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RANGAL SUPERMODEL 2015: THE RANGAL-BARALABA-BANDANNA COAL MEASURES IN THE BOWEN AND GALILEE BASINS

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ACARP

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The Rangal-Baralaba-Bandanna Coal Measures in the Bowen and Galilee Basins

For *ACARP*

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EXECUTIVE SUMMARY

The ACARP Project C22028 Rangal Supermodel 2015, compiled over 7000 company boreholes supplemented by more than 1000 open file petroleum (mostly CSG) wells to develop a regionally consistent stratigraphy for the Rangal-Baralaba-Bandanna Coal Measures in the Bowen Basin and the Galilee Basin. In the Galilee Basin. The results are presented as a series of cross sections and maps that illustrate the regional scale distribution of major coal seams and their interburdens. This exercise resulted in a revised stratigraphy and confirmation of the relationship between the Betts Creek beds and the Late Permian coal measures in the Bowen Basin, confirmed through age dating. The Yarrabee Tuff was correlated regionally and samples from mine sites and drill holes returned a consistent CA-IDTIMS date of 252.88 ± 0.07 Ma. More detailed dating from a single location confirmed reproducibility and suggests that the Yarrabee Tuff event was akin to a small super volcano that could have been instantaneous, or else erupted over a 40,000 to 70,000 year time period. The geochemistry was quite evolved but the silicic nature of the tuff could also reflect its deposition and alteration in acidic peat mires. Regardless, it corroborates the long-lived periods of low siliciclastic sediment input and basin stability resulting in laterally extensive peat mires that form the Rangal and equivalent coals. The late Permian Rangal-Baralaba-Bandana coal measures formed in less than 1 MY, and their thickness preserved in the Nebo Synclinorium is less than 120m whereas that in the eastern Taroom Trough is over 220m. Isopach maps of the underlying Fort Cooper Coal Measures (including the Black Alley Shale) show a shift in depocentre from west along the strike of the basin to southeast in the Taroom Trough in response to foreland loading. This loading continued, resulting in the accumulation of over 1600m of the overlying Permian to Triassic Rewan Group sediments. Isopach maps of the Late Permian and Triassic corroborate early interpretation of the basin axis extending due north, parallel to the Marlborough Thrust that would have been active at that time. The base of the Rewan in Galilee and western limb of the Bowen Basin is floored by a 1 to 10m thick carbonaceous mudstone that transitions upward into the thinly interbedded, red and green siltstones and sandstones commonly associated with the Rewan Group. This sequence continues to coarsen upward into thicker, lithic sandstones that collect on the western margin to form the wide and thick belt of the erosively based, often conglomeratic Sagittarius Sandstone. This coarsening upwards transition suggests a base level rise that drowned the coal measures regionally, perhaps even across the Anakie Inlier and Springsure Shelf, most likely in response to down-warping of the foreland basin before the massive influx of sediment from the rising hinterland and the change to more arid climate culminated in the global "Coal Gap". The distribution, thickness and splitting character of the coals follows the basin paleo depocentre. The net coal is highest, > 30m, in the Baralaba Coal Measures in the south-eastern Taroom Trough but is distributed into a greater number of thinner seams separated by thick but almost regular interburdens. Along the western edge, roughly parallel to the Roma, Springsure and Collinsville shelves, the Bandana and Rangal Coal Measures thin, coal net to gross increases and coal seams tend to be thicker (>6m). In these lower accommodation areas of the basin, multiple seams can converge to form crab-like geometries. These coal crabs are rare but significant in locations like Scotia, Fairview, Ensham, Burton and South Walker Creek, among others. Within the Nebo Synclinorium, thick crabs occur along the Collinsville Shelf in the older Fort Cooper and Moranbah Coal Measures. These "peat islands" were stable locations of peat accumulation for long periods of time, ~100,000 years or more, and fluvial channel courses divert around them. The nature of the interburden sediments are basically continental throughout the Late Permian, although responding to local (compaction) and regional subsidence. Similar to previous interpretation, basin drainage is generally southward but thick (60m), stacked trunk channels also traverse the basin. The channelised belts, as defined by the seam splitting patterns, show local compensational stacking, but are thicker and wider in the Nebo Synclinorium. In the south, as the basin subsides more rapidly (confirmed by age dates in multiple tuffs), smaller scale channels drain westward into the trough. In the Baralaba Coal Measures, the channels exhibit steeply inclined master bedding known as Inclined Heterolithic Strata, which could also reflect tidal or estuarine influence through the section. This follows for increasing subsidence in the basin towards the Permo-Triassic boundary. Subsidence driving coalification is evident in the thermal maturity or rank of the coal seams, but elevated rank towards the east of the Nebo Synclinorium, and west of the Marlborough Thrust, suggests deeper more rapid burial in a higher heat flow. However, these same areas are also structurally more deformed, and evidence of hydrothermal overprinting is suggested by a combination of the thermal maturity and clay mineralogy.

1 INTRODUCTION

1.1 Background and scope

The ACARP project Supermodel 2000 provided a regional context in which to develop predictive models for overburden geotechnical behaviour in open cut and underground mines operating in the Moranbah-German Creek Coal Measures on the western limb of the Bowen Basin. The project developed a series of mine site interburden models integrated with structural deformation that stimulated more regional studies (Le Blanc Smith, 2004; SRK, 2008), but more so provided a template for geological hazard mapping, a basis for technical exchange and an educational reference for the industry.

The last ten years saw an increase in global demand for Australian coal, increased exploration and development, and new personnel entering the workforce. Mining conditions in the Rangal, Baralaba and Bandanna Coal Measures are varied and in places structurally complex. Each formation in the Bowen and Galilee Basins poses different geotechnical issues for its Permian and younger overburden. Exploration drilling, seismic survey and geophysics are used to populate sophisticated geological models to JORC standards for a given mine site, but these are commonly developed independently of adjacent leases. Similar to the successful Supermodel 2000, the opportunity to quilt together a series of mine scale models for the Rangal-Baralaba-Bandanna Coal Measures provides insight to the architectural elements of these coal measures that impact on mining conditions.

The project addresses the ACARP objective: Research to improve understanding of key aspects of Australia's coal basins (including structure, stratigraphy, rank and quality trends), by exploring:

- A consistent stratigraphic framework for the Rangal CM and their equivalents within the Bowen Basin;
- The relationship between the Rangal CM and equivalents in the Galilee and Sydney Basins, using geochemical fingerprinting and dating of tuffs (this data already exists for the Sydney Basin and some key stratigraphic holes in the Bowen Basin);
- Links between gross geotechnical properties and sedimentological trends across the Bowen and Galilee Basins, including the distribution of thick stacked coals; and
- Links between faulting, seam splitting, massive sandstone dimensions and basement architecture.

1.2 Objectives

The objective of the project is to develop a regionally consistent stratigraphic framework for the Rangal-Baralaba-Bandanna Coal Measures in the Bowen and Galilee basins (Figure 1), in which to examine:

- controls on coal seam architecture;
- variability in sedimentary facies and structure propagation; and
- their impact on geotechnical behaviour of open cut coal mines.

The outcome is an industry wide reference that serves to educate current and future geologists and engineers in the industry and provide a platform for effective geotechnical assessment and mine design for both open cut and underground coal mines.

1.3 Work program

Data compilation

Data was sourced from the public domain and requested from companies, and included:

- Representative borehole data (with wireline logs) chosen to maximise the vertical section of the coal measures intersected, and to allow the development of a series of representative regional correlation sections around the Bowen and Galilee Basins;
- Seam split line locations and modelled grids for selected regionally significant seams to explore the regional depositional patterns;
- Public domain geophysical data (magnetics, gravity, 2D seismic) and regional studies (e.g. SRK SeeBase Bowen Basin) to underpin the regional analysis.

Geochemical fingerprinting and age dating

Yarrabee Tuff samples were collected from minesite drill core and pit samples for geochemical fingerprinting and age dating to constrain the correlations across the basin and assist in determining deposition rates that impact on sedimentary interpretations (in conjunction with Dr Bob Nicoll at Geoscience Australia and Jim Crowley at Boise State).

Stratigraphic correlation

Representative seam and correlation sections were built along strike that highlight the continuity of significant seams and the correlation between the Rangal equivalent coal measures. The correlations were corroborated by tuff age dating.

Out of scope were detailed correlation of seam plies for a given area and high resolution models of individual sites, although some more detailed regional models were built.

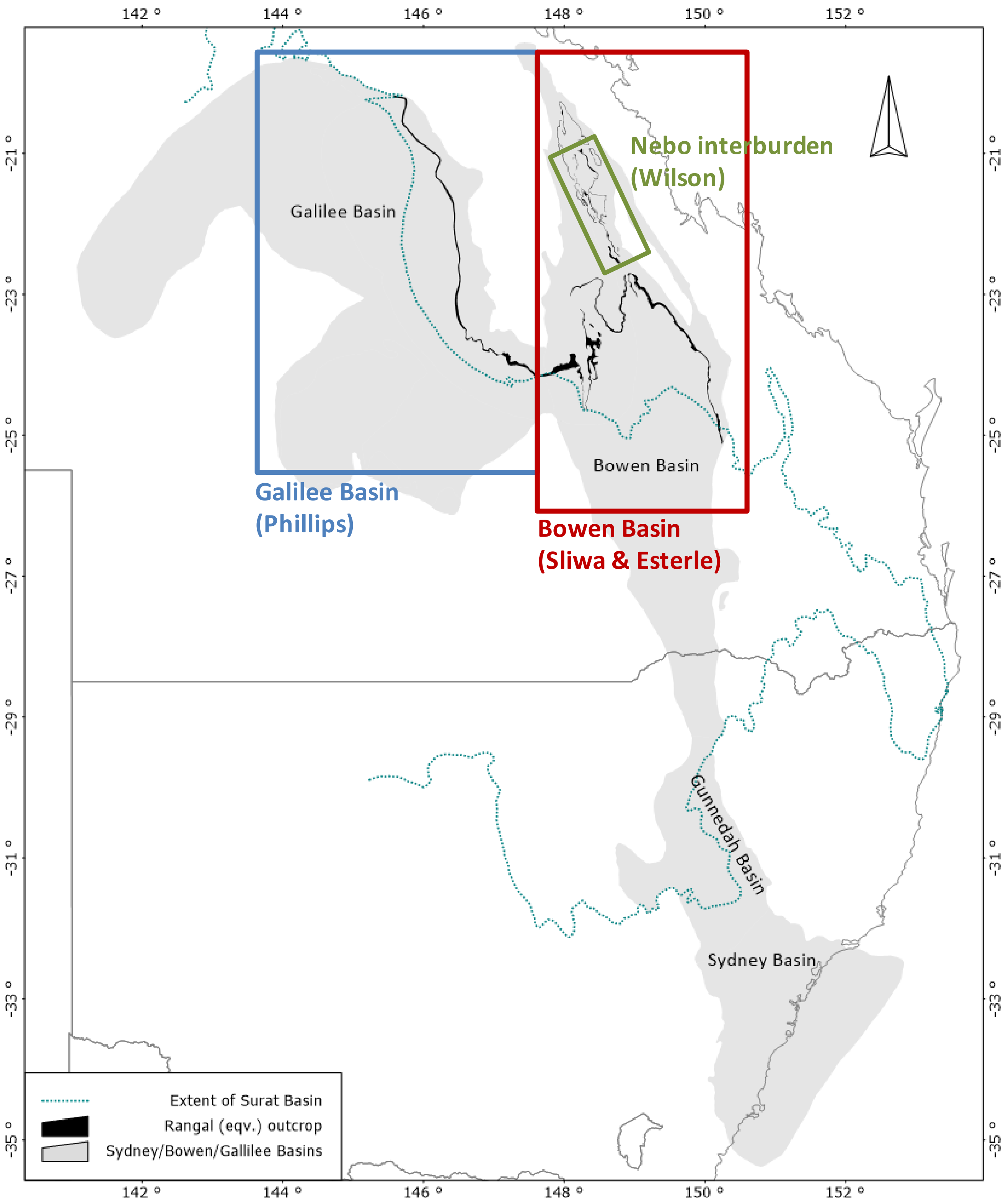


Figure 1 Modern distribution of Sydney-Bowen-Galilee Basin complex, and Rangal Coal Measure outcrop areas (Basin outlines from Geoscience Australia). Outlines show the major components of the study.

1.4 Team and student projects

Dr Joan Esterle (UQ) is a coal geologist with an extensive background in the geology of the Bowen and Surat Basins and responsible for the execution of Supermodel 2000. She co-led the project with Dr Sliwa and was responsible for sedimentary and geotechnical analysis of the data, and liaison between UQ and industry.

Dr Renate Sliwa (Integrated Geoscience Pty Ltd) is a structural geologist with 21 years' experience in regional- to mine-scale geological analysis and interpretation of geophysical data. She previously worked on the structural and modelling components of Supermodel 2000. She was responsible for the data compilation, spatial/geophysical analysis and the structural analysis.

Dr Bob Nicoll (Geoscience Australia) is a biostratigrapher and geologist who is currently working on age dating tuffs and aligning the Permian biostratigraphy.

Students on the project included (see Figure 1 for extent of the two regional studies):

- *Esdras Villeja*- Depositional systems, composition of sandstones and gamma ray signature of the Baralaba Coal Measures (MSc 2015 Brazil)
- *Laura Phillips* - Sequence stratigraphic analysis of Permo-Triassic coal measures in the Gallilee Basin (PhD 2017 target)
- *Steven Wilson* - Sedimentary analysis of the overburden of the Permo-Triassic Girrah to Leichhardt Coal Seams (MPhil 2017 target)
- *Rachelle Caldwell* – Re-evaluation of inclined heterolithic strata within the interburden of the Baralaba Coal Measures (Honours 2016)

1.5 Project deliverables

The output is a report that explains and illustrates the stratigraphy, sedimentology and structural features of the Rangal-Baralaba- Bandanna Coal Measures and their variability across the Bowen and Galilee Basins.

1.6 Acknowledgements

This project could not have been conducted without the support and generous data contributions from the coal industry.

The data contributions from the Bowen Basin include:

- Anglo American – Dawson, Foxleigh;
- BHP Billiton Mitsubishi Alliance (BMA) – Red Hill, Daunia, Picardy, Blackwater, Humboldt, Ridgelands;
- BHP Billiton Mitsui Coal (BMC) – South Walker, Bee Ck, Poitrel;
- Cockatoo Coal Ltd – Baralaba;
- Idemitsu Australia Resources – Ensham;
- Glencore – Newlands, Rolleston;
- Peabody Energy – Burton, Coppabella, Millenium, Moorvale;
- Rio Tinto Coal Australia – Hail Ck/Elphinstone, Winchester;
- Stanmore Coal - Isaac Plains;
- Vale – Carborough Downs, Red Hill, Broadlea, Belvedere;
- Westfarmers Resources – Curragh; and
- Yancoal – Yarrabee.

The data contributions from the Galilee Basin include:

- AMCI Capital – South Galilee Coal Project;
- Adani – Carmichael;
- Cockatoo Coal Ltd – South Pentland
- TerraCom - Hughenden and Clyde Park
- GVK Hancock Coal – Alpha, Kevins Corner
- Macmines Austasia Pty Ltd - Project China Stone
- Resolve Coal – Hyde Park Coal Project
- Waratah Coal – North Alpha, China First Coal
- Comet Ridge Ltd, Samgris Resources, Vale – exploration projects.

Open file drilling data from coal seam gas and petroleum companies were obtained through the Geological Survey of Queensland.

The authors also thank ACARP, in particular John Brett and the various industry monitors for their continued support of this project.

2 METHODS

The study area includes the exposed as well as subsurface extent of the RBB coal measures in the Bowen and Galilee Basins. All companies that were actively mining or exploring the RBB coal measures were asked to contribute a collection of representative boreholes with significant stratigraphic coverage across the major coal seams, along with wireline logs, coal seam picks and mine site correlation charts. In total 5775 company boreholes were compiled from the Bowen Basin and 1195 boreholes from the Galilee Basin (Figure 2).

In addition, 1117 open file boreholes with digital wireline data were compiled from QDEX. These boreholes mostly targeted coal seam gas and traditional petroleum resources, and facilitated the correlation of seams into the deeper parts of the basin.

The clear majority of the company boreholes were provided with density and gamma logs, supported by less common neutron, sonic and resistivity logs. The open-file boreholes included gamma, spectral gamma, resistivity, self-potential and sonic logs. Density logs were less common in the older open-file wells that targeted conventional oil and gas. Due to their scarcity and complexity, imaging and full waveform sonic logs were excluded from this study.

There are two main applications for wireline data in this project: regional correlation of coal seams, and the characterisation of seam interburden lithology. The range of tools, data resolution and data quality varied significantly between companies and in particular across the open-file data, so that it was necessary to generate standardised logs across the whole dataset. The standardisation consisted of bulk-processing a range of representative logs for efficient and consistent display, without optimising each individual well.

The main steps in the log processing procedure include:

1. *LAS file quality control.* Files without logs or corrupt LAS format were quarantined, and LAS headers standardised to include the well name. The deliverable form this step is a collection of LAS files that can be bulk loaded into a range of software.
2. *Selection of representative logs.* A list of prioritised log acronyms was chosen to represent gamma, density (compensated, long & short), calliper, resistivity (deep & shallow), sonic, self-potential, neutron (long & short) and spectral gamma (U, TH & K). The highest priority log for each borehole was loaded for further processing.
3. *Data quality control.* Each of the logs were subset to 10cm spacing, had extreme outliers removed and were visually checked for "bad logs" which were discarded.
4. *Density Logs.* All available logs were consistently re-scaled to g/cc. Where processed logs were not available, logs in counts per second were used for correlation.
5. *Gamma logs.* A top and bottom processing limit was manually picked for each borehole that excluded casing and bad data near the top and bottom of each borehole. The logs were then normalised to a so that the mean gamma for the processing interval is equal to 100 and two standard deviations fit a range of 40-160. A display range of 0-200 was used for all correlation purposes.

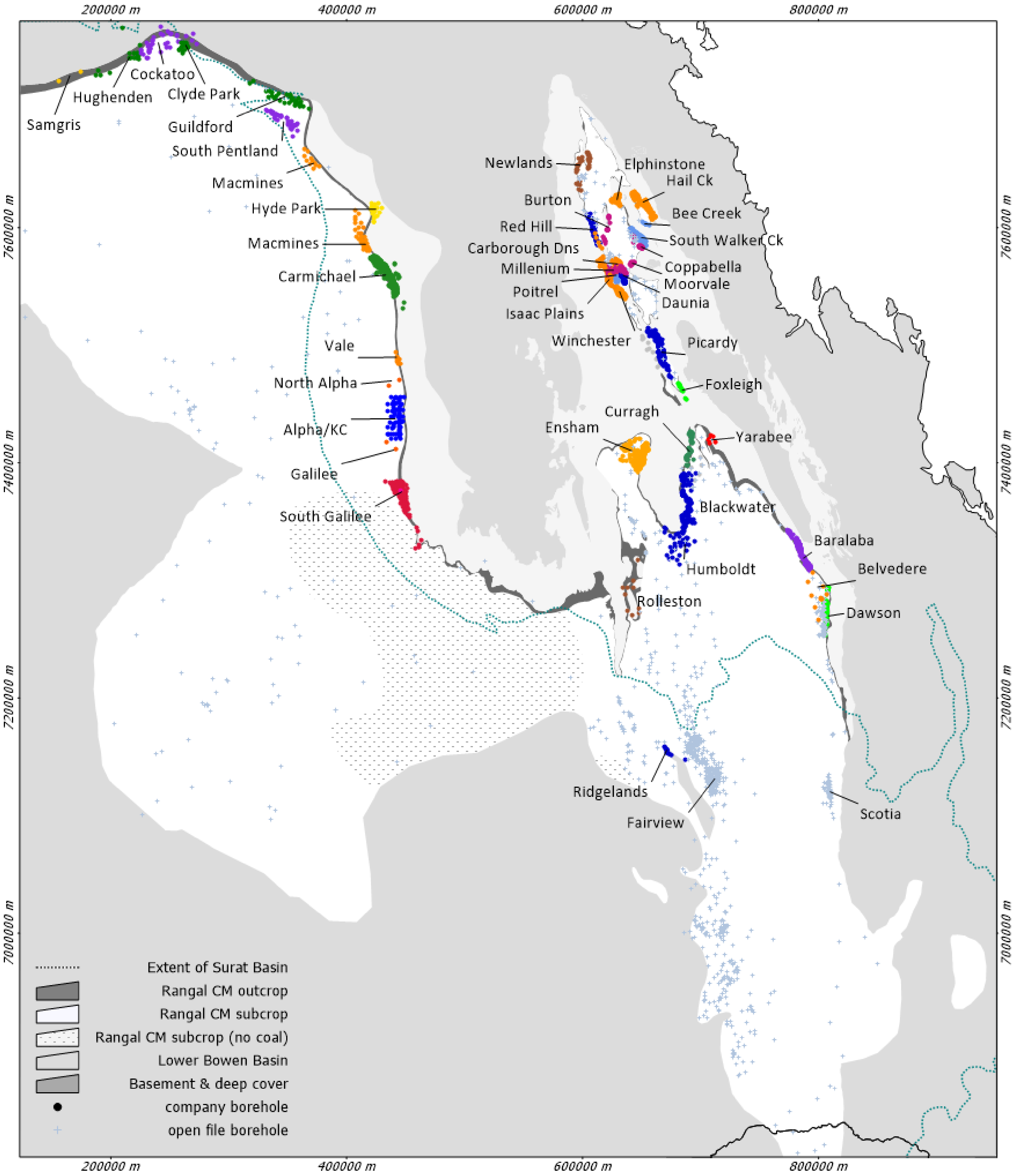


Figure 2 Distribution of boreholes contributed to this study. Light blue coloured boreholes are open file exploration boreholes compiled from QDEX.

The density logs, or resistivity logs if density was not available, were used to supported the regional coal seam correlations, while the normalised gamma log was the main tool for characterising the interburden lithology.

The regional coal seam correlations relied strongly on the coal seam picks provided by each mine. Seam picks were loaded and checked for internal consistency against mine correlation charts. Major seams and the regional Yarrabee Tuff marker horizon were then used to correlate minor seams between the mines, and to build a simplified regional "Supermodel" schema for the three regional subdivisions (discussed in Section 4.2). The mine seam codes were then translated to Supermodel codes to generate sections and maps. Tables that show the mine code to Supermodel schema translations are listed in Appendix A.

Most of the mines operate detailed ply models, where the code for the top and bottom of the main seams changes where seams split off. This approach to seam naming is not practical for the regional analysis presented in this study. For the regionally significant seams a working seam approach was used where the top and bottom of the main seams maintain the same code across the study subdivision, and seams that split off the main seam take on a new code.

In areas with larger gaps between mines (e.g. Denison Trough) and less control on the major seam correlations, the thickest seams were followed to define the main working seams.

All digital borehole geophysical data were processed and stored in *IHS Kingdom*^{TM} software, which was also used to calculate formation thickness and net/gross lithology maps, and to generate all the sections in this report. The UQ student projects associated with this study used *Paradigm Geolog*^{TM} software for wireline log manipulation and interpretation. Map production and other spatial tasks were completed with a combination of *Golden Software Surfer*^{TM}, *Manifold*^{TM} and *ESRI ArcGIS*^{TM}.

All spatial data received for this study was consistently re-projected to GDA94 Zone 55. This projection was used for all maps displayed in this report.

3 REGIONAL TECTONIC OVERVIEW

The eastern Australian continental margin was dominated by subduction for a long period of time from at least as far back as the Cambrian through to the Early Cretaceous (Veevers 2000). The subduction process was complex, with episodes of trench subduction (accretion), slab rollback or retreat (extension and bending) and slab advance (orogeny) leading to the formation and deformation of various superimposed basins and volcanic arcs. A detailed recent review of the major tectonic episodes and related geological terranes was published by Jell and GSQ (2013), which also includes the schematic sections shown in Figure 3a.

Before the initiation of the Sydney-Bowen Basin (SBB), a prolonged phase of subduction and accretion established the Wandilla accretionary wedge, Yarrol forearc basin and Camboon volcanic arc, which are now preserved as the metamorphic terranes of the New England Orogen to the east of the modern basin extent (summarised in Holcombe *et al.* (1997b)). It is not clear how far these terranes extend underneath the SBB. The intracratonic Drummond Basin that partially underlies the Galilee Basin was subsiding during this time, possibly due to extension driven by far-field stresses rather than due to the subduction in the east (Van Heeswijck 2010).

Slab rollback or retreat during the Late Carboniferous caused significant extension in Queensland, and to a lesser extent in NSW. The roll-back is now thought to have been slower in NSW than in QLD, initiating an oroclinal bend (Texas Orocline) to accommodate the different rates of extension (Li *et al.* 2012). Most of the extension in Queensland was accommodated by the exhumation of a number of core complexes developed in an accretionary wedge that exposed blue-schists and serpentinites. Further west the Torsdale-Camboon-Lizzie Creek volcanics accumulated in narrow fault bounded basins that are exposed along the eastern margin of the Bowen Basin. There is evidence at this time that the eastern margin of the Galilee Basin (lower Jo Jo Group) subsided in response to foreland loading (Van Heeswijck 2010), but the exact timing and setting for this compression is poorly understood.

As extension continued into the Early Permian, the volcanic arc shifted eastward, possibly to Gympie, terminating the core complex attenuation (and oroclinal bending?). Rift-controlled extension now spread westward forming numerous fault bounded grabens and half-grabens filled with thick fluvial and lacustrine sediments (East Australian Rift System, Korsch *et al.* (2009)). Some of these rift basins underlie the Bowen Basin (Denison Trough, Arbroath

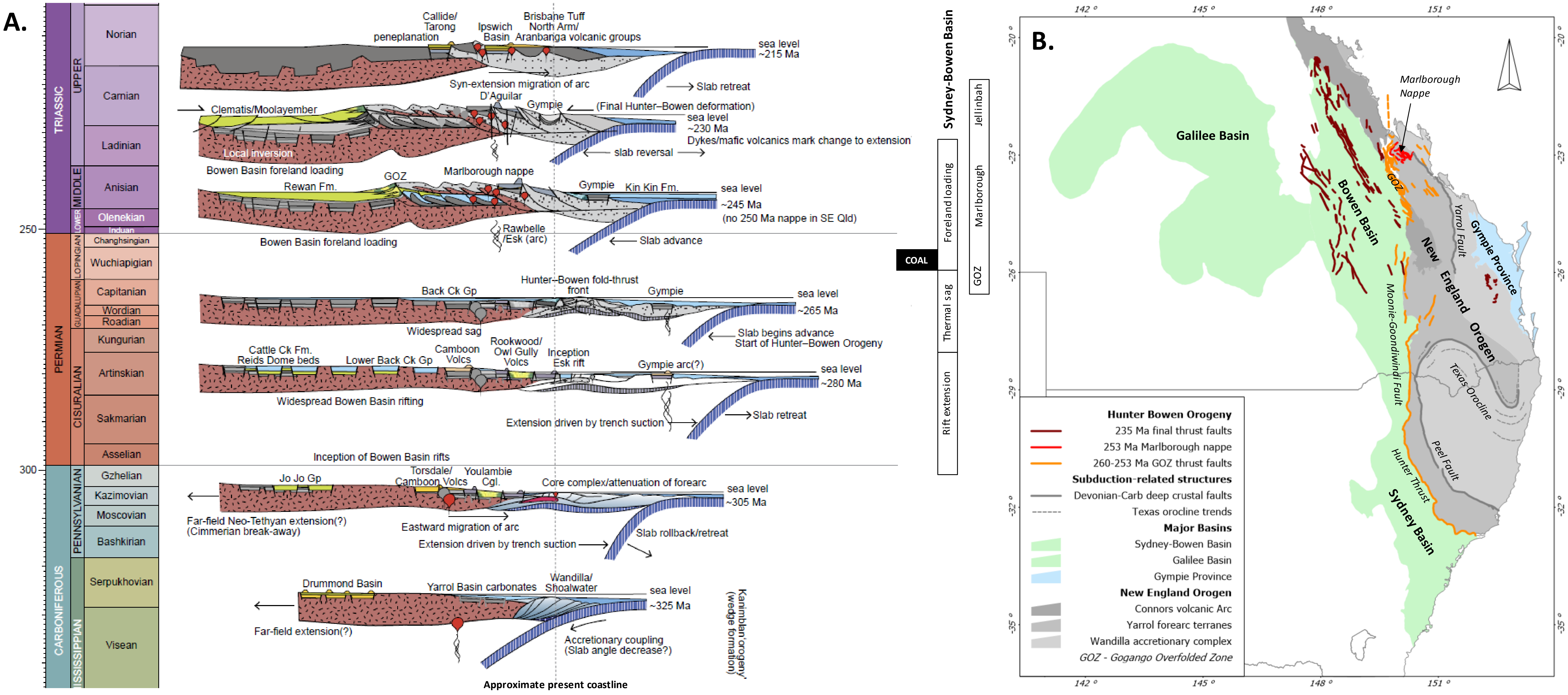


Figure 3 A. Schematic sections showing the tectonic evolution of eastern Queensland during the Carboniferous to Triassic (modified from R.J. Holcombe in: Jell and GSQ (2013)); B. Map of eastern Australia showing the major tectonic elements relevant to the formation of the Bowen-Sydney Basin. (Texas Orocline and under cover Yarrol Terrane interpretation from Brooke-Barnett and Rosenbaum (2012))

Trough), while others are entrained in the older forearc and accretionary terranes (e.g. Rookwood Volcanics, Berserker Beds). In contrast, sediments around the new Gympie volcanic arc accumulated in a marine continental margin setting (Li *et al.* 2015).

During the middle Permian there was a major shift from slab retreat to slab advance which drives the Hunter-Bowen Orogeny (HBO) until the Middle Triassic (Holcombe *et al.* 1997a). The compression began slowly. As the rifting ceased, thermal relaxation facilitated a wide-spread marine transgression across the SBB (Back Creek Group, Rutherford Formation in the Hunter Valley), with modest amounts of sediment received from the craton to the west (Fielding *et al.* 2001).

As east-west compression increased the strain was first taken up by folds and thrusts within the New England Orogen (NEO). The thrusts are wide-spread, creating a complex melange of juxtaposed basement blocks from contrasting crustal levels. Strain is particularly focussed along the boundary between the old Yarrol forearc basin and the craton to the west (Figure 3b). In the north where this zone trends north-northwest, it is wide and associated with pervasive folding in the Gogango Overfolded Zone (GOZ). While the faulting and folding is mostly confined to the NEO, it does affect the marine Bowen Basin sediments along the eastern basin margin, where the onset of thrust faulting is recorded in the development of large slump structures within the deep marine sediments of the Moah Creek Beds (Fielding *et al.* 1997). South of the GOZ, all the way along the Gunnedah and Sydney Basins, a number of aligned thick-skinned thrust faults (Moonie-Goondiwindi-Hunter Thrust systems) may have initiated at this time.

The slab-driven compression culminated during the late Permian in a major thick-skinned thrust stack, the Marlborough Nappe, which propagated across the earlier structures and provided significant crustal loading in the northern NEO (Holcombe *et al.* 1997a). Further south, large movements occurred on the Moonie-Goondiwindi-Hunter Thrust systems. As a result, foreland loading took over from thermal sag as a mechanism for subsidence in the SBB, and deposition changed from marine to terrestrial as the rising mountains provided a flood of sediment from the east (Rewan Group, Clematis and Moolayember Formations) (Fielding *et al.* 2001). At the start of the loading subsidence accelerated before the supply of sediments caught up, so that there was a brief period ideally balanced for the formation and preservation of major coal deposits in the SBB. I.e. subsidence was fast enough to allow peat to grow, but not be drowned, and sediment supply was not sufficient to smother the peat mires completely.

While the Marlborough and other thrusts in the NEO continued to build mountains along the eastern Australian margin during the Early and Middle Triassic, the GOZ-Moonie-Goondiwindi-Hunter fault systems acted as frontal thrusts that were associated with alluvial fans shedding into the SBB (Fielding *et al.* 2001). This implies that the Late Permian to Middle Triassic depositional margin of the SBB coincides with the current erosional margin south of the Baralaba-Dawson area. Further north the GOZ passes out to sea, suggesting that the depositional margin of the northern Bowen Basin lies to the east of the current coastline.

The last major episode of HBO deformation occurred at ~235Ma during the Middle Triassic (Holcombe *et al.* 1997a). The compression was directed NE-SW in contrast to the earlier east-west compression, and focussed on the northern NEO. The main effects include the docking of the Gympie foreland basin against the mainland (Kin Kin Phyllite) and fold-thrust belts in the Bowen Basin (Jellinbah Thrust, Wallumbilla Fault) that terminated subsidence and deposition in the basin. There was no substantial crustal loading and no foreland basin development associated with this event. Also, this event has not been observed in the southern NEO.

Further developments along the eastern Australian subduction margin included a phase of slab retreat that was associated with widespread erosion and peneplanation (Totterdell *et al.* 1991). Mild extension across the NEO led to the development of the Late Triassic coal basins (Tarong, Callide, Ipswich). Subduction probably continued at some unknown location further east throughout the deposition of the intracratonic Surat and Clarence Moreton Basins until the early Cretaceous, when sea floor spreading in the Coral Sea led to the development of the modern-day passive margin (Schellart *et al.* 2006).

4 BOWEN BASIN

4.1 Late Permian to Early Triassic sedimentary framework

The previous section summarised the evolution of the Bowen-Sydney Basin within a tectonic framework for eastern Australia. There are three well-published phases of basin evolution: 1. Rifting during the Late Carboniferous to Early Permian; 2. Thermal subsidence during the Late Permian; and 3. Foreland loading until the mid-Triassic (Fielding *et al.* 2000b).

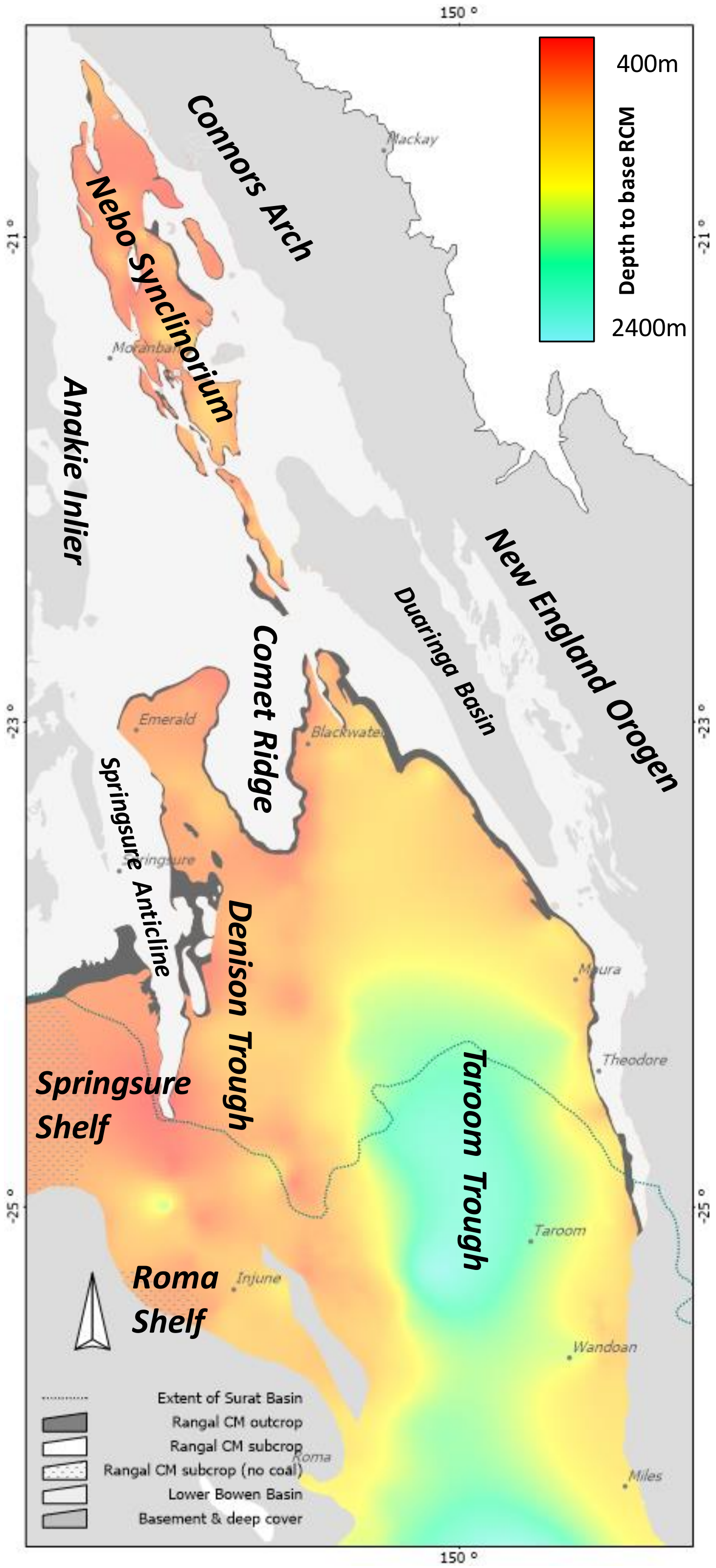


Figure 4 Structural elements of the Bowen Basin and surrounding terranes.

During the Late Permian to Early Triassic transition from thermal subsidence to foreland loading, deposition in the Bowen Basin went through a number of transgressive-regressive cycles that ended in continental conditions that lasted until the closure of the basin during the Mid-Triassic (Fielding *et al.* 2000b). When Geoscience Australia (GA) applied a sequence stratigraphic analysis to the larger Bowen-Gunnedah Basin, they mapped seven regional seismic horizons (B45-B80) that divide the Late Permian to Early Triassic interval into five Supersequences (C, D, E, F and G) (Brakel *et al.* 2009).

The GA interpretation is controlled by numerous regional seismic lines and tie wells beneath the Surat Basin and across the Denison Trough (see Figure 4 for location of structural elements mentioned in this report). However, seismic surveys are sparse further north, so that the model terminates at 23.5°S (~ Rockhampton). GA also acknowledge that due to the depth of the Taroom Trough, correlation between the Denison Trough and the eastern basin margin is difficult to impossible. In this study we use the sedimentary sequences defined by GA and paleogeographic reconstructions developed by Fielding *et al.* (2001), combined with validated correlations of company and open file well data to refine and extend the model across the northern Bowen Basin. The re-interpreted relationships between the seismic sequences and lithostratigraphic units are shown in Figure 5.

The following sections summarising the major sequences are summarised from Brakel *et al.* (2009), except where referenced to other authors.

Supersequence C: upper Aldebaran Sandstone and Oxtrack Formation

Supersequence C includes the upper Aldebaran Sandstone in the west and the Oxtrack Formation in the east which is only mapped in outcrop. The Aldebaran Sandstone includes coarse fluvial-deltaic sandstones in the north, but grades to finer-grained reworked clastic sediments in the south. The Oxtrack Formation consists of fossiliferous limestone and calcareous siltstone. Lithostratigraphic correlations in the northernmost Bowen Basin (Johnson & Martini 1985) suggest that the Collinsville Coal Measures also belong to Supersequence C.

The base of Supersequence C (B45) is defined by a subtle unconformity that has been mapped across the Denison Trough, but does not appear in the Taroom Trough to the east.

The Aldebaran Sandstone has been interpreted as large deltas shedding into the open marine basin from the west. The Oxtrack Formation records quiet shelf conditions in the east, but the actual eastern limit of the Bowen Basin at

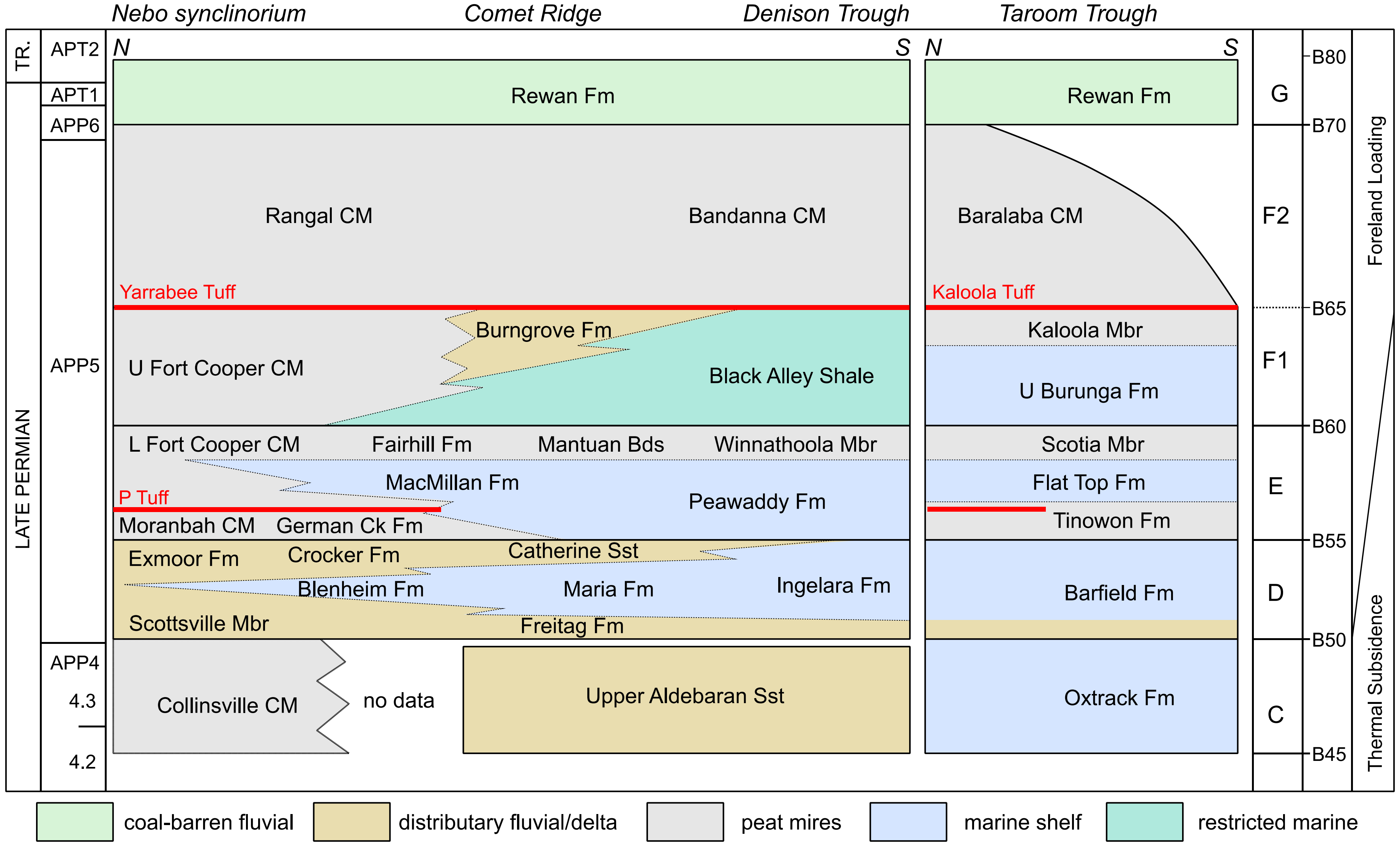


Figure 5 Relationships between stratigraphic supersequences and lithostratigraphic units in the Bowen Basin (modified from Brakel et al. (2009), Fielding et al. (2001) and others).

this time is not known (Figure 6A).

Supersequence D: Freitag Formation, Ingelara Formation, Catherine Sandstone and correlatives

Supersequence D comprises a group of marine shelf to deltaic deposits including the Freitag Formation, Ingelara Formation and Catherine Sandstone in the Denison Trough, and the Barfield Formation along the eastern Basin margin. Lithostratigraphic correlations (Draper 1985) suggest that these units correlate with the Maria and Crocker Formations on the Comet Ridge and the Exmoor and Blenheim Formation in the far north of the basin.

The lower boundary of the sequence is a mild disconformity at the top of the Aldebaran Sandstone. As sea levels rose, the Freitag Formation and lower Blenheim Formation (Scottsville Member) were deposited in a near shore environment followed by the Ingelara, Maria and upper Blenheim Formations in a quieter deeper marine environment. Although separated by a short disconformity, the palaeogeography changed little between Supersequences C and D (Figure 6B) (Fielding *et al.* 2001).

The Bowen Basin was still dominated by thermal subsidence in the west and north. The Barfield Formation in the east includes a succession of turbidites and pebbly conglomerates suggesting that foreland loading had begun and subsidence outpaced sediment supply, until the rising uplands to the east provided a fresh supply of sediments (Fielding *et al.* 1997). The Catherine Sandstone and correlatives marked a return to higher energy, near shore, environments that characterise the regional regression at the top of Supersequence D.

Supersequence E: Moranbah-German Creek Coal Measures, Peawaddy Formation and correlatives

A last major marine transgression and a first major phase of coal measure formation characterise Supersequence E. Marine mudstones in the Peawaddy Formation of the Denison Trough are equivalent to deltaic sediments of the Scotia Member in the east, and have been correlated with the MacMillan and Flat Top Formations further north (Falkner & Fielding 1993). As sea levels rose, the marine mudstones transgressed across the German Creek and Moranbah Coal measures but then gave way to extensive coal mires during the deposition of the lower Fort Cooper Coal Measures, Fairhill Formation, Mantuan Beds and Tinowon Formation.

The base of Supersequence E is conformable with the sandy sediments of Supersequence D, but is marked by a rapid transition from shallow to deep water depositional environments. Subsidence is driven by foreland loading from the east. Numerous primary and reworked volcanic ash deposits appear for the first time in the Moranbah/German Creek Coal Measures, most likely related to volcanic activity in the uplands to the east of the basin (Figure 6C) (Fielding *et al.* 2001), or far-field volcanism in the New England Orogen to the south.

