ash relative to its specific energy (Figure 26b), while GSQ Jericho 1 contains very little ash (Figure 26d). Also in the south, the Wendouree and Laglan samples have

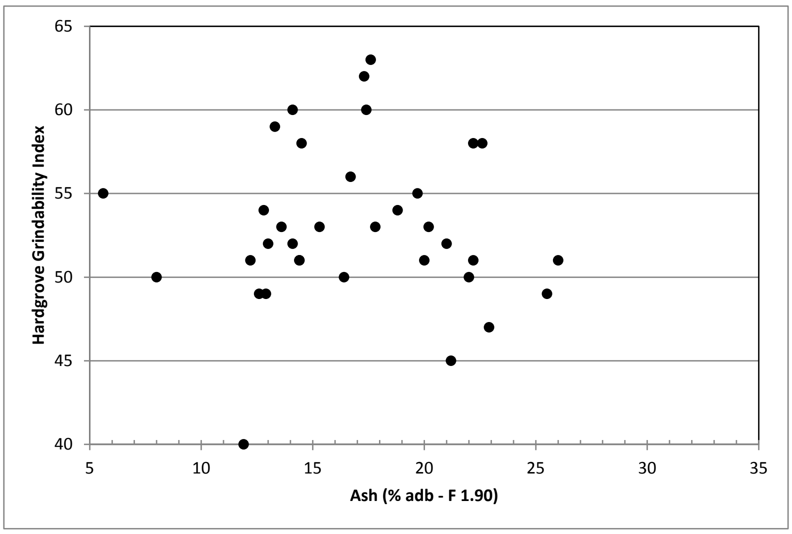

Figure 23. HGI versus Ash (n=35).

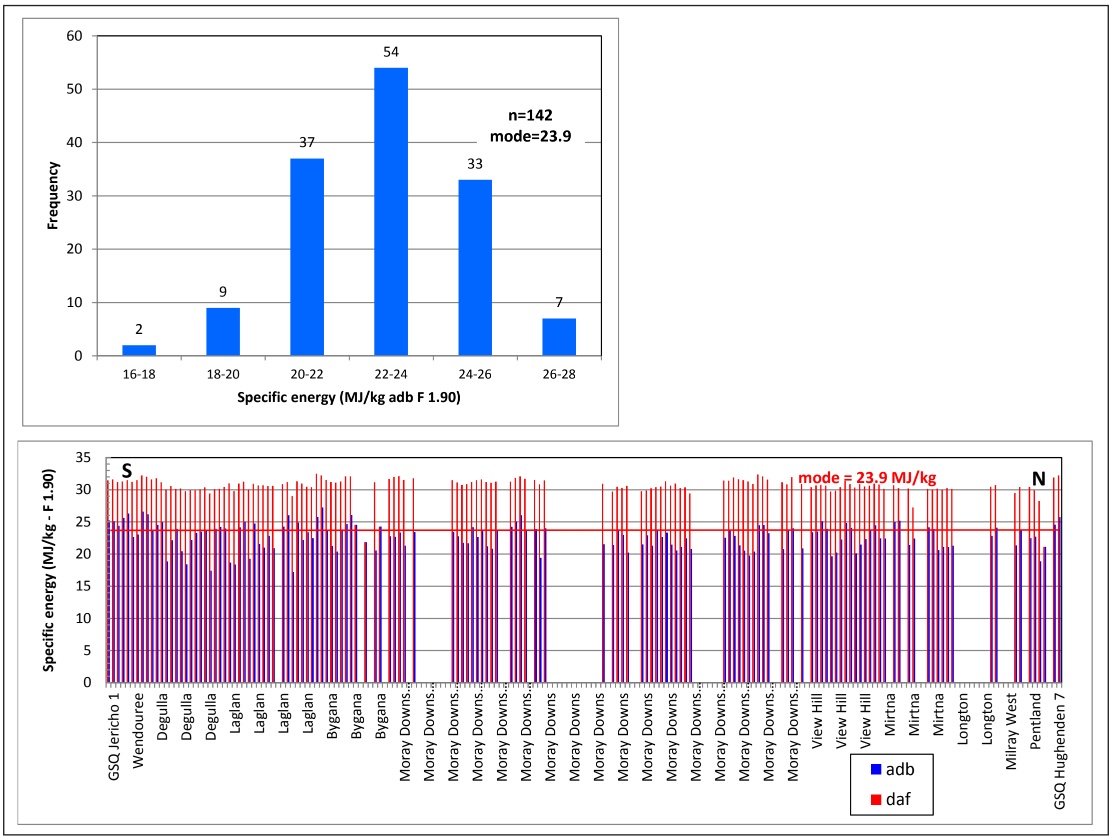

Figure 24. (a) Range of Specific Energy values and mode value based on 142 samples; (b) south–north spatial distribution. Locations shown in Figure 18.

relatively greater specific energy than the Degulla coal for the same ash content. The central area appears to be very homogenous (Figure 26c) by comparison.

The complete set of analytical results and additional diagrams are presented respectively in Appendix 12 and Appendix 13. The analytical results (Appendix 12) are provided in two formats as: all ply analyses incorporating calculated seam composite values, sorted in sequential borehole number order (labelled as 'Original'), and as all full seam analysis results calculated to various adjusted bases, either as analysed or calculated composite values, sorted in approximate north to south order (labelled as 'Various Bases Rounded').

The Fixed Carbon values (virtually all < 69% dmmf) indicate that, at best, the analysed coals generally classify with no higher rank than High-volatile B bituminous, in accordance with the ASTM classification system (Standard D388-12) and are largely sub-hydrous according to Seyler's classification (Figure 27). At this lower level of rank, the ASTM classification system requires that classification be based on the moist, mineral-matter free Gross Calorific Value of the coal. However, this has not been possible for this data set, since the analytical tests undertaken on the coal samples did not include the determination of the Equilibrium Moisture content that would have allowed an estimate of the inherent moisture content of the coals to be made, in order to make the necessary moisture adjustments.

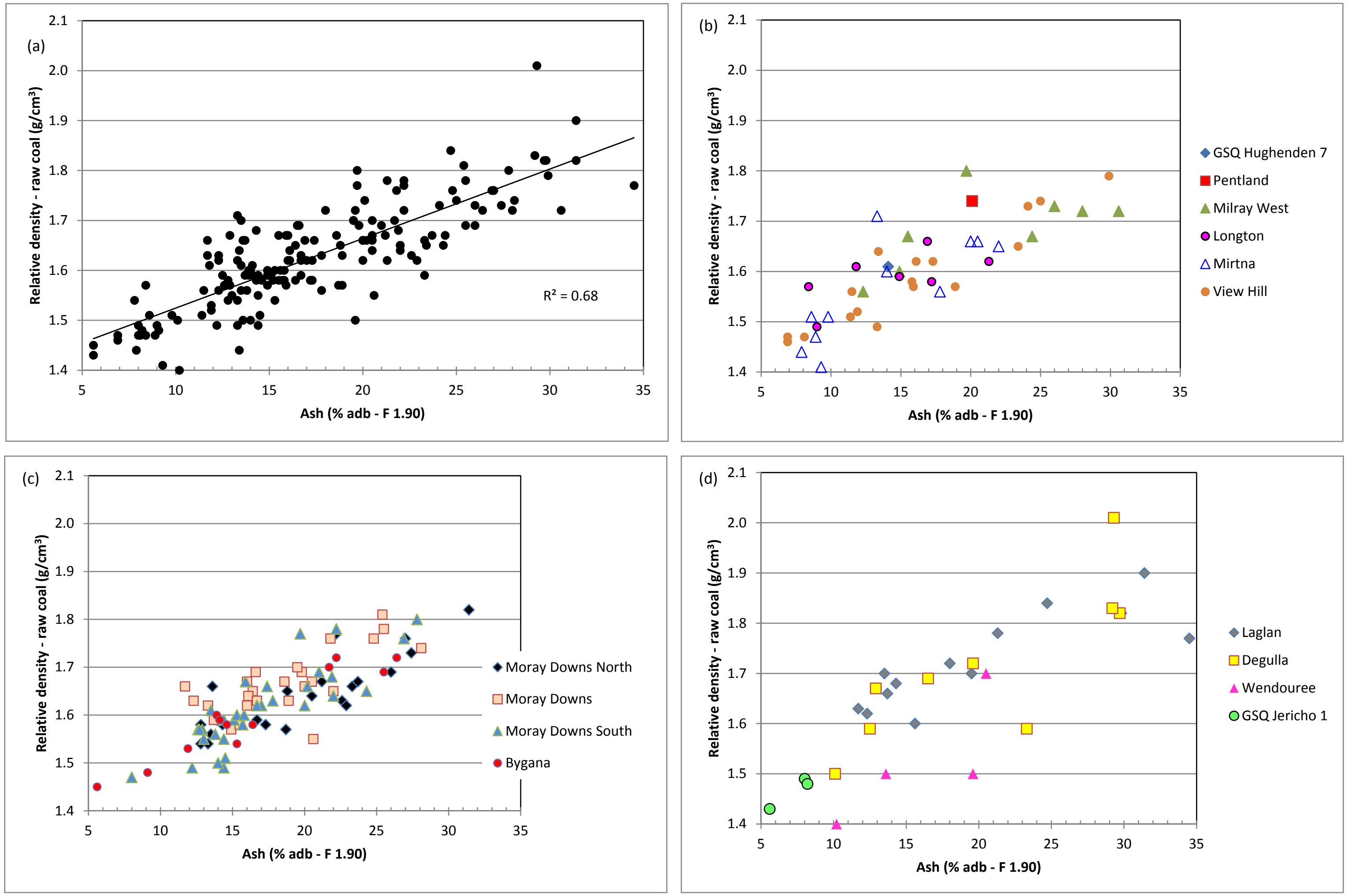

Figure 25. (a) The relationship between Relative Density and Ash for the entire dataset; (b) northern section of the basin; (c) centre and (d) south.

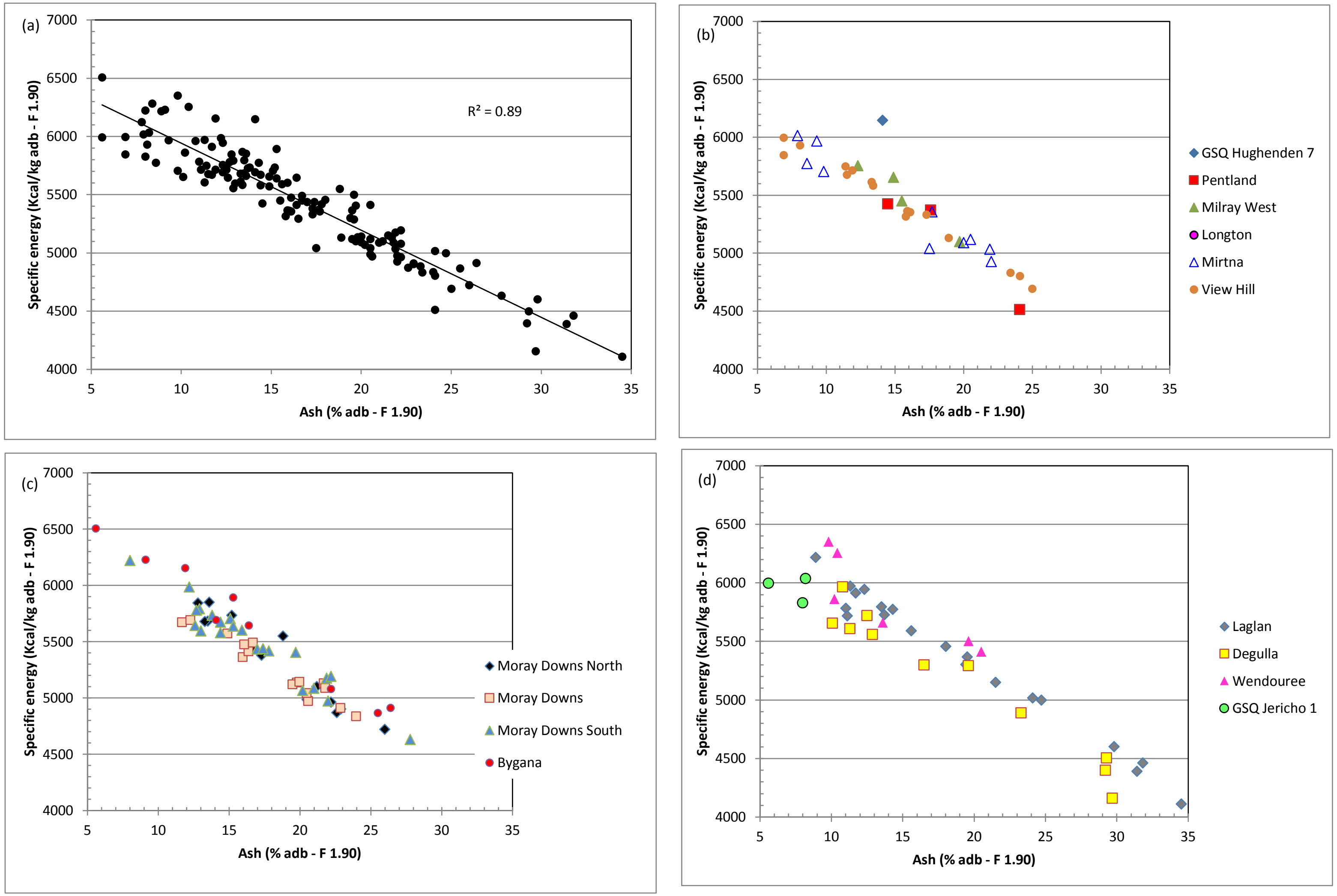

Figure 26. (a) The relationship between Specific Energy and ash for the entire dataset; (b) northern section of the basin; (c) centre and (d) south.

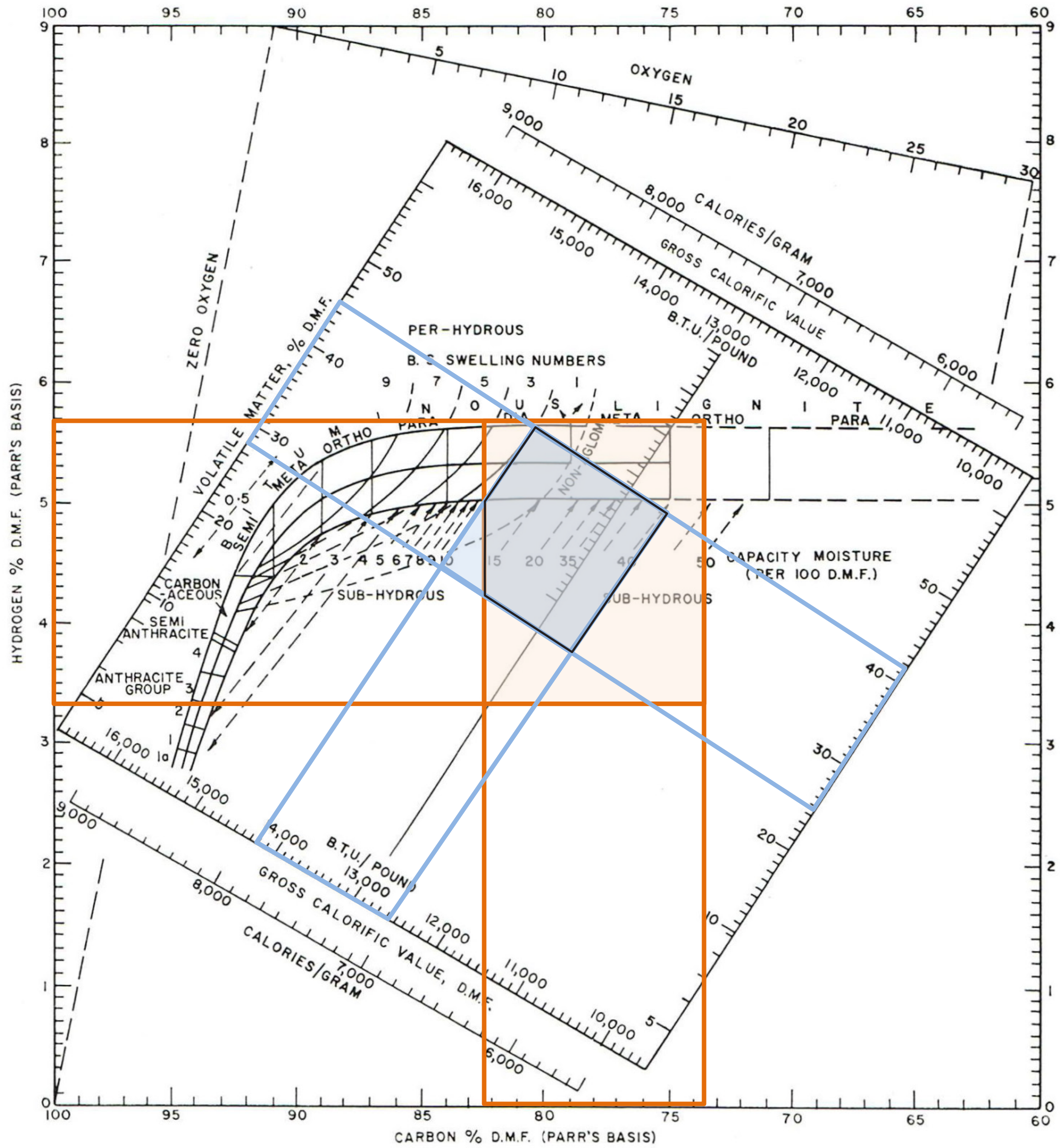

Figure 27. Galilee coal quality dataset (grey polygon) plotting within the sub-hydrous coal domain (after Seyler's (1933) classification scheme).