Supersequence F1: Fort Cooper Coal Measures, Black Alley Shale and correlatives

F1 represents the transgressive lower portion of Supersequence F and includes a number of stratigraphic units including the: upper Fort Cooper Coal Measures, Black Alley Shale, Kaloola Member, Burngrove Formation and the upper Burunga Formation (Figure 5). The Black Alley Shale was a dark oxygen-starved mud that accumulated either in a restricted marine shelf or lagoon environment. It transgressed rapidly across the underlying coal measures north across the Comet Ridge. Further north and east peat mires continued in the upper Fort Cooper Coal Measures and the Kaloola Member.

Borehole correlations from this study show that Supersequence F1 is up to 270m thick with a depocentre spread across the Denison Trough and the Comet Ridge (Figure 7a), and thinner towards the eastern and western basin margins. The sequence remains thick into the northern Bowen Basin. The

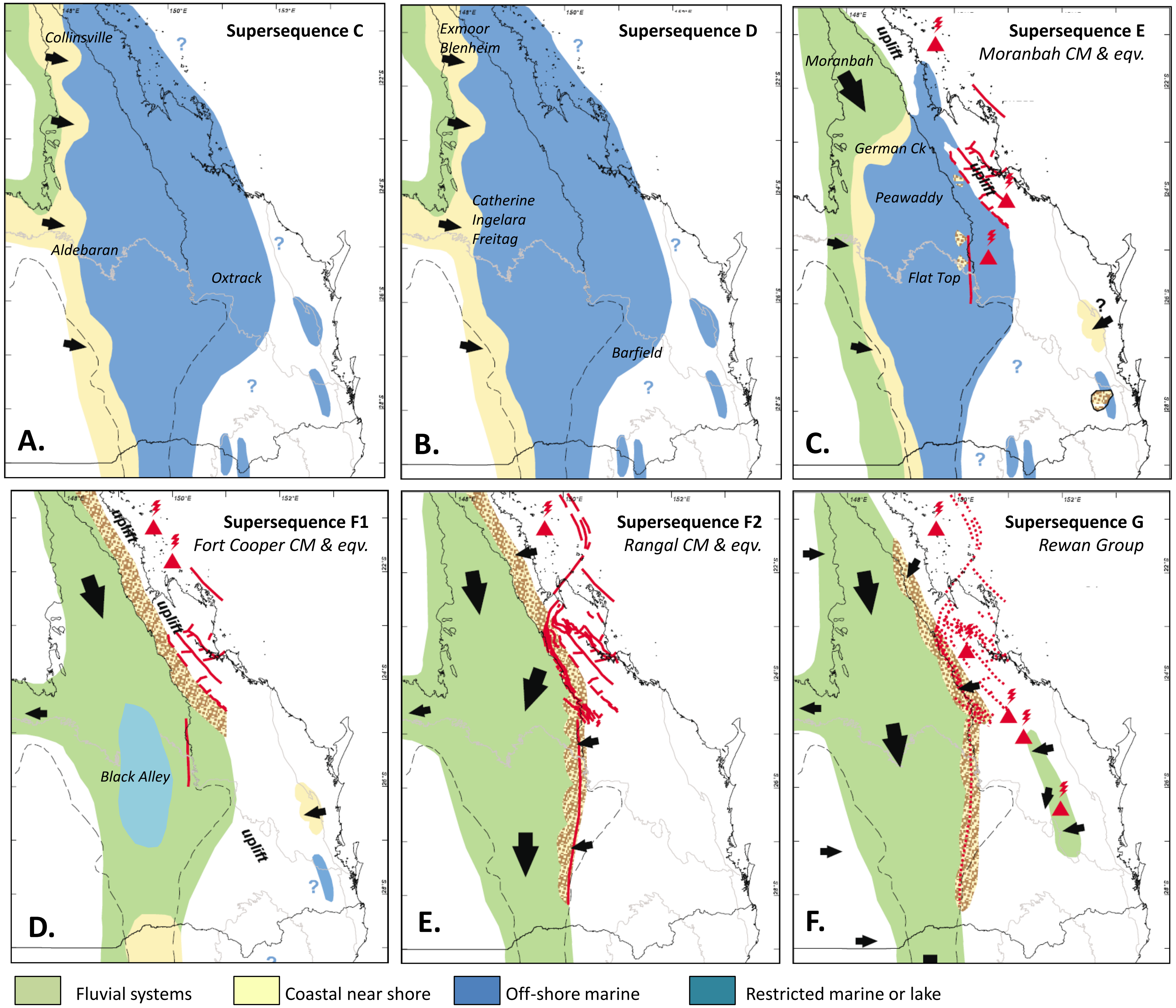


Figure 6 Palaeogeographic reconstructions for Supersequences C to G. Modified from Fielding et al. (2001)

Black Alley Shale which comprises the lower part of the sequence has its thickest distribution in the southern part of the main depocentre. This accumulation of sediments over a broad area some distance away from the active thrusts in the Gogango Overfolded Zone (GOZ), suggests that foreland loading had not yet fully taken over from thermal sag as the main mechanism for subsidence in the Bowen Basin, although at least some of the thrusts must have been active at this time.

Abundant volcanic tuff and detritus continued to shed into the basin from a postulated volcanic arc in the east (Fielding *et al.* 2001), but may have had a source further to the south in the NEO. Palaeocurrent directions suggest that a major south-directed axial drainage developed during this period (Figure 6d)(Fielding *et al.* 2000b).

Supersequence F2: Rangal, Baralaba and Bandanna Coal Measures

F2 represents the regressive portion of Supersequence F and includes the deltaic to fresh water alluvial Rangal, Baralaba and Bandanna Coal Measures which correlate across the basin. This sequence marks a shift to continental deposition across the basin, and has been interpreted as a shift towards basin overfilling (Fielding *et al.* 1993). Fielding *et al.* (2001) suggest deposition in an axial southerly draining river system that continues into the Sydney Basin (Figure 6e).

On seismic section the sequence is defined by a package of strong reflectors caused by coal seams, rather than by boundary discontinuities. During this study we have defined the regional boundaries of the coal measures as the interval between the last occurrence of tuff (Yarrabee Tuff) and the last significant coal seam (Leichhardt Rider).

The coal measures as correlated in this study occur throughout the northern Bowen Basin and continue underneath the Surat Basin, where they pinch out between Roma and Miles. The depocentre is located just to the west of Theodore, where the coal measures are up to 280m thick (Figure 7b). The depocentre is smaller and more pronounced than that of the preceding F1 interval, and lies adjacent to the active GOZ which was the frontal thrust zone during this time. This easterly shift and contraction of the depocentre suggests that subsidence was now dominated by foreland loading. Importantly, the depocentre is located along the northern part of the GOZ, with no equivalent depocentre along the Moonie-Goondiwindi Faults further south. One explanation for this is that most the foreland loading was driven by the thick-skinned Marlborough Nappe that initiated about this time. There are no equivalent deep-seated structures in the central and southern NEO (Holcombe *et al.* 2015). The coal measures are relatively thin in the northern Bowen Basin, which was in a distal position relative to the north-south trending frontal thrusts.

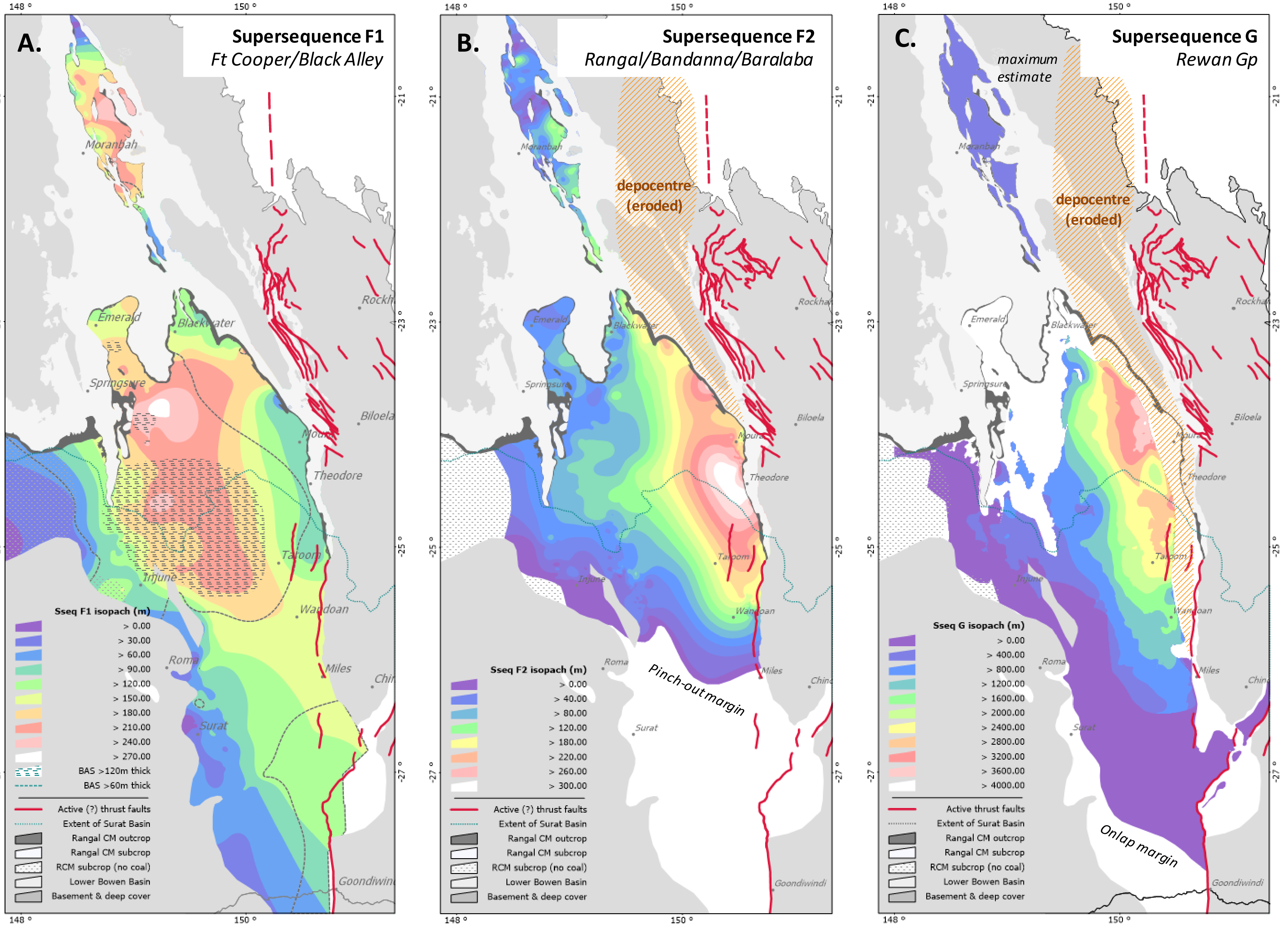


Figure 7 Thickness distribution of Supersequences: A. F1 (upper Fort Cooper Coal Measures, Burngrove Formation and Black Alley Shale); B. F2 (Rangal-Baralaba Coal Measures, Bandanna Formation); and C. G (Rewan Group). The isopachs were generated from well correlations completed during this study combined with QPED formation tops and the B80-B70 Horizons from the SBEA model from Wells et al. (1994).

Supersequence G: Rewan Group

Supersequence G comprises the Rewan Group which consists mainly of sandstones, siltstones and mudstones deposited in fluvial channel and floodplain environments. Poorly connected sand bodies and the accumulation of large volumes of inter-channel sediments suggest rapid subsidence, which is supported by subsidence curves from regional boreholes (Korsch & Totterdell 2009). The subsidence is driven by foreland loading that resulted in the preservation of >1000m of Rewan Group sediments in the Taroom Trough north of Taroom township (Figure 7c).

The seismic model defines the base of the sequence just above the uppermost coal seam reflectors of the underlying coal measures. The boundary has been interpreted from outcrop and drill core as a regional disconformity with mild erosional incisions across most of the GA model area. However, field visits to open cut mines in the northern Bowen Basin associated with this study suggest a conformable relationship between the Rewan Group and the coal measures in this area.

Fielding *et al.* (2001) suggest that transverse drainage from the east and west converged into a major south-draining fluvial system that continued into the Sydney Basin to the south (Figure 6F). However, this is in disagreement with palaeocurrent directions interpreted by Grech (2001) and Jensen (1975), which suggest a northerly drainage at least in the Denison Trough.

Basin extent during foreland loading

The active thrust system that divided the subsiding foreland from the eroding highland during the deposition of the F2 and G Supersequences was a >1000km long, north-south trending fault system that linked the Marlborough Nappe with the Moonie-Goondiwindi Fault and the Hunter Thrust (Figure 3B). The character of this major structure varied along strike with sections dominated by strike-slip deformation, and others by steep thrust faults (eg. Babaahmadi (submitted)). The Marlborough Nappe near Rockhampton is the only structure within this system that generated enough uplift to cause significant foreland loading in the Bowen Basin. This localised foreland loading is supported by the location and trend of the thickest parts of the F2 and G Supersequences shown in Figure 7B&C. Both sequences thicken towards the fault system in the east and towards the north where they are truncated by erosion. It is likely that the foreland basin depocentre continued to the north past the core of the Marlborough Nappe.

Subsequently, the Late Triassic deformation associated with Jellinbah Fold Thrust Belt and parts of the Gogango Overfolded Zone imposed a northwest trending structural grain on the Bowen Basin that was enhanced during the uplift of the Connors Arch, the subsidence of the Duaringa Basin, and ultimately the modern day erosive margin of the Bowen Basin.

One consequence of the proposed north-south trending depocentre of the foreland basin is that the Nebo Synclinorium, Comet Ridge and Denison Trough are all located distally with respect to the main thrust front.

4.2 Rangal-Baralaba-Bandanna Coal Measures

Regional subdivisions

The late Permian coal measures are widespread but poorly exposed in the Bowen Basin, which lead to a number of local names used by early workers until the 1960's, when the BMR and GSQ systematically mapped and published 1: 250,000 scale geological maps across the basin (Malone *et al.* 1964, Olgers *et al.* 1966, Malone 1969, Mollan *et al.* 1969a). It was recognised early on that the coal measures mark a basin-wide change from marine dominated deposition to terrestrial environments, and that the coal measures correlate across the basin, although they change character.

The *Bandanna Formation* was defined by Phillips (1960) from outcrops on the southern Reids Dome and from exploration borehole Morella 1 (Figure 8). The formation included a lower section of tuffaceous sandstone, shale, coal and oil shale and an upper section of carbonaceous and calcareous shale and mudstone. Later, Mollan *et al.* (1969a) re-defined the lower Bandanna Formation as the Black Alley Shale and re-correlated the upper Bandanna Formation on the Springsure Shelf as undivided Blackwater Group (Table 1).

Olgers *et al.* (1966) defined the *Baralaba Coal Measures* from outcrops along the Dawson River near Baralaba (Figure 8), but pointed out that only the basal part of the formation was exposed. The tuffaceous Kaloola Member was later separated from the Gyranda Formation in the Theodore area by (Goscombe 1968) and given a member status within the Baralaba Coal Measures. Quinn (1985a) then suggested that the Rangal and Baralaba Coal Measures are equivalent and should have equal status to the Kaloola Mbr. He upgraded the Kaloola Mbr to Kaloola Fm, and introduced the Baralaba Subgroup to maintain the Baralaba name usage. However, this definition was never formalised. Recent work has shown that the Kaloola Member correlates with the Burngrove Formation and is a part of the Fort Cooper Coal Measures (Ayaz *et al.* 2015).

The *Rangal Coal Measures* were first defined by Malone (1969) as the topmost unit in the Blackwater Group, which also includes the Burngrove and Fairhill Formations. The type section was mapped along Deep Creek, south of Blackwater and has been since mined out. In a review of the stratigraphy of the northern Bowen Basin, Koppe (1978) suggested that the "Upper Bowen Coal Measures" discussed by Malone *et al.* (1964) are equivalent to the Blackwater Group, and that the Rangal Coal Measures should be expanded northward to replace "Elphinstone Coal Measures" of earlier workers. Koppe also defined the tuff-rich Fort Cooper and Moranbah Coal Measures as correlatives of the Burngrove and Fairhill Formations.

The mapped locations and exploration wells discussed in these studies are widely spaced, and there is no discussion about the relative spatial extent of the Rangal Coal Measures, Baralaba Coal Measures or the Bandanna Formation. We use the term Rangal Coal Measures (RCM) in this report to represent a basin-wide unit that includes all three formations.

However, the coal seam correlations presented in this study naturally divide the RCM into three consistent areas that are separated by structurally complex zones such as the Jellinbah thrust belt, or poorly explored corridors such as the deep Taroom Trough, that impede seam-by–seam correlation. These areas or tiles shown in Figure 8, correspond roughly to the distribution of the three coal measure formations and are referred to as the Rangal tile in the north, the Bandanna tile in the west and the Baralaba tile in the east.

Lower boundary definition

The early stratigraphic studies relied predominantly on field mapping and a small number of widely spaced boreholes. They did not define the upper and lower boundaries of the Rangal Coal Measures precisely. Koppe (1978) was the first author to define the Fort Cooper Coal Measures as the 'sequence of abundant tuffs', but Matheson (1990a) more specifically defined the top of the Yarrabee Tuff as the lower boundary of the Rangal Coal Measures in the northern Bowen Basin. He chose the Yarrabee Tuff because it is an easily recognisable high-gamma tuff marker bed that can be correlated in exploration boreholes from Newlands to Blackwater, and with local exceptions is preserved within a coal seam. The Yarrabee Tuff is described as the youngest ash-fall tuff in the Fort Cooper volcanic episode, and separates

Table 1 Development of the Late Permian stratigraphy in the Bowen Basin

EAST		WEST				CENTRE	NORTH	
Phillips, 1960	Mollan *et al.*, 1969	Olgers *et al.*, 1966	Goscombe, 1968	Quinn, 1985		Malone *et al.*, 1969	Malone *et al.*, 1964	Koppe, 1978
Rewan Fm								
Bandanna Fm (upper section)	Blackwater Group (undivided)	Baralaba CM (= Kianga CM)	Kia Ora Cgl Main Coal Mbr	Rangal CM	Baralaba SGp	Rangal CM (= Elphinstone CM)	Upper Bowen CM	Rangal CM
Bandanna Fm (lower section)	Black Alley Shale	Gyranda Fm	Kaloola Mbr	Kaloola Fm		Burngrove Fm		Fort Cooper CM
			Gyranda Fm	Gyranda Fm		Fairhill Fm		Moranbah CM
(marine units)								

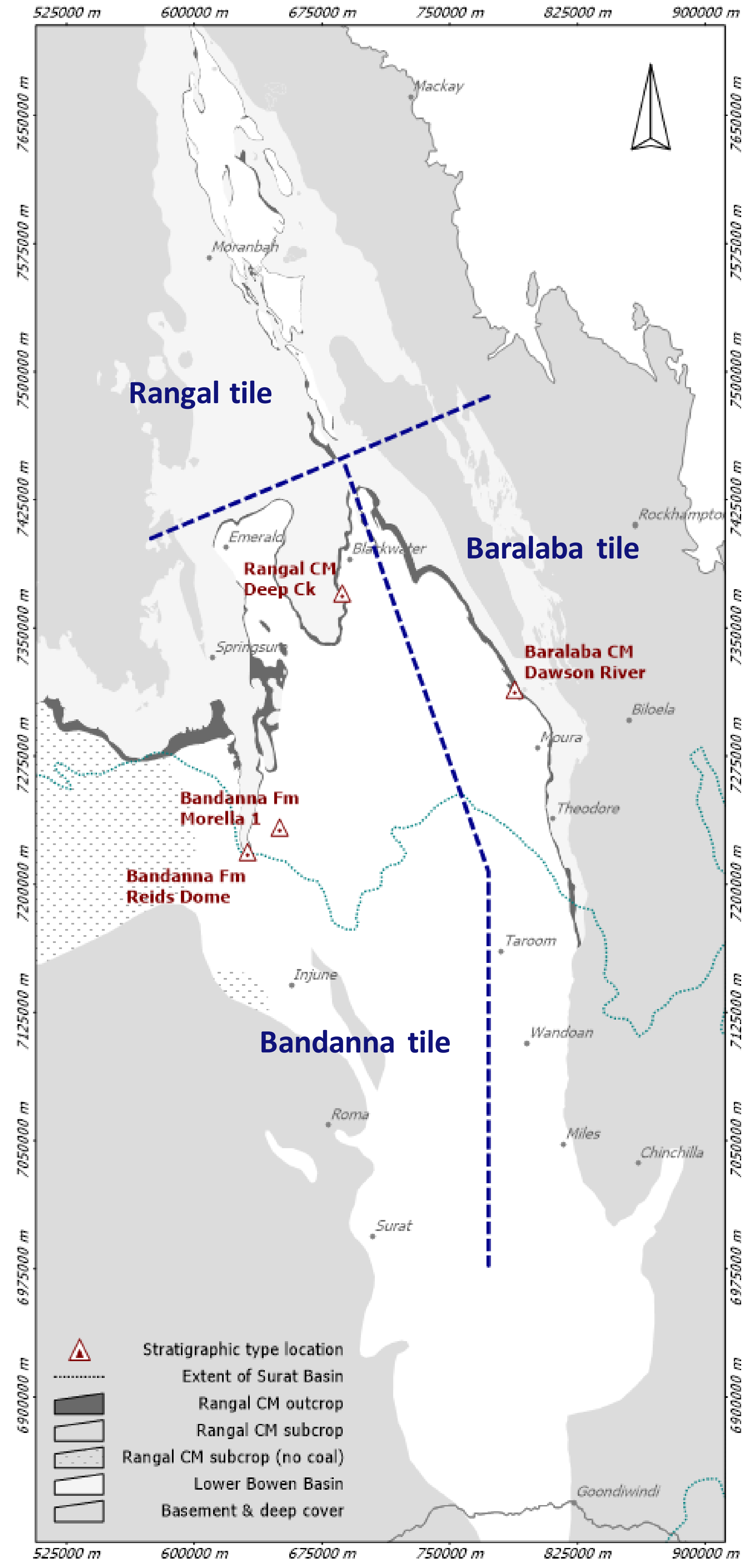


Figure 8 Map showing type locations for the definition of the Rangal - Baralaba - Bandanna Coal Measures and project subdivision.

the ‘clean’ coal seams above from the tuff-banded coal seams of the Fort Cooper Coal Measures below.

In this study we confirmed the correlation of the Yarrabee Tuff throughout the Rangal tile and along the eastern edge of the Comet Ridge with a high level of confidence. In this region the RCM are underlain by the Fort Cooper Coal Measures (Figure 9a). The tuff is generally sandwiched by the Vermont coal seams that preserved the tuff across this large area. The tuff is generally between 0.6-1.6 m thick and thickens towards the south (Figure 9b). We interpret the southern correlated limit of the Yarrabee Tuff as the limit of preservation within a large peat mire system. Further to the south the tuff fell on more varied environments that mostly reworked the tuff or preserved it locally.

Across the Taroom Trough and along the eastern basin margin the RCM are underlain by the Kaloola Member (Figure 9a), which consists of a series of interbedded tuffaceous coal seams and high-gamma siltstones. The Kaloola Member has a similar wireline signature to the Fort Cooper Coal Measures, but contains fewer sandstone units. The seam that preserved the Yarrabee Tuff in the north cannot be correlated. In its absence we defined the lower boundary of the RCM above the last high gamma tuff in the Kaloola Member in each borehole. This correlation was strongly guided by the detailed coal seam correlations within the RCM, and supported by a number of radiometric age dates that are discussed in more detail in Chapter 6. In some areas (e.g. boreholes Coomooboolaroo 5F to Isla 1 in Figure 9c) there is no high gamma marker in the wireline logs, probably due to some reworking of the tuff. In these areas the lower RCM boundary was inferred from the coal seam correlations. Note that in the southern Bowen Basin (e.g. Namarah 2) the Rewan Group directly overlies the Kaloola Member and the RCM are absent.

In the east the RCM directly overly the Black Alley Shale, which consists of siltstone and mudstone with minor thin sandstone units that have been interpreted as deposited in a lake or restricted marine environment (Fielding *et al.* 2000b). Any ash-fall tuffs that fell into this lake were reworked into the lake-bed sediments, and contributed to the overall high gamma signature of this unit. No equivalent to the Yarrabee Tuff could be identified and the base

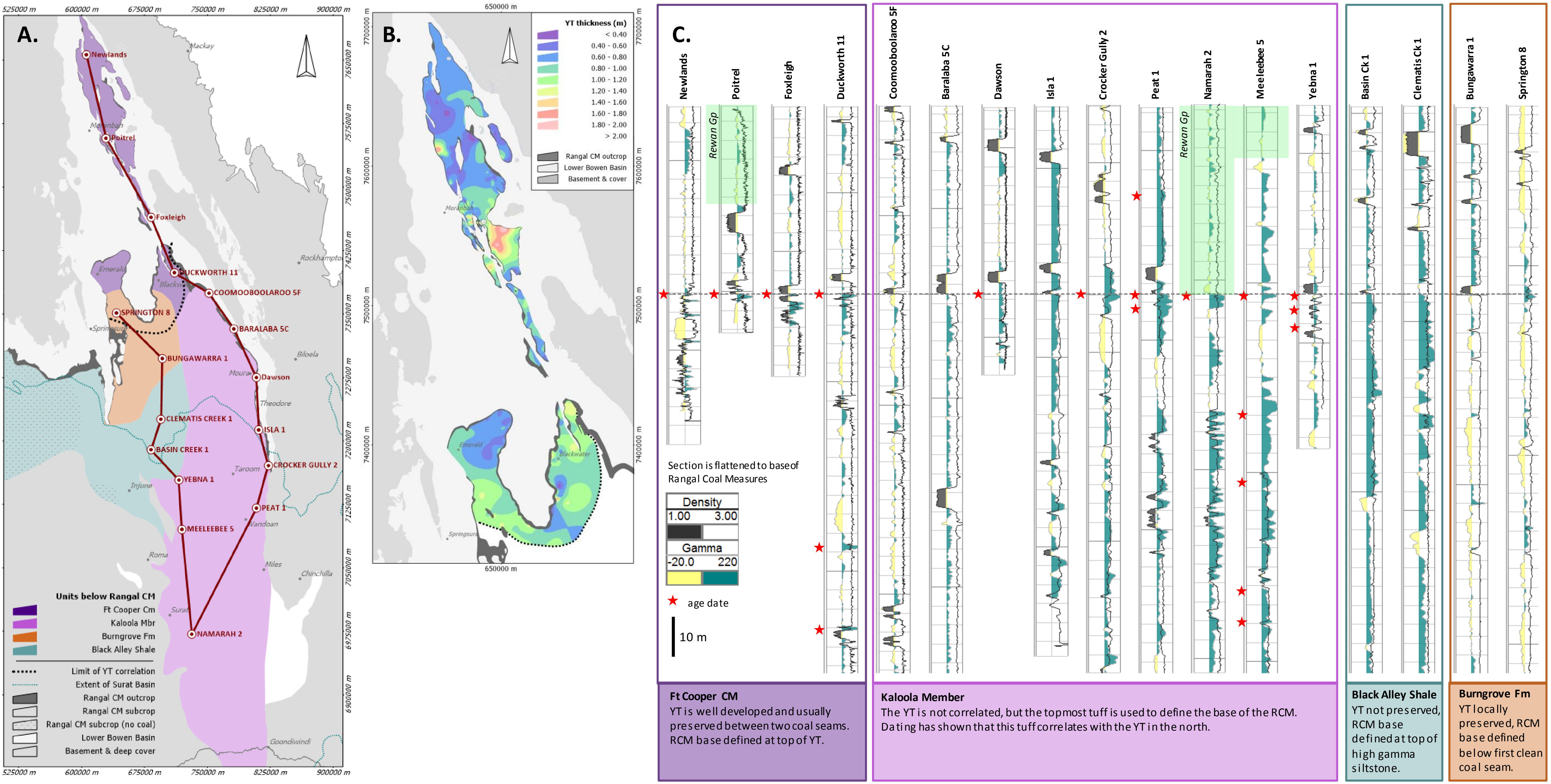


Figure 9 A. Distribution of stratigraphic units directly below RCM; B. Thickness distribution of the Yarrabee Tuff; C. Representative well section with lower RCM boundary criteria.

of the RCM was correlated at the top of the high gamma siltstone succession.

Just to the north, the Burngrove Formation is equivalent to the Black Alley Shale. The wireline log signature is characterised by a number of coarsening up sandstone units separated by siltstone and minor carbonaceous shales and coal seams. The preservation potential for tuff in this environment is low, and consequently the correlation of the base of the RCM across most of this area relied on coal seam correlations and the transition from the coarsening upwards sandstone units to the coal measures.

Upper boundary definition

Matheson (1990a) discussed the definition of the upper boundary to the RCM in the northern Bowen Basin using a number of criteria that had been used by earlier workers. The upper boundary had been defined either at the top of the uppermost coal interval, by a colour change from the grey shades of the RCM to the greenish colours of the Rewan Group, or by the presence of a mudstone marker with a high gamma response just above the last coal seam. However, neither the Phillips Seam (or equivalent) nor the mudstone marker are present in all mines, so Matheson favoured the use of the colour change to define the boundary.

The colour change is useful where exposure is continuous and unweathered such as in some coal mines (Figure 10a), but cannot be recognised in the wireline log signatures (Figure 10b), and has limited value for regional borehole correlations. In this study we have therefore defined the boundary between the RCM and Rewan Group at the top of the mudstone marker where this marker is present along the western margin of the Rangal tile (Figure 10c); or at the top of the last coal seam. Only where closely spaced boreholes show that the uppermost rider seam has shaled out was the boundary continued within the clastic sediments (see example in Figure 11).

When Brakel *et al.* (2009) discussed the sequence stratigraphy of the Bowen Basin, they inferred a regional disconformity to mild unconformity at the base of the Rewan Group based on truncated reflectors and onlap relationships interpreted from 2D seismic lines, particularly in the Springsure Shelf area. Earlier, both Dickins and Malone (1973) and Mollan *et al.* (1969a) noted that the contact is “locally disconformable and sharp” but more commonly “transitional” in the northern Bowen Basin. In the southern Bowen Basin, the contact is “sharp and probably disconformable”, while in the southwest there is an “angular unconformity”. Chiu Chong (1969) also noted an unconformable relationship in a number of boreholes at Moura. Grech (2001) later remapped outcrops in the Arcadia Valley which show local erosion and truncation of coal seam plies by the overlying Rewan Group, and noted the presence of lag conglomerate at the base of the Rewan Group in the Taroom 10 well.

In this study we could not confirm the presence of an unconformity at the base of the Rewan Group. In the Rangal tile, the persistence of the mudstone marker, abundant exposures in coal mines, and densely drilled exploration areas all suggest that the relationship between the RCM and the Rewan Group is conformable.

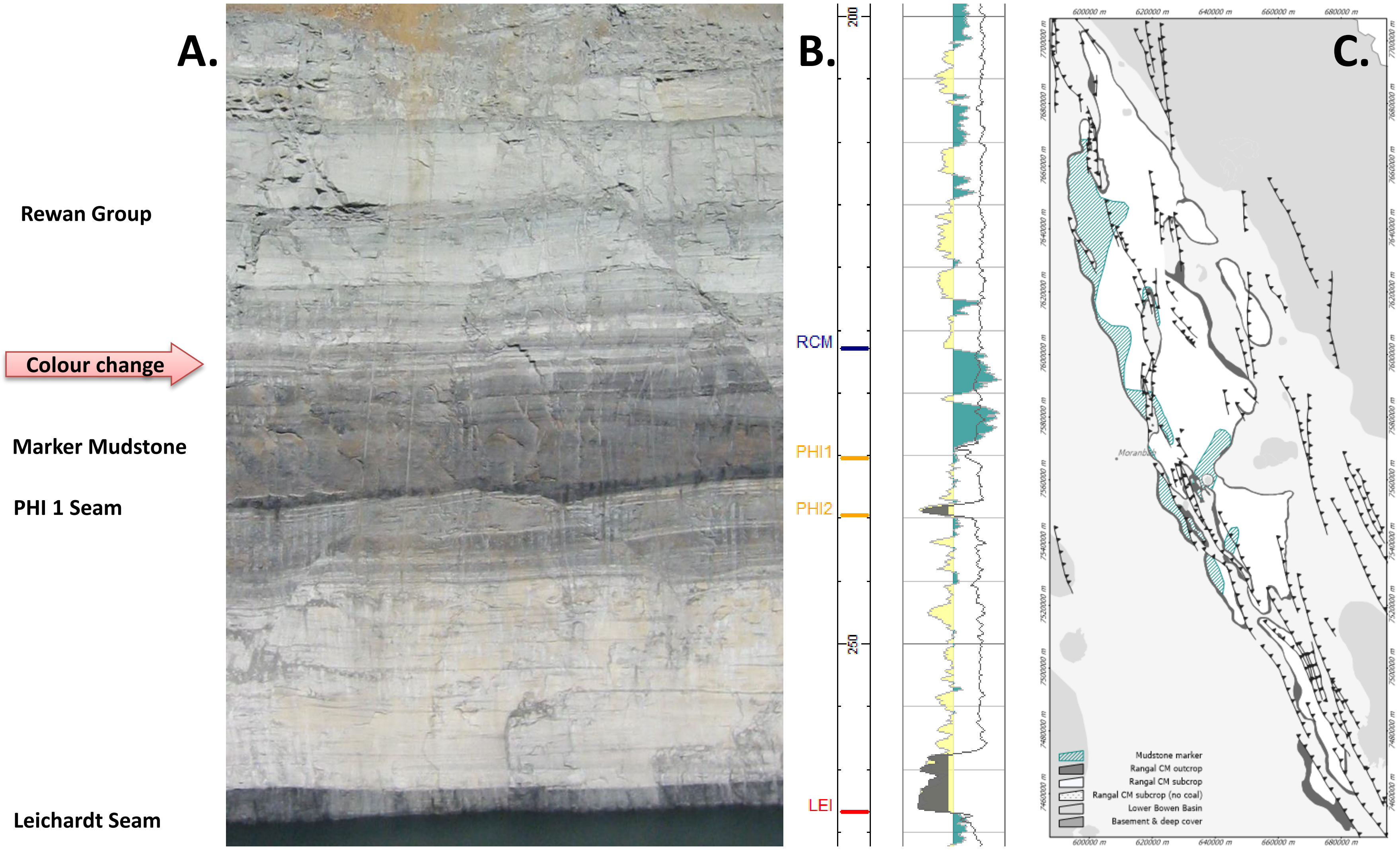


Figure 10 A. Photograph of the Leichhardt Seam overburden at Burton Mine; B. wireline log of the same section; C. Map of Rangal tile showing extent of the marker mudstone.

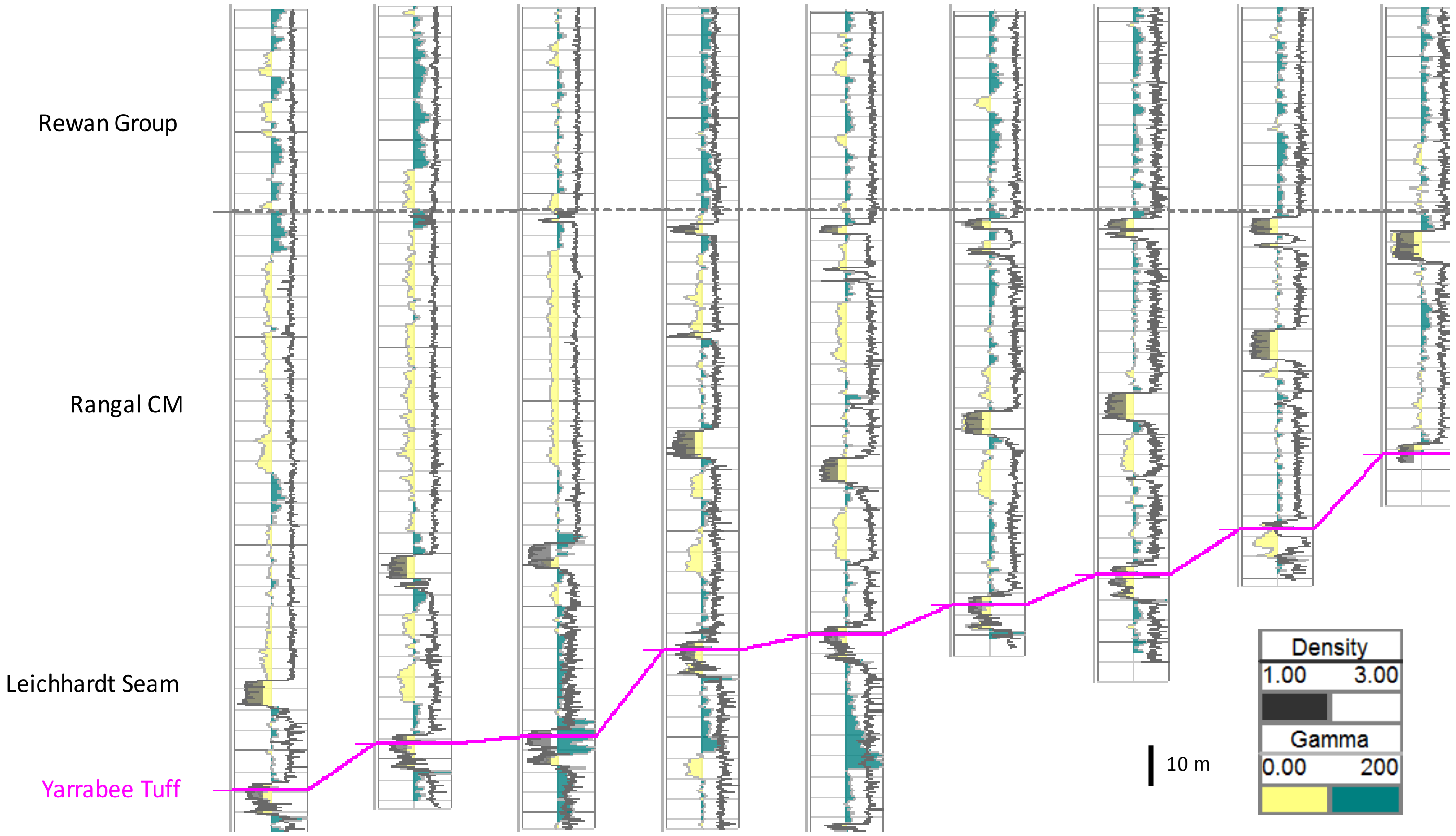


Figure 11 Borehole section at South Walker Creek showing the uppermost coal seam shaling out along the RCM/Rewan Group boundary.

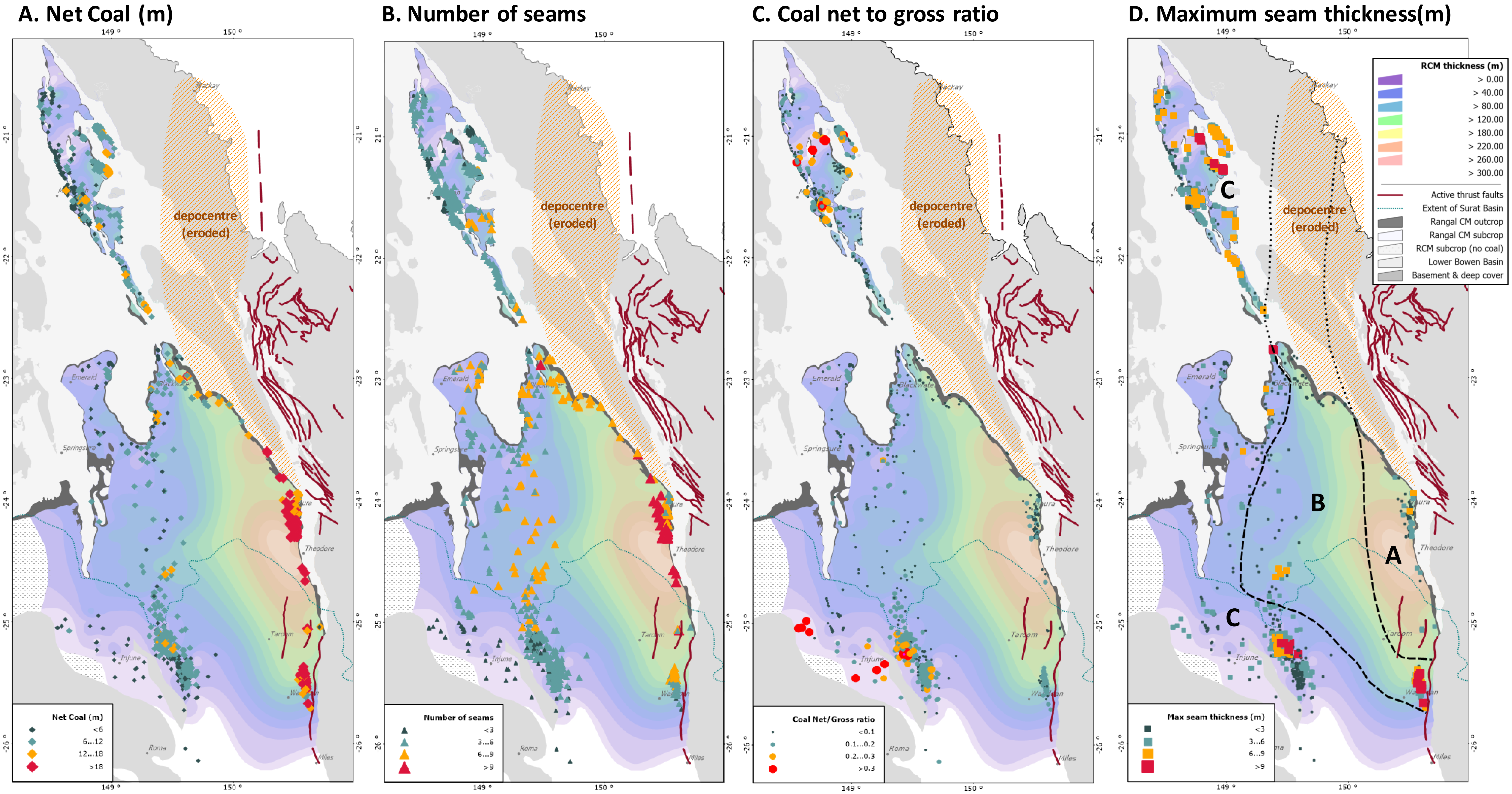
Coal distribution

The coal seam distribution was analysed between the different tiles by plotting the cumulative seam thickness (net coal), number of seams and maximum seam thickness for each borehole that transects the entire RCM (Figure 12). The net coal was calculated from the density logs where density is <1.8 g/cc. The number of seams and seam thickness were calculated from seam picks interpreted in this study. This exercise resolved domains that reflect the different tiles but put them into a regional context relative to basin subsidence.

Domain A. This domain centres on the depocentre of the Bowen Basin, where the RCM are >200m thick. This domain is located close to the frontal thrust systems active during deposition. This domain is characterised by the highest net coal accumulation (>18m) across many seams (>9). Seam thicknesses are moderate.

Domain B. Domain B is marginal to Domain A, where the RCM are 100-200m thick. Net coal accumulation is much less (<12m) than to the east, and there a still a large number of seams (6-9) which are relatively thin (<3m). Scotia is a small anomalous area where net coal is >18m, and there are mostly very thick (<6m) seams.

Domain C. The western region of the RCM is furthest away from the frontal thrusts, and are characterised by low accommodation (<100m). In this area, net coal is generally <6m, with fewer seams (1-6) that are mostly thin (<3m). However, this domain also contains pods of anomalously thick coal seams that are up to 25m thick.


A. Net Coal (m)

B. Number of seams

C. Coal net to gross ratio

D. Maximum seam thickness(m)

Figure 12 Coal seam distribution across the Bowen Basin expressed as A. net coal where density >1.8g/cc; B. number of seams; C. is a coal net/gross ratio for the RCM; and D. maximum seam thickness.

Thick seam occurrences ("crabs and squids")

The net coal thickness is highest in the domains of thickest RCM in the Taroom Trough (Domain A), but distributed across a sequence of thinner coals rather than a few thick seams. Thick seams and/or areas where a number of seams or seam plies converge, are an indicator of local and basin scale stability. Although maximum seam thicknesses were mostly <6 m, there are a number of areas where seams merge forming pods or relatively restricted areas of extremely thick coal >6 m, often referred to as "crabs" where they split in a radial pattern, or "squids" when they show unidirectional splitting in response to repeated subsidence say on the downthrown side of a fault. An example of a crab is at Fairview gas field (Figure 13). Here for a restricted area of less than 10 x 10 km, almost all seams within the Bandana Formation merge. Similar merged pods occur within Domain C at the Peak-Scotia coal seam gas field and at Ensham, distal to the thickest RCM depocentre in the Taroom Trough (Figure 14). In the northern Nebo Synclinorium, the Leichhardt Seam forms both small and large, merged pods. Thick merged seams are also present in the underlying FCCM (the Girrah Seam) and the MCM (the near convergence of the Goonyella seams, and the Harrow Creek Seam) on the Collinsville Shelf on the western edge of the Nebo Synclinorium.