Spontaneous combustion propensity

Little information is available regarding the storage and handling characteristics of these coals. However, Carter (1948; Appendix 2) did report a spontaneous combustion event that occurred in a surface dump of coal only shortly after it had been extracted by MIM from the company's 'Coal Camp' site in the Oxley Creek area (see Coal exploration section "Late 19th Century to 1950" on page 26).

Svenson (1969), reporting on behalf of Thiess Exploration Pty Ltd on coal exploration in AtP 56C and 58C in the region around Pentland, also made reference to this event, and noted that control of this phenomenon would be a necessary requirement if underground mining in the region were to be considered.

Murphy (1984b) reported detailed coal analyses undertaken on composited seam samples selected from 100 mm cores in the Lauderdale deposit (AtP 249C) south of Pentland (Table 4). These analyses included a number of relative ignition (crossing point temperature) determinations undertaken on raw coal samples which suggested that the coals there have a propensity for spontaneous combustion.

Hancock Prospecting Pty Ltd (2010a) and Hancock Galilee Pty Ltd (2011a) also reported summary results of spontaneous combustion evaluation testing, conducted by the University of Queensland on coal samples from respectively the Alpha and Kevins Corner project areas. Based on the test results obtained, the conclusion reached was that the coals have "*a high intrinsic spontaneous combustion propensity based on Queensland conditions*" (Hancock Prospecting Pty Ltd, 2010a, page 4-38). Adiabatic self-heating test results (R70 values) were reported as ranging from 3.55 and 6.70°C per hour for coal with respective ash values of 25.9% and 18.7%. Relative Ignition Temperatures (Crossing Point Values) for the coals were reported as ranging from between 110°C and 132°C.

During the course of extracting a bulk sample of coal from the Alpha deposit (MDL 285) in 2011, a spontaneous combustion event (self-heating) occurred in a raw coal stockpile about eight weeks after the coal had been extracted from the test pit (personal communication, A. Restell, Hancock Coal Pty Ltd).

Jones (1976) and Richardson *et al.* (1997) briefly outlined the generally established relationship between coal rank, coal type, and a coal's oxygen absorption propensity as an indicator of spontaneous combustion potential. Young (1983) explained that, for low rank coals, the sorption of moisture can be an influential factor in initiating the self-heating of coal, with the process involving several stages, beginning with the fast initial uptake of oxygen, probably by physical adsorption onto the coal surfaces.

Walters (1996) also provided a concise summary of the factors contributing to the spontaneous combustion of coal. His overview suggested that rank may play a more significant role in the self-heating of coal than petrographic composition.

The reviews regarding spontaneous combustion in Australian coal mining by Cliff *et al.* (1996, 2009) formed the view that the available information concerning the petrographic composition of coals and their spontaneous combustion propensity was often conflicting. Cliff *et al*. (1996) indicated that such a relationship was not well defined, and suggested that this may be due to issues relating to changes in the physical structure in a coal brought about by the grinding required when undertaking certain types of spontaneous-combustion laboratory tests.

Cliff & Boffinger (1998) have also provided a comprehensive review of spontaneous combustion as it relates to the Queensland coal mining industry.

Table 4. Raw coal seam composite coal analyses, AtP 249C, Pentland.

(This page may be printed at A3 for clarity.)

Borehole No (100 mm core samples)	Easting (metres) Aust. Mapping Grid (Datum: AGD 1966)	Northing (metres) Aust. Mapping Grid (Datum: AGD 1966)	Collar Elevation (metres above Mean Sea Level) (Datum: Australian Height Datum)	Total Depth (metres)	QDEX Reference	Date Drilled	Composite Sample No (as reported)	Composite Sample Details	Crossing Point Temp (°C)	Rv max - Mean Max Reflectance Vitrinite
PE 159A	328 860	7 719 699	484.38	149.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 159A Composite 1	Comprises four discontiguous coal intervals from 85.86m to 86.97m (sample No 4), 87.39m to 89.13m (sample Nos 6 & 7), 95.67m to 97.11m (sample No 16) and 97.82m to 98.45m (sample No 18), intervening stone partings excluded from composite	139	–
							PE 159A Composite 2A	103.44 m to 112.54M (sample Nos 25 to 36 inclusive)	144	–
							PE 159A Composite 2B	115.77m to 120.15m (sample Nos 42 to 45 inclusive)	143	–
							PE 159A Composite 3	Comprises two discontiguous coal intervals from 134.4m to 135.89m (sample Nos 54 & 55) and 138.41m to 139.3 m (sample Nos 59 to 61 inclusive), intervening stone partings excluded from composite	–	–
PE 212A	329 878	7 718 526	463.69	126.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 212A Composite 2A	67.56m to 71.49m (sample Nos 3 to 6 inclusive)	154	–
							PE 212A Composite 2B	75.55m to 79.51m (sample Nos 9 to 15 inclusive)	146	–
PE 215A	331 220	7 716 688	444.33	143.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 215A Composite 1	Comprises three discontiguous coal intervals from 51.96m to 52.8m (sample No 6), 54.02m to 54.87m (sample No 8) and 55.9m to 57.03m (sample No 10), intervening stone partings excluded from composite	140	–
							PE 215A Composite 2 (RCC*)	60.90m to 73.90m (sample Nos 16 to 35 inclusive)	143	–
							PE 215A Composite 3A (RCC*)	129.58m to 131.33m (sample Nos 47 to 49 inclusive)	136	–
							PE 215A Composite 3B (RCC*)	Comprises two discontiguous coal intervals from 122.79m to 125.68m (sample Nos 38 to 42 inclusive), 128.58m to 129.03m (sample 45), intervening stone band excluded	142	–
PE 255A	330 475	7 720 024	462.2	68.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 255A Composite 1 (RCC*)	28.06m to 30.2m (sample Nos 3 to 5 inclusive)	145	–
							PE 255 Composite 2A	32.51m to 38.24m (sample Nos 9 to 16 inclusive)	147	–
							PE 255A Composite 2B (RCC*)	43.76m to 54.54m (sample Nos 26 to 35 inclusive)	135	–
							PE 255A Composite 2C (RCC*)	Comprises two discontiguous coal intervals from 39.09m to 40.43m (sample Nos 18 and 19) and 42.26m to 43.76m (sample Nos 24 and 25), intervening stone parting excluded from composite	147	–
							PE 255A Composite 3D	54.54m to 58.89m (Sample Nos 36 to 43 inclusive)	–	–
							PE 255A Composite 3E	58.89m to 60.53m (sample Nos 44 to 46 inclusive)	–	–
							PE 255A Composite 3D+3E	Comprises a composite of two contiguous composite samples for the interval from 54.54m to 60.53m (sample Nos 36 to 46 inclusive)	142	–
								Laboratory reference sample (No 2), reported as being known to have a high propensity to spontaneously ignite	146	0.71%
								Laboratory reference sample (No 5), reported as being known to have a low propensity to spontaneously ignite	200	1.36%

Composite Sample No (as reported)	Proximate Analysis % adb				Specific Energy MJ/kg adb	Total Sulphur % adb	Moisture Holding Capacity % adb	Relative Density g/cm³	Hardgrove Grindability Index^ adb	Chlorine % adb	Phosphorus % adb	Ash Fusion Temperatures °C (Reducing Atmosphere)			
	Ash	Moisture	Volatile Matter	Fixed Carbon								Initial Deformation	Spherical	Hemispherical	Flow
PE 159A Composite 1	36.5	8	21.7	33.8	16.70 (30.10)	0.39	12.1	1.72	54 (43)	0.05	0.01	1510	1570	1590	>1600
PE 159A Composite 2A	30.5	8.2	21.3	40.0	18.32	0.18	11.6	1.59	70 (45)	0.02	0.004	>1600	>1600	>1600	>1600
PE 159A Composite 2B	20.4	10	23.4	46.2	21.34	0.21	13.2	1.53	64 (49)	0.03	0.004	>1600	>1600	>1600	>1600
PE 159A Composite 3	23.5	10.7	24.8	41.0	30.46	0.36	13.0	1.51	61 (51)	0.02	0.003	>1600	>1600	>1600	>1600
PE 212A Composite 2A	29.1	7.6	21.9	41.4	18.46	0.2	12.3	1.61	72 (46)	0.02	0.005	>1600	>1600	>1600	>1600
PE 212A Composite 2B	31.6	7.8	21.1	39.5	17.95	0.28	11.9	1.67	71 (49)	0.05	0.024	>1600	>1600	>1600	>1600
PE 215A Composite 1	42.0	6.8	21.4	29.8	15.06	0.36	11.1	1.74	65 (40)	0.03	0.007	1470	1540	1550	1600
PE 215A Composite 2 (RCC*)	31.7	8.3	29.4	30.6	17.94	0.25	12.1	1.62	74 (48)	0.03	0.005	1560	>1600	>1600	>1600
PE 215A Composite 3A (RCC*)	26.6	8.4	31.0	34.0	20.08	0.36	11.7	1.59	60 (45)	0.04	0.006	>1600	>1600	>1600	>1600
PE 215A Composite 3B (RCC*)	33.4	7.9	31.1	27.6	17.16	0.40	12.5	1.68	62 (51)	0.01	0.006	1590	>1600	>1600	>1600
PE 255A Composite 1 (RCC*)	43.7	7.0	20.9	28.4	13.86	0.39	11.7	1.80	58 (52)	0.02	0.236	>1600	>1600	>1600	>1600
PE 255 Composite 2A	34.9	7.5	20.7	36.9	16.88	0.30	11.7	1.7	70 (49)	0.04	0.006	>1600	>1600	>1600	>1600
PE 255A Composite 2B (RCC*)	23.7	8.5	24	43.8	20.46	0.34	12.0	1.59	64 (49)	0.04	0.007	>1600	>1600	>1600	>1600
PE 255A Composite 2C (RCC*)	34.0	6.9	21.0	38.1	17.10	0.27	11.1	1.69	67 (45)	0.04	0.011	>1600	>1600	>1600	>1600
PE 255A Composite 3D	28.5	8.1	25.3	38.1	18.90	0.45	12.4	1.62	60 (48)	0.02	0.007	>1600	>1600	>1600	>1600
PE 255A Composite 3E	37.7	6.5	19.8	36.0	16.44	0.42	12.3	1.71	68 (48)	0.04	0.009	>1600	>1600	>1600	>1600
PE 255A Composite 3D+3E	35.5	6.0	23.4	35.1	16.98	0.46	12.3	1.7		0.02	0.009	>1600	>1600	>1600	>1600

Composite Sample No (as reported)	Ultimate Analysis % adb				Forms of Sulphur % adb			Ash Analysis % Reported on the "ignited basis @ 815°C"													
	Carbon	Hydrogen	Nitrogen	Oxygen	Pyritic	Sulphate	Organic	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	Mn_3O_4	SO_3	P_2O_5	BaO	SrO	ZnO
PE 159A Composite 1	42.70	2.60	0.88	8.93	0.263	0.003	0.124	75.8	18.3	3.68	0.21	0.15	0.05	0.13	0.76	0.07	0.02	0.040	0.04	<0.001	0.03
PE 159A Composite 2A	47.60	2.72	0.97	9.83	0.085	0.014	0.081	64.6	32.2	0.53	0.26	0.08	0.02	0.09	1.45	0.01	0.01	0.039	0.03	0.006	0.02
PE 159A Composite 2B	54.60	2.68	1.14	10.97	0.001	0.013	0.116	58.4	37.6	0.68	0.26	0.09	0.04	0.10	2.38	0.01	<0.01	0.064	0.04	0.001	0.05
PE 159A Composite 3	–	–	–	–	0.154	0.021	0.185	57.1	39.3	0.93	0.27	0.11	0.04	0.25	1.41	0.01	0.02	0.079	0.03	0.010	0.05
PE 212A Composite 2A	48.63	2.39	1.07	11.01	0.052	0.003	0.145	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PE 212A Composite 2B	46.83	2.65	0.98	9.86	0.067	0.008	0.205	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PE 215A Composite 1	39.03	2.31	0.78	8.72	0.131	0.009	0.220	78.6	15.3	3.92	0.19	0.18	0.05	0.19	0.76	0.08	0.01	0.038	0.05	<0.01	0.05
PE 215A Composite 2 (RCC*)	46.22	2.46	0.97	10.10	0.086	0.007	0.157	66.9	28.8	1.47	0.27	0.16	0.06	0.38	1.15	0.01	0.06	0.039	0.02	0.009	0.05
PE 215A Composite 3A (RCC*)	51.44	2.82	1.07	9.31	0.215	0.010	0.135	63.6	33.5	0.81	0.22	0.13	0.05	0.15	1.57	0.01	0.01	0.053	0.03	0.005	0.06
PE 215A Composite 3B (RCC*)	43.45	2.83	0.94	11.08	0.192	0.012	0.196	70.3	27.3	0.70	0.13	0.09	0.03	0.12	1.37	0.01	<0.01	0.039	0.03	0.009	0.08
PE 255A Composite 1 (RCC*)	35.44	3.08	0.69	9.70	0.012	0.085	0.293	60.3	37.6	0.96	0.13	0.08	0.03	0.15	0.91	0.02	0.02	0.046	0.01	0.009	0.06
PE 255 Composite 2A	44.35	2.05	0.90	10.02	0.110	0.010	0.180	64.3	32.4	0.61	0.15	0.06	0.03	0.07	1.35	<0.01	<0.01	0.039	0.03	<0.001	0.04
PE 255A Composite 2B (RCC*)	52.66	2.95	1.13	10.72	0.182	0.009	0.149	61.4	34.7	1.01	0.22	0.10	0.05	0.34	2.14	<0.01	0.02	0.064	0.04	0.001	0.11
PE 255A Composite 2C (RCC*)	43.93	2.47	0.90	11.53	0.115	0.012	0.143	59.1	37.9	0.58	0.14	0.05	0.03	0.08	2.28	<0.01	<0.01	0.072	0.03	0.014	0.06
PE 255A Composite 3D	48.45	3.06	1.03	10.41	0.126	0.017	0.307	58.3	39.3	0.79	0.14	0.04	0.03	0.15	1.04	<0.01	0.02	0.064	0.04	0.001	0.11
PE 255A Composite 3E	43.87	2.27	0.88	8.36	0.126	0.021	0.273	57.9	38.4	1.06	0.14	0.08	0.03	0.31	1.48	<0.01	0.01	0.053	0.02	<0.001	0.11
PE 255A Composite 3D+3E	43.79	2.61	0.95	10.69	0.204	0.021	0.235	57.8	38.6	1.20	0.13	0.07	0.03	0.19	1.13	<0.01	<0.01	0.058	0.02	0.012	0.07

Note: Denotes composite sample comprised of discontiguous coal intervals, intervening stone partings excluded

*'RCC' (raw coal composite) Note: Laboratory analytical results for the Crossing Point Temperature determination results have been reported with the suffix tag 'RCC'. All other laboratory analytical results for this composite sample number have been reported without the 'RCC' tag corresponding with those listed in the sample details table.