Areas of thick and merged seams represent a balance of subsidence and peat accumulation (Wadsworth *et al.* 2002). Le Blanc Smith suggested that these areas of low accommodation were basement controlled, as they are often associated with gravity or magnetic highs (in Esterle and Sliwa (2002)). This worked well for the Goonyella seams, but not for all crabs. Others suggest that thick peat accumulation would stabilise the system, causing water courses to divert, keeping the peats free from clastic influx for long periods of time. In the case of the 6 to 15m thick coal seams of the RCM, this would be at least 60,000 to 150,000 years where there was little or no clastic influx except during extreme flooding. The differential compaction of peat relative to the adjacent clastic sediments could also influence the topography sequentially through time. At a basin scale, Ferm and Cavaroc (1968) suggested that thicker coals are more likely to occur up-river, associated with stabilised systems that are influenced but not overrun by base level rise; thinner but more laterally extensive coals would form in the paralic areas of the delta or coastal plains. This conceptual model fit well with the MCM (Esterle & Sliwa 2002), but during the time of RCM deposition, the basin is considered essentially continental (i.e. there is no evident coastal plain setting). The splitting character of the RCM varies between the different domains (see Chapter 4.4), and in addition to compensational stacking there could also be a larger structural control on the fluvial system architecture (Wilson, Section 4.5). Hunt (1988)'s analysis of Permian coal basins in eastern Australia concluded that the overall percentage of coals is greatest in areas of lower subsidence, whereas within foreland basins the total (cumulative coal) thickness increases but overall percentage of coal decreases towards the orogenic front as there is an overload of clastic sedimentation. Depocentres

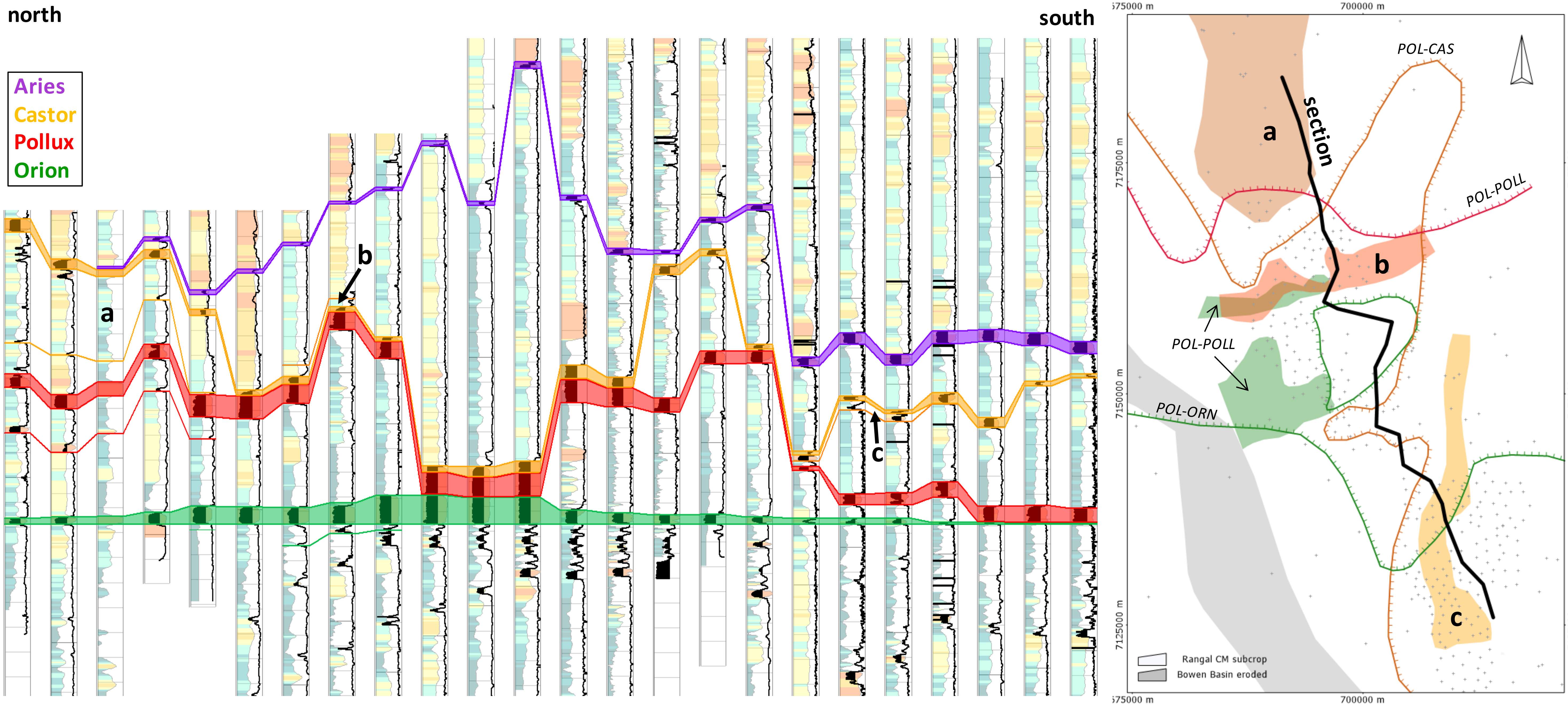


Figure 13 North-south correlation section through the Fairview seam pod, highlighting the thick seam splitting pattern. (Minor interburden channels: a. CAS/CASL; b. POL/POLU; and c. CAS/POLU)

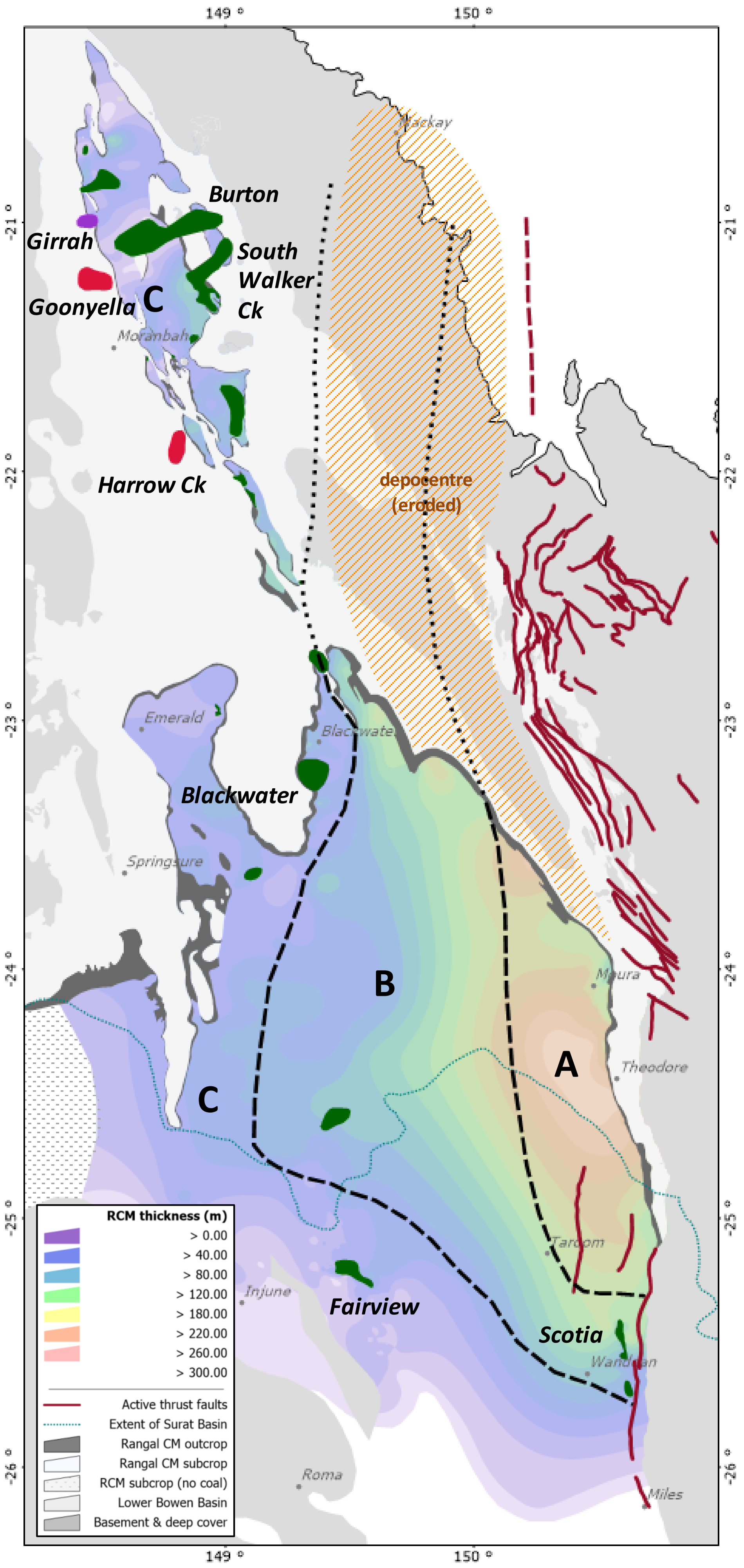


Figure 14 Distribution of crabs.

would shift stratigraphically relative to pulses of uplift, and be recorded in the offset of seam splitting patterns that are observed in the RCM, and in fact all coal measures. The splitting patterns also define the sedimentary features such as channels or splays that deposit the sediments. Regardless of the ultimate mechanism, the distribution of merged seams is prevalent regionally in the basin, associated with the Domain C of lower overall RCM thickness suggesting low subsidence rates distal to the foreland loading.

Coal rank distribution

Vitrinite reflectance is a sensitive geothermometer that captures the maximum temperature a coal sample has reached during coalification, and may provide insights into the burial and deformation history of sedimentary basins (Damberger 1974, Barker & Pawlewicz 1986). Isoreflectance maps for the Rangal and Moranbah Coal Measures were first published by Beeston (1986), based on a limited number of boreholes. A major update to these early maps, including report and comprehensive database, has just been released by the DNRM (McKillop 2016), who concluded that despite the large amount of new data, the fundamental reflectance trends across the basin have not changed. This new compilation of reflectance data was used for all maps and plots shown in this section.

Figure 15 shows the median vitrinite reflectance (RVmax) distribution of all RCM seam samples in each well. The reflectance is highest in the centre of the Taroom Trough, within the Baralaba Coal Measures north of Theodore and within the eastern part of the Nebo Synclinorium. The high coal ranks in the Taroom Trough and the Baralaba Coal Measures coincide with the partially eroded Triassic depocentre of the Bowen Basin, and may reflect the maximum burial of the coal measures in these areas (Beeston 1986). However, the high coal ranks in the Nebo Synclinorium occur outside the Triassic depocentre and cannot be attributed to maximum burial alone. Uysal *et al.* (2000) suggested thermal maturation was elevated by later thermal and fluid flow events in the Mesozoic and possibly Tertiary.

Maximum coalification depends on the depth of burial and the geothermal gradient at the time, which can be shown to be proportional to the vitrinite reflectance gradient (rank gradient) with depth (Teichmueller 1987). Figure 16 shows examples for boreholes from the Denison Trough and from the Nebo Synclinorium that highlight the higher, and more variable, reflectance gradients in the Nebo Synclinorium. The same boreholes also show a significant increase in the y-intercept compared to the Denison Trough boreholes. The y-intercept is the projected modern surface value for RVmax and is an indicator for the amount of missing section or exhumation since coalification. This indicator is only a relative measure, as there is no information about the geothermal gradient at the time of exhumation, or even if the uplift took place during one or more tectonic events. However, the exhumation must have occurred after the gradient was established (maximum coalification).

To analyse the rank gradient and exhumation trends across the basin, RVmax measurements from all coal measures in the DNRM database were included. Some data quality controls were applied, where RVmax values greater than 4 %RVmax were deleted to exclude the localised effects of intrusions. Also boreholes with a data spread of less than 20m were excluded to improve the reliability of the regression calculations. The results calculated for each borehole are plotted in Figure 17A&B.

The rank gradients across the Denison Trough and Taroom Trough are consistently low (< 1.2 %RVmax/km), but increase rapidly across the northern Comet Ridge into the Nebo Synclinorium where the gradients are variable but generally above 1.5 %RVmax/km. The highest gradients occur in the Moranbah Coal Measures between Goonyella and Saraji, where gradients greater than 2 %RVmax/km are common. There seems to be a decrease in the gradient towards the north near Newlands, and the east, between the Hail Creek Syncline and the Bundarra Granodiorite.

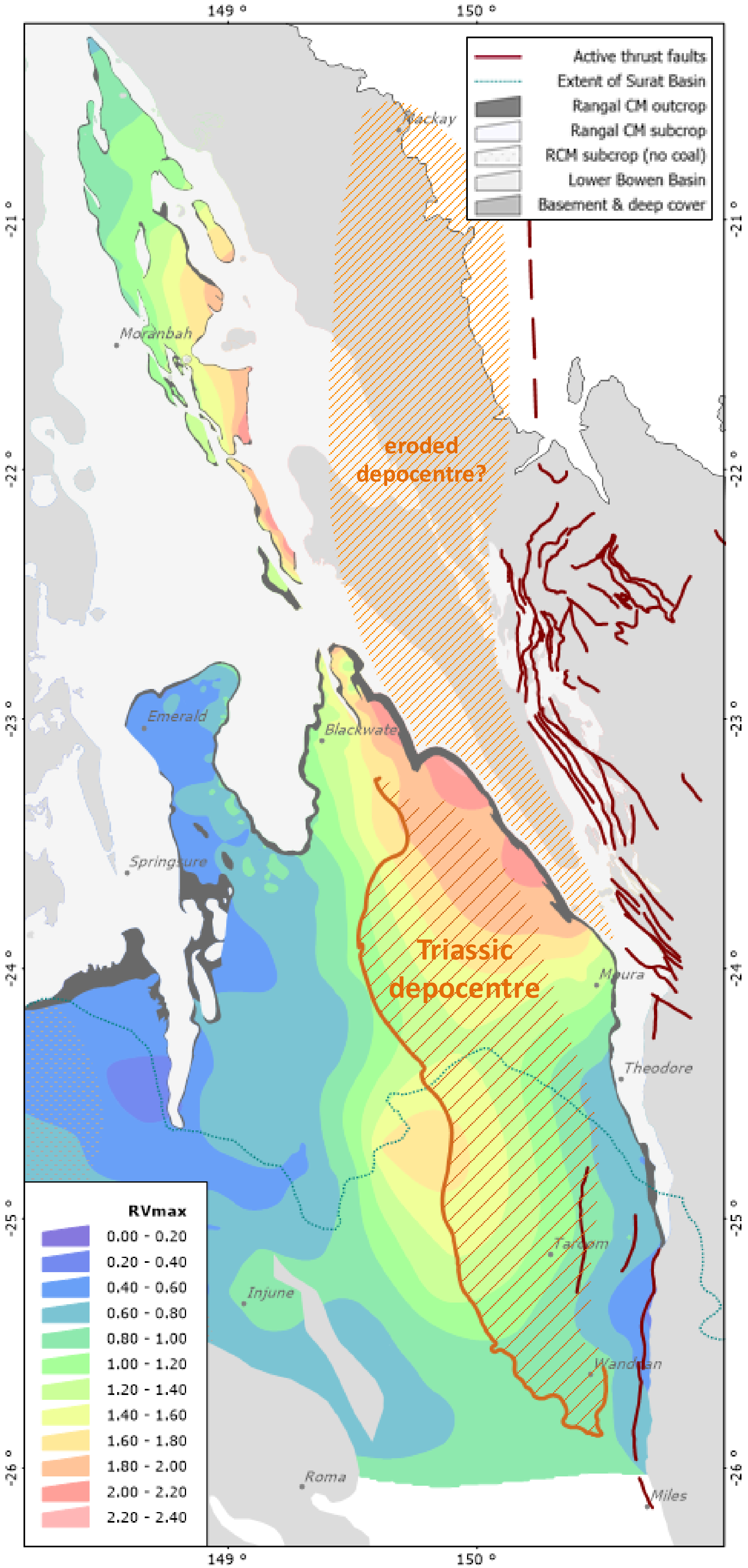


Figure 15 Coal rank distribution across the Bowen Basin, measured by the median RVmax for all seams from the Rangal Coal Measures. (Vitrinite reflectance data from McKillop (2016)).

The rank surface projections are consistently low (< 1 %RVmax) across most of the Bowen Basin, including the western margin of the Nebo Synclinorium. The surface rank then increases rapidly to about 2 %RVmax in the eastern Nebo Synclinorium and northern Comet Ridge. The surface rank increase starts gradually on the Comet Ridge, jumps abruptly across the Jellinbah thrust zone, and keeps rising towards the east. This suggests that the exhumation along the eastern Nebo Synclinorium was associated with the development of the Jellinbah Fold Thrust Belt, and included components related to faulting as well as a more regional uplift.

In their comprehensive study on clay mineralogy and vitrinite reflectance in the Bowen Basin, Uysal *et al.* (2000) argued that the steep and highly variable rank gradients in the northern Bowen Basin do not match the expected cold gradients in a rapidly subsiding foreland basin, but are more consistent with a rift setting. They found a lag between the temperatures recorded by clay mineral reactions and the vitrinite reflectance that suggests that the heating

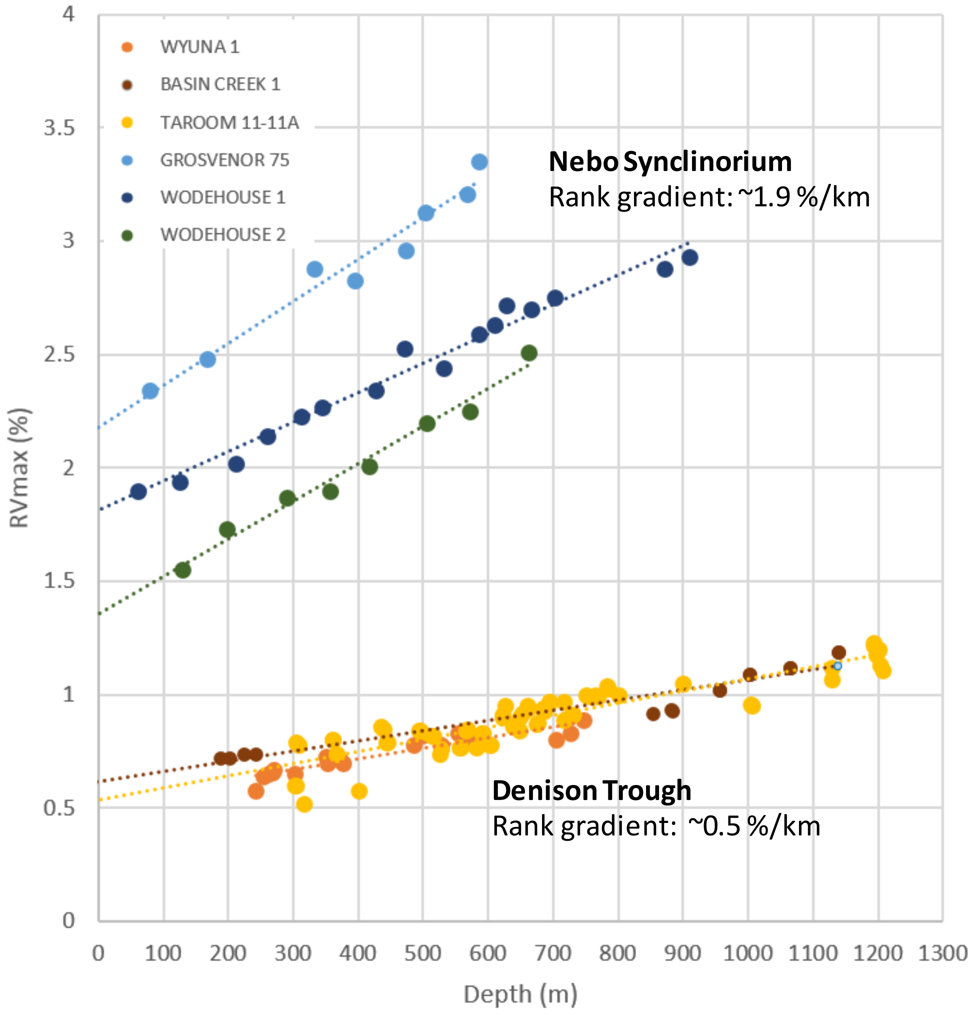


Figure 16 Plot of vitrinite reflectance versus depth for selected boreholes from the Denison Trough and Nebo Synclinorium.

was short lived. The study concluded that the variability of the gradients combined with the short life-span of the heating is consistent with a convective hydrothermal system, most likely related to rift extension during the latest Late Triassic. The study also noted the minimal and localised effect of the Cretaceous intrusions.

Similar hydrothermal systems have been proposed to explain vitrinite reflectance and trace element distributions in other basins such as the Appalachian foreland basin in the USA. Here, rank gradients reach 0.3 %RVmax/km in the footwall of the regional-scale Pine Mountain Thrust (O'Hara *et al.* 1990, Ruppert *et al.* 2010). These coal rank gradients formed during thrusting and are significantly higher than in the northern Bowen Basin. This shows that high geothermal gradients can be achieved in front of an active thrust front. Maximum coalification in the northern Bowen Basin predates the end of the long-lived Hunter-Bowen compression, suggesting that the hydrothermal heating is related to compression rather than rifting.

The timing of coalification and subsequent uplift are constrained by numerous K-Ar dates of illite-smectite from mudstones, siltstones and sandstones across the Bowen Basin that suggest that the hydrothermal heating was active during the latest Late Triassic, between 205-215 Ma, (Uysal *et al.* 2001). These ages are slightly younger than cleat mineralisation ages from the Blackwater/Dawson areas between 212-219 Ma that have been interpreted as a period of rapid uplift (Faraj *et al.* 1996). At the same time, the formation of extensional coal basins across the New England Orogen (e.g. Callide Basin, Ipswich Basin) have traditionally been interpreted to post-date the compression and uplift (Holcombe *et al.* 1997a). We now suggest that the Hunter-Bowen Orogeny may have lasted longer in the northern Bowen Basin than previously thought.

Conclusions. The distribution of vitrinite reflectance, rank gradients, and projected surface reflectance across the Bowen Basin suggests that:

- The rank increase in the Rangal Coal Measures towards the eastern margin of the Nebo Synclinorium is a result of exhumation along the Jellinbah thrust fault system;
- Coalification occurred before exhumation by the Jellinbah thrust system;
- Anomalous coal rank gradients in the Nebo Synclinorium are caused by short-lived hydrothermal heating as suggested by Uysal *et al.* (2000), but probably during Hunter-Bowen compression, not rift extension; and
- The effect of intrusions in the coal measures is localised and regionally insignificant.

The timing of structures within the Bowen Basin and the Hunter-Bowen Orogeny will be addressed further in an ACARP companion study to the current project.

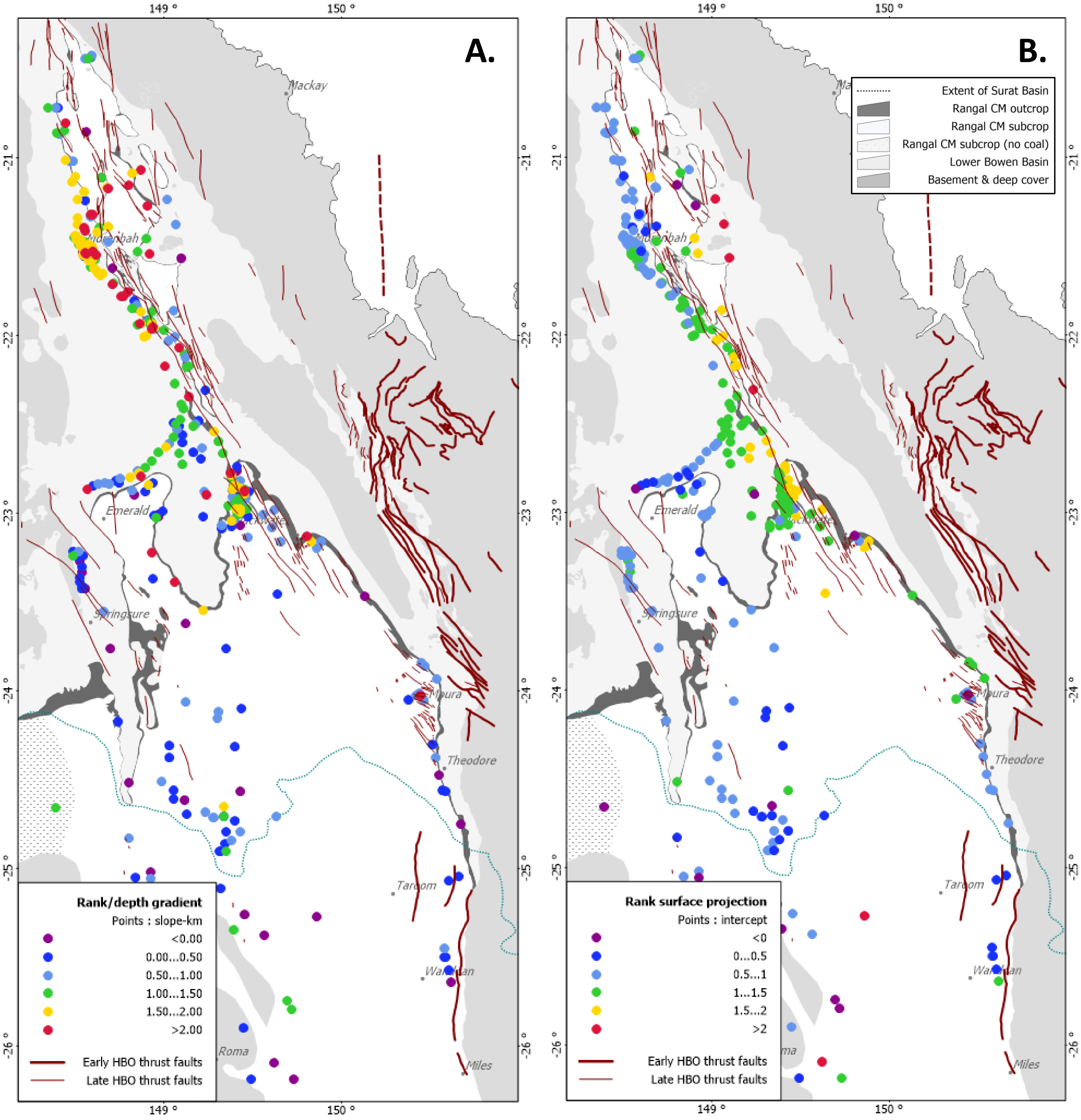


Figure 17 Coal rank gradient (A.) and rank surface projection (B.) distribution across the Bowen Basin. (Vitrinite reflectance data from McKillop (2016))

4.3 Rewan Group

The lower part of the Rewan Group is exposed in many of the highwalls that mine the upper seams in the RBB Coal Measures. While these rocks have not been assessed in detail during this study, they form an important geotechnical unit.

The current stratigraphic division of the Early to Middle Triassic succession of the Bowen Basin was proposed by Jensen (1975), who elevated the Rewan Formation and Clematis Sandstone to group level, and subdivided the two groups into the Sagittarius Sandstone & Arcadia Formation, and the Glenidal Formation & Expedition Sandstone respectively (summarised in Table 2). The main reason given for the re-definition of the Triassic stratigraphy was the recognition that the RBB Coal Measures and the Rewan Group accumulated in the same drainage basin, and that palaeocurrent directions only changed significantly at the base of the Clematis Group.

The thickness of the lowest formation, the Sagittarius Sandstone ranges from 165m in the southeast to 400m in the north (Jensen 1975), which suggests that this is the only Triassic stratigraphic unit that is or will be exposed in the open cut coal mines, and therefore the only unit relevant to this study.

As part of his PhD project, Grech (2001) mapped outcrops of the Sagittarius Sandstone in the southern Denison Trough, where the basal section consists of medium to coarse grained volcanolithic sandstone, interbedded with dark grey to greenish mudstone. The sandstone beds are 0.1-0.7m thick, fine upwards, and commonly have erosive bases associated with pebble lags. The sandy base of the unit gives way to grey to greenish mudstone interbedded with volcanolithic sandstone beds that have sharp but non-erosional bases. The depositional environment for the Sagittarius Sandstone in this region was interpreted as fluvio-lacustrine with palaeocurrent directions suggesting north-westerly drainage. Grech (2001) then interpreted a number of open file stratigraphic boreholes in the southern Bowen Basin and recognised at least two alluvial fans shedding from the east (see large arrows on Figure 19) with aprons of sand and mud-dominated fluvial sediments in the Taroom Trough.

Further north there have been few studies of the Rewan Group other than the regional work by Jensen (1975). The characteristic array of interbedded sandstone, siltstone and mudstone is consistent regionally but with variations in the proportion and grain size of the sandstone (see examples in Figure 18). In the far north of the Bowen Basin the Sagittarius Sandstone contains medium to fine grained green lithic sandstone, while in the Moura-Theodore region medium to very coarse and locally conglomeratic sandstones are dominant. Along the Comet Ridge the Sagittarius Sandstone is more thinly interbedded with a very fine to medium grained sandstone component. This regional variability is consistent with the relative proportion of sandstone estimated from gamma logs for the lowermost 100m of the Rewan Group, as shown in Figure 19. The yellow to orange colours highlight sandstone dominated areas near the entry points of the northern alluvial fan, near Theodore-Moura (another alluvial fan?) and within the Denison Trough (northwest flowing trunk channel). The southern alluvial fan has a characteristically higher gamma signature (annotated on Figure 19) , suggesting a different provenance for the sediments in this part of the Bowen Basin.

Sediment dispersal at the time of deposition of the Sagittarius Sandstone was mostly from the rising thrust belt in the east into or across the Taroom Trough. The north-westerly palaeocurrent directions in the Denison Trough suggest that the Bowen Basin may have drained into the Galilee Basin at this time. Cross-bedding analysis in the Elphinstone area indicate southerly drainage in the Rangal Tile (Jensen 1975).

Table 2 Summary description of the Early to Middle Triassic stratigraphic units in the Bowen Basin (modified from Jensen (1975))

Stratigraphy		Lithology	Thickness (metres)	Sst : Sltst ratio
Clematis Gp	Expedition Sandstone	Very fine to very coarse sandstone with rare siltstone lenses.	300-335	1:0
	Glenidal Formation	Fine to coarse sandstone with grey to green mudstone.	80-350	3:2 to 4:1
Rewan Gp	Arcadia Formation	Red mudstone, green siltstone and fine to very coarse sandstone. Conglomerate.	230-800	1:1
	Sagittarius Sandstone	Fine to medium grained sandstone with interbedded grey mudstone and siltstone. Some conglomerate.	165-400	1:1 to 3:2

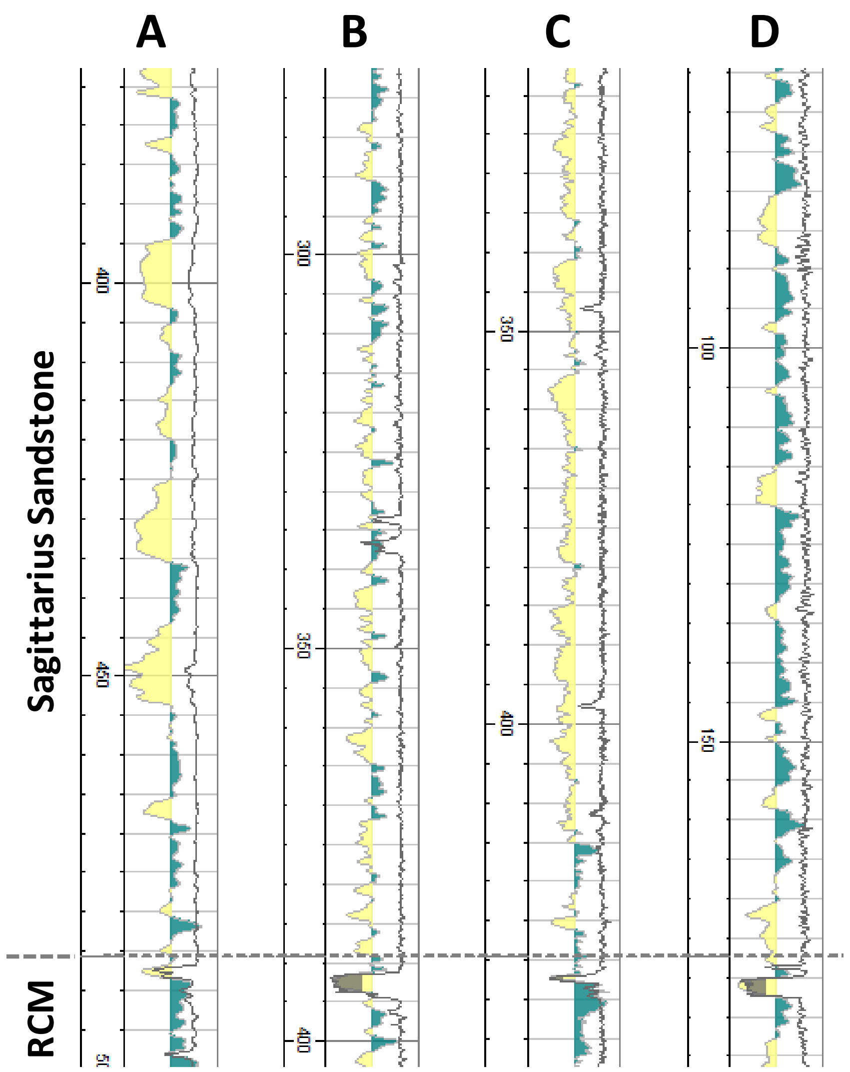


Figure 18 Example wireline log signatures of the Sagittarius Sandstone, showing the variability in sandstone proportion and bedding thickness. The borehole locations are shown on Figure 19.

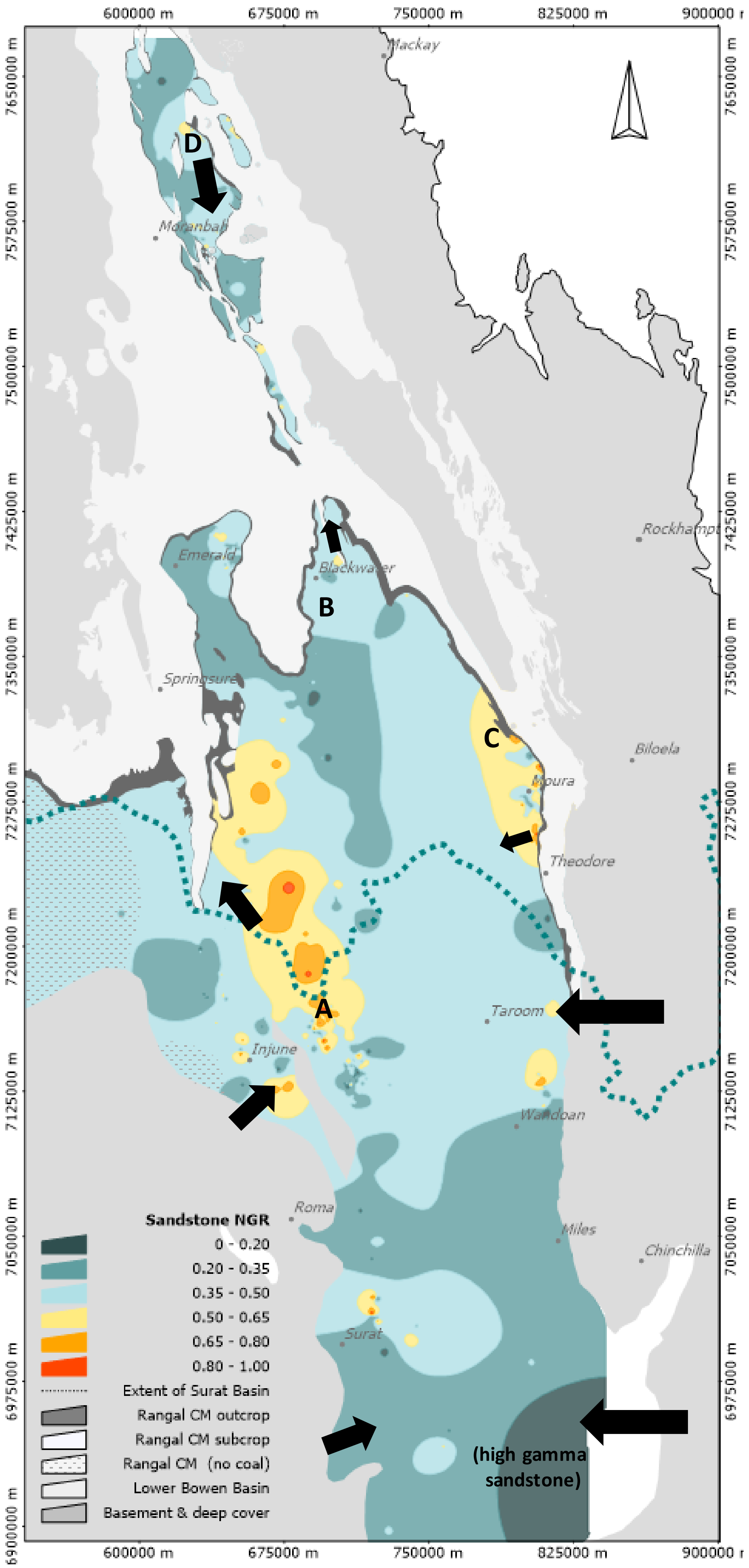


Figure 19 Map showing the net-to-gross sandstone ratio for the lower 100m of the Sagittarius Sandstone. The arrows a palaeocurrent directions from Grech (2001) and Jensen (1975).

4.4 Coal seam correlations

Renate Sliwa

Rangal tile

One of the main objectives for this study was to present a regional coal seam correlation that links not only the two major economic seams, but also minor seam splits, across all the coal mines in the area. The regional persistence of the two major economic seams and a rider seam, as well as the uppermost seam in the Fort Cooper Coal Measures has been well established in literature and was reviewed in detail by Matheson (1990a). Matheson proposed a regional naming convention based on the most widely used seam names, which in ascending order are the Girrah, Vermont, Leichhardt and Phillips Seams, which we have adopted for this study. Local names for the major seams persist in a number of mines (Table 3), but there is no doubt about their correlation at a regional scale.

To constrain the correlation of the minor seams, and to highlight regional trends we have used four marker horizons that can be mapped from standard wireline logs:

Rangal top. The top of the RCM as defined in Chapter 4.2, has been mapped just above Mudstone Marker or else just above the last coal seam or carbonaceous shale.

Leichhardt Seam. This is the main economic seam in all mines. We have adopted a “working seam” approach to its definition, and always followed the thickest, or in some locations the brightest seam split to be used as the regional marker.

Yarrabee Tuff. This high gamma tuff was preserved within the Vermont Seam across all of the Rangal Tile, and is the most reliable marker for regional correlation purposes.

Girrah Tuff. The Girrah Seam is a thick tuffaceous coal interval that contains many splits at various levels. A prominent high-gamma tuff near the top of the seam was chosen as a regional marker to represent the top of the Girrah Seam.

Minor seam splits were then correlated between mine sites, and assigned simplified codes to generate regional cross-sections. The correlation of seam plies was beyond the scope of this project, so that some split codes that occur in disconnected areas might not refer to exactly the same seam split. A table that shows the detailed correlation between mine codes and our regional codes are presented in Appendix A.

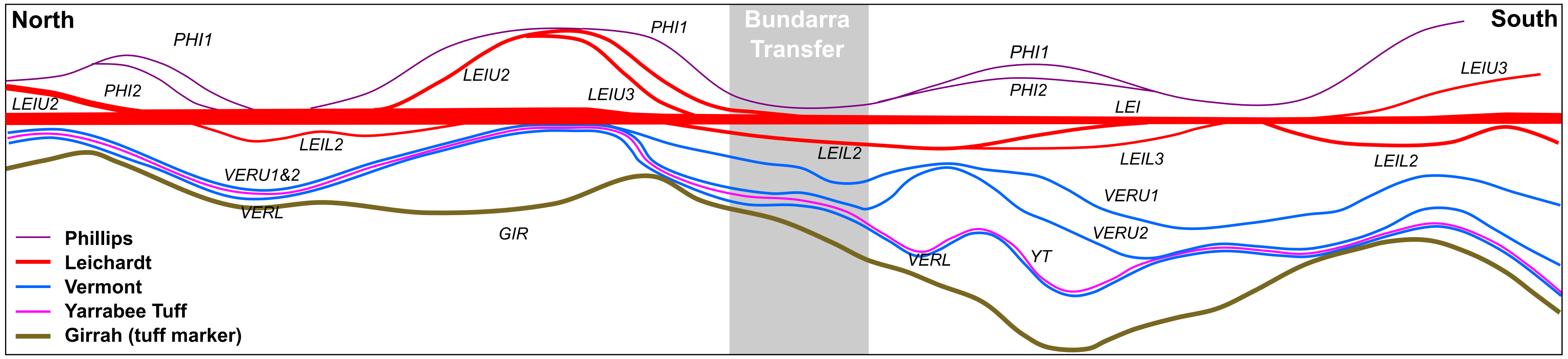


Figure 20 Schematic section of coal seams in the Rangal Coal Measures laid flat to the Leichhardt Seam marker horizon.

Table 3 Names of major coal seams that differ from the regional schema proposed by Matheson (1990a).

Matheson (1990)	**Newlands**	**Hail Creek**	**South Walker Creek**	**Coppabella**	**Foxleigh**
Phillips	Newlands Rider				Roper
Leichardt	Upper Newlands	Elphinstone	Main & Tops	Macarthur	Middlemount
Vermont/Yarrabee Tuff	Lower Newlands	Hynds	Hynds		Lindsay/Tralee/Pisces
Girrah		Fort Cooper			

The main observations from the regional seam correlation are:

- The Leichhardt, Vermont and Girrah Seams are regionally persistent across the Rangal tile;
- Seam splits are regionally consistent and rarely shale out;
- Z-splits connect the Leichhardt and Vermont Seams at Elphinstone/South Walker Creek, and are common in the upper Girrah Seams; and
- The overall number of seams stays more or less constant along the Rangal tile, but the splits diverge toward the south.

The distribution of all seam splits and areas of thick seams are shown in Figure 21. The following sections describes the coal seam distribution in detail by mine site.

Newlands/Eastern Creek. Coal is currently mined at Newlands from the Upper Newlands Seams and the Eastern Creek B Seam, which are correlated with the Leichhardt Seam. The Leichhardt Seam is between 4.5 and 7.2m thick, with a lower bright banded section and an upper dull section divided by a tuffaceous claystone bed (Peou 1995). In the northern part of the deposit the Leichhardt Seam splits locally below the claystone bed (coded as LEIU2, but not equivalent to LEIU2 further south). The two Newlands Rider Seams, correlated with the Phillips 1&2 Seams split along northwest trending split lines (Figure 21a). The rider seams directly underlie the Mudstone Marker which is up to 12m thick in the Newlands pits, but thins and disappears towards the east.

The Lower Newlands Seam contains the Yarrabee Tuff and is equivalent to the VERU/YT/VERL package (Vermont package), which stays together across this deposit. The Vermont package merges with the Leichhardt Seam in the north, and with the underlying Girrah Seam to the east.

Hail Creek/Bee Creek. The two mining seams at Hail Creek are the Elphinstone and Hynds Seams. The Elphinstone Seam is equivalent to the Leichhardt Seam, while the Hynds Seam includes the Yarrabee Tuff and correlates with the Vermont package, similar to Newlands. The Leichhardt Seam does not split across the deposit and is up to 8m thick. It is directly overlain by the Rewan Group. A thin lower split (LEIL2) splits off towards the south and is present across the Bee Creek deposit.

The Vermont package stays merged across the mining area and is consistently 6.5-8.5m thick (Preston 1995). In the very north of Hail Creek, the upper Vermont Seam splits off the Yarrabee Tuff to accommodate >50m thick interburden. Another thin split in the Vermont Seam defines a 3 km wide northeast trending channel between Mt Roberts and Hail Creek. The Girrah Seams follow closely below the Vermont Seams, but dive off abruptly between Hail Creek and Bee Creek.

Burton/Lake Elphinstone/Red Hill. These three deposits span the Nebo Synclinorium to the south of Newlands and to the west of the Hail Creek syncline. Seam nomenclature at Burton follows the regional seam names, while Lake Elphinstone follows the Hail Creek conventions.

The Leichhardt Seam is merged with the underlying Vermont/Yarrabee Tuff package across Burton and southern Lake Elphinstone where it reaches a thickness of more than 10m. This coal “crab” thins to all sides by splitting down the Vermont package and a lower Leichhardt Seam split (LEIL2). The Phillips Seams split up to the northeast and southwest. Further east, at Red Hill, the Leichhardt Seam becomes thinner and divides into several thin seams. This zone of split and thin Leichhardt Seams continues to the north and south parallel to the western outcrop margin of the Rangal Coal Measures.

South Walker Creek/Coppabella/Moorvale. The eastern flank of the Nebo Synclinorium is characterized by some of the thickest Leichhardt Seam in the Rangal tile, but also the most complex splitting patterns. The Leichhardt Seam (MacArthur Seam at Coppabella) is locally >10m thick, but splits into up to three seams that merge again in some areas (z-splitting). The seams splits are commonly 1.5-2m thick, but some shale out locally.

Thin rider seams (Phillips Seams) occur at Coppabella and were correlated into South Walker Creek, marking the boundary with the Rewan Group. However, the 2m thick seam coded as the Phillips Seam at Moorvale was reinterpreted as an upper Leichhardt split due to its thickness. The high Phillips Seam splits contribute significantly to the ovall anomalous thickness of the RCM.

The Vermont Seams are thin and split apart from the Yarrabee Tuff at Moorvale, where the Girrah Seams are low. To the east, the Vermont package merges with the Girrah Seams at Coppabella and South Walker Creek.

Isaac Plains/Millennium/Carborough Downs/Poitrel/Daunia. This structurally complex zone of regional folding and thrust faulting to the southwest of the Bundarra Granodiorite is also known as the Bundarra Transfer (Figure 20a). One consequence of the deformation is that the RCM stay close to the surface, accounting for the number of closely spaced mines in this area. The RCM as a whole are consistently thin (20-80m) across this region, except for an anomaly across Millennium where the RCM are >100m thick. Where the RCM are thin, the Phillips Seams are merged with the Leichhardt Seam and the Yarrabee Tuff runs 10-40m below the Leichhardt Seam.