^HGI values: the number in brackets is the percentage of the original sample material retained on the 600 micron screen during the sample preparation procedure in order to make the 'granular' size fraction (1.18mm x 600 micron) for testing in the HGI apparatus as required by AS 1038.20-1981. This requirement was dispensed with in the revised standard, AS 1038.20-1992.

Source: Murphy, 1984b (Appendices 1 & 2; CR13306)

Proposed coal mining projects

Overview

At the present time, there are six large-scale coal mining projects which extend northwards for about 230 km from the Dawson Development Road in the south up to Lake Buchannan in the north, planned for development in the northern Galilee Basin. Locations are shown in Figure 28.

The combined (maximum) output of saleable production from all currently planned projects would amount to more than 200 Mt of thermal coal. This would be obtained from a combination of open-cut and underground (retreat longwall) mines. The Ash content of the proposed saleable product coal varies between projects, but nominally ranges between about 9.5% and 13.5%. Further details regarding nominal yield and saleable product coal specifications are limited.

Since most of the geological data and reports that relate to these projects remain confidential at the time of compiling this review, the information summarised below has been sourced from publicly available material. This primarily comprises documentation provided by the proponents for the purposes of completing various regulatory and statutory approvals processes. These sources include Initial Advice Statements (IAS), Environmental Impact Statements (EIS), and Supplementary Environmental Impact Statements (SEIS). These documents may include a variety of appended specialist consultants' reports. Where possible, references and/or links to the source documents used are provided, although it should be noted that future access to these documents through the links provided may not always be available. Accordingly, relevant sections of these documents are compiled as Appendix 14.

Prior to the most recent spate of coal-exploration activity in the northern Galilee Basin, Mutton (2003) reported tonnage estimates of the identified coal resources in the basin as being about 2.2 billion tonnes of raw coal *in situ*, as shown in Table 5.

Table 5. Coal inventory—Galilee Basin deposits (after Mutton, 2003).

Deposit	Open-cut (Provisional)* raw *in situ* tonnes x 10^6		Underground (Provisional)* raw *in situ* tonnes x 10^6	
	Measured	Indicated	Measured	Indicated
Alpha	525	140	530	
Kevins Corner	280	630		
Pentland		103		
Total	**805**	**873**	**530**	

* The 'provisional' flag as used by Mutton (2003), denotes estimates included at that time, that were not stated as having been prepared in accordance with the then current (1999) version of the Australasian Joint Ore Reserves Committee Code for Reporting of Mineral Resources and Ore Reserves ('JORC Code').

Currently, estimated tonnages of coal identified by the various proponents as having either a Measured or Indicated level of confidence to support these projects collectively total more than 10 billion (x 10^9) tonnes of coal. Additional very large tonnages of coal have been classified as Inferred.

The estimates presented in Table 6 have been rounded to the nearest 5 million tonnes, in keeping with the size of the numbers involved and the uncertainties inherent in the resource estimation process. Estimates of resources assigned an Inferred level of confidence have not been included.

Summary details for each of the proposed projects are presented in the following sections in south to north order. A summary list of the some of the more advanced coal projects being proposed in Queensland, including those in the Galilee Basin, as at July 2016, is presented in Appendix 15.

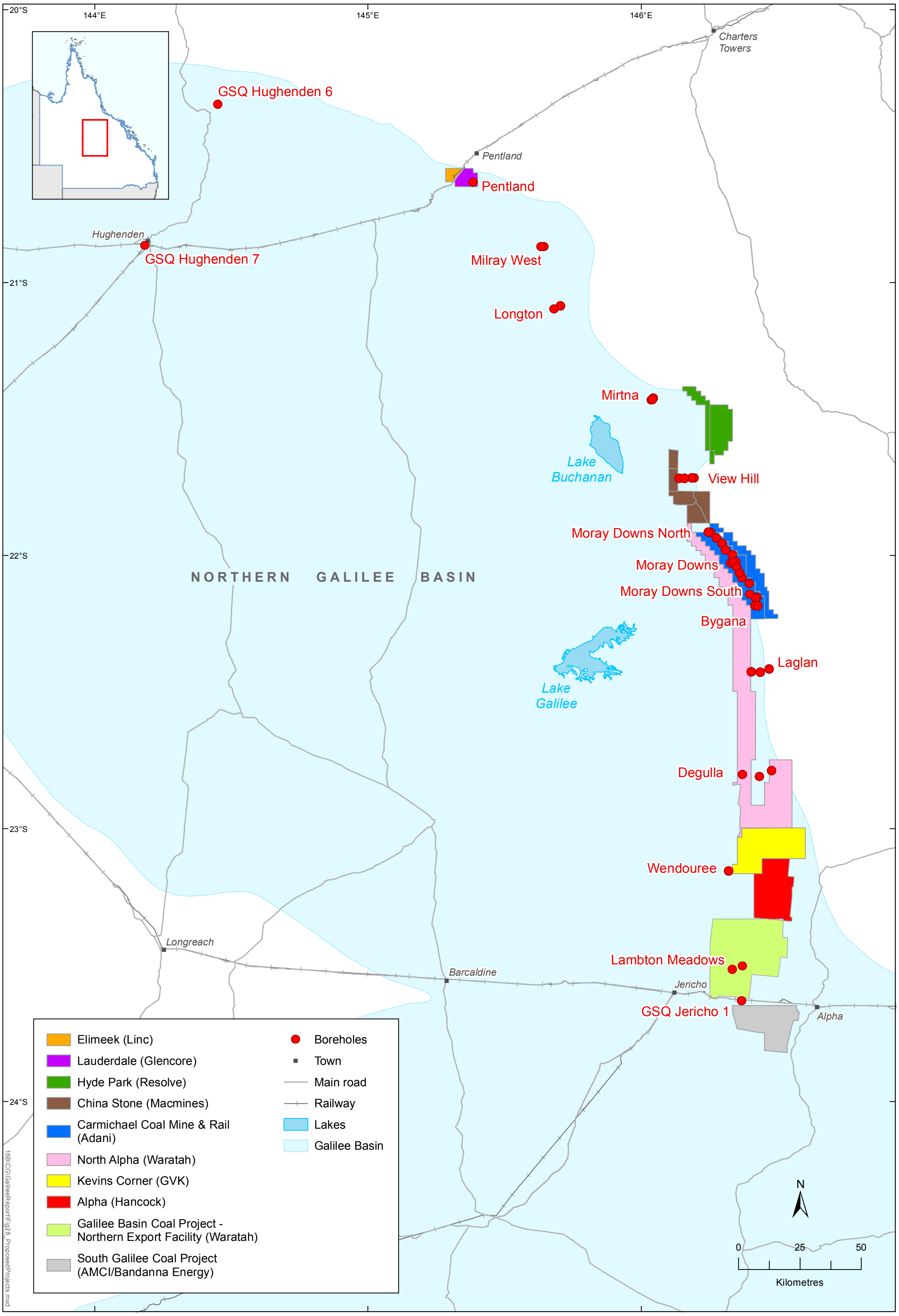

Figure 28. Proposed coal mining projects.

Table 6. Coal resource estimates by project (as nominated by proponent).

Project (south to north) Proponent	Confidence Classification* tonnes X 10^6 (raw *in situ* basis)		Estimate Date*	Comments	Initial Advice Statement Release Date	References (see also Appendix 14)
	Measured	Indicated				
South Galilee Coal Project AMCI Group/ Bandanna Energy Limited	~165	~205	Feb. 2011	D Seams (split as D1 & D2 Seams); compliant with 2004 edition of the JORC Code	May 2010	AMCI (Alpha) Pty Ltd., 2012e; Collective Experience Pty Limited, 2011; Echelon Mining Services, 2012
Galilee Coal Project (Northern Export Facility) Waratah Coal Pty Ltd	~1975	~570	Feb. 2010	B,C,& (split) D Seams; compliant with 2004 edition of the JORC Code	October 2008	Waratah Coal Pty Ltd, 2011f; Waratah Coal Pty Ltd., 2013a and 2013b
Alpha Coal Project Hancock Coal Pty Ltd	~820	~700	July 2010	C & D Seams; compliant with 2004 edition of the JORC Code	September 2008	Hancock Prospecting Pty Ltd., 2010o
Kevins Corner Coal Project Hancock Galilee Pty Ltd (GVK Group)	~230	~1040	March 2010	A,B,C & D Seams; compliant with 2004 edition of the JORC Code	July 2009	Hancock Galilee Pty Ltd, 2011c and 2011i
Carmichael Coal Mine and Rail Project Adani Mining Pty Ltd	~1160	~3240	April 2013	Breakdown of estimates by seam and confidence category not provided. Nominally compliant with the JORC Code - edition not specified.	October 2010	Adani Mining Pty Ltd, 2013c
China Stone Coal Project MacMines Austasia Pty Ltd	~830	~1230	July 2015	Coal seams unspecified; compliant with 2012 JORC Code.	September 2012	Hansen Bailey Pty Ltd, 2015f; Gordon Geotechniques Pty Ltd, 2014

*Estimates as stated by proponent and rounded to the nearest 5 million tonnes. Estimates are presumed to be on a raw, *in situ* basis. Cited versions of the Australasian Mineral Resources and Ore Reserves Reporting Code prepared by the Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy—often more generally referred to as 'the JORC Code', vary as indicated.

South Galilee Coal Project

This project is a joint venture between AMCI (Alpha) Pty Ltd and Alpha Coal Pty Ltd, a subsidiary of Bandanna Energy Limited. AMCI through its subsidiary company AMCI (Alpha) Pty Ltd is manager of the project on behalf of the Joint Venture. The primary coal-exploration tenure covering the project area is EPC 1049. The area of the proposed project itself is located in Mining Lease Application (MLA) 70453.

The project area is located south of the township of Alpha and just to the south of the Capricorn Highway (Figure 28).

The project as described in the EIS is for the construction of combined open-cut and underground mining operations to produce (collectively) up to 17 Mtpa of saleable thermal coal for export with a nominal ash content of around 13.5% Ash [AMCI (Alpha) Pty Ltd, 2012a].

Strip-mining methods using draglines are planned for the open-cut operation with prestripping of overburden by a truck and shovel fleet. Underground mining is planned to use continuous miners for development of mine headings and longwall panel gateroads using a conventional bord and pillar method, with secondary extraction of the target coal seams undertaken by the (retreat) longwall mining method. Underground mining is planned initially for the D1 Seam with access provided from a box-cut development. Subsequent underground mine development in the underlying D2 Seam is planned via a series of interseam (D1 Seam to D2 Seam) cross-measure drifts [AMCI (Alpha) Pty Ltd, 2012b; 2012c].

The coal-seam nomenclature used for this project is a modified (alpha-numeric) version of that adopted by Carr (1973a,b, 1974a,b,c, 1976, 1977, 1978), seemingly to accommodate the anastomosing nature of the individually recognisable coal seams throughout the project area.

Although a number of coal seams are noted as being present in the (Lopingian) late Permian succession in the project area, only two seams are considered by the proponents to be of commercial interest at the present time. These occur as a split D Seam, referred to (in descending stratigraphic order) as the D1 and D2 seams [Collective Experience Pty Limited, 2011; AMCI (Alpha) Pty Ltd, 2012d].

The coal interval representing the D1 Seam has been described as comprising three individual coal plies, D1 Upper (D1U), D1 Middle (D1M) and D1 Lower (D1L), which may also be present in various combinations as a D1 Upper/Middle (D1UM), D1 Middle/Lower (D1ML) or as a full D1 (D1) Seam. In a similar vein, the coal interval representing the D2 Seam has also been subdivided into three coal plies, the D2 Upper (D2U), D2 Middle (D2M) and D2 Lower (D2L), once again also present in locally variable combinations as a D2 Upper/Middle (D2UM), D2 Middle/Lower (D2ML) or as a combined D2 (D2) Seam. (Collective Experience, 2011).

The inter-seam parting between the D1 and D2 seams ranges from approximately 8 to 18 m with the depth of cover to these seams in the project area, ranging between 50 and 240 m [Collective Experience Pty Limited, 2011; AMCI (Alpha) Pty Ltd, 2012d].

Dips of Bandanna Formation strata in the project area have been described as being "*approximately 2 to 3 degrees to the west-southwest*" (Echelon Mining Services, 2012, page 12). The average depth of weathering over the project area is about 50 m [AMCI (Alpha) Pty Ltd, 2012e].

Splitting and thinning of both the D1 and D2 seams are noted as increasing to the south and west of the project area (Collective Experience Pty Limited, 2011; Echelon Mining Services, 2012).

Totalled estimates of coal resources (Measured and Indicated categories only) for all various ply combinations of the D1 and D2 seams have been reported (Collective Experience Pty Limited, 2011) as:

- ~ 165 Mt 'Measured' status (presumably raw coal *in situ* basis) of which ~ 60 Mt are estimated at depths <120 m
- ~ 205 Mt 'Indicated' status of which ~ 60 Mt are estimated at depths < 120 m.

Very large additional tonnages of coal for other combinations of both the D1 and D2 seams are estimated to be in the range of 500 to 1000 Mt (combined) Inferred, between subcrop to depths greater than 120 m and extending in places to the western tenure boundary of EPC 1049 (Collective Experience Pty Limited, 2011, table 2, appendix A, figures A33 to A41).

Resource estimates are limited up-dip by the interpreted limit of oxidation. These resource estimates were prepared in accordance with the 2004 edition of the JORC Code. The date assigned to the estimates is February 2011 (Collective Experience Pty Limited, 2011).

Summary details of the raw coal quality for each of the plies or combinations of plies (working sections) of the D1 and D2 seams where estimates have been prepared are presented as Appendix C of the Collective Experience Pty Limited (2011) report. Of note are the very high Total Sulphur content values (typically > 0.9% adb), which range from about 0.79% (adb) for the D1L ply/working section to

1.71% (adb) for the D1UM ply/working section. The project EIS also indicated that the coals planned for mining are high in Total Sulphur, with an "indicative" Total Sulphur content of 0.9% (adb) and further noted that "*Coal samples are significantly more enriched in sulfur (i.e. median Sulfur content of 1.2%) than other lithologies, which have medians of less than 0.2%*" (AMCI (Alpha) Pty Ltd, 2012f, page 7-20).

Construction of the project, when first proposed, was planned to commence in 2013 with mining operations scheduled to begin in 2015, having a planned mine life exceeding 30 years.

Public consultation on the project EIS commenced in the latter part (October to December) of 2012. In December 2014, the Queensland Coordinator General (Department of State Development, Infrastructure and Planning) gave approval for the project to proceed, subject to certain conditions and recommendations and to the joint venture obtaining all other necessary statutory approvals.

The link to the project environmental approval documentation on the Department of State Development website (last viewed August 2017) is
http://www.statedevelopment.qld.gov.au/assessments-and-approvals/south-galilee-coal-project.html

The link to the EIS documentation on the proponent company's webpage is
http://www.southgalilee.com.au/SGCPEIS.aspx

Bandanna Energy Limited was placed into voluntary administration in September 2014 and went into liquidation in March 2016. Although development of this project as summarised above has been deferred, consideration is being given to the development of a much smaller open-cut mine (~3 Mtpa) as an initial operational phase. Further details are provided at http://www.southgalilee.com.au/ProjectUpdates.aspx

Galilee Coal Project (Northern Export Facility)

The proponent for this project is Waratah Coal Pty Ltd, a privately owned Australian company wholly owned by Mineralogy Pty Ltd. EPC 1040 is the principal exploration tenure with MLA 70454 covering the project area.

The mining component of the project, as outlined in the EIS (Waratah Coal Pty Ltd, 2011a), is for the construction of a series of open-cut and underground mines having a combined nominal capacity of 56 Mtpa of run-of-mine (ROM) coal to produce about 40 Mtpa of saleable thermal coal for export). The nominal project life is 30 years.

Open-cut mining is planned as a series of dragline strip mining operations, each supported by a truck and shovel pre-stripping fleet for overburden removal.