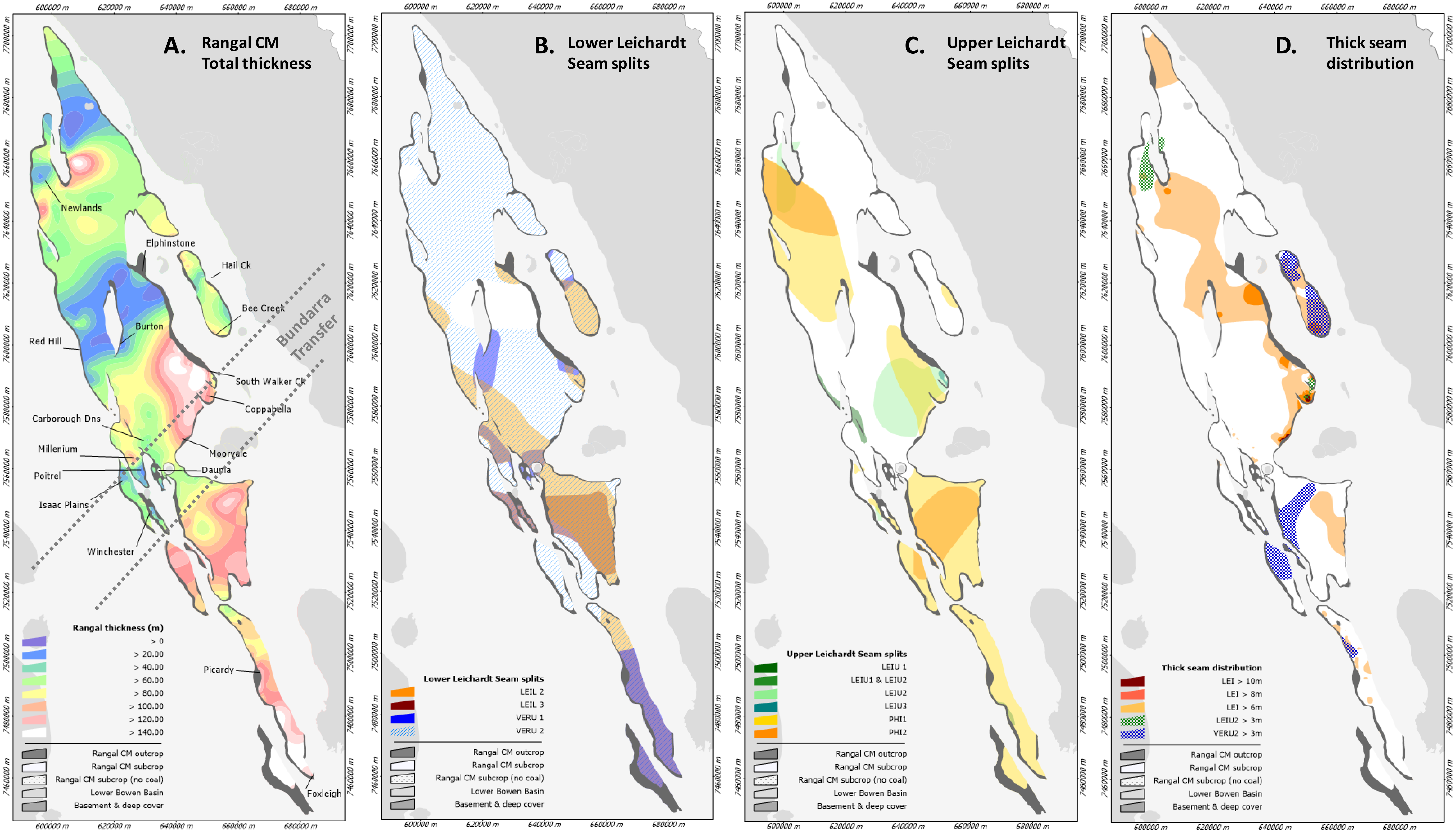


Figure 21 A. Total thickness of the Rangal Coal Measures between the base of Rewan Group and Yarrabee Tuff; B. Interburden distribution of the lower Leichhardt Seam splits; C. Interburden distribution of the upper Leichhardt Seam splits; and D. Distribution of thick seam areas including the Leichhardt, LEIU2 and VERU2 seams.

The Leichhardt Seam is moderately thick (3-5m), except in a 2.5km wide, north-south trending corridor between Isaac Plains and Poitrel, where the seam thins down to 1-1.5 m thick above a thick channel sandstone in the interburden below. There is only one local upper seam split (LEIU2) in the northwest of the area, and the two Vermont Seams split towards the south and northwest.

The Girrah Seams and Vermont package generally stay close together in this area. The upper Vermont Seam splits into two to accommodate a well-defined northwest trending channel.

Winchester/Coxendean. The Winchester deposit is characterised by relatively simple coal seam stratigraphy. The Leichhardt Seam directly underlies the Mudstone Marker with localised development of the Phillips Seams. The Vermont package stays together 20-30m below the Leichhardt Seam, and is merged with the upper Girrah Seam in the northern part of the deposit.

Coal seam correlations in the Coxendean area were more difficult, as only a few, widely spaced, open file boreholes were available to this study, and these each contain a number of significant seams, some of which may be thrust fault repetitions. The uppermost significant seam and a couple of carbonaceous riders were correlated with the Leichhardt and Phillips Seams. The lowermost thick seam is clearly the upper Vermont Seam as it is merged with the Yarrabee Tuff. Thinner seams between the Vermont and Leichhardt Seams have been tentatively correlated as lower Leichhardt Seam splits.

Picardy/Foxleigh. The coal seam characteristics change significantly in the southern part of the Rangal tile. The RCM thickness increases from 60m in the north to >140m in the south, controlled by seam splitting in both the Leichhardt and Vermont Seams. At Foxleigh, the Leichhardt Seam (Middlemount Seam) thins to the south as the lower Leichhardt split and upper Vermont Seams (Lindsay and Tralee Seams) thicken. The distances between seams stay consistent across large areas giving the southern RCM a “train-track” appearance that is typical for the Baralaba Coal Measures further south.

Baralaba tile

Coal was first mined in the Baralaba Coal Measures during the 1940’s at Moura. Exploration was supported by a departmental drilling program that established a regional stratigraphy for the coal seams, and estimated resources within three economic seams (Chiu Chong 1969). Alphabetic codes were applied to the intersected seams, where A was always the top seam, and marked the transition to the overlying Rewan Group, and E marked the boundary with the underlying Kooloola Member. The economic seams were B, C and D, with C mined in the Moura underground workings.

This alphabetic seam nomenclature has been maintained by most exploration companies south of Baralaba, and was adopted as the regional schema for this study. Further north, gaps in the exploration data along strike of the coal measures, and structural complexity made regional correlation difficult and other local seam naming conventions emerged.

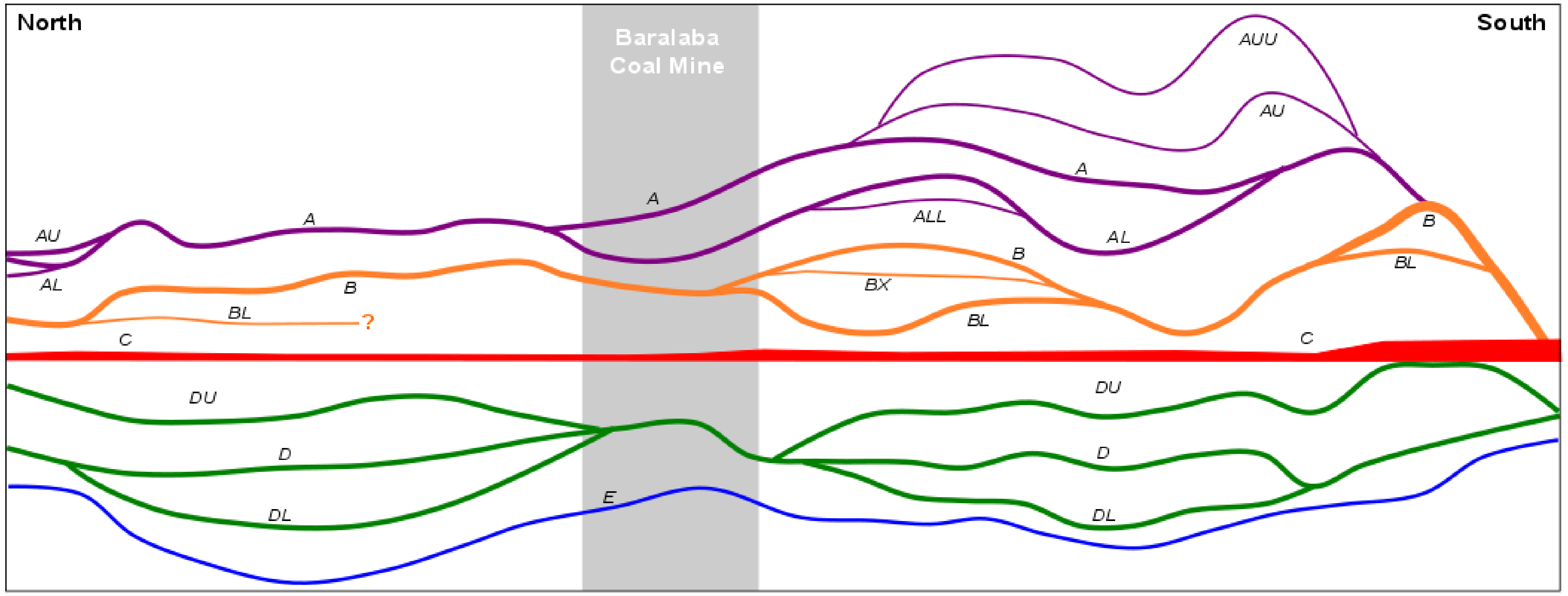


Figure 22 Schematic section of coal seams in the Baralaba Coal Measures laid flat to the C Seam marker horizon.

To attempt a regional correlation that links Yarrabee all the way to Scotia we defined three marker horizons that we could map from standard wireline logs:

Rangal top. The top of the RCM as defined in Chapter 4.2, has been mapped just above the last coal seam, which is a split of the A Seam in most areas.

C seam. This is one of the three economic seams targeted along the eastern margin of the basin. The seam itself is difficult to differentiate from the B and D Seams, but there is a characteristic change from higher gamma siltstones and sandstones below the C Seam to low gamma sandstone-dominated interburdens above the C Seam.

E Seam. This thin non-economic seam marks the boundary between the Baralaba Coal Measures and the tuffaceous Kaloola Member below. The E Seam commonly rides on a thin tuff, but mostly marks the transition from sandstone/siltstone dominated interburdens above to tuffaceous siltstones, mudstones and carbonaceous shales below.

Detailed seam correlation between these marker horizons proved to be difficult and was completed with a lower confidence than the correlations in the Rangal tile. The wireline signature of many seams is nearly identical, so that thrust repetitions are difficult to identify. Large distances between clusters of boreholes suggest that smaller seam splits may have been missed. In some areas where alternative seam correlations are equally valid we chose the one that resulted in the simplest regional seam schema, while honouring the company seam correlations where possible (Figure 22). Appendix A lists the detailed correlation between our regional seam nomenclature, and the local company seam names.

Seam splitting patterns in the Baralaba Coal Measures are directly related to the overall thickness distribution of the coal measures. Along a transect from Yarrabee in the north to Scotia in the south, the total thickness of the coal measures varies from ~120m to a local maximum of ~300m, then to a pinch point near Baralaba of 220m, and to the main depocentre that is >300m thick, before thinning down to <100m near Scotia (Figure 23). This hourglass-shaped thickness distribution is mostly controlled by seam splits in the D and A Seam groups. Seams in general are merged and thicker at Yarrabee, Baralaba and Scotia. The seam split lines either trend perpendicular to the basin margin with splits opening up toward the thicker regions, or run subparallel to the basin margin, opening up towards the basin centre.

The following sections contain notes on the coal seam distributions and correlations for various mining areas.

Belvedere/Dawson. These two deposits span the thickest region of the Baralaba Coal Measures and contain the highest number of seams anywhere in the Bowen Basin. Our regional correlation maintained the company seam names where possible, but using the C Seam regional marker, we identified a number of local inconsistencies that required re-correlation (see Appendix A for details). The main observations for coal seam distribution in this region are:

- There are no seams splitting off or approaching close to the C Seam;
- The D Seam splits into three seams, which track remarkably parallel to each other; and
- The A Seams split and merge with numerous z-splits, and minor seams that shale out into the interburdens.

Scotia. Scotia is characterised by two to three thick seams that locally merge into a pod, and a couple of lower seams. We correlated the thick seams with the C and B Seams, as the high to low gamma signature transition of the interburden can be observed. However, the large distance to the closest boreholes near Theodore makes this a lower confidence correlation.

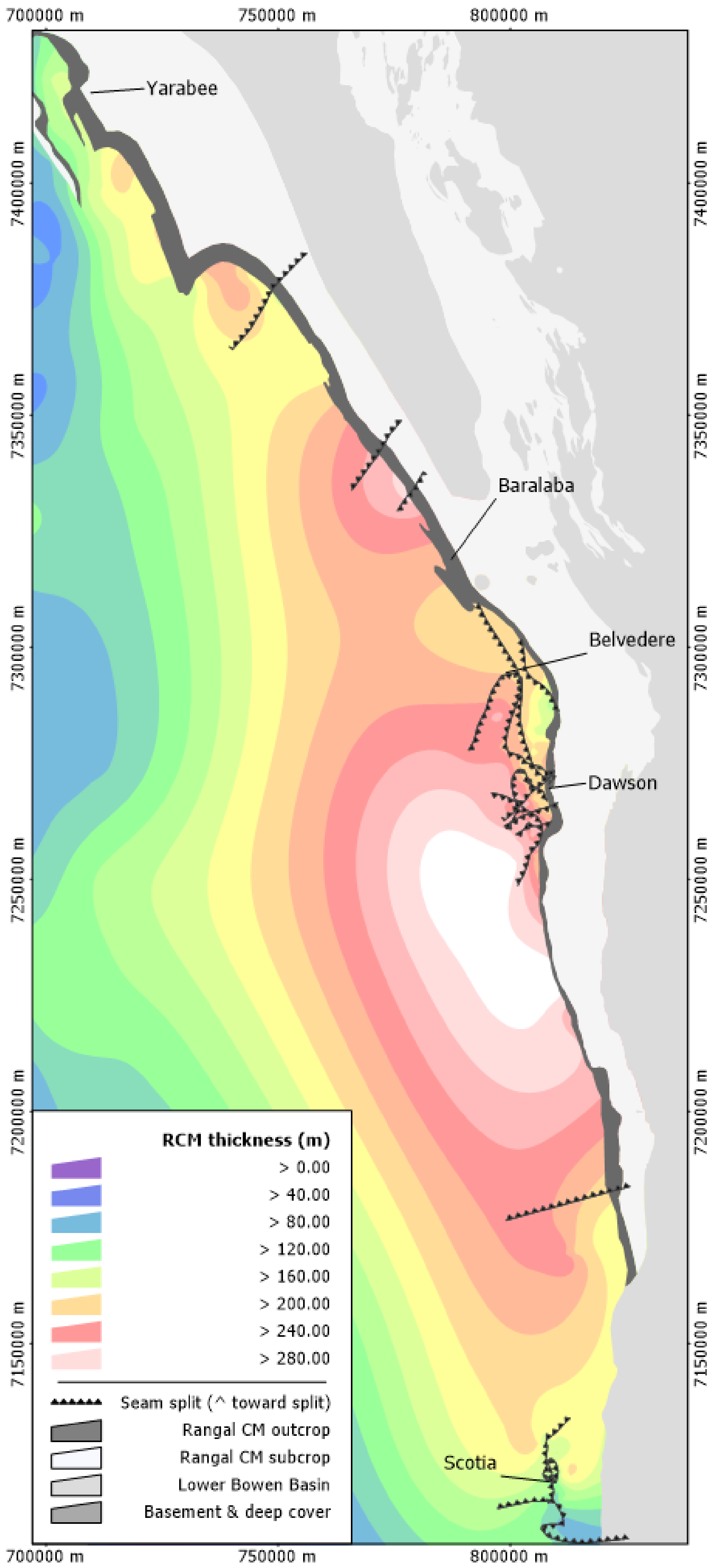


Figure 23 Thickness distribution and split lines of the Baralaba Coal Measures.

Baralaba. The seam naming convention at Baralaba is considerably different from the alphabetic codes used to the south, and includes >10 named seams, including several economic target seams. The Baralaba deposit is folded at mine-scale resulting in local seam dips > 50°, and two widely spaced mining areas. Near mine exploration boreholes that target open cut resources only partially transect the Baralaba Coal Measures, hindering consistent correlations across large distances. The closest deep boreholes with a complete section of the Baralaba Coal Measures are Baralaba 2C & 5C in the north and Banana 1 in the south of the deposit. We correlated the local seam names with the seam intersections in these open file boreholes, which were then tied into the regional correlations with sufficient confidence.

Near Baralaba 2C & 5C in the north, the C Seam clearly correlates with the Doubtful Seam. The seams above tie in with the B and A Seams as expected, as do the Dawson and Dunstan Seams with the D and E Seams. This places the lower seams (Wright, Double and Coolum) into the Kaloola Member, even though they are unusually thick and lack the typical tuffaceous character of this unit.

Near Banana 1 in the south, the C Seam correlates with the Double Seam. The seams below fit with the D (Coloola) and E (Dirty) Seams, and the character of Dirty Seam is typical of the Kaloola Member. The correlations of the upper seams with the A and B Seams are also a good fit. Note that the three upper seams in the mine schema are not intersected in this area. These upper seams may have been eroded, but we suggest that they never existed in this area.

Yarrabee. Yarrabee is located in the far north of the Baralaba Tile, and is geographically closer to Curragh and Blackwater than to the long-established mines near Dawson. The coal seam schema at Yarrabee follows the "Galaxy" names used along the Comet Ridge. Correlation along the Baralaba tile suggests that the Pollux Seam is equivalent to the C Seam, the Castor to the B Seam and the Orion/Pisces Seam to the D Seams. The Yarrabee Tuff is a recognisable unit to mark the base of the Baralaba Coal Measures in this area.

Bandanna tile

The Bandanna tile covers the western part of the Bowen Basin including the Denison Trough, Comet Ridge and Roma Shelf. Most of the coal mines are located around the Comet Ridge in the north and along the Springsure Anticline to the west. Further south and east the RCM dip underneath the cover of the Surat Basin, but stay within the exploration target depth for coal seam gas (CSG). Many of the regional exploration boreholes across the region and the CSG development wells at Fairview are now open file, and were used to complete the RCM characterisation in this part of the Bowen basin.

A consistent regional seam nomenclature for the Bandanna region was first proposed by Staines (1972) who expanded the BHP convention of using the names of constellations for all Late Permian coal seams in the Bowen Basin. The seams names that apply to the RCM include from bottom to top: Pisces, Orion, Pollux, Castor and Aries. We decided not to use several seam names designed for merged seams (Argo = Orion & Pollux; Gemini = Castor & Pollux; Taurus = Castor & Pollux & Orion) as we kept a working seam approach to our correlations that follows the thickest seam in most locations. Most mines today follow an alpha-numerical code that is based on the constellations nomenclature, or attempts to link across to the A-to-E convention used in the Dawson area. Table 4 summarises the main seam codes for mines where the constellations names are not used. Appendix A lists a detailed correlation between our regional nomenclature, and the mine seam codes.

The complex seam schemas provided by most mines suggest that seam splitting is common, and that regional markers are important to control correlation between mines. We defined three marker horizons that we could map from standard wireline logs:

Rangal top. The top of the RCM has been mapped just above the last coal seam, which is the Aries Seam across all of the Baralaba tile.

Pollux Seam. The thickest seam in each mine is generally defined as the Pollux Seam, although multiple seams are mined. Our working seam approach follows this convention, although the abundant seam splits provide alternative correlations. There is no wireline signature in the interburdens around the Comet Ridge that helps to identify the Pollux Seam as a regional stratigraphic marker. In the south, at Fairview, where the Dawson seam nomenclature is used, the C Seam with its characteristic gamma shift is correlated with the Pollux Seam.

Rangal base. Around the Comet Ridge the Yarrabee Tuff is preserved within the Pisces Seam, forming a package very similar to the Vermont package in the Rangal tile. This seam-tuff package does not continue to the south where the RCM overly the Burngrove Formation and Black Alley Shale. Here the first seam above the generally coal poor underlying units was defined as the base of the RCM.

Table 4 Names of major coal seams in use that differ from the regional schema proposed by Staines (1972).

Staines (1972)	Blackwater	Ensham	Rolleston	Durham (CSG field)	Fairview (CSG field)
Aries	Top & Top Rider	A1	X		A
Castor	Middle & Middle Rider	A2	A		A1 & A2
Pollux	Lower	A2 & C	B & C	CRB2 & CRB3	B & C
Orion	SG	P & Q	D	CRB1	D
Pisces	PS-YT	V			
Virgo (Fairhill Fm)					E & F

Regionally the Pollux Seam is neither as consistently thick as the Leichhardt Seam in the Rangal tile, nor does it mark a major shift in interburden character such as the C Seam in the Baralaba tile. A number of other seams are locally prominent, such as the Castor Seam along the eastern flank of the Comet Ridge and north of Fairview and the Orion Seam south of Fairview (Figure 24).

Overall the seam distribution in the Bandanna tile is less predictable than in other parts of the basin. Major seams such as the Orion and Aries shale out and disappear towards the Springsure Shelf (Figure 25), and it is difficult to distinguish between seam splitting and shale-outs on sections. Where seam splits are well defined, they generally trend east-west to northeast, but do not open towards a preferred orientation. Minor seam splits commonly define narrow channels, highlighting the complex geometry of the coal measures across the Bandanna tile.

The following sections contain notes on the coal seam distributions and correlations for the mining areas.

Curragh. Curragh is the northernmost deposit in the Baralaba tile, and is located in the footwall of the Jellinbah Thrust, a regional-scale structure with >600m throw. All seams from Pisces to Aries are mined, but the Pollux Seam is very thick (> 10m) and is merged with the Pisces/Yarrabee Tuff package. The Castor Seam is also a thick seam as it has merged with the Aries Seam.

Blackwater/Humboldt. South of Curragh, the Castor Seam approaches and merges with the Pollux Seam, before lifting off again at Humboldt. The Aries Seam rides consistently above the Castor Seams most of the way from the north, but then merges with the Castor to form a regional scale z-split. The Orion Seam is the lowest seam mine at Blackwater. It splits off the Pollux Seam south of Curragh, but merges again across a small area north of Humboldt.

Ensham. The Ensham deposit centres on a small coal pod where the main mining seam is thick but splits off several minor seams towards the west and south. While this seam was correlated with the Castor Seam in earlier publications (Dawson 1995), we have now correlated it with the Pollux Seam to fit our working seam regional approach. The Aries, Castor and Orion Seams exist at Ensham, but do not merge with the Pollux Seam.

Rolleston. The Rolleston deposit is one of a small group of deposits along eastern flank of the Springsure anticline that also includes the Freitag Creek and Meteor Park deposits (Sides 1995, Grimstone & Thomas 2005). Although the coal seams clearly belong to the Bandanna Formation, correlation with the established coal seam stratigraphy around the Comet Ridge is tentative. There are 3 to 5 coal seams in each deposit. We have correlated the thickest seam in each mine with the Pollux Seam, and a significant seam below with the Orion Seam. A thinner rider seam may correlate with the Castor or Aries

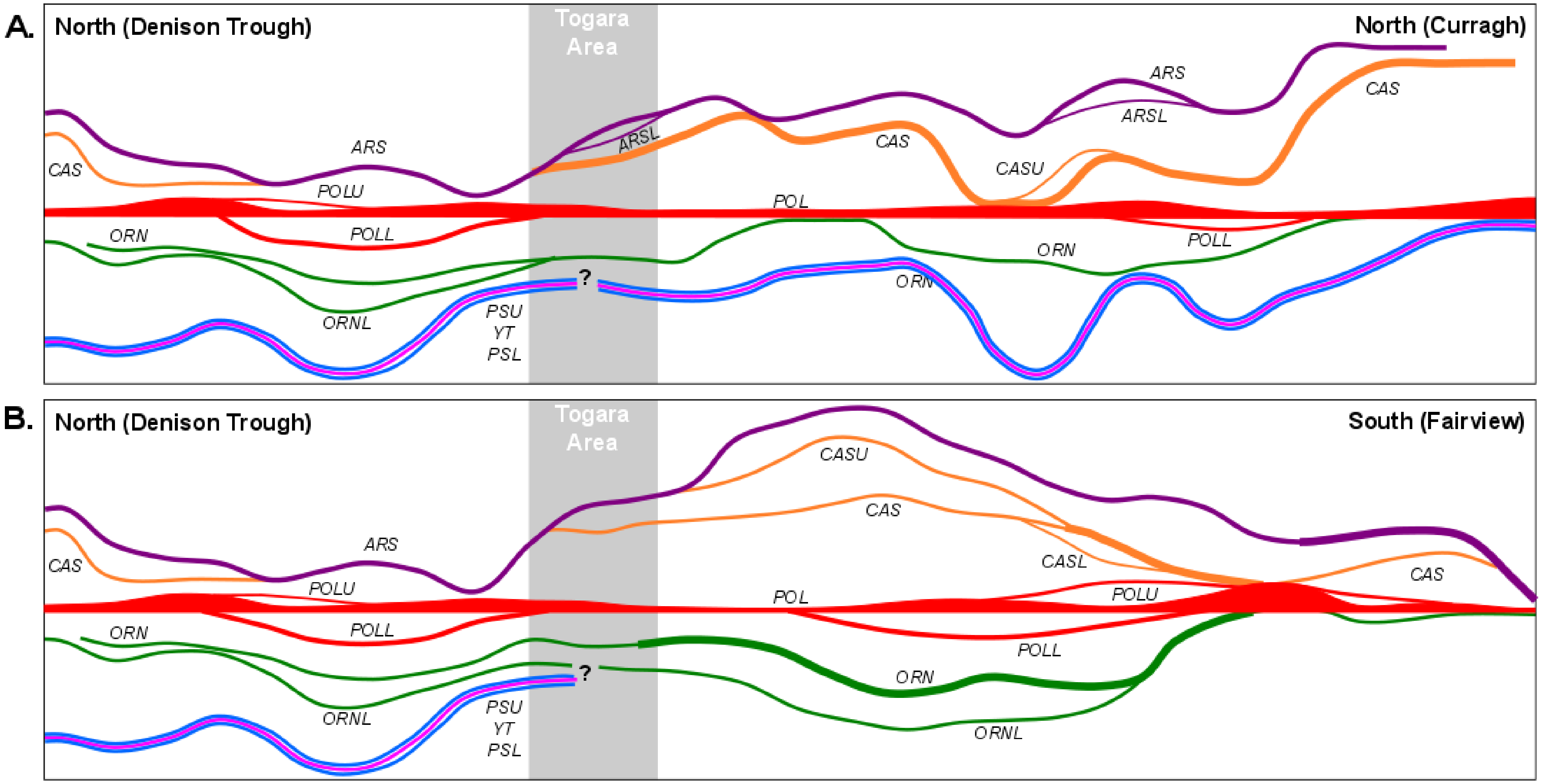


Figure 24 Schematic sections of coal seams in the Baralaba Coal Measures laid flat to the Pollux Seam marker horizon. A. Section from Ensham to Curragh around the Comet Ridge; B. Section from Ensham south to Fairview.

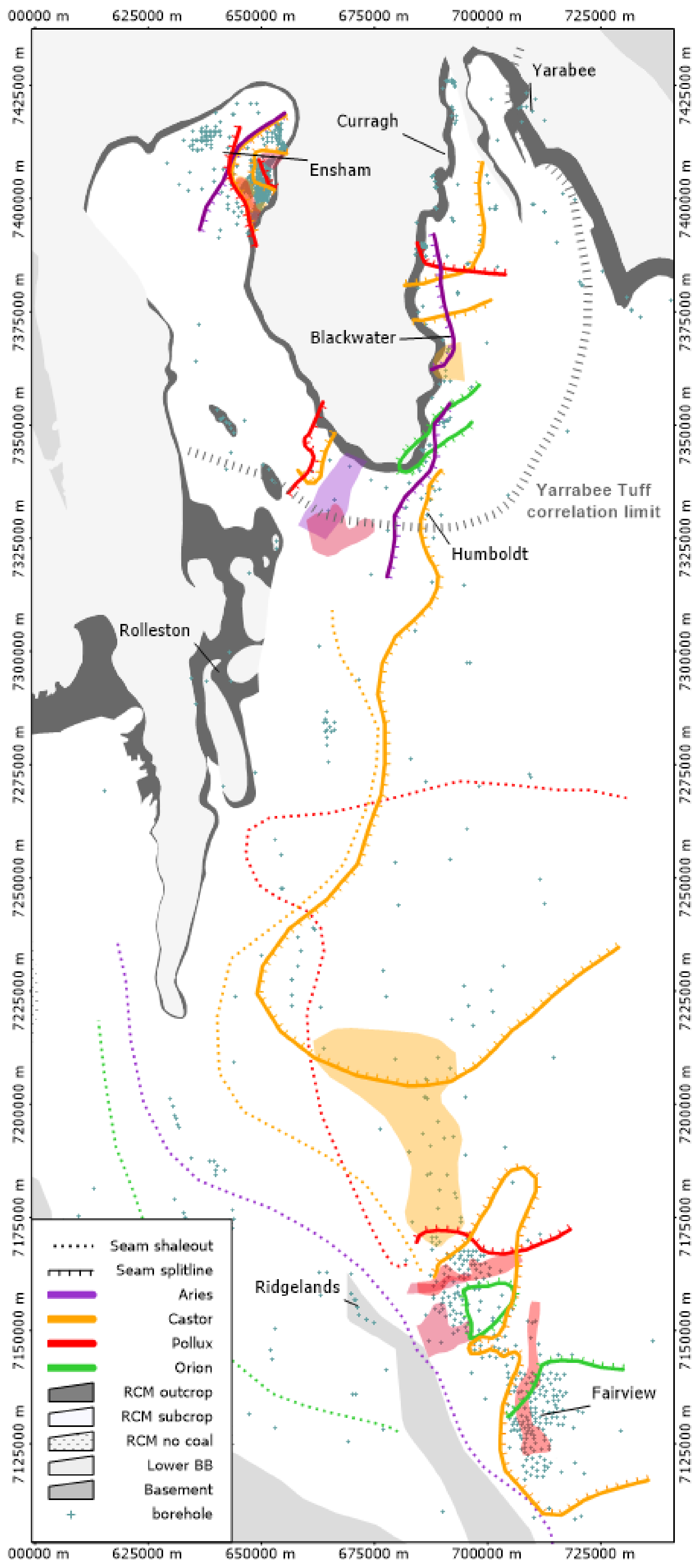


Figure 25 Major split lines and minor channel areas.

seams.

Fairview. Fairview is a major producing coal seam gas field that centres on a >12m thick coal pod correlated with both the Pollux Seam and the C Seam of the Baralaba tile. In the seam pod both the Castor and Orion Seams merge with the Pollux Seam. Minor seam splits define a series of narrow channels that surround the thickest part of the seam pod.

Seam correlation between tiles

Coal seam distribution patterns are significantly different between the three tiles. Across the Baralaba tile five coal seam packages track separately and only merge at Scotia, while in the Bandanna tile a number of major z-splits connect the all the major seams from Pisces up to Aries. In both of these tiles the Pollux/C Seam is a regional marker, but other seams are locally significant as well. In contrast there is only one major seam package in the Rangal tile (Leichhardt Seam), which provides most of the economic coal resources. This seam merges locally with the seam packages above or below. The seam splitting patterns suggest that all seams in the RCM are connected to the seams above or below somewhere, so that you could “tunnel” your way from the lowest seam to the highest seam without leaving coal. Coal mires existed somewhere in the basin at all times during the formation of the RCM.

As discussed in the previous sections, we used a “working seam” approach within each tile that followed the thickest part of the major seams while maintaining a relatively simple seam nomenclature. This approach resulted in five seam packages each in the Bandanna and Baralaba tiles and three packages in the Rangal tile (Figure 26). The changes in coal seam distribution are abrupt across the boundaries of the three tiles. In addition, the region where the three tiles meet between Foxleigh, Curragh and Yarrabee is structurally complex and poorly explored. There is a 30 km wide erosional gap in the Rangal Coal Measures that separates the Rangal tile to the north, and the Jellinbah thrust fault system separates the Bandanna from the Baralaba tile to the south. Thus the major changes in seam distribution also correlate with lack of closely spaced exploration data.

The seam correlation between the tiles is therefore limited to correlating major seam packages, and does not attempt to correlate individual seam splits or plys (Figure 26). Each seam package correlation is has a different level of uncertainty:

Virgo/Girrah/Kooloola. These seams are the last tuffaceous seams in the Fort Cooper Coal Measures and equivalent formations. The coal seam architecture of these coal measures is far more variable that that of the RCM (Ayaz *et al.* 2015), and the seam names only capture the topmost seam ply in each area.

Pisces/Vermont/Yarrabee Tuff/E. The Yarrabee Tuff is the most persistent and reliable regional marker in the northern and central Bowen Basin, allowing confident correlation between the upper and lower Pisces and Vermont Seams. At Dawson the E Seam lies above a number of unnamed tuffs of similar age to the Yarrabee Tuff, and the correlation with the upper Pisces Vermont Seams is made with confidence.

Pollux/Leichhardt/C. These three seams were chosen as regional markers in their respective tiles, as they are consistently thick, or mark a notable change in sediment supply. The Leichhardt and Pollux Seams are both dominant in their tile with a number of splits that ride near the main seam. The correlation is therefore made with moderate to high confidence. The correlation from the southern Rangal tile to the Baralaba tile is less certain. The RCM rapidly become thicker and develop a number of seams with similar wireline characteristics and no dominant seam. It is only further to the south that the C Seam marks a regional change in interburden character. The correlation between the Leichhardt and the C Seam is only tentative, as equally valid correlations could be made with the B or D Seams.

Orion/D. These seams and their splits are positioned between the Pollux/C seams and the tuffs at the base of the RCM in the Bandanna and Baralaba tiles, and are equivalent only if the Leichhardt/C Seam correlation is correct. Both may have developed from the lower Leichhardt Seam split in the southern Rangal tile.

Castor/B. The correlation of the Castor and B Seams also depends on the validity of the Leichhardt/C Seam correlation. If correct, it is likely that Castor/B Seams developed from the upper Leichhardt Seams in the southern Rangal tile.

Aries/Phillips/A. The seams within these packages are generally thinner than the older seams, and mark the transition to the Rewan Group. Individual seams may shale out, and localised splitting complicates their geometry. The correlation between tiles is made at the level of the seam package, but cannot be taken to individual seams.

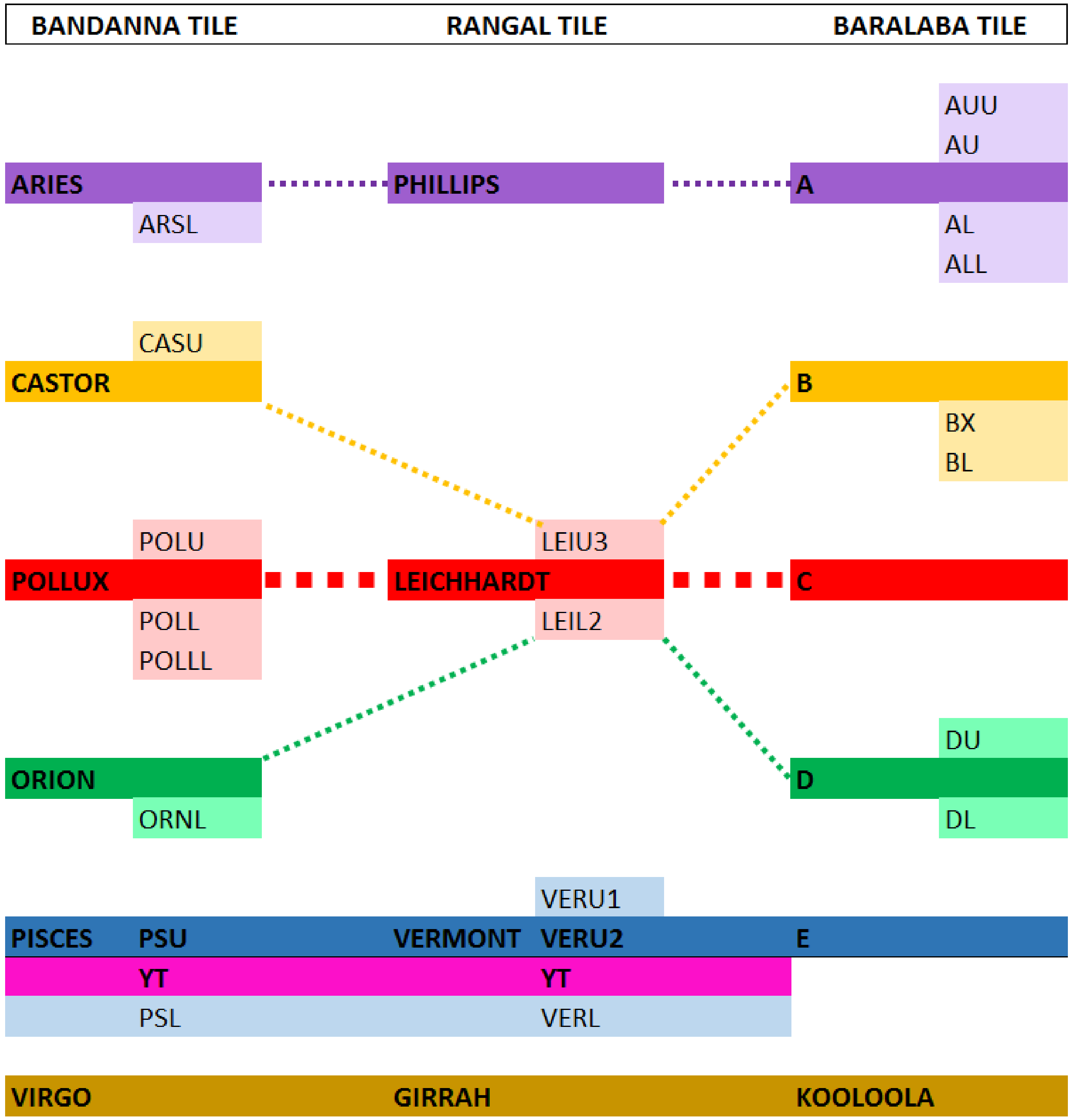


Figure 26 Regional correlation of major seam packages between the Rangal, Baralaba and Bandanna tiles.

Occurrence of regionally extensive seams

Coal seams within the RCM are laterally extensive and their regional correlation is supported by the consistency in age of the Yarrabee Tuff across the basin. The occurrence of thick, low ash yield, coal seams represent a period of prolonged stability, free of clastic influx, and with peat growth in balance with subsidence or rising base level (Bless *et al.* 1981). Extensive peat mires occur today in high and low latitude climatic belts (Figure 27) inhabited by a range of vegetation types and associated with variety of tectonic and depositional settings that influence the size and shape of individual peat deposits (Greb *et al.* 2008). Although the tectonic setting of peatlands in foreland basins, e.g. the Andean or Sumatran are analogous to the Bowen Basin, the climatic setting of high latitude, cold temperate to boreal peat mires in Siberia or Canada are more often cited (Martini & Johnson 1987, Stuart *et al.* 2014). Here individual peat deposits range from a few to hundreds of kilometres, accumulating in the interfluves of large river systems or along broad coastal plains (summarised in Greb *et al.* (2008)), comparable in areal extent to the coal seams, referred to as “super seams” by Michaelsen and Henderson (2000a), observed in the RCM and MCM in the Bowen Basin.

Michaelsen and Henderson (2000a) proposed eustacy-driven cyclic periods of extensive and prolonged peat accumulation during times of sediment starvation associated with low sea levels. Peats would be drowned through rising sea levels and buried by thick clastic packages deposited during relative high stands, thus recording the spectrum of terrestrial to paralic and offshore environments in the interburdens in packages deposited over times spans of about 100,000 years. Bohacs and Suter (1997) were less prescriptive, and suggested that peat (coal) accumulation would initiate in a rising and often accelerated base level, and accumulate in pace until eventually drowned. During the high stand peat would continue to accumulate and expand even through a reversal of trend until base level drop was severe or longer lived, resulting in exposure and potential stranding or erosion of the peat. Diessel (2010) integrated the coal quality and maceral composition into these cycles with high vitrinite coals being preserved in rising or transgressive cycles until they “give it up” and drown with abundant clastic influx; an accommodation reversal might result in the transition to increased oxidation and inertinite rich coals. Through time, these cycles would stack, punctuated by partings, as the basin subsided and peats were buried into the rock record. The amount of time involved and lateral extent of the cycles would vary in response to the mechanisms invoked. Small scale cycles might be autogenic with water level responding to differential compaction of underlying sediments (on the order of 6,000 to 10,000 years); larger cycles could respond to eustacy (on the order of 100,000 years). These smaller order sequences can then be bundled into thicker, unit scale cycles that respond to tectonic accommodation within a foreland basin setting (~1 MY or longer; Van Wagoner, 1998 cited in Michaelsen and Henderson (2000a)) such as the Hunter Bowen Orogeny (Brakel *et al.* 2009). This is supported by the age dating (Metcalfe *et al.* (2015); Laurie *et al.* (2016); this study) that estimates accumulation of the peat and clastics of the RCM over less than 1 MA. If one does a simple 10:1 decompaction of the RCM coals, coupled with a boreal peat accumulation rate of 1mm per year, then the ~30m of cumulative coal represent a minimum of 300,000 years during that 800,000 year period.

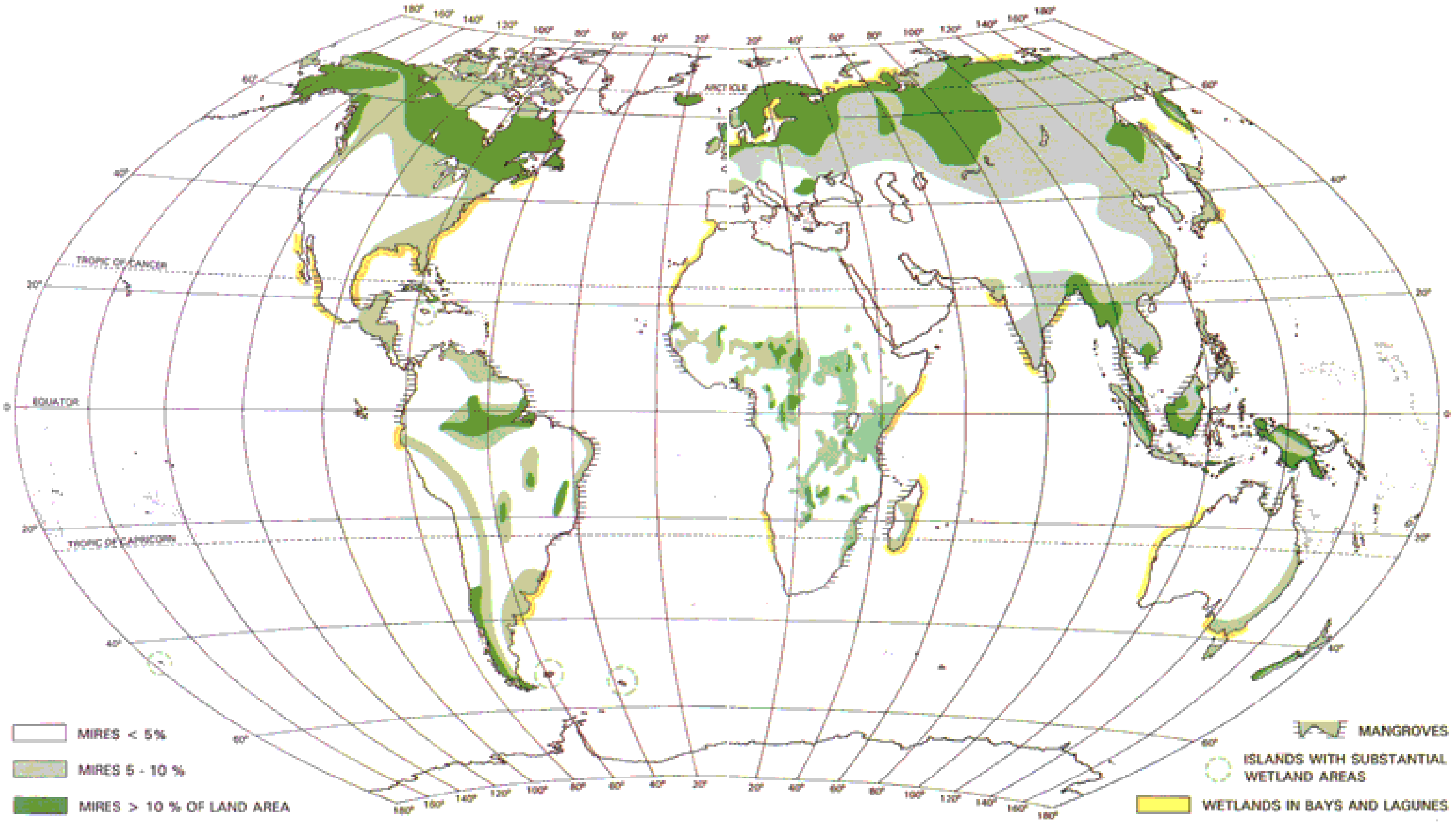


Figure 27 Map comparing size of peat accumulating mires globally across different climatic belts. Reference http://www.peatlandsni.gov.uk/formation/global.htm#globalmap.

4.5 Interburden Character: Rangal tile

Steven Wilson

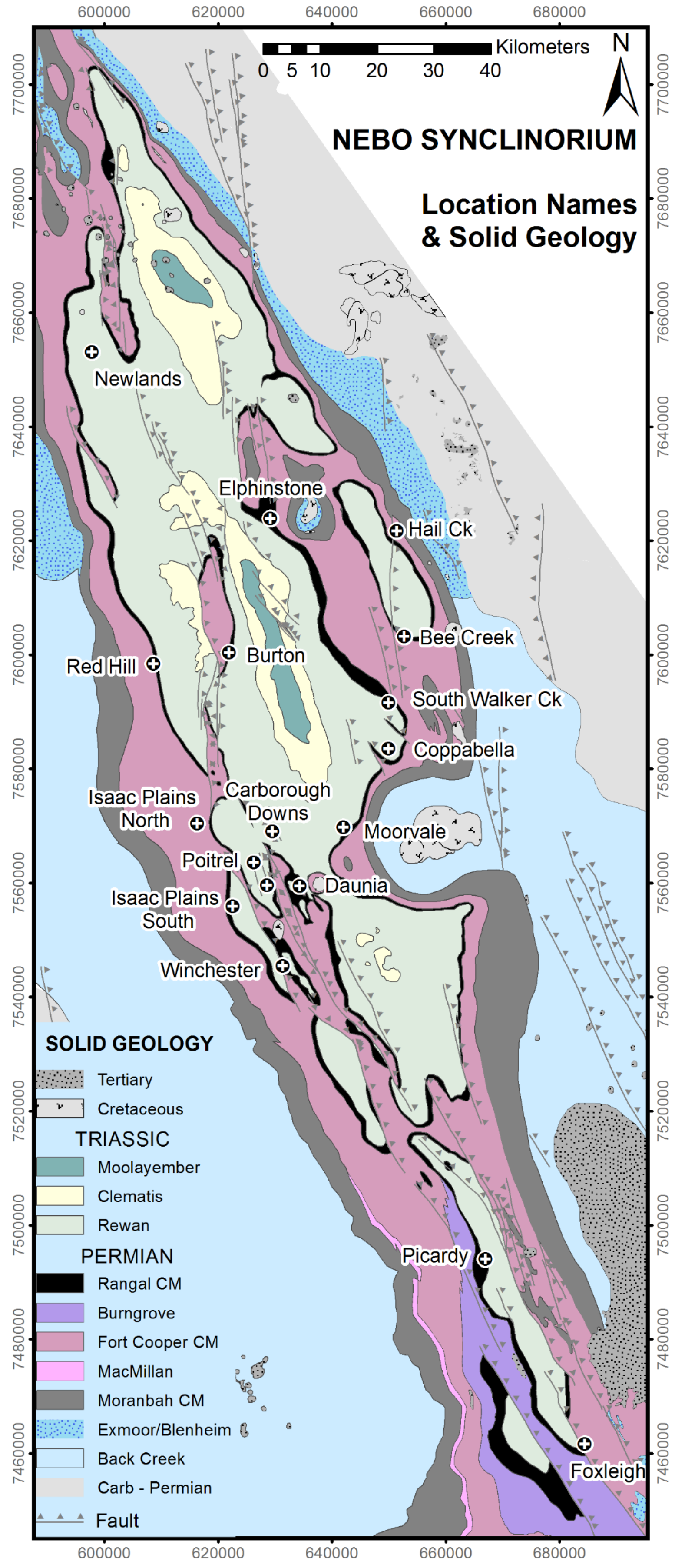


Figure 28 Interpreted solid geology of the Nebo Synclinorium (Sliwa et al. 2008), and location names used in text.

Introduction

The Nebo Synclinorium (Figure 28) hosts numerous mines exploiting coals of the Rangal Coal Measures (RCM). Sediments exposed in these mines include those of the upper Fort Cooper Coal Measures (FCCM), the RCM and the Sagittarius Sandstone of the overlying Rewan Group. These sedimentary units are further divided into distinct interburden packages by several regionally consistent tuff markers and coal seams. Discussion of the distribution and composition of these interburden packages in the following chapter is assisted by numbering the packages from oldest (interburden 1) to youngest (interburden 10) (Figure 29).

The upper part of the FCCM is represented as a single high-ash seam (the Girrah Seam) in the north, which is split to the south through the alternate stacking of sandstone rich interburden units. Three main interburden packages are recognisable:

1. The lower Girrah interburden (interburden 1) splits the Girrah Seam into near equal parts;
2. The upper Girrah interburden (interburden 2) splits the seam in the upper third, below the Girrah Tuff (GT) but higher in the sequence than interburden 1; and
3. The Girrah Seam overburden (interburden 3) occurs between the GT and the YT and represents the youngest of the FCCM sediments in the Nebo Synclinorium.

The RCM ranges from a single 12m thick coal seam (the merged Leichhardt and Vermont Seams) in the central north to stacked sedimentary packages exceeding 140m thick in the south and east of the synclinorium. Sediments can be divided into those below the main Leichhardt Seam and those above. Four interburden packages are recognised between the Yarrabee Tuff (YT) and the main Leichhardt Seam:

4. The YT to upper Vermont interburden (interburden 4) is the lowermost unit in the RCM and directly overlies the YT with occasional thin coal developed at the base. The top of this unit is defined by the upper Vermont Seam (VerU2);
5. The upper Vermont interburden (interburden 5) splits the upper Vermont Seam and is bounded at the base by VerU2 and at the top by VerU1;
6. The upper Vermont to lower Leichhardt interburden (interburden 6) separates the Vermont Seam package from the Leichhardt Seam package; and
7. The Leichhardt lower interburden (interburden 7) splits the Leichhardt Seam toward the base separating thin floor splits from the main Leichhardt Seam.

Several interburden units belonging to the RCM are present above the main Leichhardt Seam:

8. The upper Leichhardt interburden (interburden 8) splits the main Leichhardt Seam in the upper half of the seam;
9. The Leichhardt to Phillips interburden (interburden 9) separates the Leichhardt Seam package from the Phillips Seam package.; and
10. A regionally persistent mudstone unit directly overlies the Leichhardt or Phillips Seams along the western margin of the synclinorium. East of this unit there are sandstone bodies above the Leichhardt Seam that show characteristics more closely aligned to those of the RCM than those found in the overlying Rewan Group. These lithological units are grouped together as interburden 10.

The boundary between the RCM and the Rewan Group is not easily recognised and often taken as the top of the highest coal in the sequence. A colour change from the predominantly grey sediments of the RCM to a greenish hue in the sandstones of the Rewan Group has been proffered as characteristic of this boundary (Matheson 1990a) but this is not obvious in down-hole wire-line logs. A change in sedimentary architecture from lenticular sandstone morphology to more tabular, sheet-like sandstones has been recognised at this boundary (Michaelsen 2002) and it is this characteristic that has been used to define the boundary in this chapter.

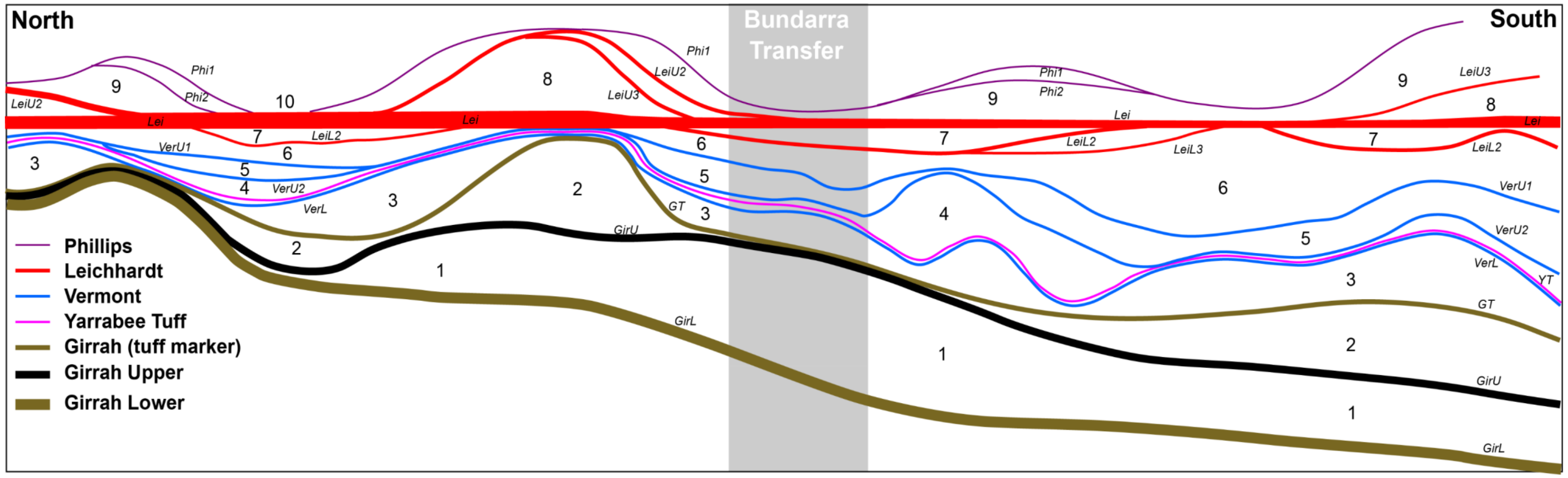


Figure 29 Schematic representation of the seam correlations in the Nebo Synclinorium with interburden units numbered for reference.

Upper Fort Cooper Coal Measures

The RCM conformably overlie the FCCM across the Nebo Synclinorium. The type section for the FCCM is located in the upper reaches of Hail Creek where approximately 400m of conglomerate, green lithic sandstone, carbonaceous shale, coal and cherty tuff are described in detail by Hutton *et al.* (1998). Fossil logs and leaf imprints are common with at least one fish fossil reported from the Red Hill area (Matheson 1986a). The defining characteristic of the FCCM sediments is the presence of numerous tuffs throughout the sequence but most notably preserved in the coaly horizons. The presence of these tuffs distinguishes the FCCM from the relatively tuff poor Moranbah Coal Measures below and the tuff deficient RCM above.

The fine grained sediments and coal seams of the middle FCCM have been correlated with the marine mudstones of the Black Alley Shale to the south (Ayaz *et al.* 2015). In the north, this fine-grained sequence is capped by a regionally extensive accumulation of coal, mudstone and tuff known locally as the Girrah Seam (Matheson 1986a). Regional correlations of this seam show it splitting to the south and east (Ayaz *et al.* 2015) to incorporate thick sequences of predominantly coarse grained sediments (Figure 30 and Figure 31). Similar coarse grained units are found overlying the Girrah Seam package containing pebble and cobble conglomerates carrying clasts of acid and intermediate volcanics and quartz rich sandstone toward the top of the sequence (Jensen 1975, Matheson 1986b). In the Bee Creek area, a massive 30 – 40m thick conglomerate near the top of the FCCM has been interpreted by Hutton *et al.* (1998) as the coarse grained basal fill of a major channel system.

Measurements of cross-stratification reported by (Jensen 1975) suggest some sediment input from the east feeding an overall southward draining system. The sandstones of the Girrah Seam interburden units are therefore likely to represent the upstream equivalents of the Burngrove Formation which is associated with progradation of fluvial dominated environments over the Black Alley Shale to the southwest.

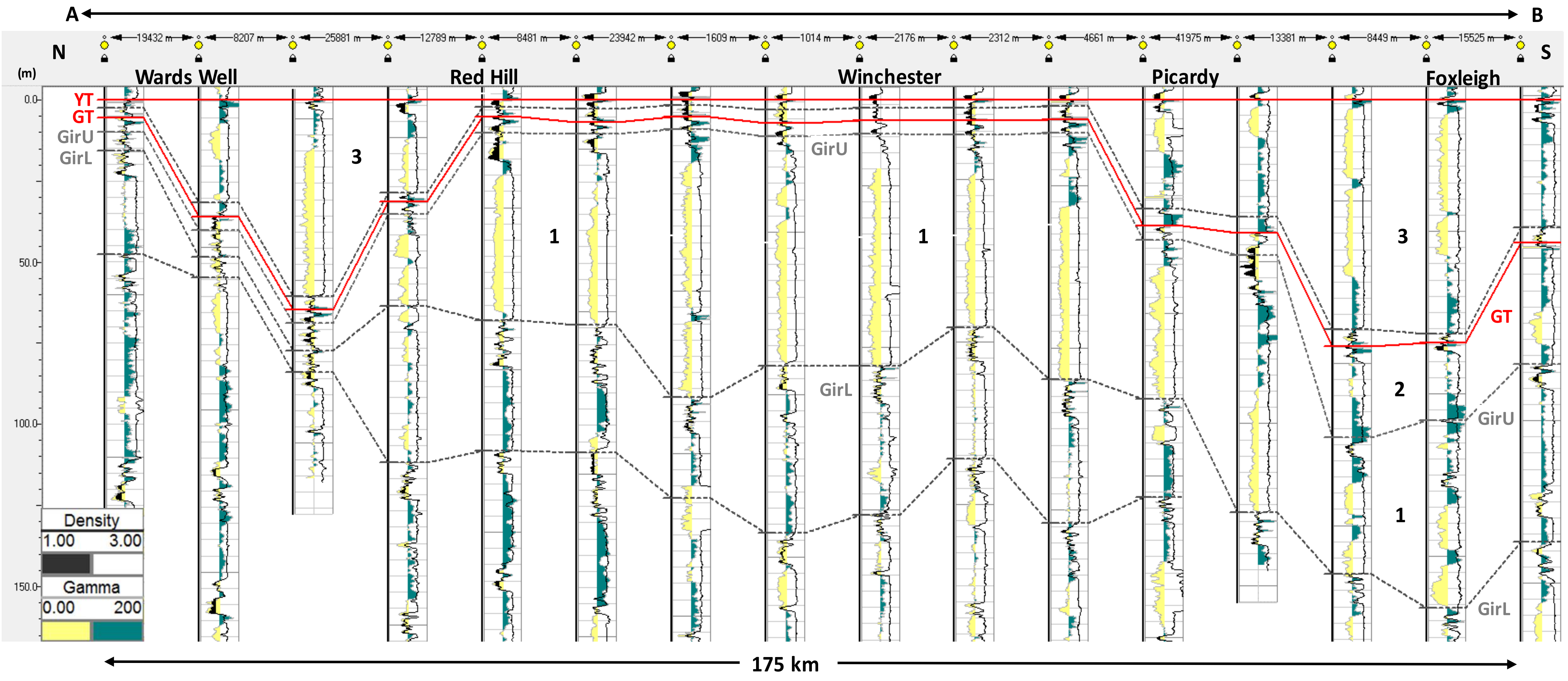


Figure 30 North – south correlation section for the upper Fort Cooper Coal Measure interburden units. Section location is shown on Figure 32.

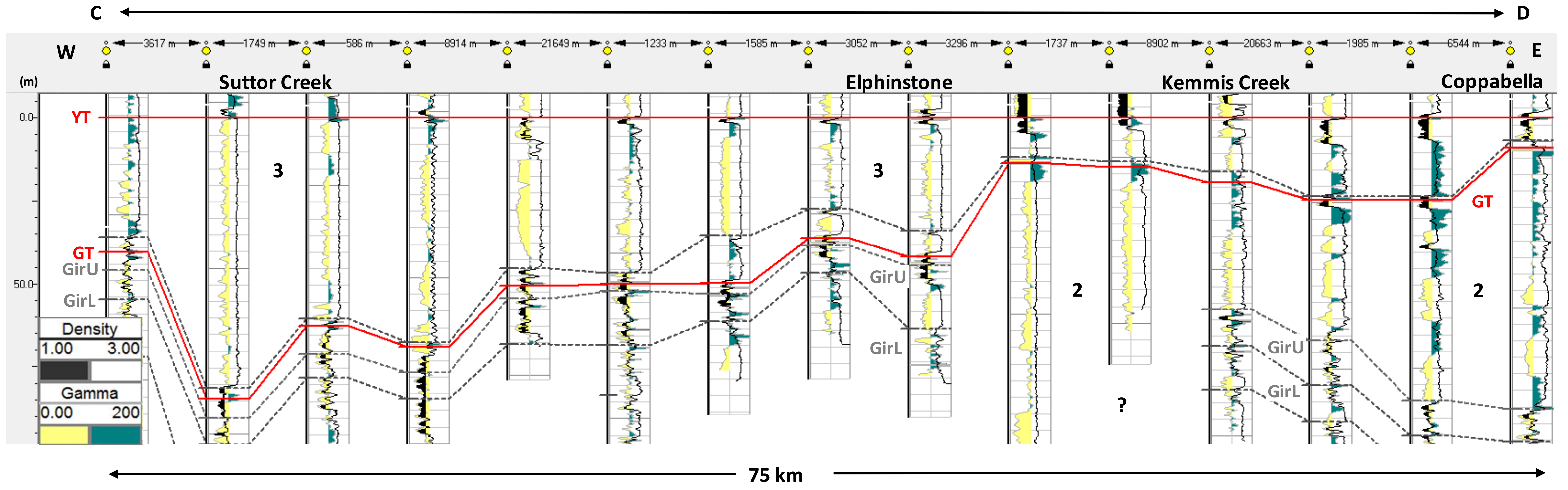


Figure 31 West - East correlation section for the upper Fort Cooper Coal Measure interburden units. Section location is shown on Figure 32.

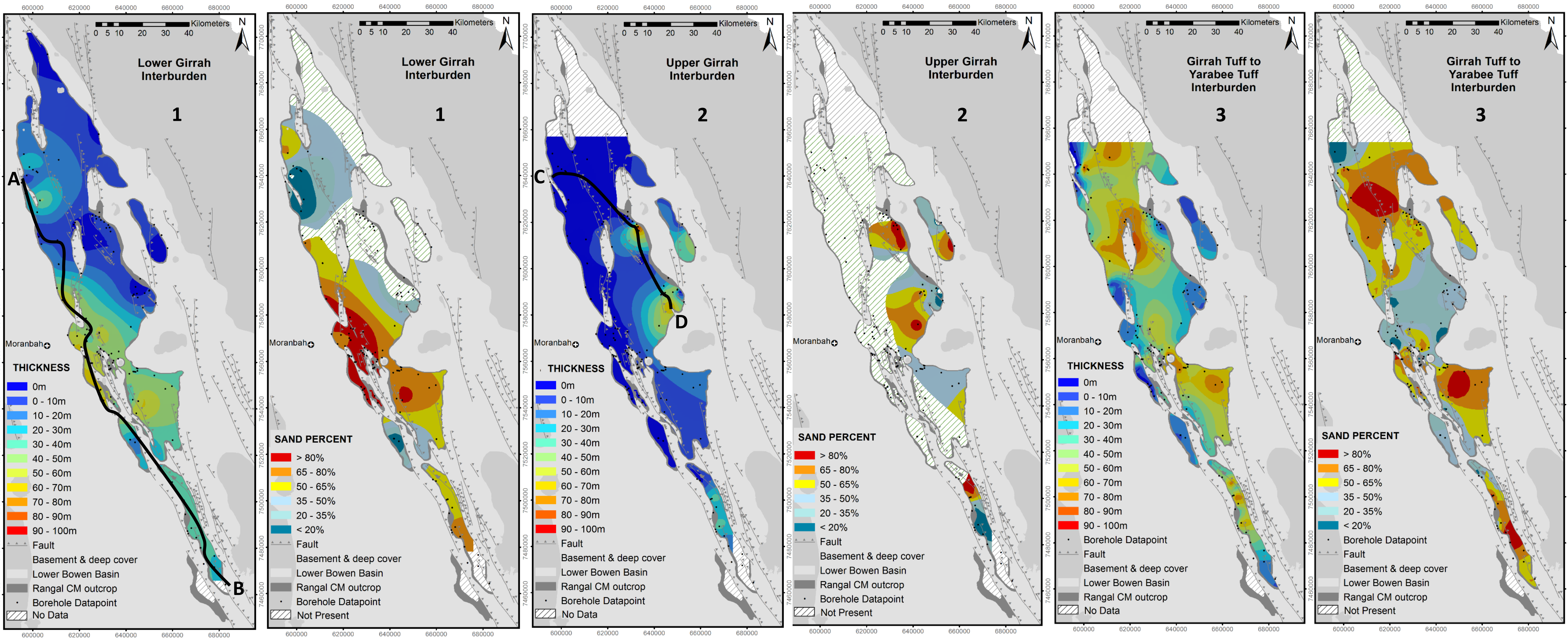


Figure 32 Thickness maps, and sandstone proportion maps calculated from normalised gamma logs, for the upper FCCM interburden units. 1 = lower Girrah Interburden, 2 = upper Girrah Interburden, 3 = Girrah Overburden.

Interburden 1: The Girrah Seam is merged north of Burton and Elphinstone where it approaches 40m thick. The lower part of the seam (GirL) splits to the west enveloping 5 – 20m of mainly fine-grained sediments with occasional basal sandstones to 10m and an overall fining upward trend. Sediments in this interval increase in thickness south of a line from Red Hill to Moorvale (Figure 32) and are dominated by thick (up to 50m) amalgamated sandstone across the central areas. Section A – B (Figure 30) shows these sandstones contribute significantly to the overall southward thickening of the sequence between the lower Girrah plies and the Yarrabee Tuff across the Nebo synclinorium.

Interburden 2: The upper Girrah interburden attains a thickness of greater than 40m at Moorvale (Figure 32) where it is entirely composed of coarsening upwards sandstone. The sediments become finer northeast towards Coppabella and South Walker Creek where 30m of interbedded siltstone and mudstone show some tendency toward coarsening upward. The few intercepts of this burden package west of South Walker Creek show stacked 3 – 15m sandstones with sharp bases and sharp to fining tops separated by thinner intervals of siltstone. An upper Girrah interburden package is also present between Picardy and Foxleigh in the far south of the synclinorium. Mudstone, carbonaceous shale and coal transition upwards over 20 – 30m to interbedded heterolithics capped by coal and the Girrah Tuff.

Interburden 3: The Upper Girrah plies diverge from the YT in a southward trending band that runs axially through the synclinorium. Along the eastern boundary of this split at Elphinstone, thick (to 40m), coarse sandstones showing sharp tops and bases thicken westward from the split to Burton where 50m of sandstone with gradational bases and overall fining up gamma signatures have accumulated. This lobe of sandstone overlies the thickest undivided Girrah Seam and is in turn capped by very thick accumulations of coal in the Vermont/Leichhardt Seam equivalents.

In the south of the synclinorium, the GT – YT interburden comprises 20 – 30m of siltstone overlain by 20m thick sandstones occasionally stacked to 50m thick. The GT to YT interburden package fines northward before becoming entirely composed of amalgamated sandstones up to 40m thick at Winchester and to the east.

Figure 32 illustrates the offset stacking of the sandstone rich upper FCCM. The distribution of the three interburden packages shows interburden 1 thickest in the west and south, interburden 2 thickest in the east and interburden 3 thickest in the north.

Yarrabee Tuff to Leichhardt Seam

The thickness distribution of the YT to the main Leichhardt Seam (YT - Lei) is illustrated in Figure 33 which also shows the locations of the focus areas discussed below. The package is thickest in the far south and along the eastern boundary and thins north-westward being entirely absent across the central north and in localised areas along the western margin. Comparing the thickness of this package in the north with that of the underlying GT – YT interburden (Figure 32) reveals the offset stacking pattern seen in the upper FCCM continues upward into the RCM. The trend toward southward thickening seen in the upper FCCM interburden is also reflected in the YT to Leichhardt Seam interburden. The YT – Lei interburden is divided by several minor seams that diverge from either the Leichhardt Seam above or the

Vermont Seam below occasionally showing z-splitting relationships in proximity to the Vermont - Leichhardt Seam split.

In the central north of the Nebo Synclinorium the Leichhardt Seam is contiguous with the Vermont/YT seam package forming a thick (>10m) 'superseam' directly over the thickest development of interburden 3. North of this confluence the seams diverge, bracketing coarsening upwards sandstones close to the split at Elphinstone, then thickening and fining northwards where up to 80m of fine-grained interbedded heterolithics have accumulated. The Leichhardt Seam merges with the YT again westward toward Newlands where a similar pattern of coarsening upwards sandstone can be discerned close to the split. Intrusions are common throughout the RCM in the north and often contribute significant thicknesses to the burden units in this area.

Along the western boundary of the synclinorium, the YT – Lei interburden remains relatively thin. Ten to twenty metres of fining upwards sandstone separates the YT/Vermont Seam package from the Leichhardt Seam across the Red Hill deposit. The interval thickens and fines to the southeast where a north-south trending sedimentary trough preserved between Red Hill and Carborough Downs is described in more detail in focus area 2 below. Along the south-eastern boundary of this sedimentary trough, a 10 – 40m thick lobe of fine-grained thinly bedded siltstones and sandstones divided by thin coal seams occurs over most of the Millennium, Poitrel, Daunia and Winchester deposits.

South of Winchester the YT to Leichhardt Seam interval thickens to a consistent 70 – 90m through Picardy to Foxleigh. This thickening is accommodated by a Leichhardt floor split and local development of an upper Vermont interburden package. Sediments are thinly bedded, fine-grained sandstones and siltstones below the upper Vermont Seam with thick (40m) amalgamated sandstones developed between the upper Vermont Seam and the LeiL2 and between the LeiL2 and the main Leichhardt Seam. Amalgamated sandstones up to 20m thick are more prevalent in both of these upper interburden units in the southern part of Picardy showing some coarsening upwards profiles in the north and trending toward fining up in the south.

Along the eastern margin of the Nebo Synclinorium, splitting between the YT and Leichhardt Seam is less pronounced. The sediments of the upper Vermont and lower Leichhardt interburden packages thin to the northeast where the upper Vermont Seam directly overlies the YT across most of Coppabella, South Walker Creek and the Hail Creek Syncline. The Leichhardt floor and upper Vermont Seam splits are only locally developed along the eastern margin north of Picardy.

YT to Lei – Focus Area 1: The YT to Leichhardt interburden ranges from 20 to 80m thick across South Walker Creek and the Hail Creek Syncline. Individual depositional systems are defined in areas of thickened interburden and between the various localised floor and roof splits. Sedimentary packages within these depositional units show differentiation between sandstone rich and siltstone rich areas with the sandstones often developed close to the site of seam divergence (Figure 34). Dimensions of the depositional systems range from 15m thick and 3.5km broad in a Leichhardt floor split at South Walker Creek (interburden 7) to 70m thick and 9km across between the YT/Upper Vermont and the Leichhardt Seam at Hail Creek (interburden 6).

At South Walker Creek, the YT to Leichhardt interval is divided by several coaly stringers that originate in either the Leichhardt or Vermont Seams and show a z-splitting relationship between these seams (Figure 34). Sediments below the lowest stringer (interburden 4) comprise 30 – 40m of thinly bedded mudstone and siltstone with rare sandstone beds to 5m thick developed toward the top of the sequence. A thin Leichhardt floor split (VerU1) can be traced northward to where it merges with the upper Vermont Seam before splitting off again to shale out in the far northwest.

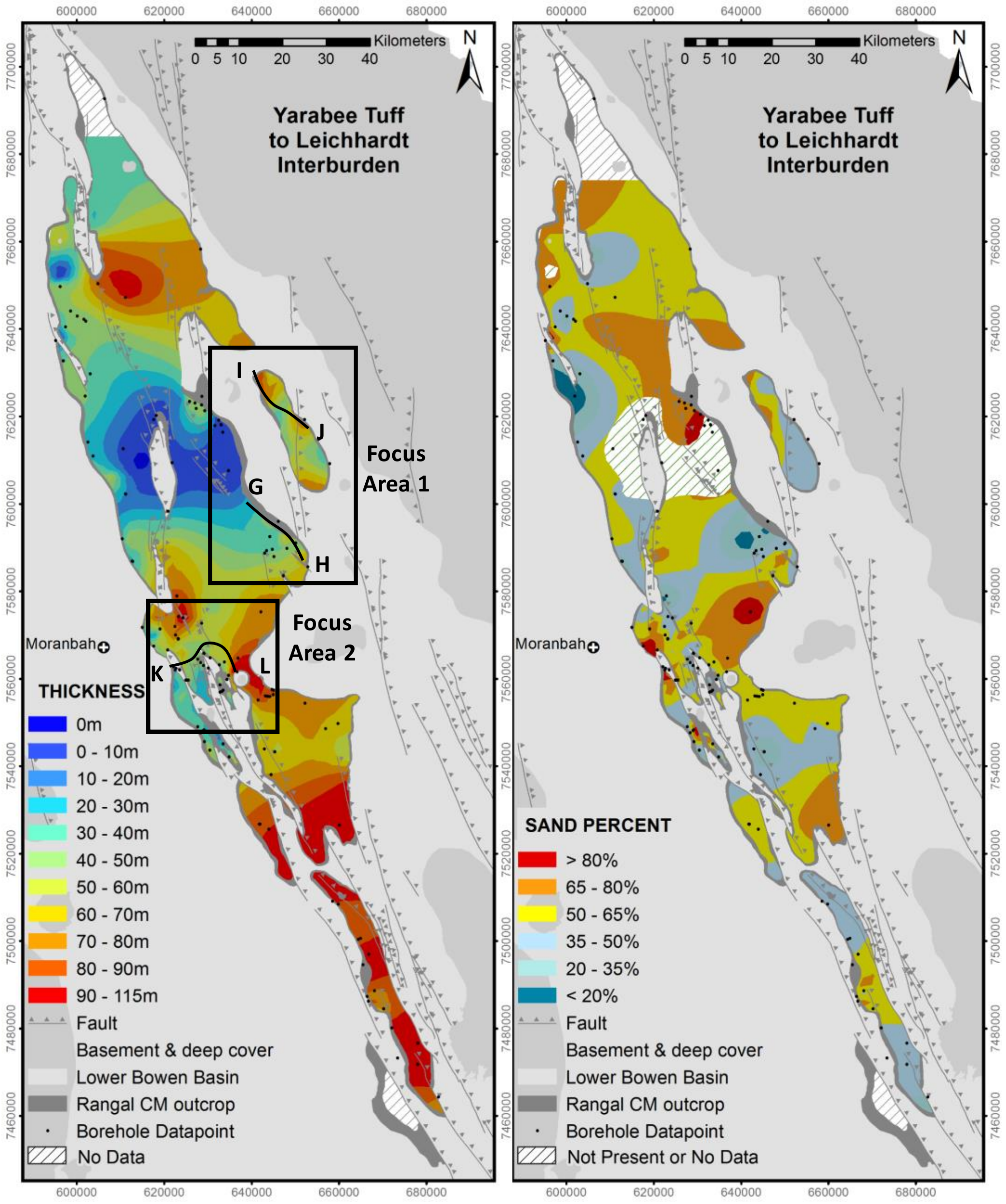


Figure 33 Thickness, and sandstone proportion maps, for the YT to Leichhardt Seam interburden.

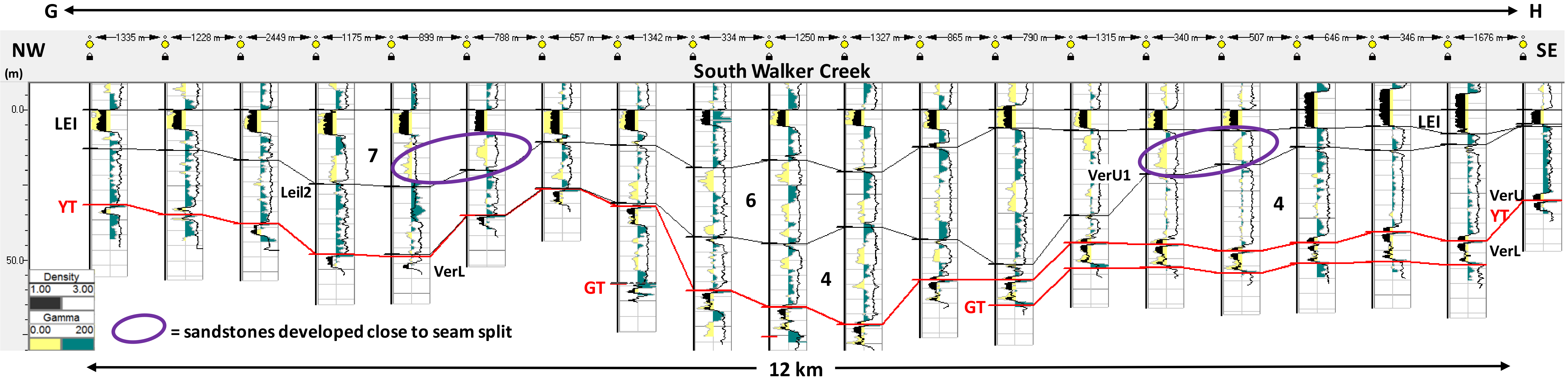


Figure 34 Correlation section of the YT to Leichhardt Seam interburden at South Walker Creek. Section location is shown on Figure 33.

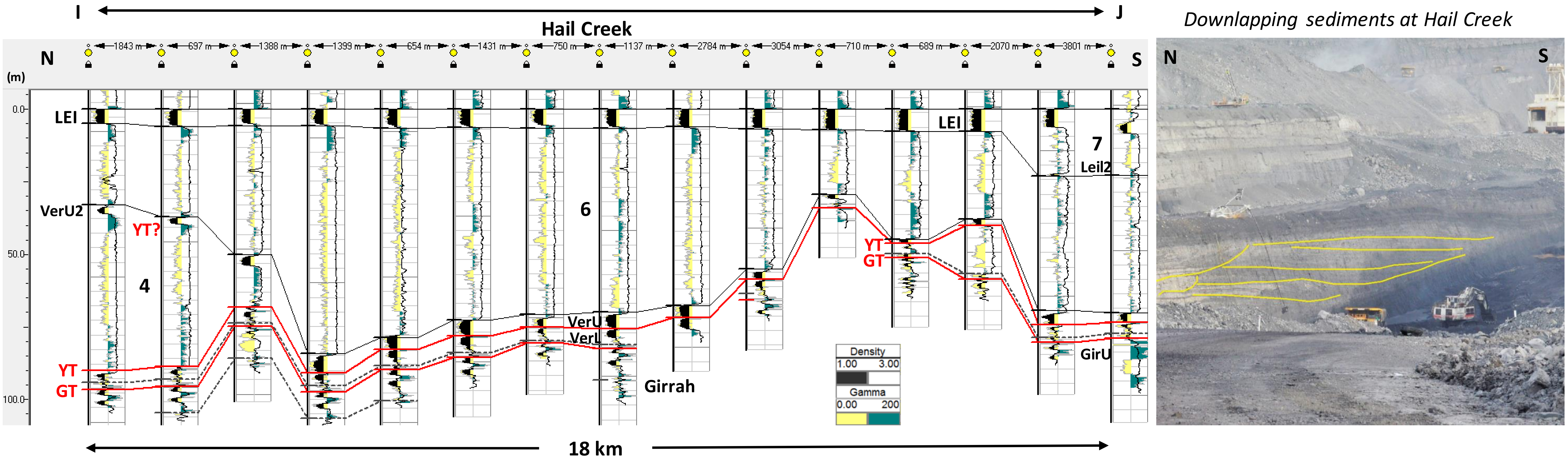


Figure 35 Correlation section of the YT to Leichhardt Seam interburden at Hail Creek. Image to right shows sediments down-lapping onto the lower seam (highlighted in yellow). Section location is shown on Figure 33.

Here a second Leichhardt floor split (LeiL2) developed bracketing a 10-15m thick package of fine-grained, interbedded heterolithics 3.5km across (interburden 7). An 8-10m thick sandstone correlatable for 1.5km accumulated adjacent to the southern margin of this depositional system.

Between these two Leichhardt floor splits (interburden 6), one or two tiers of 5-10m fining upwards sandstones occasionally amalgamated to 20m thicknesses are developed above 10-30m of interbedded, fining upwards mudstones and siltstones. To the northwest the sediments comprise interbedded heterolithics to 30m thick which are devoid of sandstone channels and can be correlated for 13km further north toward the merging of the YT/Vermont and Leichhardt Seams at Elphinstone.

The YT – Lei interburden sediments thicken and coarsen south-westwards from less than 30m of siltstone and mudstone in the north and east of South Walker Creek to 65m of amalgamated sandstones at Moorvale. This north-eastward thinning is coincident with thickening in the underlying upper Girrah interburden unit and may indicate a confluence of the YT/Vermont and Leichhardt Seams to the northeast. The presence of numerous anastomosing splits in the section shown in Figure 34 further supports this interpretation as similar z-splitting is noted at Elphinstone and Newlands where the major seams converge. This line of reasoning suggests that a superseam equivalent to that seen at Elphinstone may once have existed between South Walker Creek and Hail Creek but has since been eroded.

At Hail Creek a pattern of southward offset stacking is noted (Figure 35). In the north, the upper Vermont Seam is separated from the YT /Lower Vermont/Girrah package by a wedge of sediment thickening north-westward and coarsening upward and to the north (interburden 4). The wireline logs reveal stacked 2 – 5m sets of repeated fining upward siltstone to mudstone for up to 20m, overlain by stacked 3 – 6m sets of fining upwards sandstones to 20m. This pattern of fine-grained sediments overlain by sandstones, often with thin carbonaceous shales or coal seams between is observed throughout the Nebo Synclinorium between the YT and the Leichhardt Seam.

The upper Vermont overburden (6) is around 20m thick directly over the YT to lower Vermont wedge but thickens to the south to form a north-easterly trending deposit up to 70m thick. This interburden package is thickest immediately adjacent to the underlying upper Vermont split line showing clear offset stacking and thins south-eastward to 20m before thickening again to the southeast.

Mining exposures of this unit reveal packages of siderite rich, thinly bedded mudstone, siltstone and fine sandstone down-lapping onto the Vermont Seam in a southerly direction (Figure 35 and Figure 36). These distal sediments are in turn deeply incised by several generations of channel sands 5 to 25m thick and up to 3km across within a depositional trough open to the northeast and southwest and 9km across. The sandstones show erosive bases with abundant mud rip-up clasts, trough cross-bedding and inclined sets that are consistent with a sinuous, laterally accreting channel system cutting into muddy, pro-delta sediments (Figure 36) similar to those described by Turner and Tester (2006).

YT to Lei – Focus Area 2: Intensive drilling across the central area of the Nebo

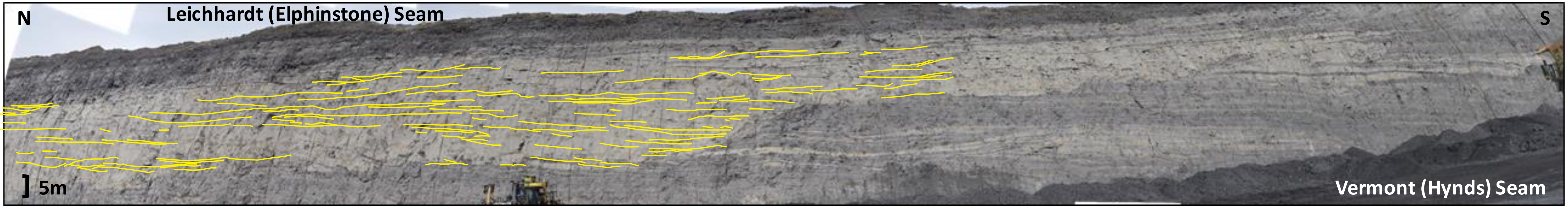


Figure 36 YT to Leichhardt Seam interburden exposed at Hail Creek with sedimentary features highlighted in yellow.

Synclinorium allows detailed resolution of the sediment stacking patterns in the YT to Leichhardt interburden (Figure 37). Several minor upper Vermont and lower Leichhardt Seams originating as far east as Moorvale bracket sediment packages with siltstone predominant in the lower units and sandstone predominant in the upper units. The western margin of this sediment package contains a linear sandstone belt where sedimentation was active when elsewhere the thick peats of the main Leichhardt Seam were accumulating (Figure 37A).

Interburden 4: Initial deposition occurred in the north and east as predominantly fine-grained sediments and was offset from the underlying GT - YT sandstones (interburden 3). The southwestern margin of this unit comprises a zone where sedimentation directly over the Girrah/Lower Vermont Seams presents challenges accurately locating the YT (Figure 37D). The high gamma marker (YT) directly over the lower Vermont Seam is thin and often absent and several high gamma mudstones or tuffs occur intercalated with channel sandstones and interbedded heterolithics above. An alternative interpretation places the YT within interburden 4 although it is difficult to trace through the stacked sediments, often appearing thicker, suggesting some reworking.

Interburden 5 and 6: At Mavis Downs an upper Vermont Seam rider (VerU1) defines a siltstone package 5 – 10m thick and 8 km broad that fills a hollow between lobes of interburden 4 (Figure 37C). Above this rider, basal stacked, coarsening upwards sandstones to 2m thick are interbedded with siltstone in a fining up succession (interburden 6) of even thickness (5-15m) across Millennium, Poitrel, Isaac Plains South and Daunia. The interval is thickened with amalgamated sandstones to 70m from Daunia and Carborough Downs eastward to Moorvale, probably representing the source channel system for these distal sediments (Figure 37B).

Interburden 7: The sediments overlying the floor split of the Leichhardt Seam also form an even 10-15m blanket over Millennium and Carborough Downs displaying characteristics of basal stacked coarsening upwards sandstones in fining upwards heterolithic strata. These sediments are interpreted as a splay or meander deposited early in the development of a channel belt to the west (Figure 37A). This channel system is illustrated in cross-section in Figure 37. Sharp based amalgamated sandstone comprising stacked, variously fining and coarsening upwards 5m sets resulting in an overall blocky gamma response show sharp to fining tops. These sandstones are capped by a 1-2m thick coal seam representing the entire Leichhardt Seam in this area. The Leichhardt Seam is similarly thin and split north into Red Hill where the equivalent sediments are finer grained.

Figure 38 is an image of the YT – Lei interburden exposed in the southeast of Daunia with lines added to highlight sedimentary features. The geometry of the sandstones shows tabular sheets interpreted as splay deposits in the lower right of the image cut by what is interpreted to be a channel margin showing slumping in green. Internal sandstone bedding is highlighted in yellow. These splays are cut by the thicker sandstone to the left which show sediment aggradation toward the right of the image. The geometry of this sandstone conforms to that expected of a point bar. Thick mudstone drapes toward the top suggest decreasing sediment supply and the mudstone lens resembles an abandoned channel. These sediments are marginal to a thicker sandstone wedge to the southeast.

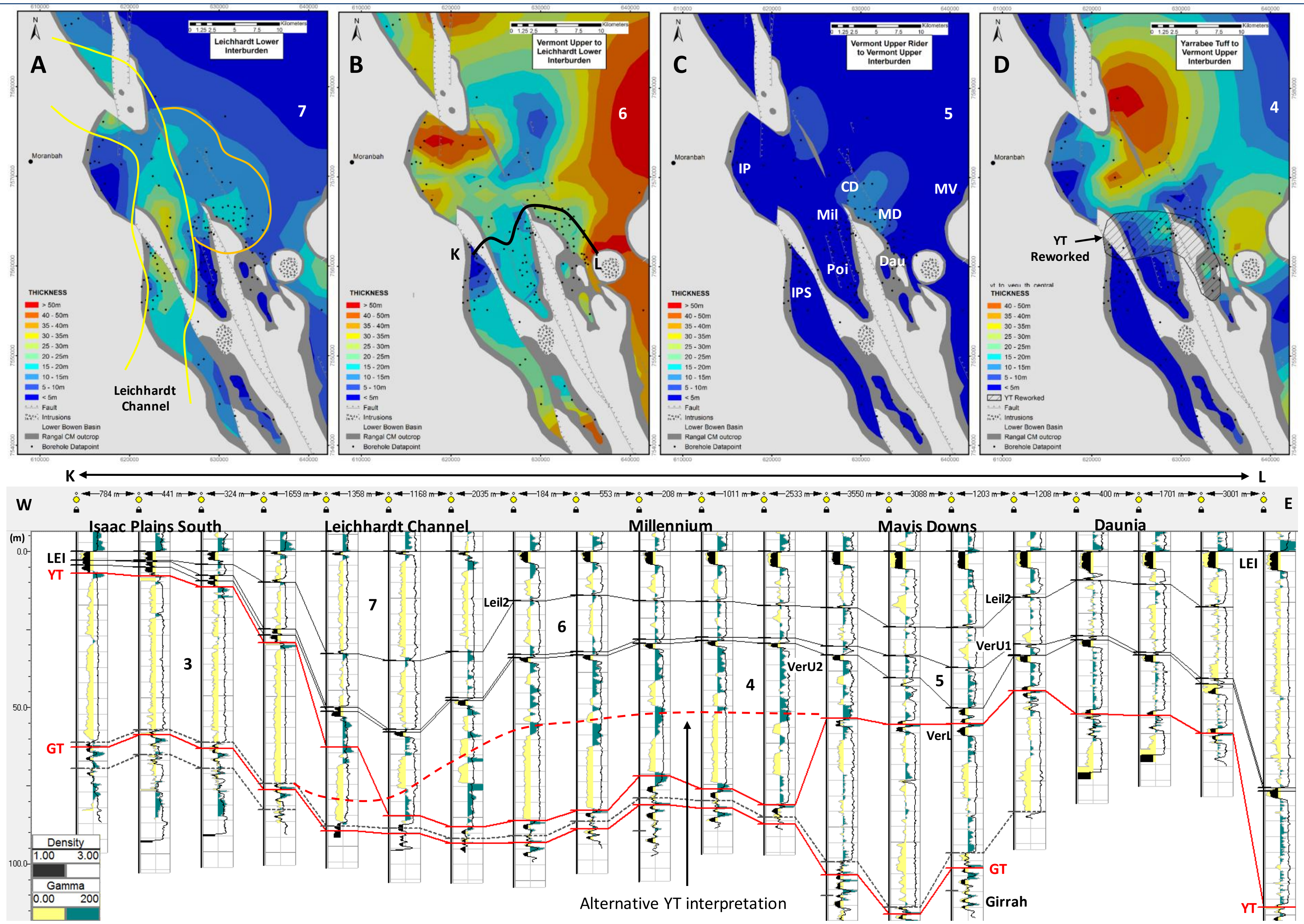


Figure 37 Thickness maps for sediment packages between the YT and Leichhardt Seam in the central Nebo Synclinorium with associated correlation section K to L. Map A shows the distribution of interburden 7, map B = interburden 6, map C = interburden 5 and map D = interburden 4.