The underground mines are planned as a series of retreat longwall mining operations, with access to the coal seams via surface to in-seam drifts.

The proponent has adopted a modified coal-seam nomenclature based on that used by Carr (1973a,b, 1974a,b,c, 1976, 1977, 1978) to describe the coal seams present in the project area. Seams targeted for extraction are the B Seam, C Seam and a split D Seam, described as the D Upper (DU) and D Lower (DL) seams. An interval of thinly banded stony coal and carbonaceous mudstone (~2 m thick) was noted as being present in the immediate roof of the C Seam (Waratah Coal Pty Ltd, 2011b). This feature of the C Seam is also noted as occurring within the area of the Alpha Coal Project to the north (see comments below). Scott & Hawkins (1992) also made mention of the banded nature of the top portion of the C Seam and suggest that this characteristic makes this coal interval a useful marker for the purposes of regional correlation.

The four seams are all noted as dipping at very shallow angles to the west and with "*little or no recognised faulting*" apparent in the project area (Waratah Coal Pty Ltd, 2011c).

Throughout the project area, thick surficial accumulations of pre-Triassic, Quaternary/Paleogene-Neogene strata were noted, having a combined thickness of up to 125 m (Waratah Coal Pty Ltd, 2011d). The weathering profile is also noted as being variable and deep, extending at times from between 30 to 50 m into the underlying Triassic and/or Permian strata (Waratah Coal Pty Ltd, 2011e).

Tonnage estimates of coal (Waratah Coal Pty Ltd, 2011f; also see Table 6) to support the project are reported in the EIS as comprising:

- about 1.975 billion (x 10^9) tonnes (basis unspecified), assigned a confidence classification of 'Measured'
- some 570 million (x 10^6) tonnes of coal, assigned a confidence classification of 'Indicated'
- additional estimates of more than 1 billion tonnes of coal, classified as 'Inferred'.

The individual seam estimates [stated as "JORC compliant coal resources" as at February 2010 (Waratah Coal Pty Ltd, 2013b)], as presented in the Supplementary EIS by the proponent, are presented below (Table 7).

**Table 7. Galilee Coal Project (Northern Export Facility)—
Coal tonnage estimates by seam.**

Confidence Category	Estimated Tonnes (x10^6) by Seam (density range t/m^3 bracketed; *in situ* densities assumed)				
	B (1.62 to 1.74)	C (1.36 to 1.38)	DU (1.38)	DL (1.40 to 1.43)	Total
Measured	~975*	~220	~365*	~415*	~1,975
Indicated	~220*	~65*	~65	~220*	~570

* Rounded to nearest 5 Mt

Public consultation on the project EIS commenced in the latter part of 2011. In August 2013, the Queensland Coordinator General gave approval for the project to proceed, subject to certain conditions and recommendations and to the joint venture obtaining all other necessary statutory approvals.

The link to the project environmental approval documentation on the Department of State Development website (last viewed August 2017) is http://www.statedevelopment.qld.gov.au/assessments-and-approvals/galilee-coal-project.html

Alpha Coal Project

The project proponent is Hancock Coal Pty Ltd, a privately owned Australian company and a wholly owned subsidiary of Hancock Prospecting Pty Ltd. The principal pre-requisite tenure over most of the project area is MDL 285, with a smaller section of the project area located within part of MDL 333 which adjoins MDL 285 to the north. The project area is covered by MLA 70426.

The proposal is to develop an open-cut mine as four separate pits collectively capable of producing about 30 Mtpa of saleable thermal coal for export from 42 Mtpa of ROM coal. The nominal ash value of the saleable product is planned to be around 9.5%, although the basis was not stated (Hancock Prospecting Pty Ltd, 2010b). The planned mining operation has been designed as a conventional dragline strip mining operation, using truck and shovel combination for pre-stripping of overburden (Hancock Prospecting Pty Ltd, 2010c).

At the commencement of mining operations initial overburden removal would be by truck and shovel, transitioning over time as the project is scaled up to the introduction of multiple draglines. At the scale proposed, mining equipment requirements at full production capacity have been estimated at nine draglines and 12 pre-stripping truck/shovel fleets (Hancock Prospecting Pty Ltd, 2010d). No underground mining was proposed as part of the project.

The combined thickness of Quaternary and Tertiary sediments was noted as ranging from less than 20 m to more than 60 m throughout the project area (Hancock Prospecting Pty Ltd, 2010e). These sediments were described as unconformably overlying either the Lopingian (late Permian) Colinlea Sandstone – Bandanna Formation succession in the eastern and central parts of the project area or the Early Triassic Rewan Formation further to the west (Hancock Prospecting Pty Ltd, 2010e, 2010f).

The depth of weathering (determined visually from core and cuttings) ranges from 10 to 70 m, and averages around 40 m (Hancock Prospecting Pty Ltd, 2010g).

The coal-seam nomenclature adopted appears to be based on the work by Carr undertaken in the 1970s. The proponent regards what they have correlated as the 'C' and 'D' seams, as those which are of primary commercial interest to support the mining proposal (Hancock Prospecting Pty Ltd, 2010i,j).

In the project area, the coal interval correlated as the C Seam has been placed by the proponent as the uppermost coal interval in what they regard as the Colinlea Sandstone. The C seam was described as consisting of an essentially non-coal upper portion, comprising interbanded carbonaceous mudstone–stony coal and possibly tuffaceous claystone (an interval referred to as the 'C Upper') and a coal-dominated lower component.

The lower coal-dominated interval is variously and interchangeably referred to in the EIS as either, the 'C Lower' (when it was used to distinguish it lithologically from the banded largely non-coal 'C Upper' unit), or as the 'C Seam' (in discussions about the section of it that is planned to be mined as part of the mining proposal) (Hancock Prospecting Pty Ltd, 2010k). Tuffaceous claystone is also noted as occurring in association with the overlying B seam (Hancock Prospecting Pty Ltd, 2010l).

The underlying D Seam has been subdivided into three main plies as the D Upper (DU), D Middle (DLM) and D Lower (DLL) (Hancock Prospecting Pty Ltd, 2010m). For resource-modelling purposes, the inter-seam parting between the C and D Seams reportedly averages around 9 m but can range up to 20 m in thickness (Hancock Prospecting Pty Ltd, 2010n).

The coal was noted to have a high propensity for spontaneous combustion (Hancock Prospecting Pty Ltd, 2010h—see section "Spontaneous combustion propensity" on page 60).

Resources of raw coal *in situ* in the C and D seams in the project area (MDL 333 and part of MDL 285) were estimated by the proponent in July 2010 as comprising:

- ~820 Mt assigned a Measured level of confidence, comprising some 240 and 580 Mt in the C and D seams respectively
- an additional ~700 Mt assigned an Indicated level of confidence, comprising about 250 and 450 Mt in the C and D seams respectively.

The resource estimates were prepared in accordance with the requirements of the 2004 edition of the JORC Code (Hancock Prospecting Pty Ltd, 2010o)

Public consultation on the project EIS commenced in the latter part of 2010. In May 2012, the Queensland Coordinator General (Department of State Development, Infrastructure and Planning) gave approval for the project to proceed, subject to certain conditions and recommendations and to the joint venture obtaining all other necessary statutory approvals.

The link to the project environmental approval documentation on the Department of State Development website (last viewed August 2017) is http://www.statedevelopment.qld.gov.au/assessments-and-approvals/alpha-coal-project.html

Between November 2010 and September 2011, an open-cut pit was excavated near the subcrop of the C and D Seams in MDL 285 to extract a bulk sample of coal for undertaking large-scale combustion testing at selected power stations in Asia.

About 122,900 tonnes of raw coal was extracted. The coal was subsequently transported by road to the Jellinbah Mine coal-preparation plant, where it was washed to produce some 90,300 tonnes of product coal which was then shipped in two consignments for testing. One consignment of around 64,300 tonnes was sent to a power station in South Korea and the other of about 26,000 tonnes to a power station in China.

Kevins Corner Coal Project

The project proponent is Hancock Galilee Pty Ltd. This company is currently wholly owned by GVK Coal Developers (Singapore) Pte Limited (part of the GVK Group of India), having been acquired from former owner, Hancock Prospecting Pty Ltd in September 2011.

The principal pre-requisite tenure over the project area is MDL 333. The project area lies to the north of, and adjoins, the Alpha Coal Project outlined above. The Kevins Corner project area is covered by MLA 70425.

This proposal is for the construction of combined open-cut and underground mining operations to collectively produce up to 40 Mtpa of run-of-mine coal from which about 30 Mtpa of saleable thermal coal would be produced for export. Overall, "*a sub-10% ash export thermal product*" is considered to be achievable with some of the coal planned for extraction considered to have "*potential to be marketed without processing*" (Hancock Galilee Pty Ltd, 2011b).

The principal seams targeted for open-cut extraction are the D Seam, and to a lesser extent the overlying C Seam, while only the D Seam will be targeted for the underground operations. A small amount of open-cut production from the A and B Seams is also envisaged, although not until the latter part of the proposed life of the open-cut. The E Seam is not considered to be economically recoverable using either open-cut or underground-mining techniques (Hancock Galilee Pty Ltd, 2011c).

The proposed open-cut component comprises two pits using a combination of draglines and truck/shovel fleets for overburden removal. The underground component of the project plans for the staged development of three separate underground (retreat) longwall mines, with access to the target D Seam via separate surface to in-seam drifts (Hancock Galilee Pty Ltd, 2011d,e).

The coal was noted to have a high propensity for spontaneous combustion (Hancock Galilee Pty Ltd, 2011a).

The thickness of Cenozoic sediments was noted as varying from 5 m to about 60 m (averaging around 40 m) throughout the project area (MDL 333), thinning substantially in the topographically-higher, western part of the project area (Hancock Galilee Pty Ltd, 2011f,g). These sediments unconformably overly either the Lopingian (late Permian) Colinlea Sandstone – Bandanna Formation succession in the eastern and central parts of the project area or the Early Triassic Rewan Formation further to the west.

Estimates of coal resources to support the proposed mining (raw coal *in situ* basis as at March 2010) in the A, B C and D seams in the Kevins Corner project area are listed in the EIS as comprising:

- 230 Mt classified with a ‘Measured’ level of confidence, consisting of some 10, 115, 10 and 95 Mt in the A, B, C and D seams respectively
- 1040 Mt classified with an ‘Indicated’ level of confidence, comprising about 190, 600, 50 and 200 Mt in the A, B, C and D seams respectively.

The estimates were prepared in accordance with the JORC Code, although the edition of the Code and associated Coal Guidelines adopted, was not specified in the report (Hancock Galilee Pty Ltd, 2011i).

Public consultation on the project EIS commenced in the latter part of 2011. In May 2013, the Queensland Coordinator General gave approval for the project to proceed, subject to certain conditions and recommendations and to the joint venture obtaining all other necessary statutory approvals. Environmental approval from the Commonwealth Minister for the Environment was given in December 2013.

The link to the project environmental approval documentation on the Department of State Development website (last viewed August 2017) is
http://www.statedevelopment.qld.gov.au/assessments-and-approvals/kevin-s-corner-project.html

Carmichael Coal Mine and Rail Project

The project proponent is Adani Mining Pty Ltd. The exploration tenure covering the project area is EPC 1690. MLA 70441 covers the same area as the EPC and defines the ground in which the actual proposed mine workings are to be located. MLA 70505 adjoins immediately to the east and covers those areas planned for the placement of spoil and related infrastructure. The environmental approval process for the project has been completed.

The project area is divided by the Carmichael River, an ephemeral tributary of the Belyando River which traverses the southern part of the deposit.

The revised project design as described in the Supplementary EIS (November 2013) is for a series of six open-cut pits—four to the north of the Carmichael River and two to the south. These open-cut pits are proposed to be integrated with an additional five groups of panels (mines) planned for selected seams, which are intended to be mined by underground methods—three north of the river and two to the south. Collectively, these operations are planned to produce 60 Mtpa of saleable thermal coal for export, from an estimated ROM throughput of about 75 Mtpa (Adani Mining Pty Ltd, 2013a,b).

The planned operations span a strike length of more than 40 km. The nominal project life exceeds 40 years. The project area broadly corresponds with the Moray Downs site drilled by the GSQ (Figure 28). As with the other proponents of coal-mining projects further to the south, the seam-nomenclature system that has been adopted in the project area appears to be a variation of that used by Carr (1973a,b, 1974a,b,c, 1976, 1977, 1978).

The principal coal seams that are targeted for mining are various combinations of the A and B seams (the proponent’s AB1, AB2 and AB3 seams) and various discrete seams that occur as splits of the stratigraphically lower D Seam (the proponent’s D1, D2 and D3 seams). Remnant splits of the B Seam and the intervening C Seam are not considered to have commercial potential, owing to the banded nature and resulting high raw ash values of these intervals within the project area. In places, the E and F seams are also planned for open-cut mining (Adani Mining Pty Ltd, 2013c).

The open-cut operations are planned as a series of separate pits located along the strike length of the target coal seams in the project area. Initially, this component of the project is planned as a truck/shovel/excavator-type operation for overburden removal, with consideration to be given to the possibly of introducing draglines at a later stage.

Initial coal production would be from open-cut mining planned to commence in the southern part of the project area, south of the Carmichael River.

The thickness of Cainozoic sediments is noted as averaging in excess of 70 m over the project area, but exceeding 150 m in some areas (Adani Mining Pty Ltd, 2013c).

The underground mines are planned to target only the AB1 and D1 seams. These mines are to be developed as five discrete underground operations using continuous miners for mine development (i.e. driveage of mine roadways and longwall gateroads) on a conventional bord and pillar layout and using the retreat longwall mining method for secondary extraction of coal panels. As designed, the underground mines are to be developed separately from the open-cut operations to the east, with access underground to the target coal seams via surface to in-seam drifts (Adani Mining Pty Ltd, 2013d).

Blending of coals from the various open-cut and underground operations is envisaged, to produce a saleable product considered suitable for export, although a typical product specification is not provided.

The dips of the coal seams are noted as being relatively flat (< 5°) to the west with a number of east–west-trending faults interpreted. The estimated vertical displacements on these structures range between 20 and 40 m (Adani Mining Pty Ltd, 2013c).

Depth of cover over the proposed underground mine areas ranges from about 120 to 450 m for workings in the AB1 Seam and from 100 to 550 m for workings in the stratigraphically lower D1 Seam (Adani Mining Pty Ltd, 2013e).

Estimates of coal in the project area make reference to an internal confidential consultant's report and are listed as comprising:

- 1.16 billion tonnes *in situ* classified as having a 'Measured' level of confidence
- 3.24 billion tonnes *in situ* classified as having an 'Indicated' level of confidence (Adani Mining Pty Ltd, 2013c, nominally compliant with the JORC Code—edition not specified).

Public consultation on the project EIS commenced in the latter part of 2012, with a revision of the mining proposal advised in November 2013 when the Supplementary EIS was submitted. In May 2014, the Queensland Coordinator General gave approval for the project to proceed, subject to certain conditions and recommendations and to the joint venture obtaining all other necessary statutory approvals. Environmental approval from the Commonwealth Minister for the Environment was given in July 2014.

The link to the project environmental approval documentation on the Department of State Development website (last viewed August 2017) is http://www.statedevelopment.qld.gov.au/assessments-and-approvals/carmichael-coal-mine-and-rail-project.html

China Stone Coal Project

The project proponent is Macmines Austasia Pty Ltd, an Australian subsidiary of a group of companies (the Shanxi Mejiin Energy Group Limited) from the People's Republic of China. The pre-requisite exploration tenure incorporating the project area is EPC 987. The project area is situated about 165 km southeast of Pentland and lies immediately to the north of the Carmichael Coal Mine and Rail Project area (Figure 28). A group of five mining lease applications (MLAs 70514, 70515, 70516, 70517 and 70518) currently cover the proposed area of the project.

The Initial Advice Statement for this project was released in September 2012 and the draft EIS became publicly available for comment in July 2015.

The proponent refers to the Lopingian (late Permian) coal-bearing succession in the project area as the Betts Creek beds. Based upon the exploratory drilling undertaken by the proponent since 2011, the coal-bearing portion of this sequence was described as containing coal seams nominally correlated as the A, B, C D, E, F and G seams, with the coal-bearing A to G seam interval as a whole ranging in total thickness from about 90 m in the north of the project area to around 130 m in the south. The interval is described as containing a combined coal thickness of about 35 m (Hansen Bailey Pty Ltd, 2015a).