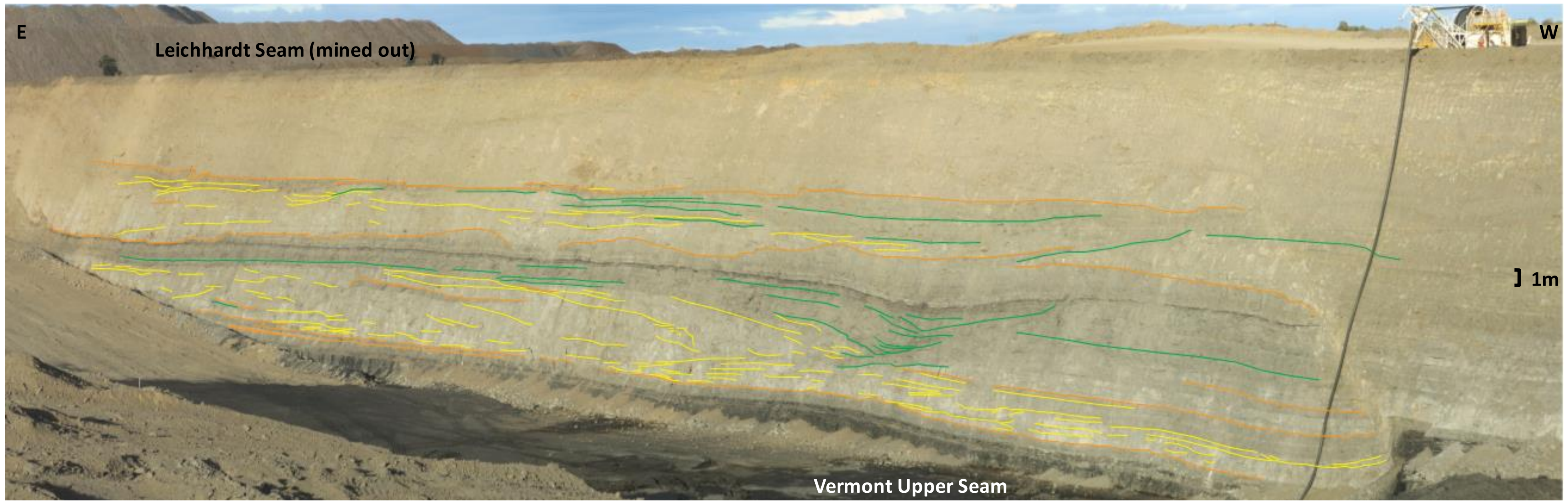


Figure 38 Mining exposure of the YT to Leichhardt interburden at Daunia showing sedimentary features highlighted in yellow (sandstone) and green (siltstone).

Leichhardt Seam to Rewan Group

This section describes the sediments within the uppermost splits of the Leichhardt Seam (interburden 8), between the Leichhardt Seam and the overlying Phillips Seam (interburden 9) and sediments overlying the Leichhardt or Phillips Seams that are not confidently assigned to the Rewan Group (interburden 10). These three sediment packages comprise the overburden of the main Leichhardt Seam equivalents across the Nebo Synclinorium.

Interburden 8: Apart from localised occurrences in the Suttor Creek area, splitting in the upper Leichhardt Seam is restricted to South Walker Creek and Coppabella where amalgamated sandstones overly the thickest portion of the Leichhardt Seam (Figure 39) and are in turn overlain by 2 – 5m of the upper Leichhardt Seam (LeiU2 and/or LeiU3). These seam splits re-join the main Leichhardt Seam to the east and west but the interburden unit remains open to the northeast of South Walker Creek and southward between Coppabella and Moorvale where erosion has removed the upper seams. Proximity to the current erosional surface also obscures the relationship between the uppermost of these seams (LeiU2) and the Phillips Seam. It is likely that the Phillips Seam splits off the LeiU2 to the south but may actually be a thinned equivalent of LeiU2 to the northwest.

Interburden 9: One or two thin rider seams that correlate with the Phillips Seam are found in a linear belt from Newlands through Burton to Coppabella and across most of the synclinorium south of Daunia and Poitrel. The interburden between these seams and the Leichhardt Seam is generally thin (up to 50m) and consists of mostly interbedded siltstone and sandstone with minor channel sandstones. The rider seams are thin and inconsistently developed, often traceable into carbonaceous shale units with little to no coal apparent in the wireline logs. This tendency toward shaling out is most commonly observed along the eastern margin of the synclinorium but is also seen above the thickest sandstones of interburden 8 (simple hatch in Figure 39 and correlation section in Figure 40).

Interburden 10: In most of the western and central parts of the synclinorium the Phillips Seam is not present and a high gamma mudstone (the marker mudstone - MM) comprises the entire interval between the Leichhardt Seam and the Rewan Group. This mudstone is generally less than 5m thick but exceeds 10m at Newlands, Burton and in parts of the Winchester and Carborough Downs deposits (Figure 14). Sandstones up to 20m thick and 5 km across are found below and within the mudstone at Carborough Downs, Mavis Downs, Millennium and Daunia. The relationship between the sandstone and mudstone is not clear as high-wall observations at Millennium suggest the sandstone has eroded the mudstone but downhole wireline signatures often show lateral gradational fining from sandstone to mudstone between drill-holes as well as development of high gamma mudstone above the sandstone as well as below (Figure 39).

Interburden 8: The anomalously thick pod within the upper Leichhardt

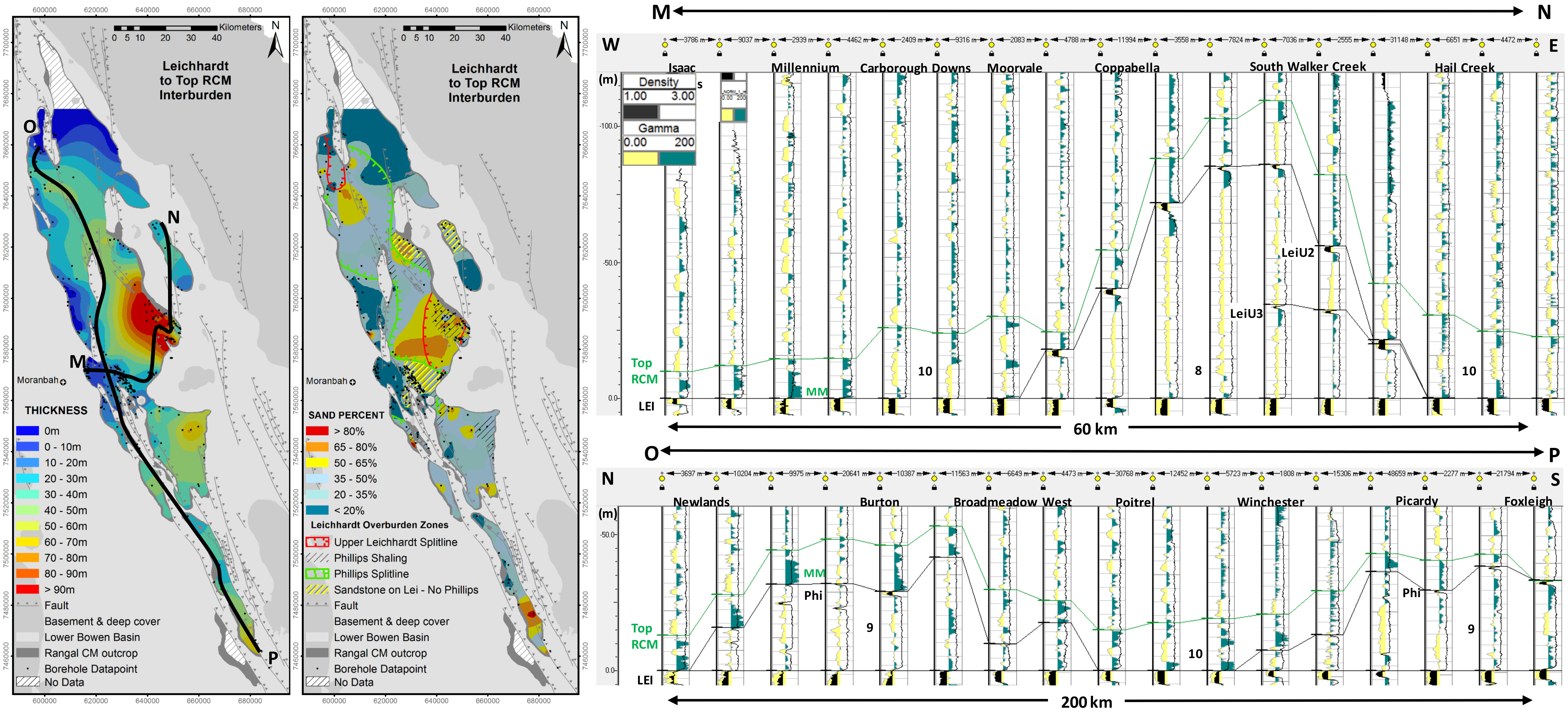


Figure 39 Thickness and sandstone proportion maps of the Leichhardt Seam overburden in the Nebo Synclinorium with associated east-west and north-south correlation sections.

interburden in the Coppabella/ South Walker Creek region (Figure 39) is controlled by the LEIU2 and LEIU3 seam splits which accommodate thick merged sandstones that are deposited directly onto the Leichhardt Seam or seam splits. Individual sandstone units are up to 80m thick and contain very few siltstone interbeds. Thin carbonaceous and coaly shales and minor roof splits are found infrequently throughout the upper Leichhardt interburden recording south-easterly stepping offset stacking (Figure 40). This south-easterly stacking is lateral to the general north-south trend of the interburden package. Highwall exposures at Coppabella show steeply inclined bedding of interburden 8 onlapping the Leichhardt Seam at the split (Figure 40) also evidencing south-easterly progradation. Similar steeply inclined heterolithic strata (IHS) in the coal measures of the Blackwater Group have been a source of controversy for some decades (Fielding 2015).

Heterolithic bodies of this nature are common in tidally influenced channels where periodic ebbs and flows allow the deposition of alternating coarse and fine-grained material over bars and banks. Many of the inclined heterolithic strata (IHS) bodies found in the RCM are unusually steeply dipping and dominated by mud rather than sand which, in light of some modern analogues suggests significant tidal influence (Nanson *et al.* 2014). Explanations for their formation in purely alluvial settings include fresh-water 'Gilbert' deltas (Conaghan 1982), crevasse splay sub-deltas (Flood & Brady 1985), alluvial fill of existing compactional moats formed at the toe of paralic deltas (Herbert 1997) and bed rotation due to peat compaction ahead of lateral accretion (Mallett *et al.* 1983). Fielding and Alexander (2001) provide commentary on these theories and largely discount them due to the presence of fossil trees at the toe, specifics of the geometry of the beds (dip directions and overall size) and lack of erosional bases or deformation of underlying strata. They conclude that no other process needs be invoked other than lateral accretion of meandering river channels under variable sedimentary influx due to seasonal run-off. A more recent re-evaluation by Fielding (2015) summarises the weight of evidence for tidal influence in the RCM, particularly at Blackwater, and concedes a reasonable likelihood for some tidal contribution during formation of the IHS bodies in the RCM.

The sandy IHS body illustrated in Figure 40 shows no coarse channel base and is not strongly erosive, neither cut-bank nor abandoned channel is preserved. The beds defined in yellow on the highwall image show the toe of each bed is thicker than the top suggesting progradational stacking over inclined foresets. This bed geometry invites postulation that the sediments were deposited into a depression likely initiated by the weight of the sands to the west. Periods of low sediment input enabled peat to re-establish forming the upper Leichhardt Seams (LeiU2 and LeiU3) which were essentially flat-lying. The fine-grained sediments deposited over the Leichhardt Seam to the east of the split (interburden 9) were accommodated by further compaction of the seam causing the beds of interburden 8 to rotate to a more steeply inclined aspect. This interpretation is supported by flattening on the Phillips Seam showing offset stacking of similarly thick sediment piles on either side of the split (Figure 40). The sandstone underlying the Phillips Seam is assumed to have been deposited as a flat sheet and completes the cycle of sedimentation initiated through compaction of the Leichhardt Seam. Similar high angle bedding is observed within splits of the Leichhardt Seam at South Walker Creek and at

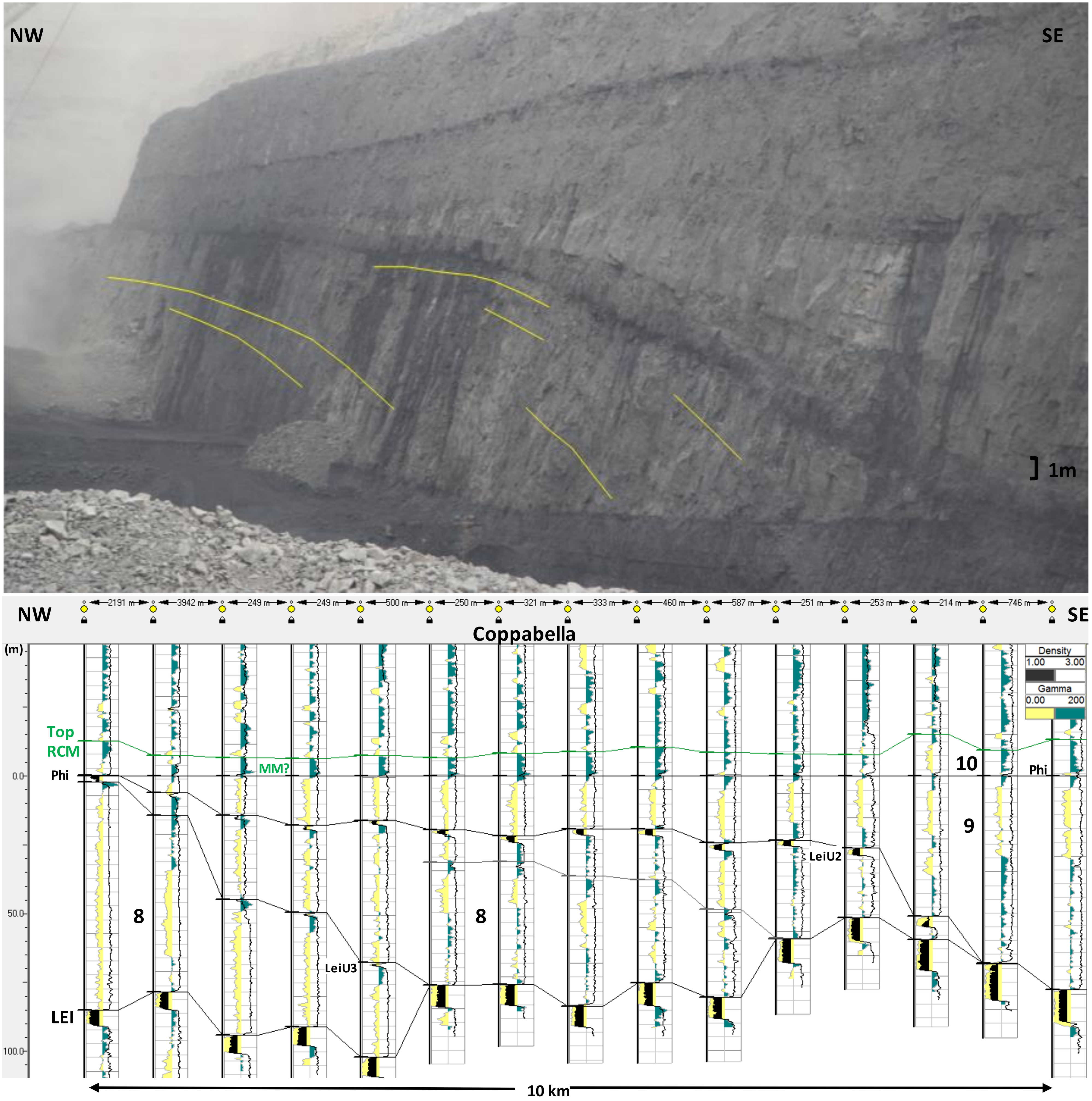


Figure 40 Highwall exposure and correlation-section at Coppabella showing the upper Leichhardt interburden sandstones.

Suttor Creek where a compaction controlled sedimentation model was presented as explanation by Michaelsen *et al.* (2000).

Interburden 10: A regionally persistent mudstone showing a distinct high gamma wireline signature occurs directly over the uppermost coal in the western half of the Nebo Synclinorium north of Picardy (Figure 41A). The thickest accumulations are in the northwest where it overlies the Newlands and Burton rider seam Phillips equivalents. The unit was described in detail at Newlands (Michaelsen *et al.* 2000), where it consists of carbonaceous siltstone with intercalated minor sheet-like sandstone bodies that were interpreted as the sediments of a lacustrine system prone to intermittent sheet floods.

The high gamma mudstone directly overlies the Leichhardt Seam at Red Hill and is often but not always present immediately above the Leichhardt Seam from Isaac Plains to Daunia and Carborough Downs. Coarsening upwards sandstones to 30m thick occur within and in place of the mudstone in the north-east of this area. The sandstone percent map for the 15m above the Leichhardt Seam (Figure 41B) suggests these sands are sourced from the east toward the large sandstone systems preserved in the upper Leichhardt splits at Coppabella and South Walker Creek.

A similar case of 20 to 30m thick sandstones developed just above the Leichhardt Seam is observed at Hail Creek and parts of Elphinstone (see yellow hatching in Figure 39). Highwall observations clearly show the sandstones eroding an underlying mudstone which in this case does not show such an elevated gamma response. Persistent mudstone layers 5 – 10m thick are observed throughout the Leichhardt Seam overburden at Hail Creek and it is likely that one of these represents the top of the RCM in this area. Highwall observations record the sandstone directly overlying the Leichhardt as an erosively based amalgamated complex of 4-6m thick, tabular beds to 18m thick with a grey hue. It is not until 20 or 30m above the Leichhardt Seam that a change to the greenish hue and sheet like architecture of the Sagittarius Sandstone of the Rewan Group becomes apparent.

It remains unclear whether these sandstones represent the proximal equivalents of the marker mudstone or have eroded the mudstone during emplacement. Down-hole wire-line data show the interval gradually fining away from the centre of the sandy lobe at Carborough Downs, with some high gamma mudstone developed above as well as below the coarser grained lithologies (Figure 41C). Although this is strongly suggestive of coeval development, observations in mining exposures at Isaac Plains and Millennium show the mudstone prograding in an easterly direction which is not expected if the sediment source is to the east.

Figure 42 is an image of the marker mudstone exposed at Millennium with internal bedding features traced. The exposed unit consists of a lower 2m thick set parallel with the underlying seam and a similar though less consistent upper set also lying parallel with the seam. Between these sets inclined strata define foresets that appear to prograde eastwards.

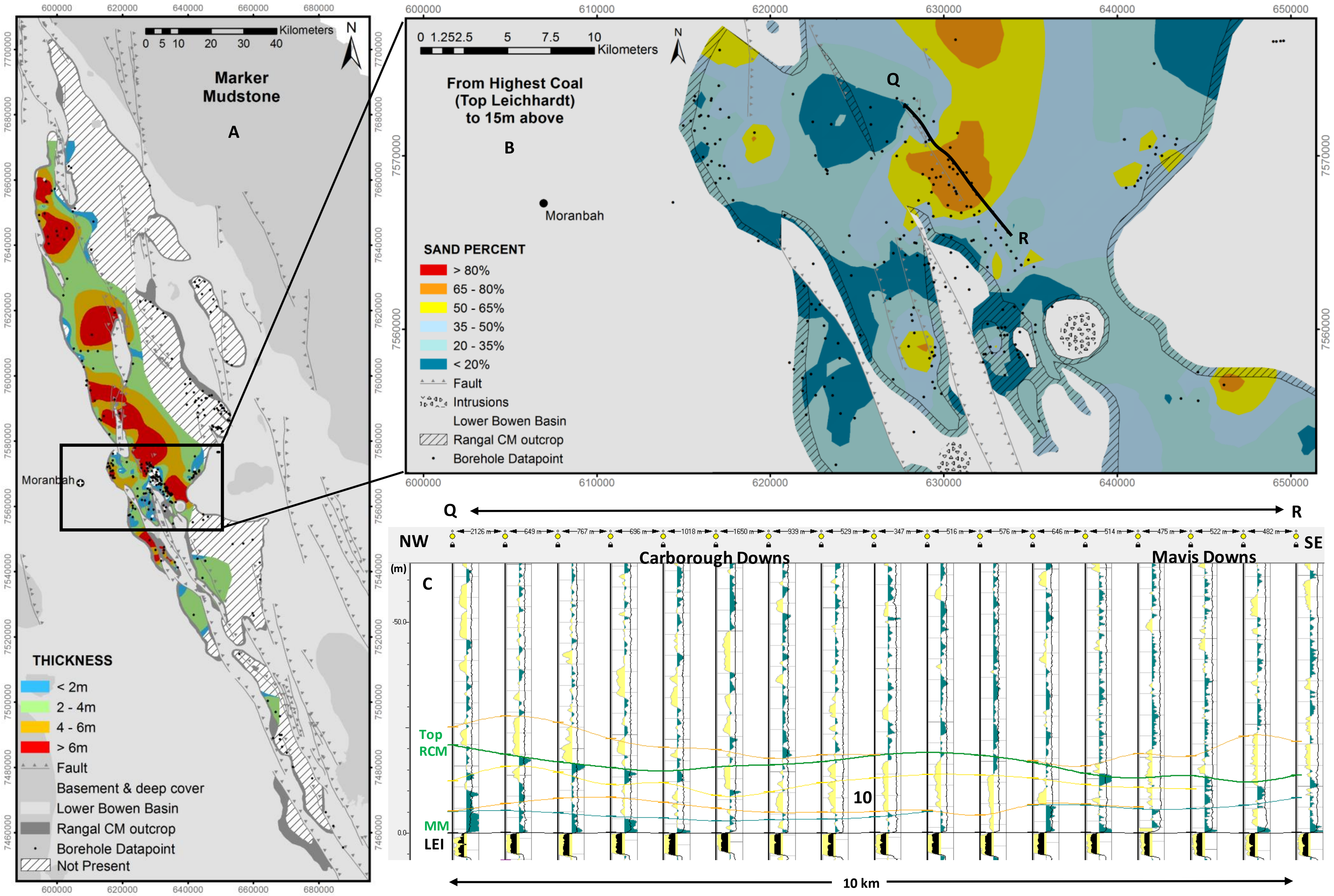


Figure 41 Distribution map for the marker mudstone (A), sand percent for the 15m overlying the Leichhardt Seam (B) and correlation section of the Leichhardt Seam overburden in the Mavis Downs – Carborough Downs area (C).

Figure 42 Mining exposure of the marker mudstone at Millennium.

Rewan Group

The Rewan Group has been divided into the lower Sagittarius Sandstone and the upper Arcadia Formation and descriptions of these units in the Nebo Synclinorium have been provided by Jensen (1975). Differences in the composition of clasts within the sandstones were used to divide the Sagittarius Sandstone into a lower 80m thick lithic unit and an upper 220m thick more quartzose unit. The lower unit comprises laminated brown and greenish-brown mudstone and siltstone containing finely disseminated carbonaceous material interbedded with similar proportions of fine- to medium-grained, green lithic sandstone. The upper unit is less well exposed and described as medium grained sandstone with interbedded brown and green mudstone devoid of carbonaceous material. The overlying Arcadia Formation is approximately 230m thick and comprises near equal proportions of lithic sandstone and thick sequences of brown mudstone (Jensen 1975).

A change in colour from predominantly grey sediments in the RCM to a greenish tinge in the Sagittarius Sandstone has been used to define the base of the Rewan Group (Matheson 1990a) and is attributed to a diagenetic chlorite-zeolite assemblage formed where carbonaceous material is no longer freely available (Mallett *et al.* 1995). Although this colour change can be observed above the Leichhardt Seam in mining exposures at Hail Creek, Lenton (Coffin 2013) and Isaac Plains, it is not so clearly discerned at Burton, Millennium, Moorvale and Daunia. Though this colour change may not be a reliable indicator of the lower Rewan Group boundary, the banded pattern of tabular sandstones separated by consistent thicknesses of siltstone is characteristic of the lower Rewan Group in the Nebo Synclinorium.

At Newlands the marker mudstone is overlain by repeated fining upwards sequences comprising basal sandstone to 7m thick fining upward to siltstone over intervals of 10-15m (Figure 43). Similar sequences are found at Burton, Elphinstone and Hail Creek where the sandstones are separated by persistent 5-10m thicknesses of interbedded siltstone and mudstone. The basal fine grained unit at Hail Creek thins to the north giving an appearance of gentle onlap to the north in the downhole correlations. Preliminary correlation of the sandstones within the Leichhardt Seam overburden at Hail Creek suggest dimensions of 3-10m thick and 3-8km broad.

Figure 44 shows an exposure of the Leichhardt Seam overburden at Isaac Plains where individual 1-2m thick channels form belts up to 5m thick and 7km across. Sandstones show erosive bases and preserve extensive ripple and trough cross-bedding. The intervening siltstone bands appear to terminate against the underlying sandstone in a northerly direction which is also suggested by the northerly thinning of the marker mudstone in the correlation section in Figure 44. Sandstone appears slightly less common 30 to 120m above the Leichhardt Seam, particularly along the western margin of the synclinorium, but evidence for a distinct change from a lower, sand rich Sagittarius Sandstone to an upper, emergent Arcadia Formation such as described further south in the Bowen Basin (Grech 2001) has not been observed in the RCM Supermodel drill-hole dataset.

Burton **Newlands** **Hail Creek**

Figure 43 Mining exposures of the Sagittarius Sandstone at Burton, Newlands and Hail Creek.

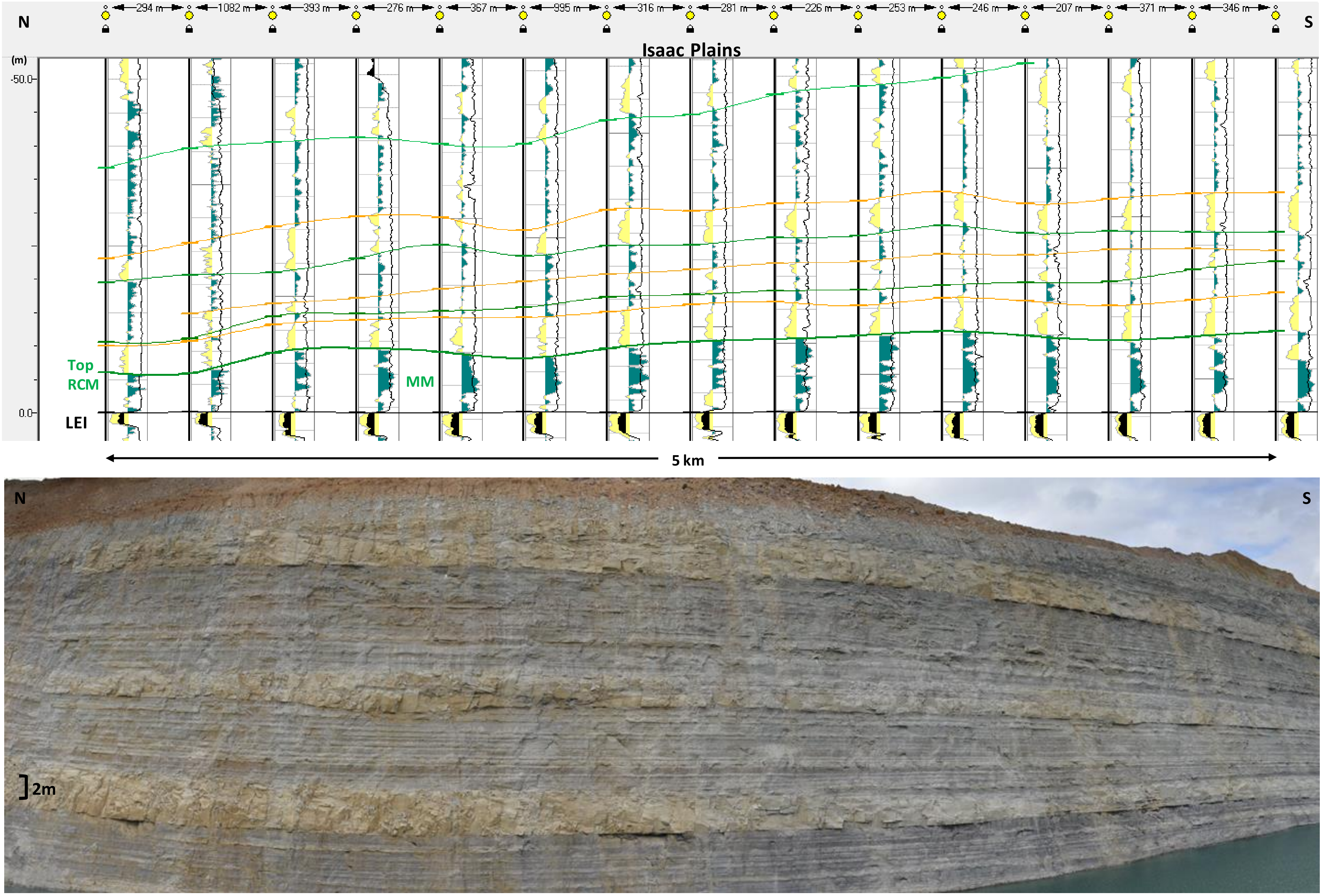


Figure 44 Correlation-section (not to scale) and mining exposure of the Sagittarius Sandstone at Isaac Plains.

4.6 Interburden Character: Baralaba tile

The Baralaba Coal Measures occupy the southeast margin of the Taroom Trough along the eastern limb of the Mimosa Syncline (Quinn 1985b). Although the stratigraphic equivalent of the Rangal and Bandanna Coal Measures, confirmed through age dating of the E Seam tuff to the YTB, the character of the coal seams and interburden is different enough to retain the colloquial use of the Baralaba Coal Measures. Difficulties in correlation through these measures were highlighted in Section 4.4, but below is the "best fit" correlation using C Seam as the datum. Below the C Seam, the interburden wireline gamma signature is relatively high, even for the sandstones as compared to above (Figure 45).

Core from the Baralaba 5C borehole was logged for lithology and sedimentary features, and put through a hyperspectral scanner Hylogger^{TM} to determine mineralogy (Figure 46). Thin sections were also analysed to support the interpretation of mineralogical change in relation to changing energy of sandstone packages (Villjea 2015). Although the wireline log would suggest more clay rich strata below the C Seam, core logging suggests some relatively coarse grained and massive sandstones. This is also observed in the highwalls at Dawson Mine. The HyLogger^{TM} results show abundant quartz in these lower sandstones, but also more abundant plagioclase feldspars. Lithic grains are sandy and occur preferable in the higher energy architectural elements of the systems (channels, sandy bars and lateral accretion).

Up-section, and above the C Seam, there is a shift from blocky sandstones to those exhibiting fining upward patterns suggesting a shift from higher to lower energy meandering channel systems, possibly in response to rising base levels. The sandstone bodies are slightly thinner, but also show a change in the mineralogy to white mica representing detrital muscovite (minority) and authigenic illite. HyLogger^{TM} data also reflects the increase in fine sediments (core logging) and white mica. This was interpreted to reflect the floodplain deposits and higher content of clay minerals. Thin section results suggested that, although the source of the lithic sandstones didn't change significantly from undissociated magmatic arcs (also observed by Michaelsen and Henderson (2000b), the higher gamma signature for the sandstones below the C Seam reflected abundant volcanic lithics and heavy minerals relative to those above.

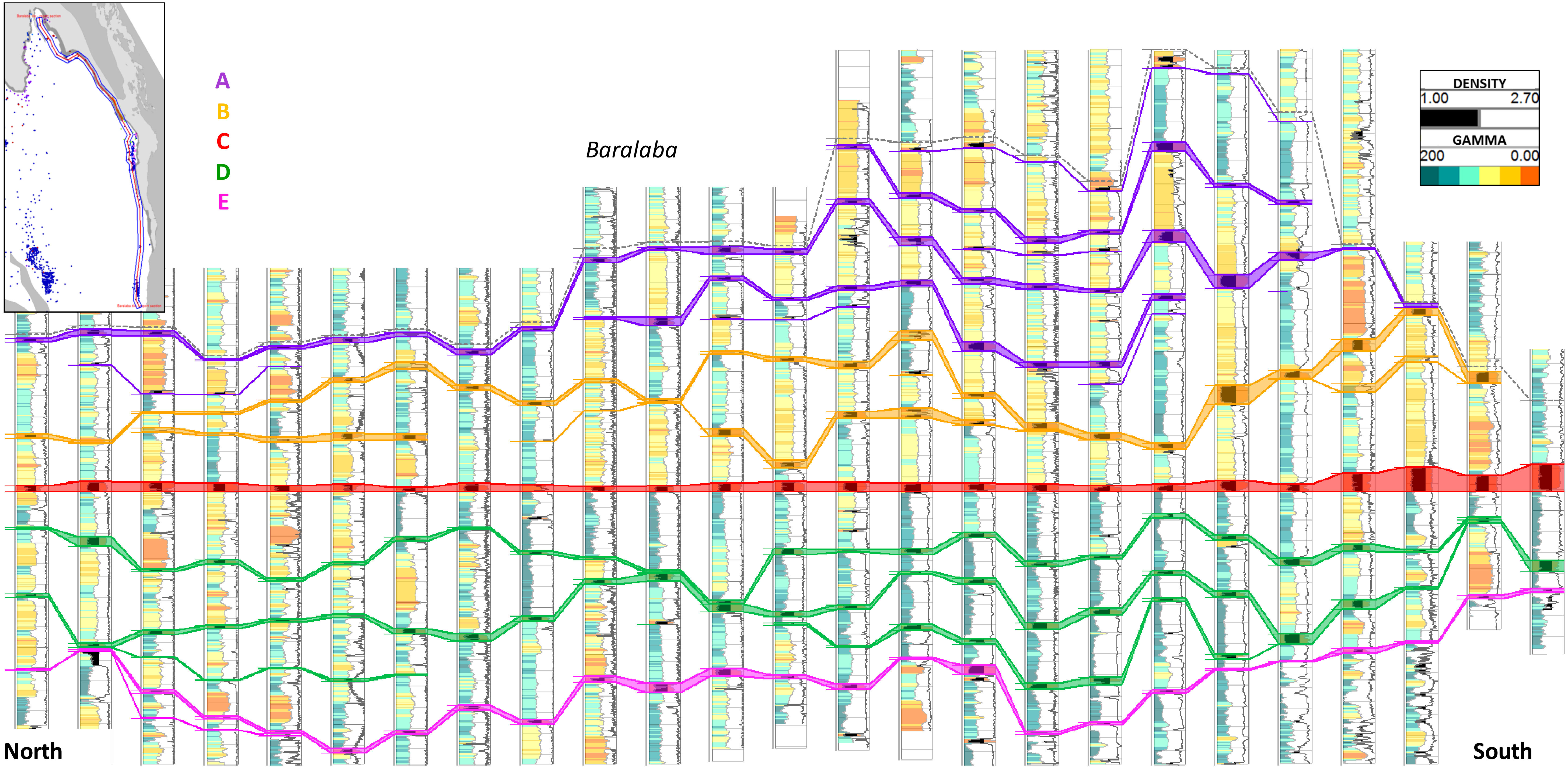


Figure 45 Regional section of Baralaba tile, flattened to C seam.

Depositional Setting

Similar to the Rangal and Bandanna Coal Measures, the depositional setting of the Baralaba Coal Measures has been interpreted as continental (Draper in Jell and GSQ (2013), although the depositional processes have been debated in the literature, using the developing highwall exposures at the Dawson Mine as evidence. The common occurrence of large scale, dipping or inclined master bedding surfaces within sandstone and siltstone dominated units(referred to as Inclined Heterolithic Strata or IHS) that alternate along the strike of the mine have been interpreted as foresets within lacustrine deltas (Flood & Brady 1985), offset channels that migrate laterally and rotate as underlying peat compacts (Mallett (1985); and illustrated in van Asselen *et al.* (2009), and laterally accreting point bars from ephemeral meandering channels (Edgar 1987, Miller 1992, Fielding *et al.* 1993). The ephemeral nature of coarse sediment input was attributed to a combination of seasonality or longer term climatic changes, and tectonically driven subsidence and clastic influx from the rising New England Orogen. More recently, Fielding (2015) suggested that IHS within the Late Permian Rangal Coal Measures could be the product of complex point bars building laterally and downstream within deep, tidally influenced channels or estuaries. The presence of coastal or marine indicators (fish, acritarch microfossils, faunal burrowing and bimodal ripple bedding) often found within the finer grained sediments support this reinterpretation, and suggest a rising in base level at this time, as also suggested by Wilson in Section 4.5 and evidenced by the "Marker Mudstone" transition into the Rewan Formation. Examples of these features recently mapped at Dawson Mine by Caldwell (2016) are presented in Figure 47, Figure 48, and Figure 49.

Caldwell (2016) reconciled all models through observation of deltaic foresets traversed by channelised topset beds, areas of over steepened slumped chute channels traversing heterolithic point bars and laterally accreting channels that fined progressively upward as the channel system was choked off during rising base level. At Dawson, the thinner E Seam overlies fine grained, at times burrowed sediments of the tuffaceous Kaloola Member. The seams become progressively thicker up to the C Seam, coincident with an increase in the interburdens from an average of 20m to 60m above the C Seam, thereafter declining slightly towards the A Seam. Although present throughout the stratigraphy, and across all pits, the propensity for IHS and alternating IHS and inclined sandstone dominated strata is increased in the C to B interburden. This could reflect the progradation of the fluvial system up to the C Seam, that would accumulate in pace with a rising base level and eventually drown. The overlying channel belts would be progressively flooded from fluvial to estuarine or lacustrine conditions (depending on the nature of the water body).

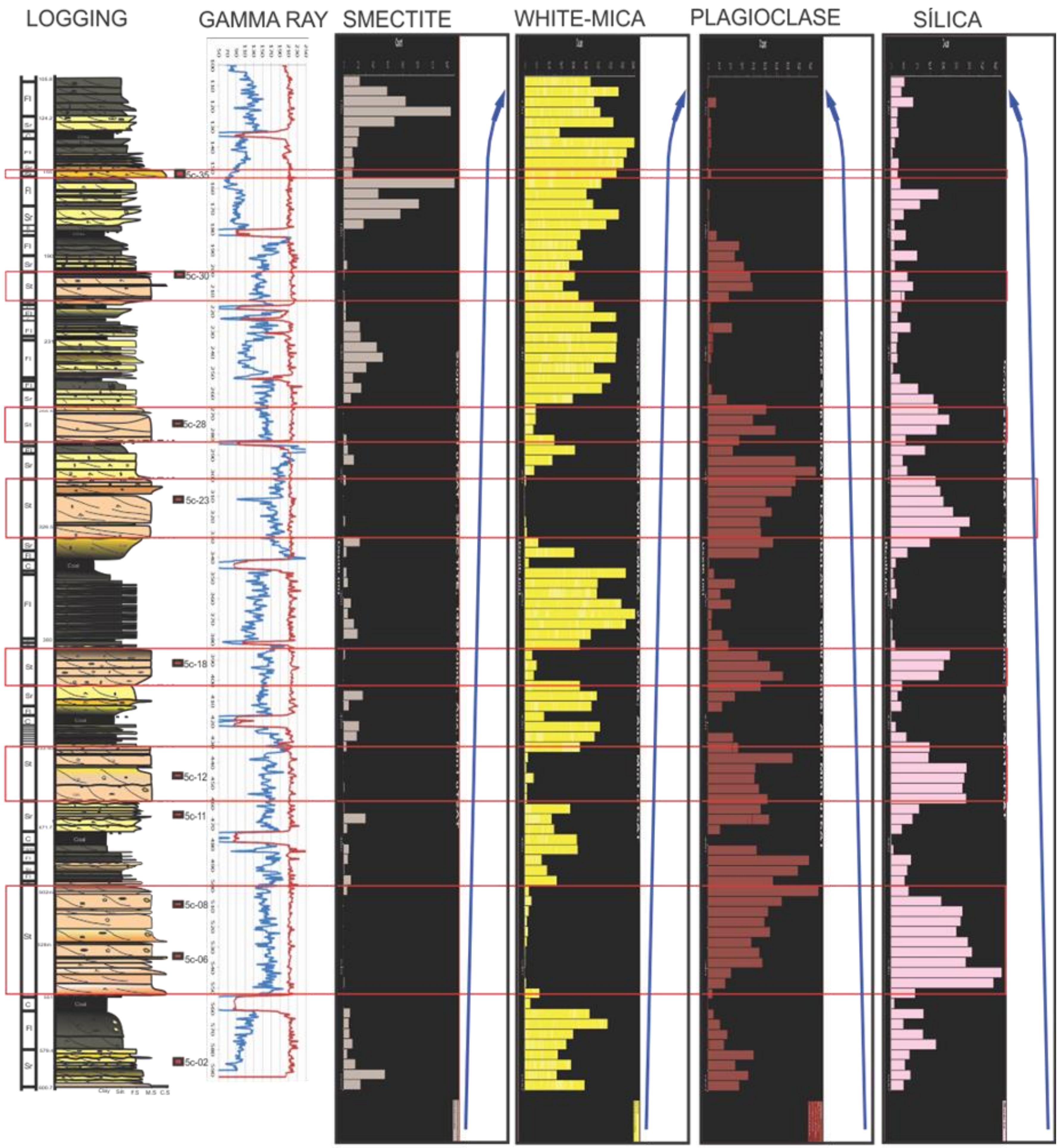


Figure 46 Comparison of interpreted mineralogy from Hylogger^{TM} , gamma ray wireline signature and core logging for the Baralaba 5C core (Villjea 2015). Red squares highlight the main sandstone packages as defined from core logging.

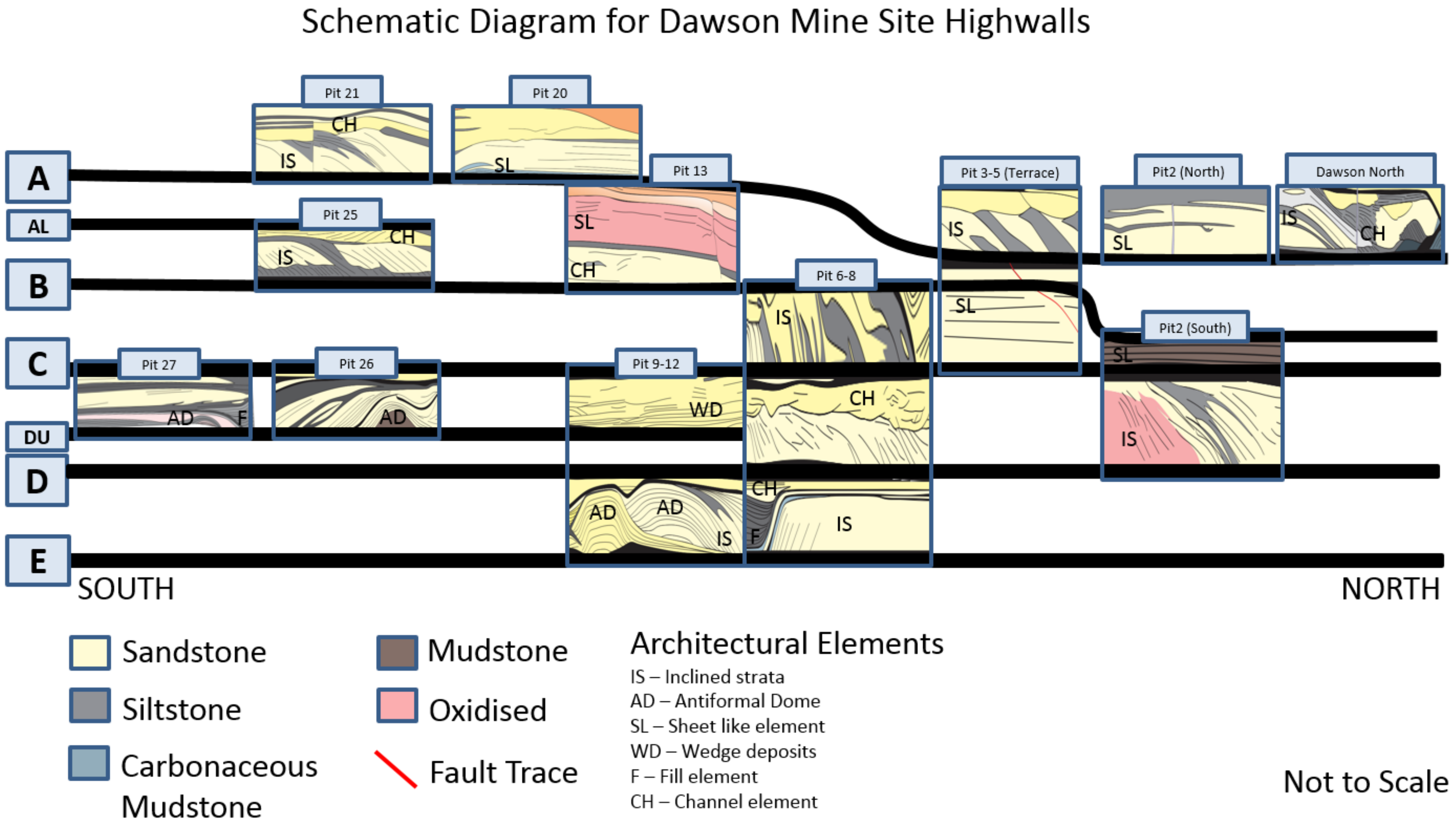


Figure 47 Schematic Diagram for Dawson Mine Site Highwalls. The seams tend to be thinner and siltier to the north. Sandstone is dominant below the C seam and above the C seam thick muds and silts are abundant. Northward trend of apparent dip is prominent with several reversals observed. Antiformal domes are more frequently observed below the C Seam. Diagram looking west. From Caldwell (2016).

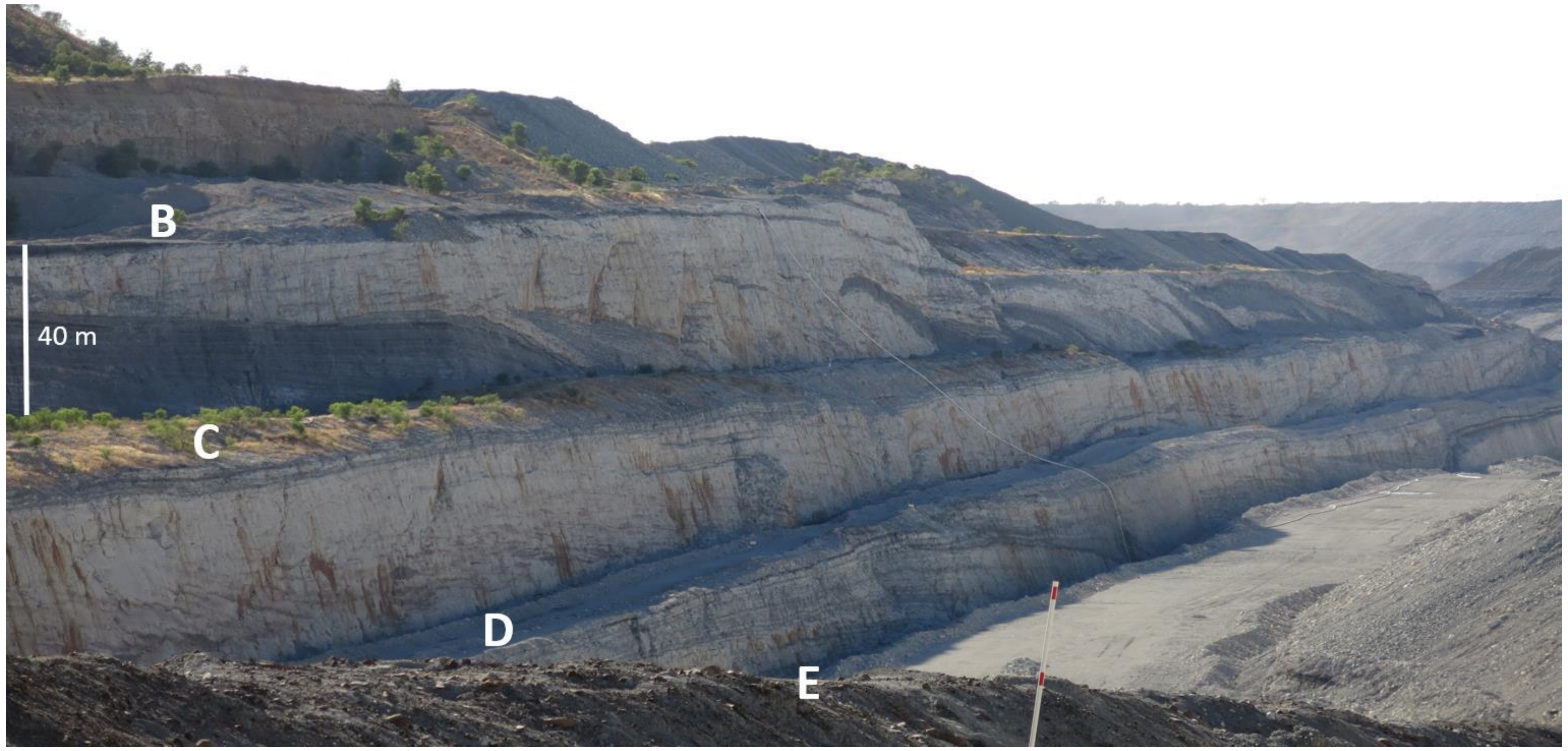


Figure 48 Photograph of sandstone bodies and inclined heterolithic strata exposed in highwalls at Dawson Mine Pits 6-8. Strata master bedding plain dip predominantly north, but with reversals common. Smaller scale sedimentary structures suggest palaeoflow to the west. This supports the notion of channels flowing westward but migrating broadly across the area.

Looking west.
From Caldwell (2016).

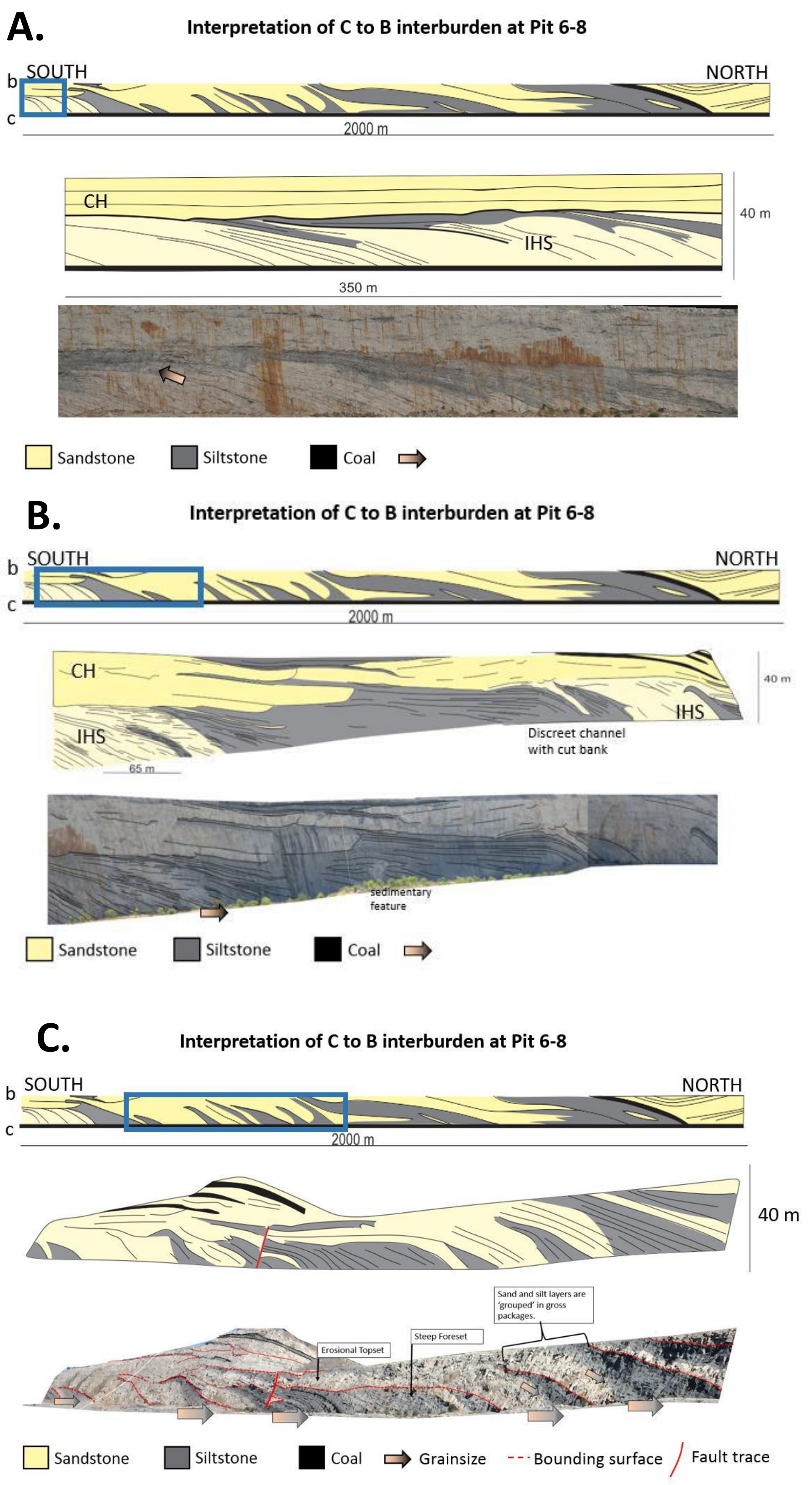


Figure 49 Evolution of sedimentary styles from sandstone to siltstone dominated inclined strata. A. shows IHS fining up strata and truncated by the overlying sandstone interpreted as channel (CH); B. shows siltstone dominated IHS truncated by discrete lenses of sandstone with cutbank margins, often rotated; C. shows alternating lenses of IHS and inclined erosively based lenses that fine towards the toesets. Looking west. From Caldwell (2016).

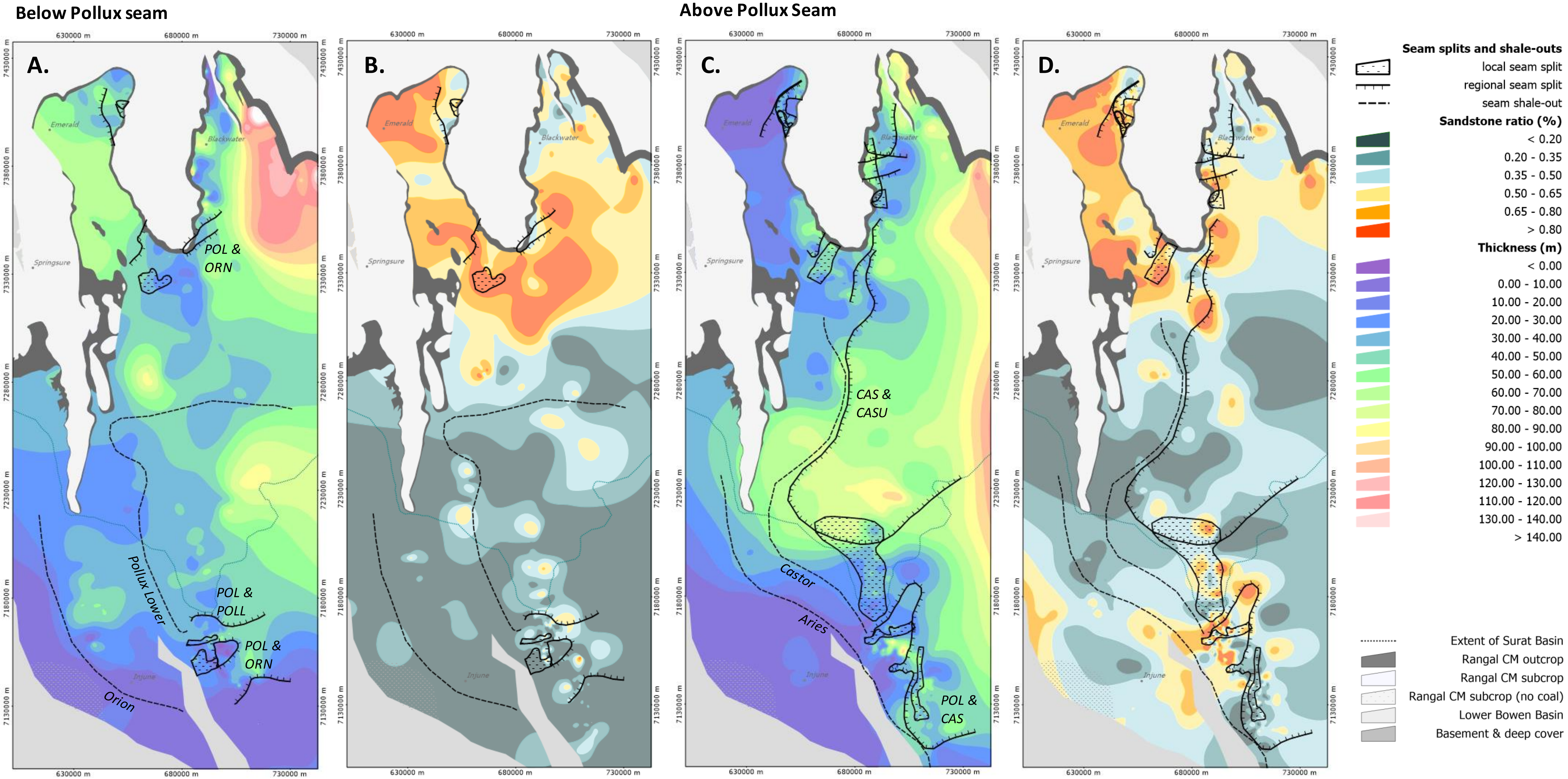
4.7 Interburden Character: Bandanna tile

The Bandanna Coal Measures stretch from the Denison Trough across the Comet Ridge and into the Taroom Trough. As discussed in Chapter 4.4, the coal seams in this region are generally thin, split towards the Taroom Trough and shale out on to the Roma/Springsure Shelf in the southwest. Only one regionally consistent marker seam was identified across the tile and correlated with the Pollux Seam along the eastern Comet Ridge. The Pollux Seam was used to divide the Bandanna Coal Measures into an upper and a lower interval. Maps of the regional distribution of thickness and sandstone proportion for each of the two intervals are shown in Figure 50.

The interburden below the Pollux Seam ranges in thickness from 10m in the south and southwest to ~90m in the Taroom Trough, and to ~60m in the Denison Trough (Figure 50A). Further to the northeast the interburden opens up to >120m towards the RCM depocentre in the Baralaba Coal Measures. The lithology of this interburden unit is dominated by sandstone in the Denison Trough and around the Comet Ridge, but grades to siltstone and mudstone further south (Figure 50B).

Across the northern Denison Trough, the interburden between the Pisces and Orion Seams is characterised by mudstones and siltstones at the base that coarsen upwards into a 15-20m thick sandstone just below the Orion Seam (Figure 51A). This characteristic upward coarsening cycle thins to the south and does not occur along the eastern margin of the Comet Ridge. Similar upward coarsening cycles area typical for the underlying Burngrove Formation, and the regional transition from sand dominated to siltstone/mudstone dominated interburden correlates with the transition from the underlying sandy Burngrove Formation and muddy Black Alley Shale (Figure 51B).

Above the Pollux Seam, the upper interburden unit is thin (<10m) in the Denison Trough and in the southwest, but again thick (up to 100m) in the Taroom Trough (Figure 50C). The sandstone proportion of this interval remains high in the Denison Trough and around the Comet Ridge. It declines to the south and into the Taroom Trough but then increases again onto the


Below Pollux seam

Above Pollux Seam

Figure 50 Regional interburden distribution of the Bandanna Coal Measures. A. Interburden thickness between base of RCM and Pollux Seam; B. Sandstone proportion between base of RCM and Pollux Seam; C. Interburden thickness between Pollux Seam and base of Rewan Group; and D. Sandstone proportion between Pollux Seam and base of Rewan Group.

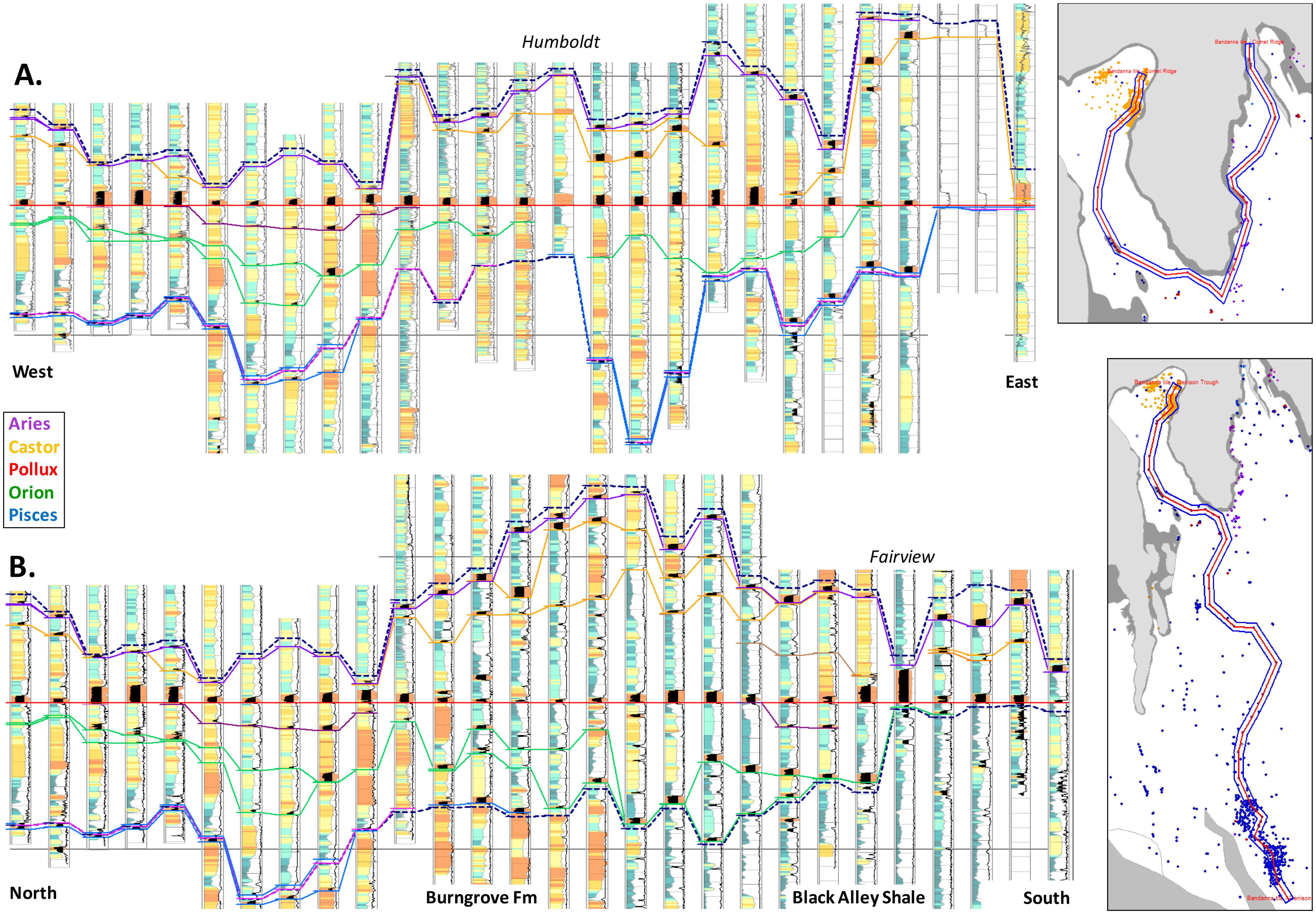


Figure 51 Representative wireline sections A. around the Comet Ridge; and B. along Denison Trough. Both sections are flattened along the Pollux Seam.

Roma Shelf (Figure 50D). This southern sandstone-rich area correlated with the sandstone dominated area within the lower Rewan Group (compare with Figure 19). So, on a regional scale, the Bandanna Formation captures the transition in regional dispersal patterns from the underlying Burngrove Fm/Black Alley Shale to the overlying lower Rewan Group.

The upper interburden unit has been investigated by a number of studies at Blackwater and South Blackwater along the eastern margin of the Comet Ridge (Fielding *et al.* 1993, Avenell 1998, Stuart *et al.* 2014). Fielding *et al.* (1993) interpreted the depositional environment above the Pollux Seam as a broad, rapidly subsiding alluvial plain with a minor proportion of channels. The authors recognised two types of streams: one that deposited sheet like sandstone bodies, probably on braided river systems, during times of sediment oversupply; and another characterised by lateral accretion in moderately sinuous streams during times of less sediment supply. Palaeocurrent directions suggested a southward flow for the system. Recently Fielding (2015) has revised the interpretation of a purely fluvial plain environment to one of a large-scale estuarine embayment.

5 GALILEE BASIN

Laura Phillips

5.1 Regional overview

Geological introduction

The Galilee Basin is interpreted as an intracratonic basin that formed adjacent to the foreland Bowen Basin. The metamorphic Anakie Inlier separates the two basins in the north, whereas to the south, the Permian and Triassic sediments from both basins are thought to converge across the Springsure Shelf and Nebine Ridge. The Cooper Basin abuts the Galilee Basin to the south west, separated by the Canaway Fault which is interpreted to have been active during much of the Late Permian and Triassic, halting the flow of sedimentation between the basins (McKellar 2012).

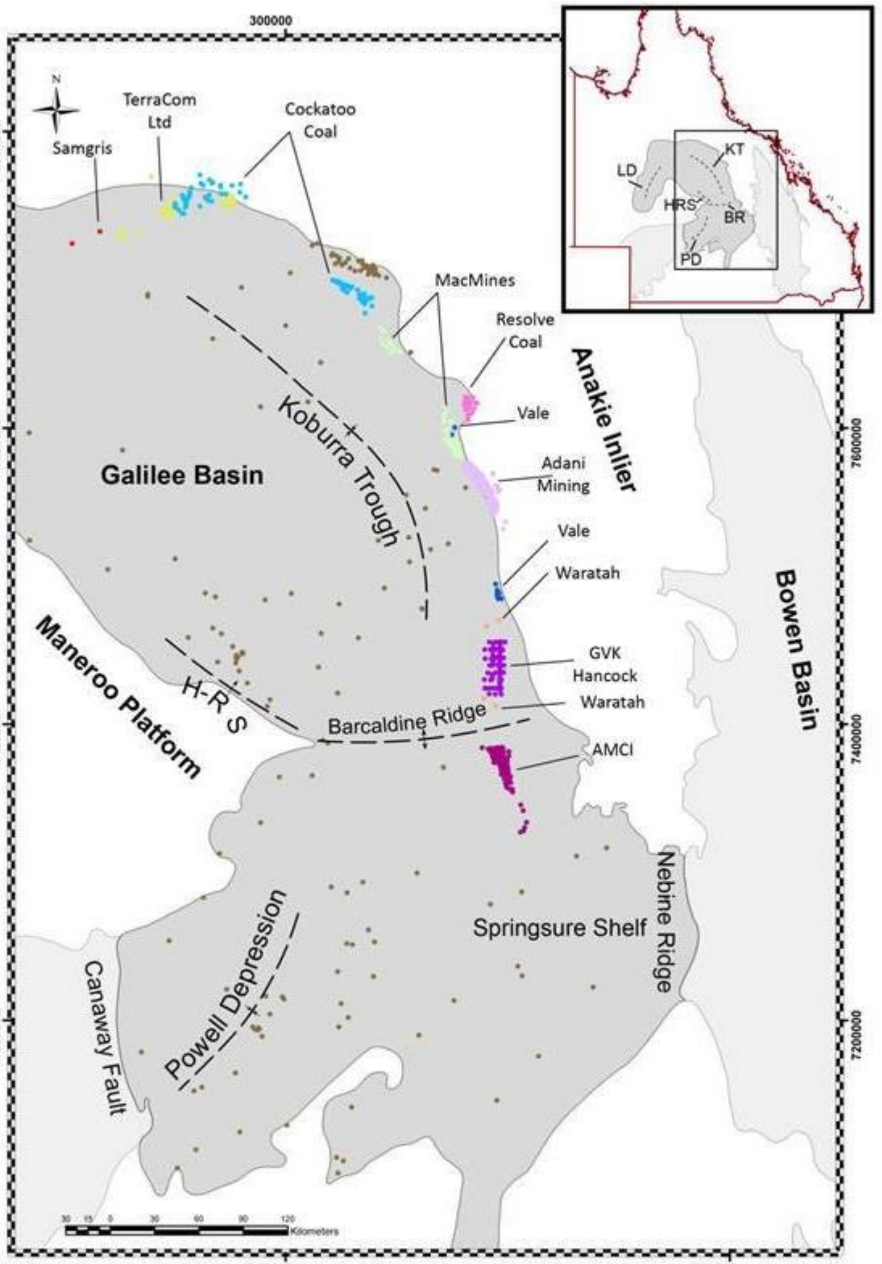


Figure 53 Map of study area, showing the location of propriety data (coloured and annotated) and open file data (brown dots) relative to major features in the Galilee Basin. Inset map shows major structural features. LD – Lovelle Depression, KT – Koburra Trough, BR – Barcaldine Ridge, PD – Powell Depression and HRS – Hulton Rand Structure.

The Galilee Basin is not structurally complex and has three major palaeo-depo centres (Figure 53 Inset). The Koburra Trough runs north to south through the centre of the basin and the Lovelle Depression runs north east-south west in the northwest limb of the basin. This limb is separated from the central part of the basin by the meta-sedimentary Maneroo Platform, that contains no Late Palaeozoic sediments. A boundary fault known as the Hulton-Rand Structure is located to the east of the platform. The third palaeo-depo centre, known as the Powell Depression, is in the southern part of the Galilee Basin, separated from the northern part by the Barcaldine Ridge (Evans & Roberts 1980) and (McKellar & Henderson 2012). Unconformably overlying much of the Galilee Basin is the Jurassic to Cretaceous aged Eromanga Basin.

Late Carboniferous (Pennsylvanian?) to Early Permian sedimentation was wide spread across the central and southern parts of the basin, represented in the stratigraphic record by the glacially influenced Joe Joe Group (Figure 52)(Scott *et al.* 1995, Jones & Fielding 2008). The Aramac Coal Measures occurred towards the later stages of the Early Permian and are located on the down dip side of the Hulton-Rand Structure and in the north western Lovelle Depression. These coal measures are the time equivalents to the Early Permian Reids Dome beds located in the Denison Trough of the Bowen Basin (Mollan *et al.* 1969b, Evans 1980). New data from Nicoll *et al.* (2015) suggest that the end of the Early Permian coal measures marks an approximate 30Ma hiatus in sedimentation in the Galilee Basin, much larger than what has previously been reported (McKellar & Henderson 2012).

The Late Permian strata can be subdivided into four sequences: Colinlea Sandstone, Peawaddy Formation, Black Alley Shale and Bandanna Formation (oldest to youngest respectively), all of which have been correlated to equivalents in the Bowen Basin. The Peawaddy Formation and the Black Alley Shale are prevalent in the southern part of the Galilee Basin, but they pinch out towards the north east (Scott *et al.* 1995). The Colinlea Sandstone and Bandanna Formation extend further north and are known collectively as the Betts Creek beds.

The use of the term Betts Creek beds is inconsistent across the basin. It is unclear if they are a separate entity or the correlative of the Bandanna Formation and Colinlea Sandstone, combined. An outcome of this study is a regionally consistent correlation.

The overlying coal barren Triassic sequences are widespread across the Galilee Basin and share similar nomenclature and lithologies to their Bowen Basin counter parts. The boundary between the oldest (Permo-) Triassic unit, the Rewan Formation and the underlying Permian Bandanna Formation in the Galilee Basin is not well described in the literature and it is commonly placed directly above the youngest Permian coal seam.

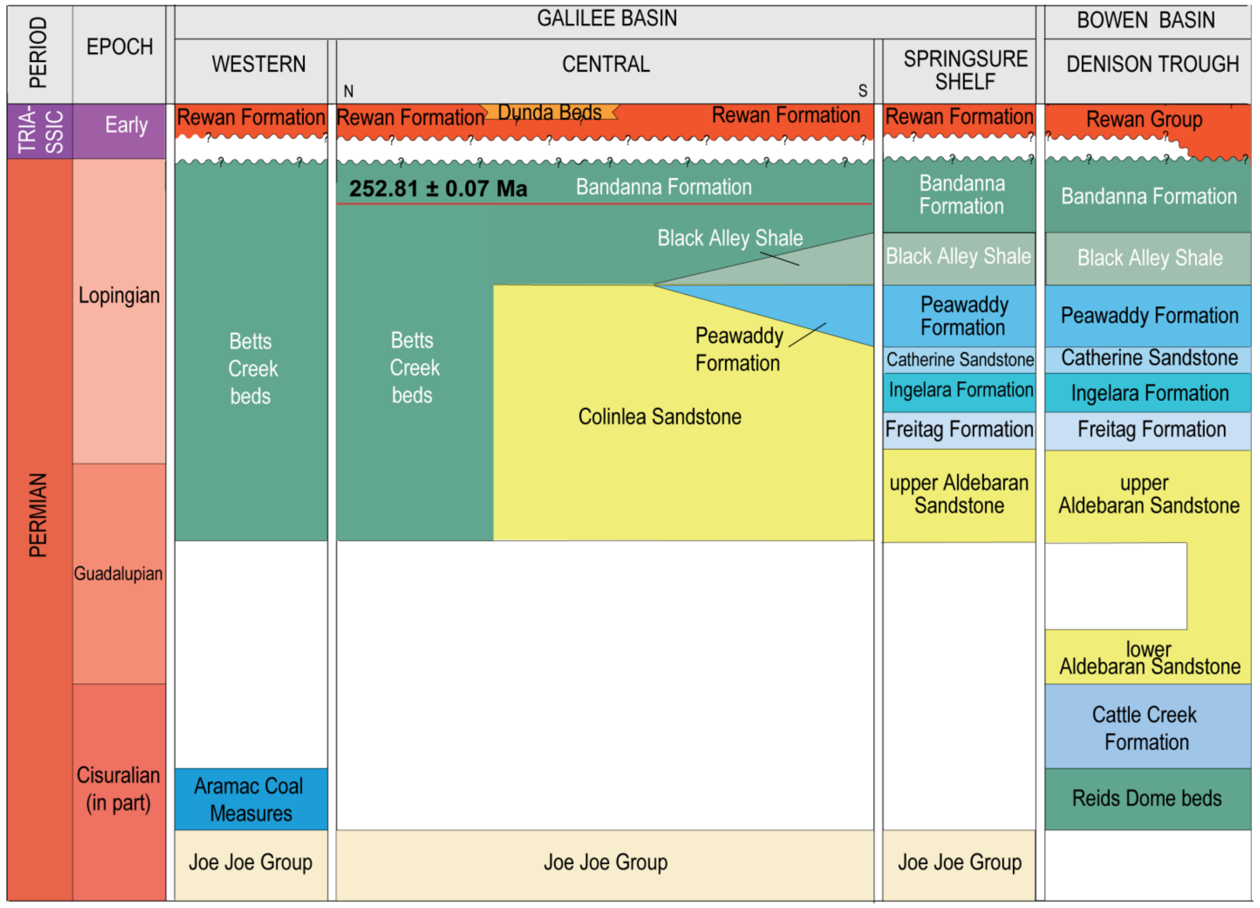


Figure 52 Stratigraphic column of Galilee Basin with Denison Trough equivalents. Modified from Allen and Fielding (2007b) and McKellar and Henderson (2012). Red line represents the placement of a CA-IDTIMS date from Phillips et al. (in review). Note time scale is approximate.

Regional seismic lines CAR82-23, CAR82-09, CAR82-25, CS86-03 and CAR82-11 located in the north eastern part of the basin were interpreted by Van Heeswijck (2006) who observed minimal large scale fault displacement in Late Permian sediments. Smaller scale faults, below the resolution of these regional seismic lines can be found locally e.g. Adani Mining Pty Ltd (2013).

Tectonic overview

The major tectonic events in the Galilee Basin parallel those in the adjoining Bowen Basin, except for the Hunter-Bowen compressive phase. Three phases have been identified in the geological evolution of the Galilee Basin; mechanical extension, and an extended period of thermal subsidence punctuated by a period of gentle uplift. A detailed description of the tectonic history of the Galilee Basin can be found in (Van Heeswijck 2006, Van Heeswijck 2010), and a summary is presented below.

Carboniferous compression and extension. The initial formation of the Galilee Basin lies in events that shaped the underlying basin to the north east, the Drummond Basin. The commencement of Carboniferous sediments in the Galilee Basin occur during a compressional phase which marks the end of the Drummond Basin sedimentation (Van Heeswijck 2010). Late Carboniferous extension and reactivation of faults from underlying basins is recognised by the emergence of the Koburra Trough (Hawkins 1978, Van Heeswijck 2010) where the thickest succession of the Late Carboniferous – Early Permian Joe Joe Group sediments is found (Gray & Swarbrick 1975).

Early to Middle Permian thermal subsidence. Thermal subsidence in the Early Permian is manifested in the depocentre thickening of the upper Jochmus Formation (Van Heeswijck 2010). Sporadic occurrence of the Aramac Coal Measures suggests periods of terrestrial infilling, but their tectonic significance is poorly understood. Vine (1975) and Hawkins and Green (1993) suggest the Aramac Coal Measures occur in isolated sub-basins similar to the Reids Dome Beds in the Denison Trough, which occurred during mechanical extension of the Bowen Basin. However, stratigraphic equivalents of the Cattle Creek Formation and the lower Aldebaran Sandstone of the Denison Trough are thin to non-existent in the Galilee Basin, suggesting a Middle Permian hiatus for which the origins are unclear.

Late Permian to Mid Triassic thermal subsidence. Isopach maps drawn by Van Heeswijck (2010) suggest that basin subsidence was gentle during the deposition of the Late Permian through to the Triassic sediments. The slowly subsiding basin provided a stable environment to promote widespread mires, which has resulted in large and laterally continuous coal seams. This sheet like architecture is indicative of low tectonic control (Allen & Fielding 2007b) promoting the idea of continued thermal subsidence towards the end of the Late Permian.

The onset of foreland loading in the Bowen Basin is marked in the Galilee Basin by a transgressive sequence. The Peawaddy Formation and Black Alley Shale are not present across the basin, instead they are restricted to the southern part of the Galilee Basin (Scott *et al.* 1995).

Continued thermal subsidence into the Triassic allowed for the laterally extensive deposition of the Rewan Formation, Clematis Sandstone and the Moolayember Formation.

5.2 Late Permian to Early Triassic Sedimentary Framework

Although there are parallels with the Bowen Basin, sedimentation patterns in the Galilee Basin differ substantially as tectonism played a minor role (Allen & Fielding 2007b, Van Heeswijck 2010). During deposition, the basin was undergoing continued but slow thermal subsidence. The sediments in the Galilee Basin represent a condensed sequence of Late Permian stratum. Thickness of the total Late Permian sequence does not exceed 350m anywhere in the basin. Interpretations of sedimentary formations from wireline log correlations and seismic survey lines, suggest the geometry of the formations have a sheet like architecture (Allen & Fielding 2007b, Van Heeswijck 2010).

Two recent studies by Allen and Fielding (2007a), (2007b), produced a sedimentary framework for the Late Permian Betts Creek beds and their correlatives within the Galilee Basin, using an outcrop of the Betts Creek beds near the town of Hughenden in Central Queensland as a type section. This framework is shown in Figure 52 and is followed in this study.

Rewan Formation. The heterolithic and coal barren Rewan Formation comprises of siltstone, sandstone and mudstone (Scott & Hawkins 1992). Although no formal colour change has been acknowledged, many companies currently exploring in the area record the Rewan Formation as having different coloured attributes e.g. green, grey, purplish-brown (Lewis *et al.* 2014). It is interpreted to have been deposited in an alluvial setting (Allen & Fielding 2007b). Foreland loading in the Bowen Basin during the Early Triassic may have induced subsidence rates in the Galilee Basin, resulting in a quick draining environment within the basin. Supporting evidence of higher subsidence rates is increased thickness of the Rewan Formation, where an average thickness of ~300m e.g. (Australia Pacific LNG 2010a, b, Comet Ridge 2010) is similar to that of the whole Late Permian succession.

In the northern and north eastern regions of the basin, the Rewan Formation is the equivalent to the lower section of the Warang Sandstone (McKellar & Henderson 2012).

Betts Creek beds. The Betts Creek beds are defined as the complete Late Permian sequence of the Galilee Basin. Although correlatives of other formations have been found within the Betts Creek beds (Scott & Hawkins 1992, Allen & Fielding 2007b), petrographic studies have found that the sediment source for the Betts Creek beds in the north of the basin may have differed from the correlatives towards the south (Scott & Hawkins 1992). Allen and Fielding (2007a) interpreted estuarine facies in the outcrop of the Betts Creek beds in the northern Galilee Basin, suggesting that marine influence extended across the basin. However, it is not understood how these facies observed in the outcrop correlate to wireline logs elsewhere in the basin.

Bandanna Formation. The Bandanna Formation in the Galilee Basin is the lateral equivalent of the last coal bearing sequence in the Bowen Basin. These coal measures are the exploration targets of mining and CSG exploration companies. Typically, the Bandanna Formation interburdens contain laminated to thickly bedded labile sandstone, which at intervals are interbedded with mudstones and siltstones (Hawkins 1978, Hawkins & Green 1993, Allen & Fielding 2007b, Grigorescu 2012).

No notable stratigraphic marker horizon similar to the Yarrabee Tuff is documented in the Galilee Basin, however, Phillips *et al.* (in review) dated a tuff situated at the top of the B seam in the Bandanna Formation (Figure 52; Table 5). The resultant age, 252.81 ± 0.07 Ma, is similar to dates published by Metcalfe *et al.* (2015) and Ayaz *et al.* (2016a) of the Yarrabee Tuff. Allen and Fielding (2007b) note that on seismic sections the Bandanna Formation base is distinct and can be used as a significant sequence boundary.

Black Alley Shale. Similar to its name sake from the Bowen Basin, the Black Alley Shale represents a restricted marine facies. It is reportedly comprised of dark shale and siltstone, with minor sandstone. Volcanic ash beds are common within the formation as well (Wallin 1975, Gray 1976).

It pinches out towards the Koburra Trough, however (Allen & Fielding 2007b) have correlated its lateral equivalents through to the northern part of the Galilee Basin. Within the Galilee Basin the Black Alley Shale is thought to represent a transition between the underlying marine Peawaddy Formation into the overlying fluvial/lacustrine/paludal Bandanna Formation (McKellar & Henderson 2012).

Peawaddy Formation. The Peawaddy Formation above the Colinlea Sandstone marks the last marine transgression into the Galilee Basin from the Bowen Basin. Similar to the Bowen Basin, the Peawaddy Formation consists of sandstones, siltstones and shales (Gray 1976). It is interpreted to have formed in a shallow basin that connected the Galilee Basin, over the Nebine Ridge, to the Springsure Shelf and Bowen Basin (Scott *et al.* 1995, Allen & Fielding 2007b). North of the shelf lacustrine and deltaic environments prevailed (McKellar & Henderson 2012). Correlatives of the Peawaddy Formation in the Koburra Trough have amalgamated paralic facies, comprising of an intensely bioturbated surface (Scott & Hawkins 1992, Hawkins & Green 1993, Allen & Fielding 2007b, McKellar & Henderson 2012) followed by a coarsening upwards sequence (Allen & Fielding 2007b), interpreted to be a southerly prograding delta (Blanco 2010).

The cocquinite bed of the Mantuan Productus Beds has been observed on the western side of the Springsure Shelf (Gray 1976) and (Wallin 1975). This bed is the last known observation of marine fauna in the Galilee Basin.

Phillips *et al.* (2015) correlated the Peawaddy Formation and Black Alley Shale, within their current stratigraphic positions, to pinch out towards the north.

Colinlea Sandstone. The Late Permian Colinlea Sandstone in the Galilee Basin has been correlated as the equivalent of the Catherine Sandstone to upper Aldebaran Sandstone in the Denison Trough of the Bowen Basin. It has been mapped across the Springsure Shelf in the south and into the Koburra Trough towards the north (Scott *et al.* 1995). The drilling report of GSQ Tambo 3 suggests that the Colinlea Sandstone thins towards the north and only represents the Catherine Sandstone (McKellar & Henderson 2012). This suggests that the marine influenced Ingelara Formation did not enter the main depocentre of the Galilee Basin, the Koburra Trough.

In type section, the Colinlea Sandstone on the Springsure Shelf is composed of fine to medium grained sandstones, with intermediate conglomerates. However when correlated northward into the Koburra Trough, the Colinlea Sandstone comprises of sandstone, siltstone, mudstone, volcanic tuffs and targeted exploration coal seams, suggesting paralic to fluvial environments of deposition (Mollan *et al.* 1969b). The northern extent of the Colinlea Sandstone, *sensu stricto*, is a subject of interpretation (Vine 1975, Scott & Hawkins 1992, Allen & Fielding 2007b).

Various well completion reports from companies currently engaged in exploration drilling along the western margin show the Colinlea Sandstone between two coal-bearing sequences, the Rodney Sequence and the Crossmore Sequence. Phillips *et al.* (2015) showed that this Colinlea Sandstone is not equivalent to the Colinlea Sandstone on the eastern margin and is older than the formation on the eastern margin.

5.3 Late Permian Bandanna Formation-Colinlea Sandstone – Betts Creek beds Coal Measures

Coal seam nomenclature – regional subdivisions

Coal seam nomenclature is different from the west to the east of the basin (Table 5). Scott and Hawkins (1992) developed a stratigraphic framework for the eastern margin of the Galilee Basin. This framework developed from correlations of coal seams along the eastern margin. This study presents a consistent correlation of coal seams, comparing previous and current application of the stratigraphic nomenclature. Coal seams in different areas of the basin are often named alphabetically (e.g. A through F), but how they correlate across the basin is not clear. This study also suggests a regionally consistent coal seam nomenclature within the different formations.

A suggested seam nomenclature relative to the formations is shown in Table 5 and its application described in detail in the different areas of the basin. Similar to current nomenclature, the Betts Creek beds can be subdivided into the Bandanna Formation and the Colinlea Sandstone, separated by the Black Alley Shale-Peawaddy equivalents, on the eastern margin of the basin. The A and B Seams are contained within the Bandanna Formation and the C through I Seams in the Colinlea Sandstone. A basal series name is proposed as the J and K Seams, and the equivalence of all seams across to the western part of the basin is presented in cross sections and discussed.

Northern Eastern Margin

In the northern part of the basin, only the Betts Creek beds are formally mapped, and the seams are not named in any formal publication, nor have they been previously correlated to the rest of the basin.

Koburra Trough and Eastern Margin

The centrally located Koburra Trough and the eastern margin share the same nomenclature. The correlated coal seams within these areas also share the same names. The Bandanna Formation contains the A and B Seams. This formation is separated from the coal bearing Colinlea Sandstone by the correlated equivalents of the Black Alley shale and Peawaddy Formation (Allen & Fielding 2007b). The Colinlea Sandstone is defined by the first occurrence of the C Seam and contains coal seams D through to F. Uncertainty lies behind the unconformity between the base of the Colinlea Sandstone and the Early Permian sediments. Therefore, the base of Late Permian sediments in the Koburra Trough and on the eastern margin is placed just below the presence of the last coal seam, as no Early Permian Aramac Coal measures are known to occur in this area.

Western Margin

The coal seams in the western margin of the basin, adjacent to the Maneroo Platform are mapped as part of the Betts Creek beds, but given a different nomenclature, according to well completion reports (e.g. Galilee Energy (2000)). In general, older well completion reports note that the 4 distinct sequences of coal beds can be recognised in the Betts Creek beds: the Thompson, Rodney, Crossmore and Glenaras Sequences (youngest to oldest respectively). Seams within each sequence are consecutively numbered. For example, the 3rd seam within the Rodney Sequence is known as R3 and the 5th seam within the Glenaras sequence would be the G5. More recent well completion reports have designated the main seams R1-R8 over the whole Betts Creek beds regardless of previous formation boundaries. Rider seams are included within the same nomenclature of their parent seam.

Phillips *et al.* (2015) interpreted the Thompson Sequence to be Bandanna Formation equivalent and the Rodney Sequence to be Colinlea Sandstone equivalent. The relationship between the Crossmore and Glenaras Sequence to the Late Permian sediments elsewhere in the basin is examined in this report.

5.4 Coal seam architectural framework – correlations

Coal seams within the Galilee Basin are laterally extensive and can occur for more than 300km. Comparatively, very little splitting of coal seams occurs within the basin, compared to some areas of the Bowen Basin. The seam nomenclature presented in Table 5 is used.

The C Seam was used as a common stratigraphic marker horizon and datum for all cross sections. The C Seam is distinguished by its high tuffaceous content. This provides an excellent tool for across basin correlations. It also marks the top of the Colinlea Sandstone from over lying formations. All correlations have been flattened to the C Seam or its equivalent.

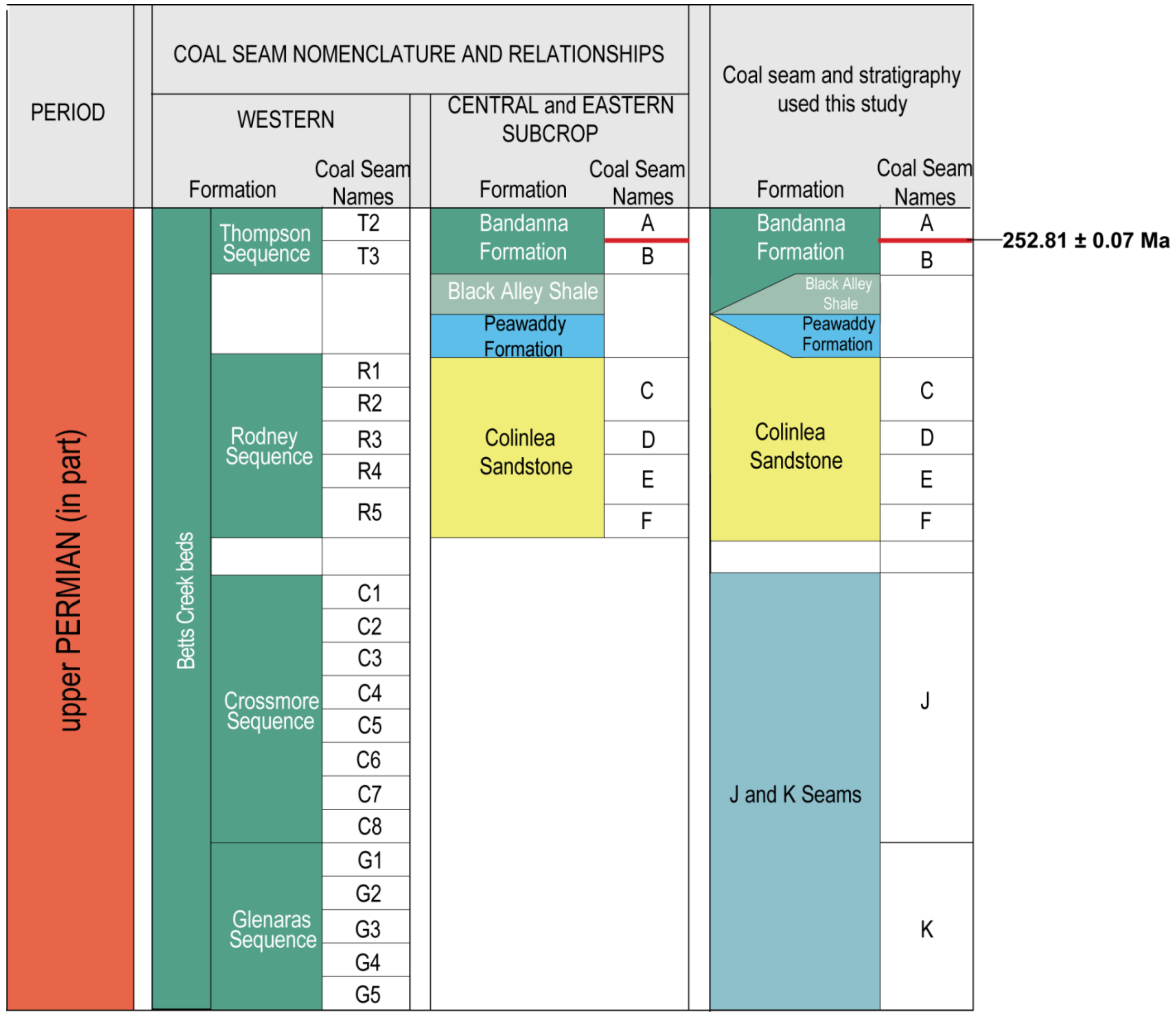
Correlations are presented for the following geographic areas, where the collated data set provided the highest resolution:

- Eastern margin
- Koburra Trough
- Central western margin.
- West to east across the central Koburra Trough
- North-eastern margin

Eastern section

The eastern margin has been the focus for the majority of mining exploration companies, who predominantly apply the nomenclature of the Bandanna Formation and Colinlea Sandstone, although with local variations and incorporation of the Betts Creek beds terminology. A regional cross section is presented in Figure 54.