The Betts Creek beds were described as being "*deeply weathered*", with a lack of coal seams in the weathering profile (Hansen Bailey Pty Ltd, 2015a).

"*Tertiary sediments*" were described as varying in thickness from between 10 to 77 m, but typically being in the range between 30 and 60 m (Hansen Bailey Pty Ltd, 2015b).

The conceptual design for this mining project, as outlined in the draft EIS, involves the staged development of both open-cut and underground mining operations collectively capable of producing about 55 Mtpa of ROM coal, from which a nominal 38 Mtpa of saleable thermal coal would be produced for export (Hansen Bailey Pty Ltd, 2015c). Nominal project life for both Phase 1 (up to year 31) and Phase 2 (years 32 to 49) of the project is estimated at about 50 years (Hansen Bailey Pty Ltd, 2015c,d).

The mine plan envisages the initial development of a multi-dragline open-cut mining operation supported by a truck and shovel pre-stripping fleet, working the A, B and C seams in the southern part of the project area (MLAs 70515 and 70516). This operation is planned to be worked in conjunction with an underground longwall mine, developed on an adjoining, but deeper, section of the C Seam in the south. Depth of cover for the southern underground nominally ranges from between 100 m to about 450 m below the surface. The open-cut operation has an expected life of about 30 years, while the current plan has coal production from the southern underground operation lasting about 13 years.

Two additional underground longwall mines are planned in the northern part of the project area to extract coal from the D Seam initially (partial extraction proposed) and, subsequently, from the A Seam. The proposal allows for a period of about five years for full subsidence to have occurred over the D Seam workings before mining the stratigraphically higher A Seam.

Seams nominally correlated as the E, F and G seams, present beneath the D Seam in the project area, are not planned to be mined owing to a combination of factors which, according to the proponent, make the extraction of these lower seams commercially unviable (Hansen Bailey Pty Ltd, 2015e).

In the northern part of the project area, a significant fault with an estimated vertical displacement of up to 100 m has been interpreted to have a north-northwest–south-southeast trend and a 'normal' sense of displacement downthrown to the east. Vertical displacements apparently diminish significantly at the fault's extremities. This structure limits the planned panel layouts in both of the northern underground mines (Gordon Geotechniques Pty Ltd, 2014).

The most recent public estimate of coal resources were included in the draft EIS for the project. This estimate stated a coal resource of 830 million tonnes in the project area (presumably as raw coal *in situ*) classified with a 'Measured' level of confidence, in addition to about 1230 Mt of coal with an 'Indicated' level of confidence. These estimates were nominally prepared in accordance with the 2012 Version of the JORC Code (Hansen Bailey Pty Ltd, 2015f).

The link to the project environmental approval documentation on the Department of State Development website (last viewed August 2017) is
http://www.statedevelopment.qld.gov.au/assessments-and-approvals/china-stone-coal-project.html

The link to the EIS documentation on the proponent company's environmental consultant's webpage (last viewed August 2017) is http://www.hansenbailey.com.au/hb-other-publications.html
The link to the proponent company's website is http://www.macmines.com/

Conclusions

Stratigraphic nomenclature

The stratigraphic nomenclature of the Galilee Basin is still evolving. A combination of complex outcrop and subsurface relationships exists over large distances in the Galilee Basin (with its three major depocentres) and across the Springsure Shelf into the southwestern Bowen Basin (Denison Trough). The current scheme has developed over a long period, with various investigations tending to focus on small regions in relative isolation without taking into consideration the complex outcrop and subsurface relationships apparent across larger distances, particularly those existing towards the basin margins. This has led to different lithostratigraphic nomenclature (schemes) being applied to the various parts of the Galilee Basin succession.

These nomenclatural schemes are often difficult to relate to one another and also difficult to relate to the other stratigraphic relationships that are currently used for the Springsure Shelf and Denison Trough, suggesting there is a need for a basin-wide re-evaluation of the nomenclatural system currently being used.

Setting aside identification of discrete facies in the basin, more general problems associated with lateral lithostratigraphic relationships and appropriate rock-unit nomenclature remain to be overcome.

The stratigraphic framework of the Lopingian (late Permian) coal-bearing units in the northern Galilee Basin has been developed over time using two different (lithostratigraphic) nomenclatures originating from opposite ends of the Koburra Trough.

Historically, the Betts Creek beds are the preferred nomenclature in the northeast of the basin in the region surrounding its type locality, while the apparent correlative of this unit, the Bandanna Formation/Colinlea Sandstone succession, is the preferred terminology used in the southern Koburra Trough—the latter terminology having been extended across the eastern Springsure Shelf from the Denison Trough (southwestern Bowen Basin) by government geologists in the 1970s.

However, the true nature of the Betts Creek beds and its apparent lateral equivalents further south, the Bandanna Formation and Colinlea Sandstone, remains unclear. Based upon their respective 'type locality'/'type section' descriptions, there appear to be few, if any, significant features that indicate when use of the Betts Creek beds nomenclature would take precedence over use of the Bandanna Formation – Colinlea Sandstone nomenclature (and vice versa). It seems, therefore, that relative proximity to type locality or area may be a primary reason for geologists opting to have chosen one terminology over the other.

In the case of the Colinlea Sandstone, apart from, as the name suggests, representing a prominent sandstone unit, the type section description offers very little assistance in determining whether or not part of it may be a possible lateral correlative with a part of the Betts Creek beds, since no coal has been described in it, and yet, in the southern and central parts of the Koburra Trough of the northern Galilee Basin, coal seams are noted as being present. Instead, it appears that it is the quartz-rich composition and presence of granule-pebble-cobble conglomerate beds, which seem to be a dominant feature, characterising the unit in type section. The situation is further confused with some workers in the Galilee Basin (towards the west of the basin and at Hyde Park, for example) noting the existence of 'the Colinlea Sandstone' beneath the Betts Creek beds.

In terms of the stratigraphy associated with the late Permian coals within the northern Galilee Basin, the current stratigraphic framework seems relatively poorly defined, suggesting that the lithological description given for the type localities are not 'typical' of the units in the subsurface. This has resulted in uncertainty and inconsistent use by geologists.

It is apparent, therefore, that the stratigraphic framework of the northern part of the Galilee Basin, or at least the coal-bearing late Permian portion of it, requires review in order to provide a more robust stratigraphic framework that can be applied consistently by industry.

Recent work by the Earth Sciences Department (University of Queensland) and Geoscience Australia has also highlighted the need for further review of the currently used formation and coal seam nomenclatures in the Koburra Trough. Their initial studies used the tuffaceous nature of the late Permian coal-bearing units—in particular a tuffaceous marker horizon associated with what they have correlated as the "C seam", as a regional marker for their correlations (west to east) across the Koburra Trough. This work, together with preliminary results more recently published of zircon dating in tuffaceous strata, has resulted in these researchers proposing alternative relationships between the coal-bearing sequences in the northern Galilee Basin and those in the Bowen Basin.

The cumulative thickness of coal development in the Koburra Trough varies both along strike and downdip, with the greatest thickness of coal development evident in the vicinity of ENL Lake Galilee 1, located down-dip of the Moray Downs area drilled by the department in the 1970s. There is, however, relatively poor development of the coal facies south of the Barcaldine Ridge.

In comparison to the Bowen Basin, the Galilee Basin has undergone significantly less structural deformation. Along the eastern flank of the Koburra Trough, only a few large scaled fault structures with estimated throws of between 100 to 200m have been interpreted in the subsurface, based upon private sector coal exploration drilling. Indications are, however, that at a mine scale, relatively small-scaled faulting, with displacements of several times seam thickness, can be expected. Along the eastern flank of the Koburra Trough, regional dips of the late Permian coal seams are regarded as being relatively flat (<5°) to the west or southwest, dependent upon locality.

The coal seam nomenclature system used by most coal exploration companies are variants (allowing for localised splitting and coalescence of coal seams) of the naming scheme first used by Allan Carr in reporting on the departmental coal reconnaissance drilling program undertaken in the 1970s.

Coal quality

The Lopingian age coals of the northern Galilee Basin are non-coking, low in rank and regarded as not being particularly well suited to liquefaction, although, over a small area southwest of Alpha, some of the coal seams are associated with high yielding torbanites and cannel coals.

The coal analytical dataset presented and reviewed comprises analyses of around 500 samples of nearly 200 coal seam intervals sampled during the departmental 1970s coal drilling program. The dataset incorporates calculated seam composite analyses for those parameters that were able to be theoretically mass proportioned. Seam correlations were not attempted.

Proximate analyses results on the floats 1.90 fraction showed little variation in the air dry basis (ad) values of Inherent Moisture, Ash, Volatile Matter and Fixed Carbon. Of these parameters, Ash (17.5 ± 6.1% adb) and Fixed Carbon (45.5 ± 4.2% adb) showed the highest variability, while Moisture (9.5 ± 1.7% adb) and Volatile Matter (27.6 ± 2.6% adb) values are quite consistent.

Few trends are obvious based on this dataset, although Volatile Matter content values (dry, ash free basis on floats 1.90 fraction) show a slight decrease from south to north. This may be due to a combination of factors of either coal rank and/or maceral composition.

Specific Energy values of the Floats 1.90 fraction (all samples) averaged around 5500 Kcal/kg (air dry basis) which is equivalent to 7500 Kcal/kg (dry, mineral-matter free basis).

Of the dataset reviewed, the Total Sulphur content of the coal seams is generally low over most of the eastern flank of the Koburra Trough (mean 0.3 ± 0.12% adb Floats 1.90 fraction). In the south, at the western edge of the Springsure Shelf, however, high sulphur values have been noted (average of ~0.9% adb) for the coals being considered for mining in that region.

Based on the dataset reviewed, these coals generally classify with no higher rank than High-volatile B bituminous, in accordance with the ASTM classification system (Standard D388-12) and are sub-hydrous according to Seyler's (1933) classification.

Along the eastern flank of the Koburra Trough, the rank of the coals, as measured by the mean maximum of vitrinite in oil, increases northwards from about 0.4% in the region around Alpha, to more than 0.6% around Pentland.

Data on a regional scale regarding the maceral group composition of the coals is very limited, although the available information suggests the coals have a higher vitrinite content in the southern part of the Koburra Trough than in the north, where inertinite appears to be dominant.

The coals are known to be have a propensity for spontaneous combustion—a factor that will require careful management particularly during mining at the scale presently proposed. Large tonnages of coal equate to large coal stockpiles at all stages of the transportation chain—each one presenting a potential spontaneous-combustion risk.

Coal exploration

Early coal exploration in the northern Galilee Basin dates from the late nineteenth century and was mainly limited to the areas of outcrop in the region around Hughenden, where occurrences of fossiliferous strata and coal had been noted. Much of this early work was undertaken by government geologists and included reports by E.O. Marks, J.H. Reid and C.C. Morton.

Based on these and other reports, during the first half of the twentieth century, attempts by the private sector to find coal seams in the region that were suitable to support a viable mining operation proved unsuccessful.

Petroleum exploration, undertaken in the 1960s in the deeper parts of the Koburra Trough, noted the presence, at depth, of Permian coals, although very little was known about the properties of these coals at that stage.

Recognising the potential of the northern Galilee Basin, at a time when significant coal exploration was being undertaken in the Bowen Basin, the Queensland Government offered two separate releases of land for coal exploration in the mid- and late 1970s, augmented by a regional coal-reconnaissance drilling program that was undertaken by the GSQ. This generated initial interest from the private sector in the coal potential of the region.

Sporadic coal exploration by the private sector followed for thirty years or so, centred on only a few localities along the eastern flank of the Koburra Trough, until global demand for coal around mid-2006 regenerated interest in the region's coal potential. A number of proposals to develop some very large-scale coal mining projects to supply thermal coal for export has been the result—most, as a combination of open-cut and mechanised longwall mining operations.

These projects (south to north order) are:

- South Alpha Coal Project
- Galilee Coal Project (Northern Export facility)

- Alpha Coal Project
- Kevins Corner Project
- Carmichael Coal Mine and Rail Project
- China Stone Coal Project.

Up to six or, depending on locality, seven coal intervals (A to G in descending stratigraphic order) have been recognised in the Lopingian (late Permian) sequence along the eastern flank of the Koburra Trough, although not all are planned to be mined. The seams regarded as being of principal commercial interest at the present time vary from north to south between projects, although the validity of, and consistency between, coal seam correlations applied by the different companies for each project area has not been verified at this time.

The combined (maximum) output of saleable production from all currently planned projects would amount to more than 200 Mt of thermal coal. The Ash values of the proposed saleable product coal vary between projects, ranging from between about 9.5% and 13.5% adb.

Current estimates of coal, identified by the project proponents as having either a Measured or Indicated level of confidence to support these projects, collectively total more than 10 billion (x 10^9) tonnes of raw coal *in situ*. Additionally, very large tonnages of coal have been classified as Inferred.

The eastern flank of the northern Galilee Basin is an extensive and emerging coal province, where a number of very large-scale mining projects are planned for development. However, there are yet-to-be resolved inconsistencies in stratigraphic interpretation of the potentially economic coal-bearing Lopingian sequence in the Koburra Trough. Further geological studies and research work will help to establish a more robust stratigraphic framework that will offer consistency to exploration and mining companies and assist with unlocking the potential of coal resources present there.

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Acknowledgments

The idea of conducting a ‘coal-focussed’ review of the northern part of the Galilee Basin was initiated by the Geological Survey of Queensland in early 2014. Coming off a period of extensive coal exploration by the private sector within the eastern Koburra Trough, it seemed the logical first step in trying to determine where deficiencies lay in our current understanding of the stratigraphic framework of the region and in particular, the geology and properties of the prospective late Permian coals seams present there.

In view of the fact that a number of very large-scaled coal mining projects to extract these coals were then and are still being contemplated, it was the intention that this review would help to direct further effort by the GSQ, in order to develop a better regional understanding of these coal seams and the rock units associated with them.

Although the time taken to complete the task has been considerably longer than first anticipated, it was greatly assisted by the reformation of the Coal Geoscience Unit within the GSQ in May 2015, which gave much needed impetus to the completion of the task.

The scope of the project has also expanded somewhat with a decision made in the latter part of 2015 to re-present all of the coal analytical data obtained from the departmental coal reconnaissance drilling program undertaken in the 1970s, and also to include for the first time (where possible) calculated composite analyses for all of the coal seams sampled during that program. To complete this part of the project, the authors gratefully acknowledge the very valuable advice and assistance given by Ray Smith, a former GSQ colleague.

At various stages during preparation of the manuscript, critical review and comment was provided by a number of geoscientists within the GSQ—namely; David Green, Manager Coal Geoscience Unit; Russell D’Arcy, Principal Coal Geologist, Coal Geoscience Unit; Sarah Sargent, Geoscientist, formerly with the Coal Geoscience Unit, and Sally Edwards, Geoscientist. Their collective efforts are greatly appreciated and acknowledged with thanks.

Acknowledgement also must go to Laura Phillips, University of Queensland, Department of Earth Sciences, for her contribution to the section on stratigraphy.

The contribution of Dr Paul Blake, Geoscientist, Coal Geoscience Unit within the GSQ is also acknowledged with thanks for providing the images and accompanying captioned geological notes used for the Plates presented in the document; taken during a field excursion into Porcupine Creek (Galah) Gorge in May 2017 (Blake & Coffey, in preparation).

Thanks also to Liam Hogan, formerly of the Spatial and Graphics Services Unit within the GSQ and Gina Nuttall, also in that work unit, for their diligent efforts in preparing the accompanying figures and drawings. Final editing of the manuscript and compilation of this review was completed by Sharon Beeston from within the same work unit.

While the authors, as four geoscientists with the GSQ, have assumed joint authorship of this review as the culmination of their collective work over the past three years, in reality, its compilation has been the result of the collaborative efforts of a good many talented geoscience and technical professionals, both past and present, affiliated with the GSQ.

Finally, in acknowledgment of the work undertaken by the Coal Section of the GSQ, two unpublished GSQ memoranda written by Allan (A.F.) Carr in April 1975 and April 1976 are presented as Appendices 16 and 17, respectively, outlining his geological assessment of the ‘Late Permian’ coals of the Galilee Basin and his assessment at that time of the potential for future coal mining in the region.

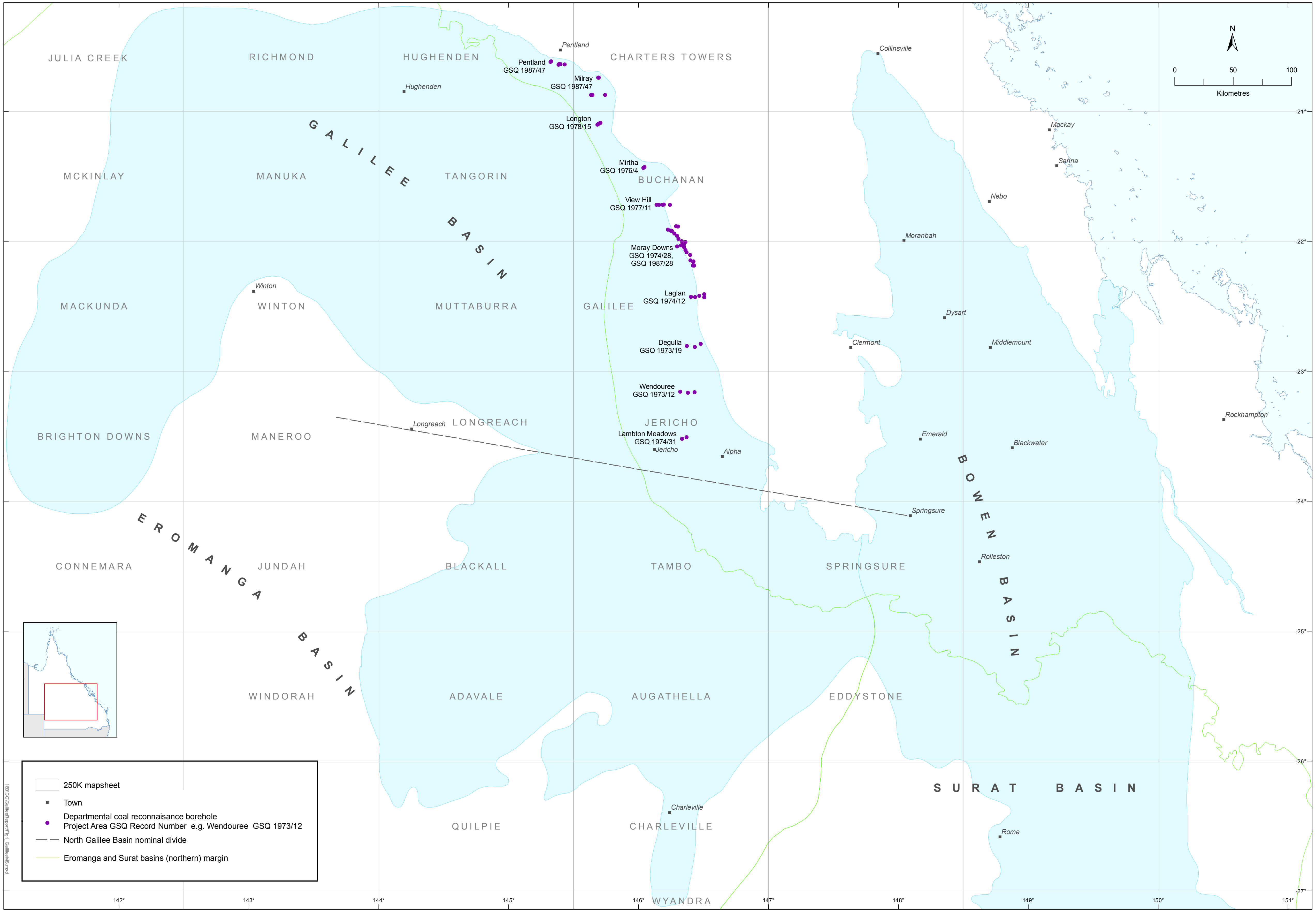


Figure 1. 1:250 000 map sheet index, Galilee Basin.

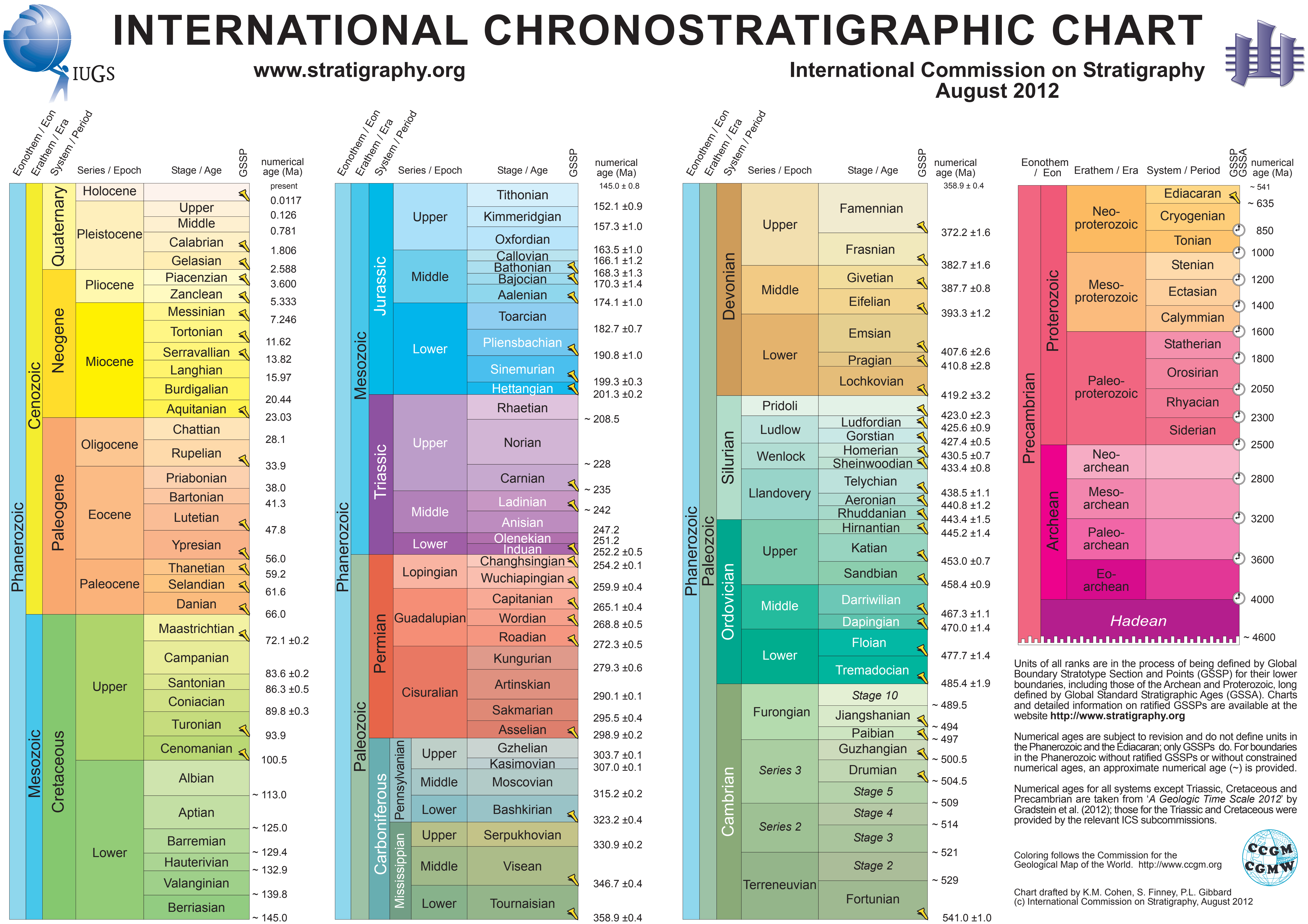
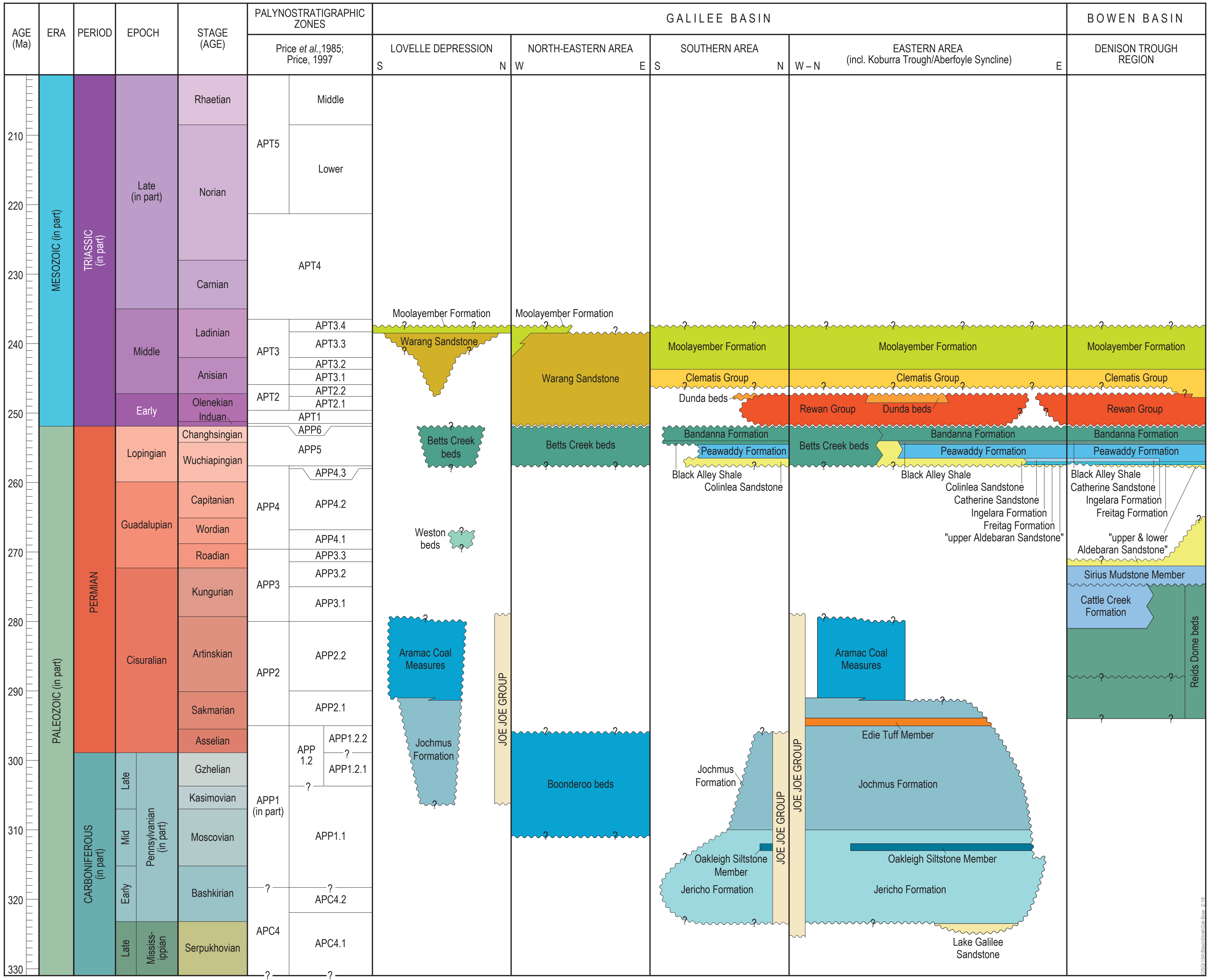


Figure 2. The ICS International Chronostratigraphic Chart (Gradstein et al., 2012).



Timescale after Gradstein *et al.* (2012). Compiled by JL McKellar (Feb 2016).

Figure 3. Stratigraphic correlations, Galilee Basin and western flank of the Bowen Basin.

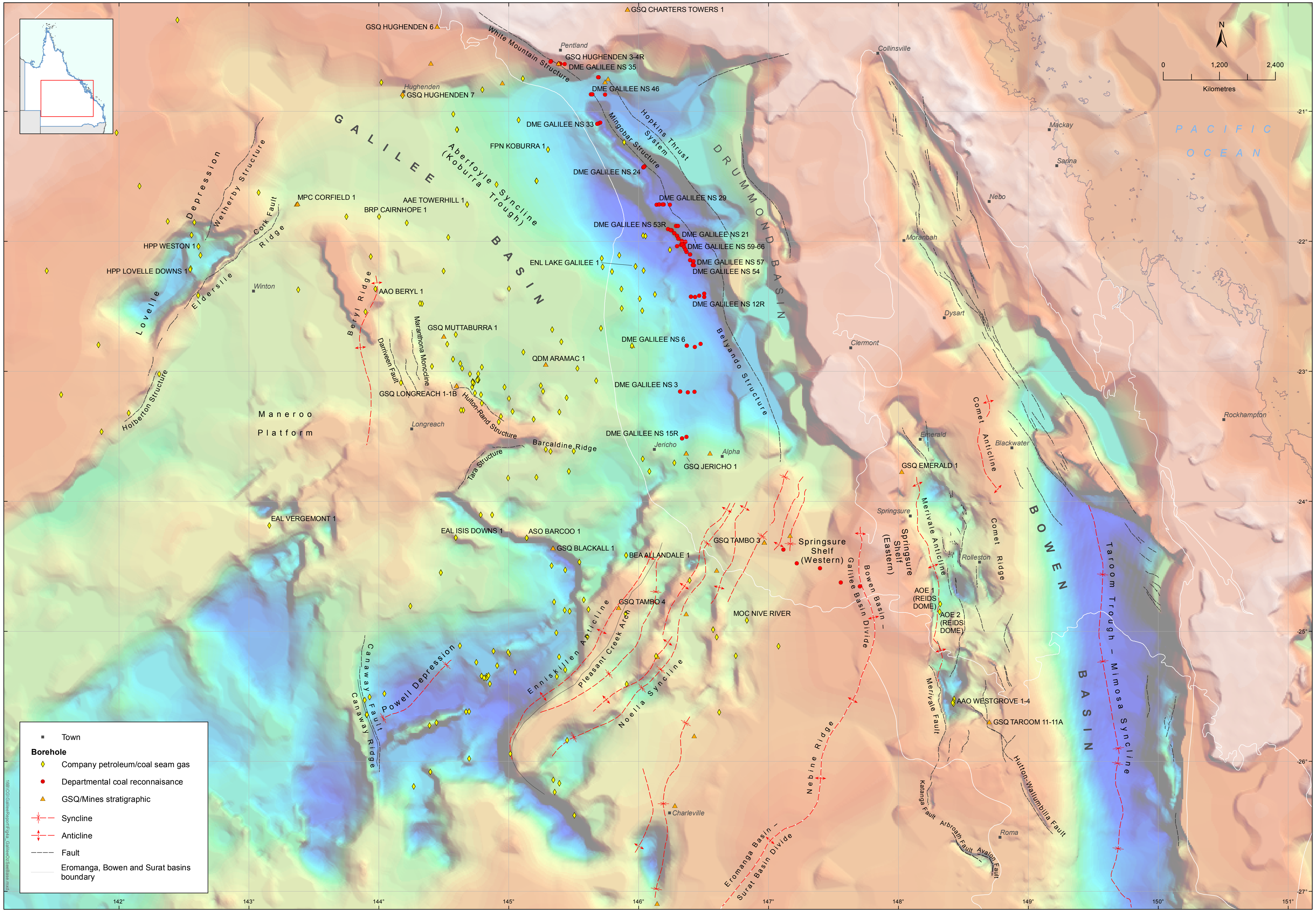


Figure 4a. Structural elements and setting, Galilee and Bowen basins, plotted over Australian Phanerozoic OZ SEEBASE (2005). Note: The colours in the SEEBASE background are blue for deep basement graduating to brown-orange for shallow basement.

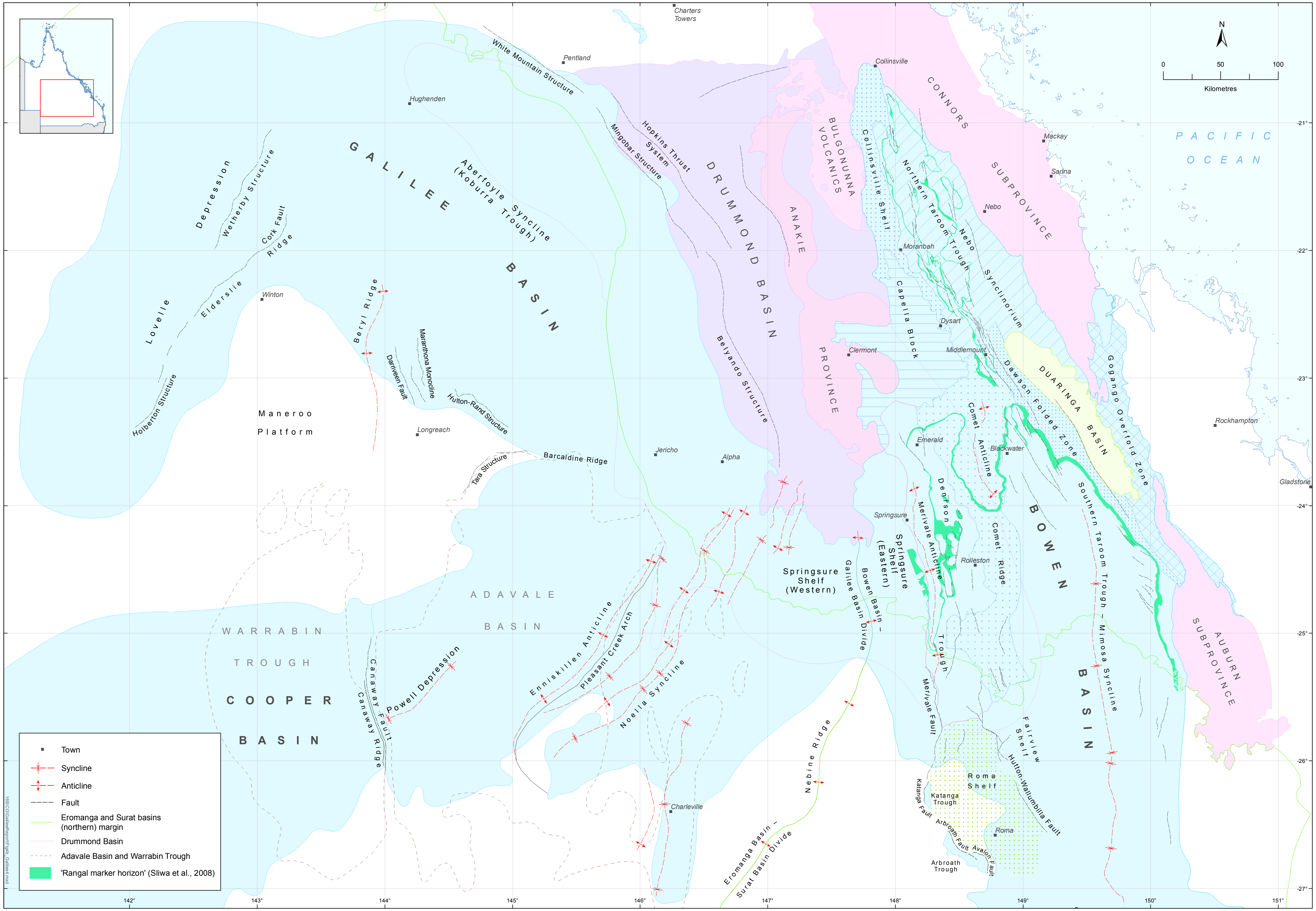


Figure 4b. Structural elements and setting, Galilee and Bowen basins.

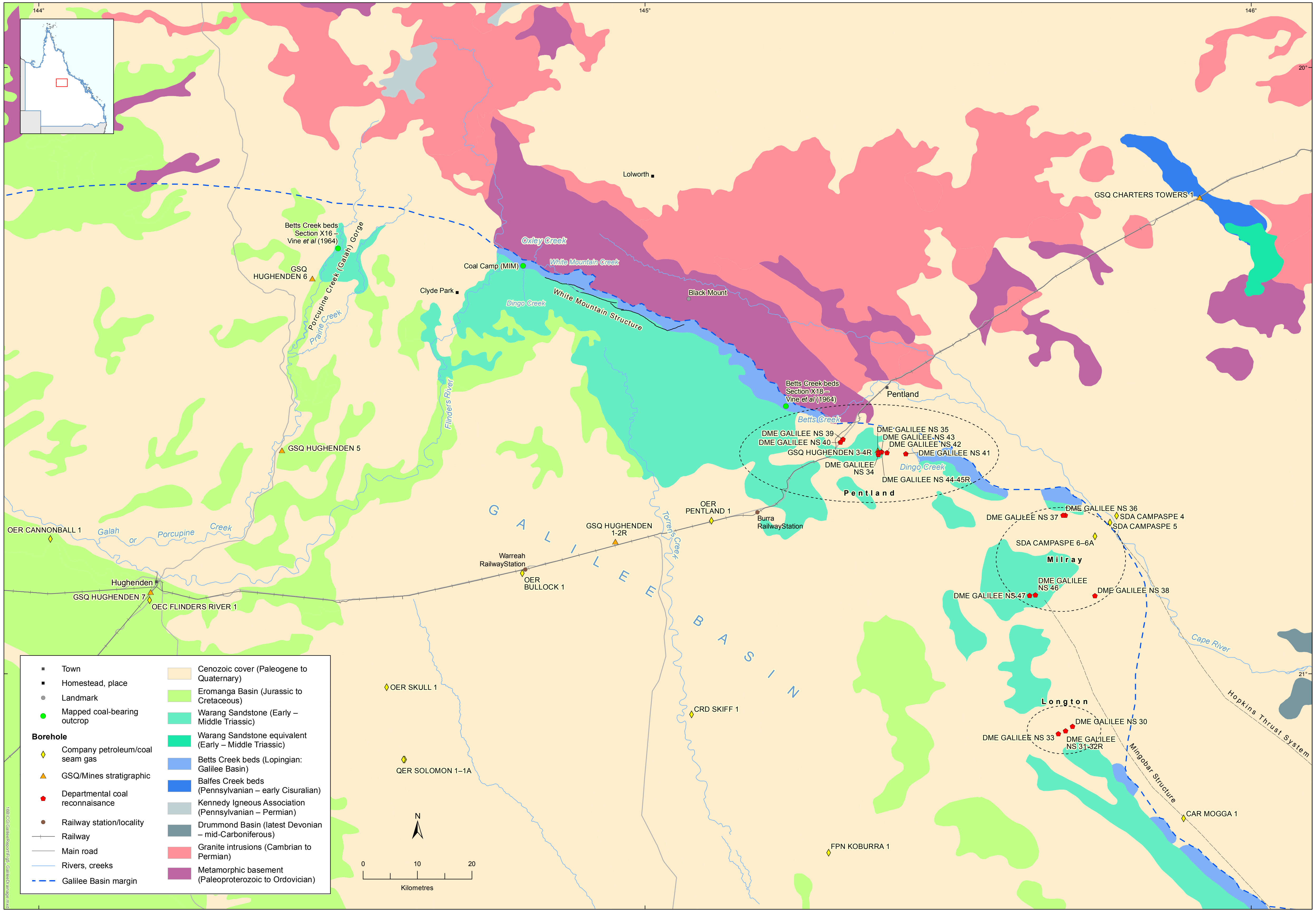


Figure 5. Generalised surface geology, Hughenden-Pentland region, northern Galilee Basin.

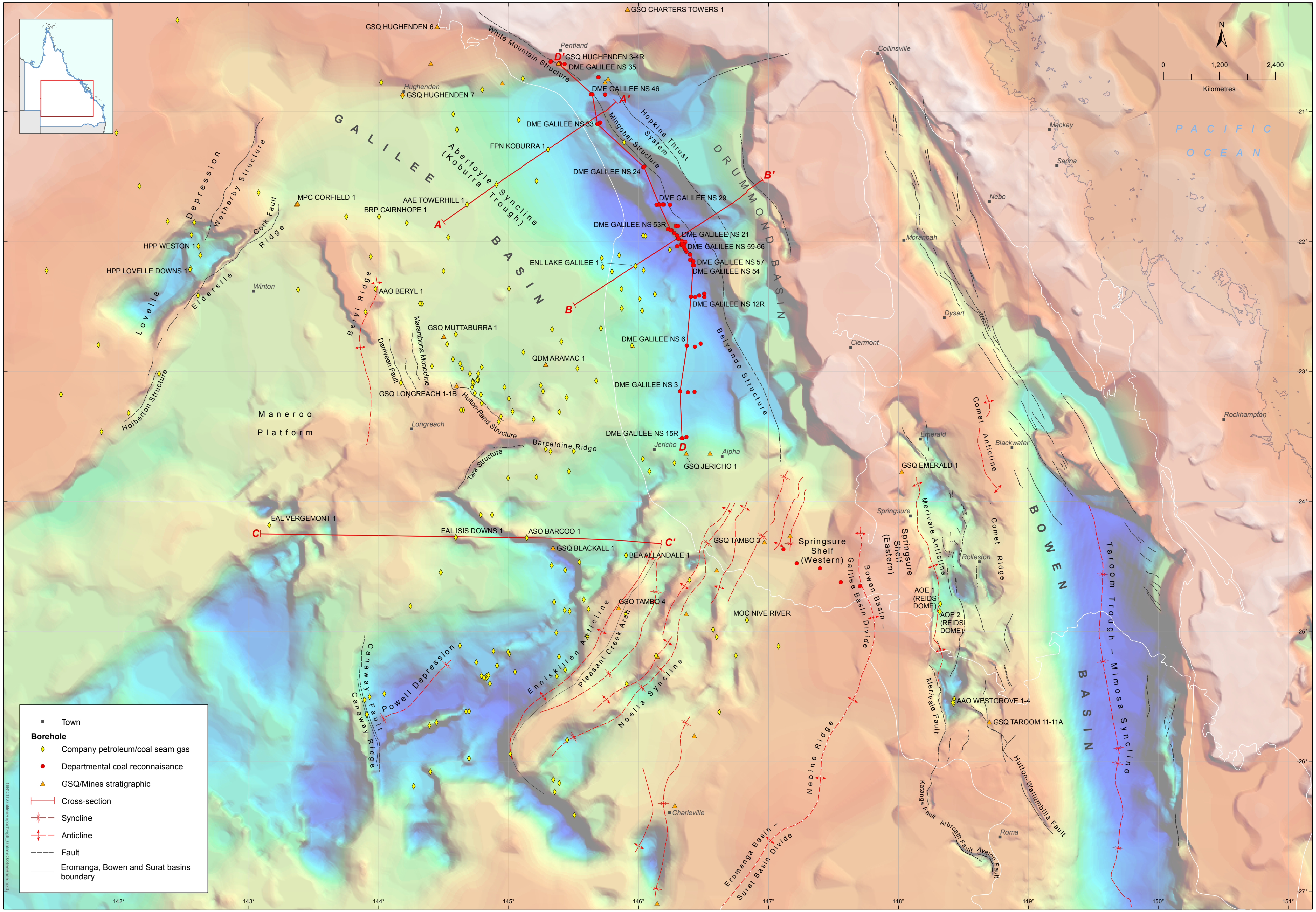


Figure 6. Cross section locations.

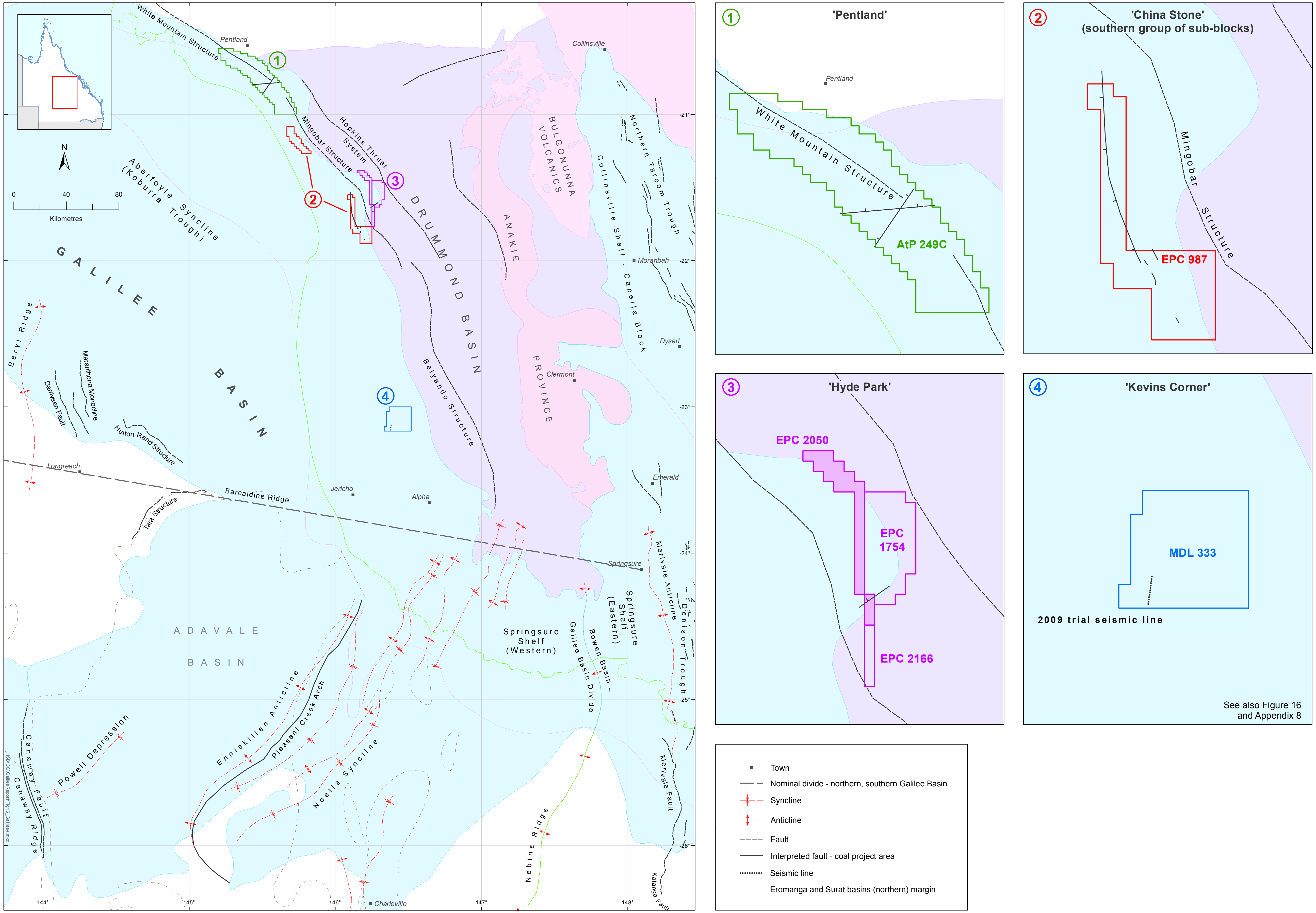


Figure 15. Local structure—eastern margin.

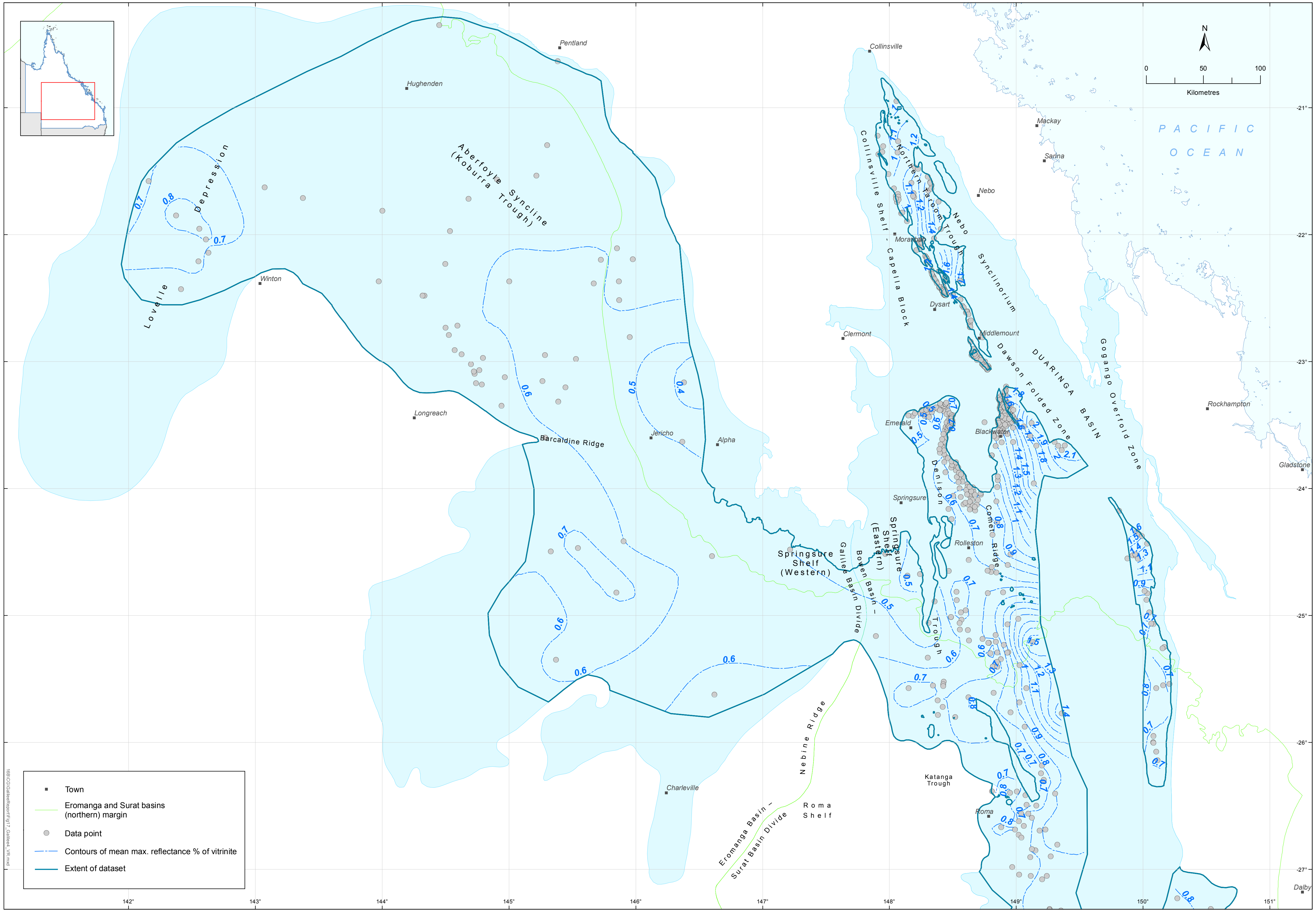


Figure 17. Spatial distribution of vitrinite reflectance of Group V coals based on departmental data (after McKillop, 2016).

Table 4. Raw coal seam composite coal analyses, AtP 249C, Pentland.

Borehole No (100 mm core samples)	Easting (metres) Aust. Mapping Grid (Datum: AGD 1966)	Northing (metres) Aust. Mapping Grid (Datum: AGD 1966)	Collar Elevation (metres above Mean Sea Level) (Datum: Australian Height Datum)	Total Depth (metres)	QDEX Reference	Date Drilled	Composite Sample No (as reported)	Composite Sample Details
PE 159A	328 860	7 719 699	484.38	149.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 159A Composite 1	Comprises four discontiguous coal intervals from 85.86m to 86.97m (sample No 4), 87.39m to 89.13m (sample Nos 6 & 7), 95.67m to 97.11m (sample No 16) and 97.82m to 98.45m (sample No 18), intervening stone partings excluded from composite
							PE 159A Composite 2A	103.44 m to 112.54M (sample Nos 25 to 36 inclusive)
							PE 159A Composite 2B	115.77m to 120.15m (sample Nos 42 to 45 inclusive)
							PE 159A Composite 3	Comprises two discontiguous coal intervals from 134.4m to 135.89m (sample Nos 54 & 55) and 138.41m to 139.3 m (sample Nos 59 to 61 inclusive), intervening stone partings excluded from composite
PE 212A	329 878	7 718 526	463.69	126.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 212A Composite 2A	67.56m to 71.49m (sample Nos 3 to 6 inclusive)
							PE 212A Composite 2B	75.55m to 79.51m (sample Nos 9 to 15 inclusive)
PE 215A	331 220	7 716 688	444.33	143.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 215A Composite 1	Comprises three discontiguous coal intervals from 51.96m to 52.8m (sample No 6), 54.02m to 54.87m (sample No 8) and 55.9m to 57.03m (sample No 10), intervening stone partings excluded from composite
							PE 215A Composite 2 (RCC*)	60.90m to 73.90m (sample Nos 16 to 35 inclusive)
							PE 215A Composite 3A (RCC*)	129.58m to 131.33m (sample Nos 47 to 49 inclusive)
							PE 215A Composite 3B (RCC*)	Comprises two discontiguous coal intervals from 122.79m to 125.68m (sample Nos 38 to 42 inclusive), 128.58m to 129.03m (sample 45), intervening stone band excluded
PE 255A	330 475	7 720 024	462.2	68.00	CR 12781 (geological logs and plan); CR 13306 Appendices 1 & 2 (coal analyses)	Sep-83	PE 255A Composite 1 (RCC*)	28.06m to 30.2m (sample Nos 3 to 5 inclusive)
							PE 255 Composite 2A	32.51m to 38.24m (sample Nos 9 to 16 inclusive)
							PE 255A Composite 2B (RCC*)	43.76m to 54.54m (sample Nos 26 to 35 inclusive)
							PE 255A Composite 2C (RCC*)	Comprises two discontiguous coal intervals from 39.09m to 40.43m (sample Nos 18 and 19) and 42.26m to 43.76m (sample Nos 24 and 25), intervening stone parting excluded from composite
							PE 255A Composite 3D	54.54m to 58.89m (Sample Nos 36 to 43 inclusive)
							PE 255A Composite 3E	58.89m to 60.53m (sample Nos 44 to 46 inclusive)
							PE 255A Composite 3D+3E	Comprises a composite of two contiguous composite samples for the interval from 54.54m to 60.53m (sample Nos 36 to 46 inclusive)
								Laboratory reference sample (No 2), reported as being known to have a high propensity to spontaneously ignite
								Laboratory reference sample (No 5), reported as being known to have a low propensity to spontaneously ignite

Borehole No	Composite Sample No (as reported)	Crossing Point Temp (°C)	Rv max - Mean Max Reflectance Vitrinite	Proximate Analysis % adb				Specific Energy MJ/kg adb	Total Sulphur % adb	Moisture Holding Capacity % adb	Relative Density g/cm³	Hardgrove Grindability Index^ adb	Chlorine % adb	Phosphorus % adb
				Ash	Moisture	Volatile Matter	Fixed Carbon							
PE 159A	PE 159A Composite 1	139	–	36.5	8	21.7	33.8	16.70 (30.10)	0.39	12.1	1.72	54 (43)	0.05	0.01
	PE 159A Composite 2A	144	–	30.5	8.2	21.3	40.0	18.32	0.18	11.6	1.59	70 (45)	0.02	0.004
	PE 159A Composite 2B	143	–	20.4	10	23.4	46.2	21.34	0.21	13.2	1.53	64 (49)	0.03	0.004
	PE 159A Composite 3	–	–	23.5	10.7	24.8	41.0	30.46	0.36	13.0	1.51	61 (51)	0.02	0.003
PE 212A	PE 212A Composite 2A	154	–	29.1	7.6	21.9	41.4	18.46	0.2	12.3	1.61	72 (46)	0.02	0.005
	PE 212A Composite 2B	146	–	31.6	7.8	21.1	39.5	17.95	0.28	11.9	1.67	71 (49)	0.05	0.024
PE 215A	PE 215A Composite 1	140	–	42.0	6.8	21.4	29.8	15.06	0.36	11.1	1.74	65 (40)	0.03	0.007
	PE 215A Composite 2 (RCC*)	143	–	31.7	8.3	29.4	30.6	17.94	0.25	12.1	1.62	74 (48)	0.03	0.005
	PE 215A Composite 3A (RCC*)	136	–	26.6	8.4	31.0	34.0	20.08	0.36	11.7	1.59	60 (45)	0.04	0.006
	PE 215A Composite 3B (RCC*)	142	–	33.4	7.9	31.1	27.6	17.16	0.40	12.5	1.68	62 (51)	0.01	0.006
PE 255A	PE 255A Composite 1 (RCC*)	145	–	43.7	7.0	20.9	28.4	13.86	0.39	11.7	1.80	58 (52)	0.02	0.236
	PE 255 Composite 2A	147	–	34.9	7.5	20.7	36.9	16.88	0.30	11.7	1.7	70 (49)	0.04	0.006
	PE 255A Composite 2B (RCC*)	135	–	23.7	8.5	24	43.8	20.46	0.34	12.0	1.59	64 (49)	0.04	0.007
	PE 255A Composite 2C (RCC*)	147	–	34.0	6.9	21.0	38.1	17.10	0.27	11.1	1.69	67 (45)	0.04	0.011
	PE 255A Composite 3D	–	–	28.5	8.1	25.3	38.1	18.90	0.45	12.4	1.62	60 (48)	0.02	0.007
	PE 255A Composite 3E	–	–	37.7	6.5	19.8	36.0	16.44	0.42	12.3	1.71	68 (48)	0.04	0.009
	PE 255A Composite 3D+3E	142	–	35.5	6.0	23.4	35.1	16.98	0.46	12.3	1.7		0.02	0.009
		146	0.71%											
		200	1.36%											

Borehole No	Composite Sample No (as reported)	Ash Fusion Temperatures °C (Reducing Atmosphere)				Ultimate Analysis % adb				Forms of Sulphur % adb		
		Initial Deformation	Spherical	Hemispherical	Flow	Carbon	Hydrogen	Nitrogen	Oxygen	Pyritic	Sulphate	Organic
PE 159A	PE 159A Composite 1	1510	1570	1590	>1600	42.70	2.60	0.88	8.93	0.263	0.003	0.124
	PE 159A Composite 2A	>1600	>1600	>1600	>1600	47.60	2.72	0.97	9.83	0.085	0.014	0.081
	PE 159A Composite 2B	>1600	>1600	>1600	>1600	54.60	2.68	1.14	10.97	0.001	0.013	0.116
	PE 159A Composite 3	>1600	>1600	>1600	>1600	–	–	–	–	0.154	0.021	0.185
PE 212A	PE 212A Composite 2A	>1600	>1600	>1600	>1600	48.63	2.39	1.07	11.01	0.052	0.003	0.145
	PE 212A Composite 2B	>1600	>1600	>1600	>1600	46.83	2.65	0.98	9.86	0.067	0.008	0.205
PE 215A	PE 215A Composite 1	1470	1540	1550	1600	39.03	2.31	0.78	8.72	0.131	0.009	0.220
	PE 215A Composite 2 (RCC*)	1560	>1600	>1600	>1600	46.22	2.46	0.97	10.10	0.086	0.007	0.157
	PE 215A Composite 3A (RCC*)	>1600	>1600	>1600	>1600	51.44	2.82	1.07	9.31	0.215	0.010	0.135
	PE 215A Composite 3B (RCC*)	1590	>1600	>1600	>1600	43.45	2.83	0.94	11.08	0.192	0.012	0.196
PE 255A	PE 255A Composite 1 (RCC*)	>1600	>1600	>1600	>1600	35.44	3.08	0.69	9.70	0.012	0.085	0.293
	PE 255 Composite 2A	>1600	>1600	>1600	>1600	44.35	2.05	0.90	10.02	0.110	0.010	0.180
	PE 255A Composite 2B (RCC*)	>1600	>1600	>1600	>1600	52.66	2.95	1.13	10.72	0.182	0.009	0.149
	PE 255A Composite 2C (RCC*)	>1600	>1600	>1600	>1600	43.93	2.47	0.90	11.53	0.115	0.012	0.143
	PE 255A Composite 3D	>1600	>1600	>1600	>1600	48.45	3.06	1.03	10.41	0.126	0.017	0.307
	PE 255A Composite 3E	>1600	>1600	>1600	>1600	43.87	2.27	0.88	8.36	0.126	0.021	0.273
	PE 255A Composite 3D+3E	>1600	>1600	>1600	>1600	43.79	2.61	0.95	10.69	0.204	0.021	0.235

Borehole No	Composite Sample No (as reported)	Ash Analysis % Reported on the "ignited basis @ 815°C"													
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	Mn_3O_4	SO_3	P_2O_5	BaO	SrO	ZnO
PE 159A	PE 159A Composite 1	75.8	18.3	3.68	0.21	0.15	0.05	0.13	0.76	0.07	0.02	0.040	0.04	<0.001	0.03
	PE 159A Composite 2A	64.6	32.2	0.53	0.26	0.08	0.02	0.09	1.45	0.01	0.01	0.039	0.03	0.006	0.02
	PE 159A Composite 2B	58.4	37.6	0.68	0.26	0.09	0.04	0.10	2.38	0.01	<0.01	0.064	0.04	0.001	0.05
	PE 159A Composite 3	57.1	39.3	0.93	0.27	0.11	0.04	0.25	1.41	0.01	0.02	0.079	0.03	0.010	0.05
PE 212A	PE 212A Composite 2A	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	PE 212A Composite 2B	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PE 215A	PE 215A Composite 1	78.6	15.3	3.92	0.19	0.18	0.05	0.19	0.76	0.08	0.01	0.038	0.05	<0.01	0.05
	PE 215A Composite 2 (RCC*)	66.9	28.8	1.47	0.27	0.16	0.06	0.38	1.15	0.01	0.06	0.039	0.02	0.009	0.05
	PE 215A Composite 3A (RCC*)	63.6	33.5	0.81	0.22	0.13	0.05	0.15	1.57	0.01	0.01	0.053	0.03	0.005	0.06
	PE 215A Composite 3B (RCC*)	70.3	27.3	0.70	0.13	0.09	0.03	0.12	1.37	0.01	<0.01	0.039	0.03	0.009	0.08
PE 255A	PE 255A Composite 1 (RCC*)	60.3	37.6	0.96	0.13	0.08	0.03	0.15	0.91	0.02	0.02	0.046	0.01	0.009	0.06
	PE 255 Composite 2A	64.3	32.4	0.61	0.15	0.06	0.03	0.07	1.35	<0.01	<0.01	0.039	0.03	<0.001	0.04
	PE 255A Composite 2B (RCC*)	61.4	34.7	1.01	0.22	0.10	0.05	0.34	2.14	<0.01	0.02	0.064	0.04	0.001	0.11
	PE 255A Composite 2C (RCC*)	59.1	37.9	0.58	0.14	0.05	0.03	0.08	2.28	<0.01	<0.01	0.072	0.03	0.014	0.06
	PE 255A Composite 3D	58.3	39.3	0.79	0.14	0.04	0.03	0.15	1.04	<0.01	0.02	0.064	0.04	0.001	0.11
	PE 255A Composite 3E	57.9	38.4	1.06	0.14	0.08	0.03	0.31	1.48	<0.01	0.01	0.053	0.02	<0.001	0.11
	PE 255A Composite 3D+3E	57.8	38.6	1.20	0.13	0.07	0.03	0.19	1.13	<0.01	<0.01	0.058	0.02	0.012	0.07

Note: Denotes composite sample comprised of discontiguous coal intervals, intervening stone partings excluded

*'RCC' (raw coal composite) Note: Laboratory analytical results for the Crossing Point Temperature determination results have been reported with the suffix tag 'RCC'. All other laboratory analytical results for this composite sample number have been reported without the 'RCC' tag corresponding with those listed in the sample details table.

^HGI values: the number in brackets is the percentage of the original sample material retained on the 600 micron screen during the sample preparation procedure in order to make the 'granular' size fraction (1.18mm x 600 micron) for testing in the HGI apparatus as required by AS 1038,20-1981. This requirement was dispensed with in the revised standard, AS 1038.20-1992.
Source: Murphy, 1984b (Appendices 1 & 2; CR13306)