The Bandanna Formation, overlain by the Rewan Formation in this area, contains the A and B Seams that are coalesced for much of the central part of the cross section, splitting towards the north and south. The split zones are dominated by relatively thick 20 to 40 m plus sandstones, but the sedimentology is variable. To the north, the A Seam is progressively difficult to track, possibly due to tapering or to erosion by the overlying Rewan Formation sediments. The coal free interburden between the B and C Seam is absent in the north and it thickens towards the south with a maximum thickness of 76.5m. This interburden has been correlated as the Black Alley Shale/Peawaddy Formation equivalents by (Allen & Fielding 2007b) and in some cored wells the roof of the C Seam contains burrowing ichnofacies indicative of open water (Blanco 2010). The C to F coal seams within the Colinlea Sandstone show complex splitting patterns and compositional stacking of sandstone bodies between the coal seams in comparison to the seams in the younger Bandanna Formation.



PERIOD	COAL SEAM NOMENCLATURE AND RELATIONSHIPS					Coal seam and stratigraphy used this study	
	WESTERN			CENTRAL and EASTERN SUBCROP			
		Formation	Coal Seam Names	Formation	Coal Seam Names	Formation	Coal Seam Names
upper PERMIAN (in part)	Betts Creek beds	Thompson Sequence	T2	Bandanna Formation	A	Bandanna Formation	A
			T3		B		B
				Black Alley Shale Peawaddy Formation		Black Alley Shale Peawaddy Formation	
		Rodney Sequence	R1	Colinlea Sandstone	C	Colinlea Sandstone	C
			R2				
			R3		D		D
			R4		E		E
			R5		F		F
		Crossmore Sequence	C1			J and K Seams	J
			C2				
			C3				
			C4				
			C5				
			C6				
			C7				
			C8				
		Glenaras Sequence	G1				K
			G2				
			G3				
			G4				
			G5				

252.81 ± 0.07 Ma

Table 5 Generalised seam names across the Galilee Basin (modified after Phillips et al. (2015)). Red line represents the placement of a CA-IDTIMS date from Phillips et al. (in review).

Bandanna Formation. The A and B Seams are laterally consistent and show relatively little variation in thickness and character (Figure 54). The A and B Seams are split in the northern part of the section, by a heterolithic interburden consisting of high and low gamma lithologies. The A Seam in the north is not always apparent and may be due to the seam sub-cropping at the basin margin, tapering or erosion by the overlying Rewan Formation sediments. The A Seam is defined in the north by two thin seams split by a thin 3-10m interburden that thickens towards the north. The B Seam is coalesced with the C Seam in the north of the basin and is approximately 9m in thickness. Towards the centre of the eastern margin the interburden between the A and B Seams becomes consistently homogenous in low gamma lithologies, before the seams coalesce in the central part of the section. The seams stay coalesced until the southern part of the cross section, where they diverge and are split by a maximum of 28m interburden.

Black Alley-Peawaddy interburden. In the north of the area, the B and C Seams are coalesced, but they split progressively southward to a thickness of approximately 85m. The interburden changes character as it thickens. In some areas there are thick (5 to 15m) sandstone overlain by a thick mudstone unit, but this transitions to a series of stacked and attenuated coarsening upward sequences to the south. Fine grained sediments sit above the C Seam

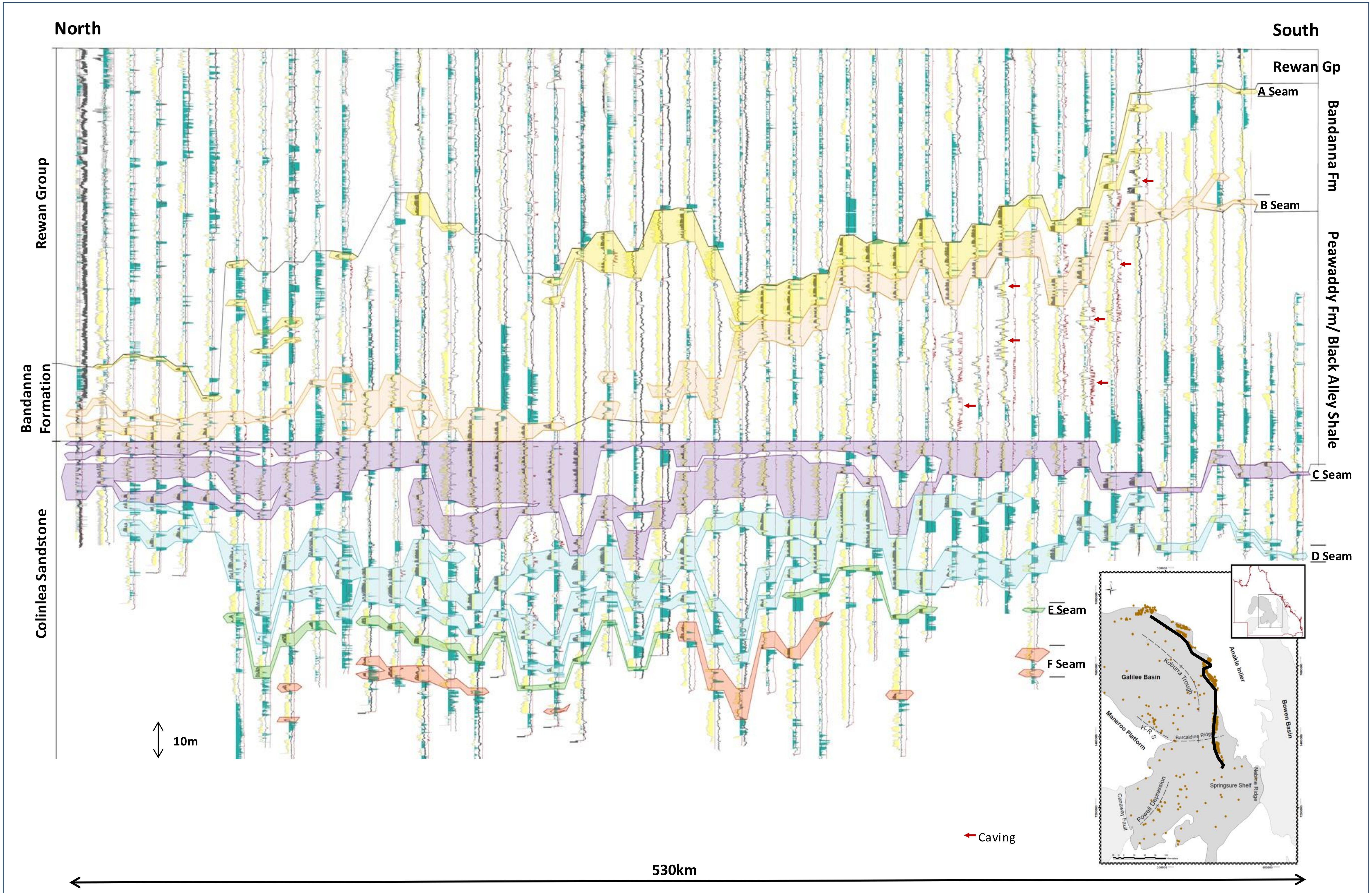


Figure 54 Cross section N-S (along eastern margin).

and eventually replace the seam in the south. Where core is available, the fine grained sediments above the C Seam are variably burrowed, indicative of restricted to open marine environments (Blanco 2010).

Colinlea Sandstone. As correlated in Figure 54, the C Seam is regionally persistent and can be mapped for almost 200km along strike. The C Seam is distinct, and contains a series of tuff beds that assist in regional correlation. Below the C Seam are a series of coals correlated as the D through to F, and these seams merge and diverge along strike, but show an overall trend of the lower coal seams (D-F) splitting towards the south. The architecture of the D Seam, splits in places and coalesces with the C Seam in others. The E and F Seams follow the geometry of the over lying D Seam. The E Seam thickens towards the north of the cross section. The F Seam is a thick coal seam, up to 9.1m, however it is not always observed.

The lithologies beneath the last coal seam on the eastern margin have a predominantly clean low gamma signature.

Koburra Trough

The Koburra Trough is thought to be the main depocentre in the accumulation of sediments during the Late Permian. The wells here are deeper, targeting coal seam gas, but also sparse relative to the subcrop coal exploration drilling. The far spacing of wells in the Koburra Trough, makes it difficult to be certain about the seam correlation, but the formation packages less so. Figure 55 shows a best fit correlation of coal seams within the trough.

Bandanna Formation. Unlike the eastern margin (Figure 54) the A and B Seams are not coalesced, and are separate entities throughout the Koburra Trough (Figure 55). Similarly, both seams are not observed in the north of Koburra Trough. They are interpreted to split and shale out, but is also possible that they are eroded by the overlying Rewan Formation. The interburden between the seams varies from north to south, displaying a high gamma silty character in the north grading into a predominantly low gamma sandy signature in the south.

The coal barren interburden between the B and C Seam is similar to the eastern section, increasing in thickness and transition to a thick coarsening upward sequence.

Colinlea Sandstone. The seams within the Colinlea Sandstone (Figure 55) vary in character and correlations between them are uncertain. However, from geologists' core logs the highly tuffaceous C Seam can be distinguished and has been used as a guide for further correlation. The C and D Seams are largely coalesced in the north of the Koburra Trough. From the correlation it appears that there is an increase in the number of seams, and a decrease in their thickness, towards the centre of the Koburra Trough. This has been correlated as different splits of the D Seam. Where these excess seams are found the interburden has a higher gamma signature. The seams thicken towards the south and appear to have a much more heterolithic interburden. The E and F Seams follow the architecture of the overlying D Seam, but do not show the same extent of splitting patterns.

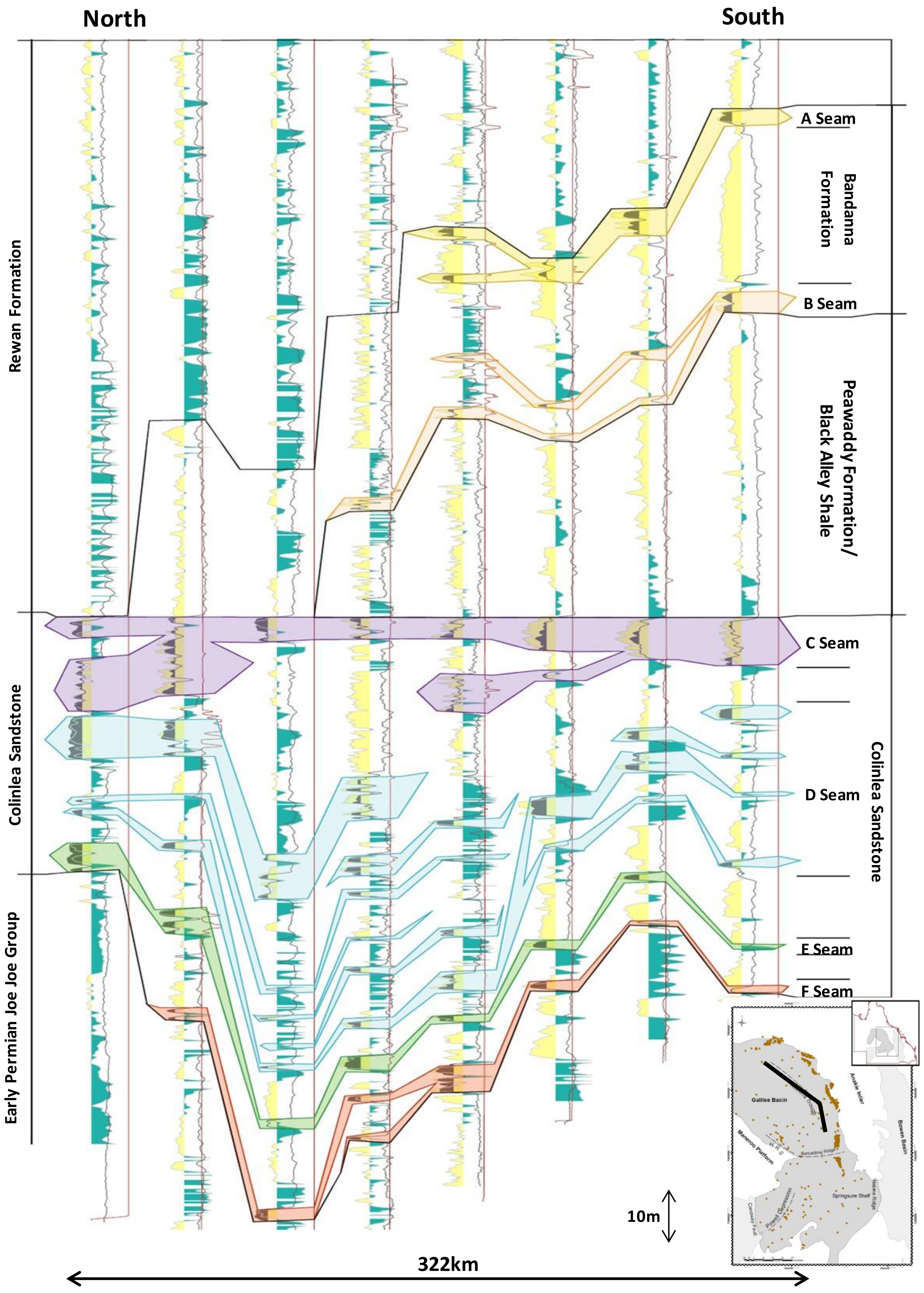


Figure 55 Cross section along the Koburra Trough, Galilee Basin.

Western section

On the western side of the basin, the so called Rodney Creek and lower sequences are potential CSG targets. Due to their depth no seams are economically viable for mining. The stratigraphic formation in the west uses the nomenclature Betts Creek beds to describe all Late Permian strata. Figure 56 shows a cross section through the drilling data, with both the currently used nomenclature for the Betts Creek beds and the individual seams. Their correlation to the eastern margin is presented in Table 5. The Early Permian Aramac Coal Measures are present in the data but their correlation is outside the scope of this project.

The datum in the cross section is the Rodney Sequence. The local marker horizon was the regionally consistent and distinctive sandstone with a blocky low gamma ray signature that occurs between the Rodney and the Crossmore Sequence. This sandstone is marked as the Colinlea Sandstone in various well completion reports, which adds to the confusion in definition of this unit on the eastern margin where it encompasses all the lower coal seams.

The coal seams show little to no splitting patterns. When flattened to the Rodney Sequence, the seams parallel and almost equidistant to each other along the strike of the Maneroo Platform and the Hulton-Rand Structure. There is a slight dip in coal seams in the Crossmore and Glenaras Sequence towards the north relative to the Rodney Sequence. More detailed descriptions are presented below.

Thomson Sequence. The two coal seams within this sequence have a constant thickness, 3m and 2m respectively. However, they are not always present. They have a constant interburden of 20m.

Rodney Sequence. The Rodney Sequence can be subdivided into four different coal packages. The thickest of which is 6.7m. This slightly decreases in thickness towards the north. The second coal package displays a lower density and has a small split towards the north. For the majority of the cross section it is coalesced with the first package and makes up the thickest coal seam on the western margin. The third and fourth packages are permanently split from the main package and are relatively thin, reaching a maximum of 11.2m in thickness.

Crossmore and Glenaras Sequences. The Crossmore and Glenaras Sequences are prevalent in this area (Figure 56) and are continuous throughout the section. They consist of four and six coal packages respectively. The Crossmore Sequence seams are less distinct in comparison and appear to shale out towards the north. The Glenaras Sequence coals have a very distinct blocky density signature. They are all of similar thickness (~4m).

West to East Correlation

Figure 57 shows the correlations of coal seams and their respective formations from west to east across the basin. This correlation shows the relationship of the Bandanna Formation/Colinlea Sandstone nomenclature on the east with the Betts Creek beds on the western side. The tuffaceous C Seam was used as the datum.

The Bandanna Formation is equivalent to the Thomson Sequence in the Betts Creek nomenclature. The Bandanna Formation maintains a constant thickness across the Koburra Trough, however the coal seams within it thin towards the west. The coal barren Black Alley Shale-Peawaddy interval maintains its coarsening upward pattern where it thickens into the Koburra Trough. The Colinlea Sandstone coals are equivalent to the Rodney Sequence. Coal seams within the Colinlea Sandstone show small scale splitting patterns when entering the Koburra Trough. Seams D to F thin towards the west of the trough, however thicken once adjacent to the Maneroo Platform. The overall pattern is somewhat offset up section.

As correlated, the Crossmore and Glenaras Sequence do not have an equivalent member across the Koburra Trough and along the eastern margin. To keep with the alphabetical nomenclature they have been assigned the J and K Seams respectively. The J and K Seams show an affinity with the Early Permian Aramac Coal Measures, which only occur in the western part of this cross section. When flattened on the C Seam it is observed that the coal seams on the east of the basin taper onto the J and K Seams on the western side. The J and K Seams pinch out towards the east. The distinct blocky low gamma interburden between the F Seam and the J Seam, described in Section 5.4.4.1, is seen to gradually shale out towards the Koburra Trough.

Bandanna Formation. From the correlation (Figure 57) there is continuity of coal occurring within the Bandanna Formation. The A and B Seams can be correlated into the Koburra Trough, before they pinch out further westward, or are eroded by the Rewan Formation.

The underlying Black Alley Shale-Peawaddy interval maintains its coarsening upward pattern where it thickens into the Koburra Trough.

Colinlea Sandstone. The coal seams within the Colinlea Sandstone can be consistently correlated from east to west across the basin (Figure 57). The geometry of the coal seams changes from east to west. In the east the coal seams are dispersed, however west of the Koburra Trough, the seams initially thin then coalesce. The C Seam is continuous throughout the correlation, but its wireline characteristics change. It is recognisable through geologist logs by its high amount of stony and tuffaceous bands. The D Seam package varies in thickness across the basin and its splits shale out towards the west, where it coalesces with the C Seam. The splits of the D Seam are thin on the western side. The oldest seams, E and F appear to shale out in the western side.

J and K Seams. Separating the J and K Seam packages from the overlying correlated Colinlea Sandstone is a distinct blocky low gamma signature. Correlated consistently through the western section (Figure 56), this signature can be followed west to east before pinching out above Early Permian sediments centrally in the basin. This distinct characteristic separates the Late Permian Bandanna Formation/Colinlea Sandstone in the east, with the combined Betts Creek beds in the west. The central correlation demonstrates that the J and K Seams (Crossmore and Glenaras Sequences) as described on the western section are dis continuous across the basin. They are locally found on the western side of the basin, abutting the Maneroo Platform. The K Seams overlie the Aramac Coal Measures. Both J and K Seams closely follow a similar architecture to the Aramac Coal Measures. The Aramacs appear further eastwards into the basin. Both the J and K Seams appear to thin and decrease in thickness towards the east before pinching out. At the time of publication, the relationship between the J and K Seams and the underlying Aramac Coal measures is not known and warrants more study.

North Eastern Section

The northern cross section (Figure 58) brings together the northern end of the Koburra Trough and the very most northern drill holes. The recent increase in drilling programs along the northern margin has seen exploratory work outside of the current basin boundary (Figure 53) and the current shape file does not fit the new basin extent. It must be noted that well control here is minimal and correlations are only preliminary. Further work is needed to confirm or refute correlations presented herein. The stratigraphic nomenclature used in the northern part of the basin is that of the Betts Creek beds, however the coal seams within them have been given consecutive alphabetical names, similar to coals along the eastern margin. Interburden between the coal seams is highly variable ranging from higher gamma lithologies in the east and west and cleaner sands in the central part of the section.

Bandanna Formation. The A Seam is present towards the east of the cross section (Figure 58). It is only a maximum of 60cm. Similar to the A Seam, the B Seam is absent in the west of the cross section however when seen in the east is up to 6m in thickness. It has a minor rider seam, which coalesces to the main seam towards the east. In the centre of the section, the B Seam merges with the underlying C Seam before splitting both to the east and to the west.

Colinlea Sandstone. The C Seam in the northern region of the basin, Figure 58, can be consistently correlated from the northern end of the Koburra Trough through to the north-eastern part of the basin (Figure 54 and Figure 55). This C Seam has two major plies across the north-eastern area. The two plies are coalesced in the central part of the section before splitting towards the west and east, where the top ply shales out. The bottom ply is consistently inundated by higher density intervals. The D Seam is variable in thickness (2m-8.9m) and contains a number of splits throughout the section. Coalesced with the C Seam towards the west at the northern end of the Koburra Trough, the D Seam is split from the C Seam by a thick sandstone body. This sandstone body coincides with the D Seam at its thinnest across the section. The E and F Seams are sporadic throughout the section in both thickness and appearance in boreholes. From the section, it is not known if the D, E or F Seams pinch out or are located at a deeper depth due to drill holes not intersecting them.

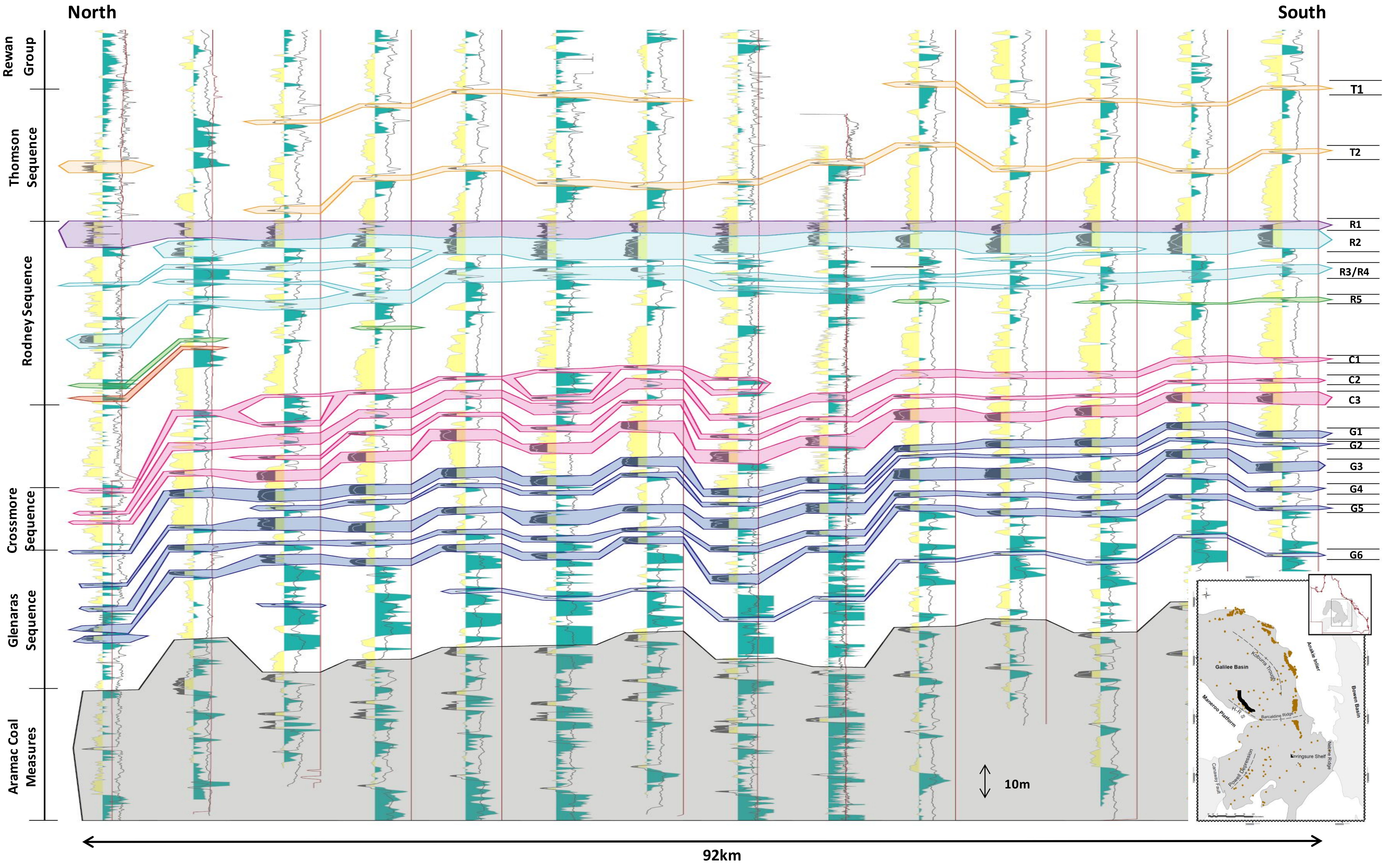


Figure 56 Cross section N-S (along western margin).

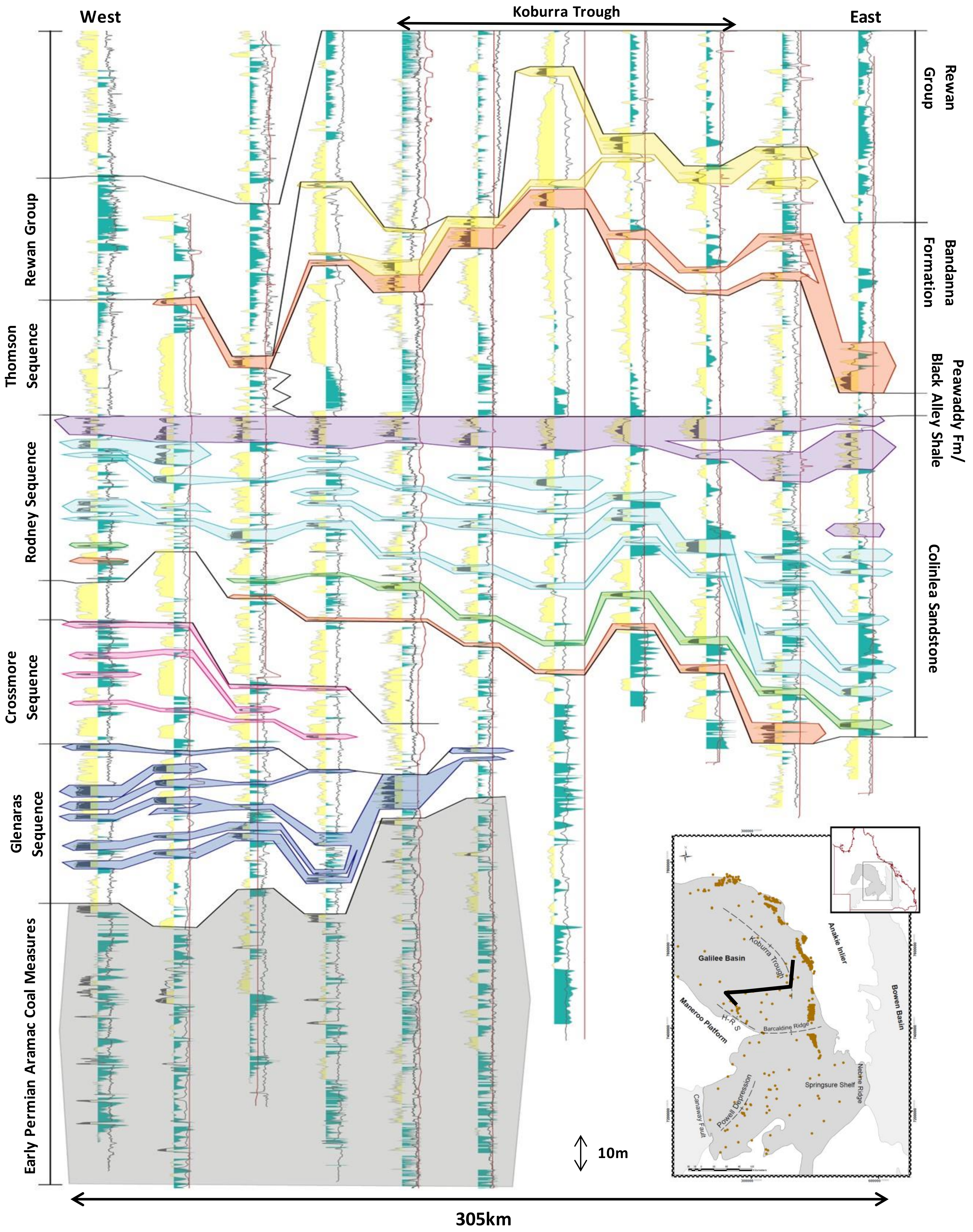


Figure 57 Cross section W-E centrally through basin (modified after Phillips et al. (2015)).

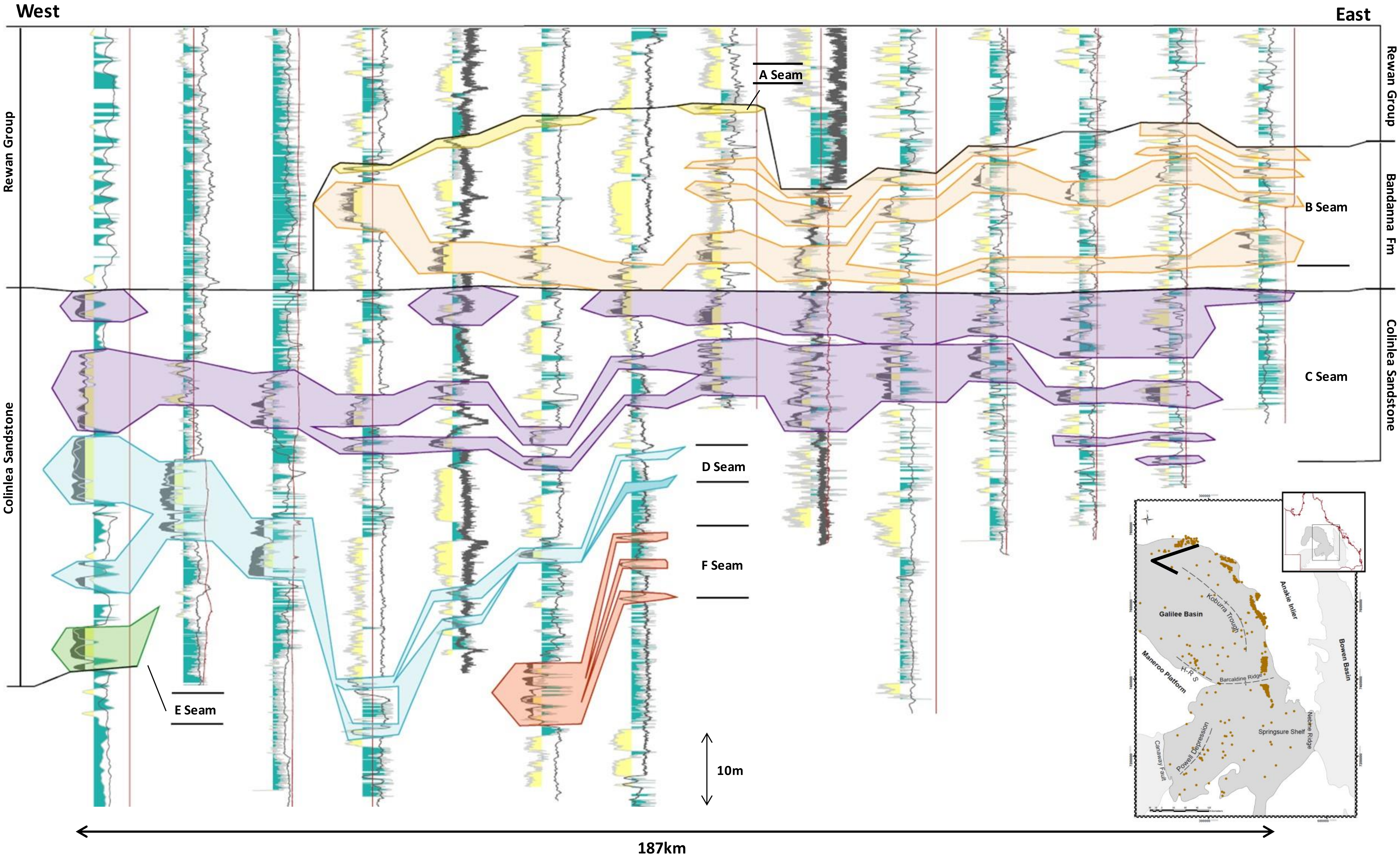


Figure 58 Cross section from the northern end of the Koburra Trough to the northern eastern margin.

5.5 Summary discussion of coal seam architecture in the Koburra Trough

This study presents a series of correlated sections through open file and proprietary drilling and provides a rationalisation of stratigraphic and coal seam nomenclature, a fresh idea to regional correlations and an understanding of coal seam splitting patterns across the basin. The correlations through coal seam packages have demonstrated that both units, the Bandanna Formation and Colinlea Sandstone, can be found within the all-encompassing Betts Creek beds. The 252.81 ± 0.07 Ma age obtained from the top of the B seam (Phillips *et al.* in review) coupled with the highly tuffaceous and youngest seam in the correlated Colinlea Sandstone package, the C Seam, provide a good datum and are reminiscent of the Fort Cooper Coal Measures in the Bowen Basin (Anderson 1985a, Ayaz *et al.* 2015). Through further tephrochronology analysis, this could be confirmed and the B and C Seams could be pivotal in correlating the two basins.

The Bandanna Formation has been correlated to contain the A and B Seams, as demonstrated by Scott and Hawkins (1992). These seams are not always present across the basin, and due to poor well control, it is not easy to tell which seam is not present. In the deeper areas of the basin, these seams may also be eroded by the overlying Rewan Formation, and this could highlight the difficulty in securing the Permo-Triassic boundary within the basin.

The convergence of the A and B Seams (Figure 54) along the eastern margin potentially show that this area was stable during the time of deposition. In contrast, as the seams split into their separate counterparts towards both the north eastern and south eastern margin a less stable environment can be inferred. During this time the adjacent Bowen Basin was undergoing foreland loading (Korsch & Totterdell 2009) and experienced a greater influx of sediments. The split of the A and B Seams towards the south east (Figure 54) may be an expression of this sediment influx across the Springsure Shelf and Nebine Ridge, however it only had limited reaches within the Galilee Basin. The foreland loading event in the Bowen Basin may have caused a tilting of the Galilee basin first postulated by de Caritat and Braun (1992) and then Korsch and Totterdell (2009). The absence of the A Seam towards the north of the basin (Figure 54, Figure 55 and Figure 58) may represent this tilt as the seam may have been eroded in places as the area was uplifted. Further studies of seismic data will help to confirm or dispel this notion.

The thickening of interburden between the B and C Seam on the eastern margin (Figure 54) highlights an increase in sediment supply. The characteristic increase in grain size, commonly bioturbated base (Blanco 2010), tied with the correlation of the unit as the lateral equivalent of the Black Alley Shale or the Peawaddy Formation indicates that this could be a southerly prograding delta into marine conditions in the Bowen Basin discussed by Fielding *et al.* (1990), (2000a). Correlations presented in Figure 54 and Figure 55 show the extent of the Black Alley Shale/Peawaddy Formation marine incursion into the basin, in line with mapping produced by (Scott *et al.* 1995). Therefore, the suggestion of marine influence in the northern part of the basin by Allen and Fielding (2007a), (2007b), may not have come from the southerly located Peawaddy Formation and Black Alley Shale. The estuarine bioturbated facies observed by Allen and Fielding (2007a), (2007b), may have had its origins from a more northern source. The absence of this thick interburden on the western margin (Figure 56) suggests that a prograding deltaic lobe was not present in this area. As the main depocentre during the Late Permian, the Koburra Trough would have experienced higher sediment influx as accommodation space was generated.

The interburden throughout the basin in what is currently known as the Colinlea Sandstone has been shown in cross sections to be highly heterolithic and coal bearing (Figure 54, Figure 55, Figure 56, Figure 57 and Figure 58). In the west of the basin, a distinctive blocky sandstone unit is called Colinlea Sandstone but on the east, this is a coal bearing unit that may need revision. Coals correlated within the Colinlea Sandstone on the eastern margin (Figure 54) show splitting and converging throughout the area. Divergent or split areas are laterally offset up section, and bound lenses of strata that suggest fluvial channel systems oriented obliquely or east-west.

Beneath the F Seam, especially towards the north east (Figure 54 and Figure 58), the sediment is dominated by sandstone. The sandstones may be representative of fluvial systems with a high sediment supply derived from upland alluvial environment. These wells are closer to the present-day basin edge, which might also have been topographically higher during the Late Permian.

The Colinlea Sandstone package (Figure 55) is thickest in the central area of the Koburra Trough. This is also where seams are most split. The thin coal seams within the Koburra Trough suggest that accommodation space was being created quicker than peat accumulation, leading to thin seams, and bigger interburden. This is unlike what is seen on the eastern margin Colinlea Sandstone package where seams are thick, however still diverge and coalesce. What is similar in both areas is the appearance of the coal seams converging to the south (Figure 54 and Figure 55). This maybe representative of an area that was a palaeogeographic high or a more stable environment during deposition, such as the Barcaldine Ridge, which is in the close vicinity.

Along the western margin Phillips *et al.* (2015) identified the Colinlea sandstone as the equivalent to the Rodney Sequence (Figure 57) and the coal architecture is different to what is observed elsewhere in the basin. Very little splitting is observed along the western margin within the Colinlea Sandstone unlike the eastern counterpart. The coalescing of the lower density C Seam and higher density D Seams create a thick seam of up to 11m that is consistent throughout the cross section. This shows a very similar signature to the C and D Seam coalesced at the northern point of the Koburra Trough (Figure 55 and Figure 58) strengthening that correlations are correct on a basin wide scale.

The distinct blocky sandstone interburden between the Colinlea Sandstone and the J and K Seams (Figure 56 and Figure 57) along the western margin is akin to the sandstone found beneath the F Seam along the eastern margin (Figure 54), albeit slightly thinner. The relationship of this sand body and the type set Colinlea Sandstone located on the Springsure Shelf is not known currently. Further mineralogical and provenance work can help determine the association between the two better.

Phillips *et al.* (2015) observed that the J and K Seams on the margin (Figure 57) do not have an equivalent along the eastern Bandanna Formation-Colinlea Sandstone nomenclature. Although the northern area of the Galilee Basin uses the nomenclature of the Betts Creek beds, similar to the western margin, the J and K Seams do not appear in the north. It can be speculated as to why these seams only appear adjacent to the Maneroo Platform, Early – Mid- Permian extension, uplift and erosion of seams towards the east, however from work conducted in this study alone, no definitive answer can be given and warrants more work on the area.

Saul *et al.* (2015) (Resolve Coal, Hyde Park Coal Project), currently exploring along the eastern margin have suggested through seismic interpretation and location of a full coal package found east of where coal is seen to subcrop, that the previous extent of Late Permian sediments was farther reaching than today's extent. Figure 54 supports this argument as the coal seams found on the Hype Park Coal Project can be correlated with the main package of Late Permian sediments found along the eastern margin.

5.6 Conclusions

This report has provided new cross sections using propriety data that has only recently become available which has not only provided a framework for further stratigraphic work within the basin but has prompted a recommendation that the boundary of the Galilee Basin needs revision, especially along the northern margin. The relationship between the nomenclatures used in different parts of the basin has been studied using coal seams as a tool for correlations. Coal seams used for correlations are largely regionally consistent and have been employed by Phillips *et al*. (2017) to propose a new stratigraphic framework for the Galilee Basin.

Correlatives of the coal seams within the Bandanna Formation and Colinlea Sandstone can be found in both the northern and western parts of the basin where the Betts Creek beds nomenclature is more commonly used. However, the differing coal architecture and the possibility of a northern marine influence suggests that this area had different sedimentary processes working on it and as a formation may differ from the more southern Bandanna/Colinlea stratigraphy.

The A and B Seams within the Bandanna Formation are thickest along the eastern margin, however thin and split into to the Koburra Trough and along the western margin. The A Seam is sporadically seen in the northern area of the basin.

The Peawaddy Formation/Black Alley Shale coal free interburden can be traced between the Bandanna Formation and Colinlea Sandstone along the eastern margin and into the Koburra Trough, however it decreases in thickness northwards and eventually pinches out with the coalescing of the B and C Seams. This marks the extent of the southerly marine incursion into the Galilee Basin.

Seams C to F are more complex than the younger seams located in the Bandanna Formation. They continuously split and coalesce on a larger scale. The interburden among the coal seams in the Colinlea Sandstone is highly variable and the Colinlea 'Sandstone' terminology may need to be revised.

The J and K Seams located along the western margin do not have a lateral equivalent along the eastern margin, Koburra Trough or along the northern margin. With current literature placing them in the Late Permian Betts Creek beds, correlations suggest that this may need to be revisited.

6 TUFF AGE DATING AND GEOCHEMISTRY

6.1 Introduction

The Yarrabee Tuff bed (YTB) is the last major tuff in the Late Permian coal measures for the Bowen Basin that is regionally correlated, and it divides the underlying tuffaceous Fort Cooper and equivalent coal measures from the Rangal and its equivalent coal measures (Anderson & Koppe 1979, Anderson 1985b, Matheson 1990b). The type section of the tuff is in the Grosvenor coal exploration boreholes GR176R and GR172, where it is "0.38m thick and described as a fawn brown tuffaceous mudstone bed with a thin carbonaceous mudstone band near the top" (Matheson 1990b). Few if any of its original primary volcanic features are apparent in hand specimen, and it has a soft, waxy or soapy texture. It has a distinctive high natural gamma ray signature, which makes it recognizable in wireline logs as a correlation tool. Mapping of the YTB in this project (Figure 9A) corroborates the thickness variation from less than 0.6 m to slightly greater than 2 m in some areas. The YTB occurs within or between coal seams that in the north are called the Vermont and to the south the Pisces Seams. Further south in the Taroom Trough, the YTB is correlated to the Kaloola Tuff that is often in the floor of what is correlated as the E Seam within the Baralaba schema. An example of the YTB in outcrop is shown in Figure 59.

Within the underlying Fort Cooper Coal Measures, the tuffs are generally thin (from a few to 400mm), but their frequency and thickness increases up section (Ayaz *et al.* 2015) until topped by the YTB. Previous studies dated the uppermost tuff in the Kaloola Member at 252.54 ±0.04 Ma (Meleebee 5 well, by Metcalfe *et al.* (2015) and 252.49 ±0.04 Ma (Yebna 1, by Nicoll *et al.* (2015). Ayaz *et al.* (2016b) found similar ages for the YTB and also dated the accessory tuffs occurring below within the Girrah Seam (see Figure 9A). The Awaba Tuff, previously mooted as the age equivalent of the YTB (Dr Michael Creech, pers. Comm. 2002) has been dated at 253.21 ±0.06 Ma (Metcalfe *et al.* 2015). All papers lean towards the YTB being an extensive event, if not in time, certainly in area.

Figure 59 Photograph of the Yarrabee Tuff within the Pisces Seam, exposed at Foxleigh Mine test pit. (Sample and image courtesy of Aastha Sharma, AngloAmerican)

Metcalfe *et al.* (2015) used dates from successive tuff samples through the Late Permian section (Tinowan through Bandana) to calculate episodic rates of subsidence and sedimentation in response to foreland loading from the rising Hunter Bowen Orogen, which particularly accelerated during the Kaloola Member-Fort Cooper Coal Measures (Metcalfe *et al.* 2015, Ayaz *et al.* 2016b). Coincident with this is a change in the nature of the coal measures, with a general increase in the amount of inertinite group macerals up section from the Moranbah and tuffaceous Fort Cooper to the Rangal Coal Measure equivalents. This is coupled with a positive shift in the stable carbon isotope δ13C (Diessel 2010, Van de Wetering *et al.* 2013, Metcalfe *et al.* 2015). These changes are commonly correlated to increasing aridity in the atmosphere, responding to local glacial cycles as well as global changes in climate in parallel to the basin foreland loading. Whether these climatic changes can also be attributed to volcanism has been argued by Ayaz *et al.* (2015).

The reliability of correlation for the Yarrabee Tuff bed (YTB) was tested through dating (Esterle *et al.* 2017) and geochemical analysis of major and trace elements (Fricker 2016). High precision Chemical Abrasion-Isotope Dilution Thermal Ionisation Mass Spectrometry (or CA-TIMS) of 206Pb/238U values was the technique used for dating zircons separated from samples of the tuff. Samples were contributed by mine sites for this study, or collected from open file cores to corroborate company correlations of the YTB. Some redundancy was built in for reproducibility at Poitrel mine, where 2 samples (spaced 40cm apart) within the 1m thick YTB were age dated, and at Daunia Mine where samples from multiple locations were tested for geochemistry (see Appendix B: Figure 68 and Figure 69). All samples were sandwiched between coals (the Vermont or the Pisces Seams), except for the Dawson Mine sample below the E Seam. Although the tuff samples were in variable states of alteration from their deposition within peat mires or associated lakes, the elemental composition might reflect their volcanic source, and so it was tested.

6.2 Sample Preparation

The location of samples discussed in this report are shown in Figure 60. For each minesite, a nearby borehole wireline log was used to tie into the regional section.

CA-TIMS sample preparation

Tuff samples (examples shown in Appendix B: Figure 68 and Figure 69) varying in mass from 500g to 2000g were processed through phases of crushing and milling so as to receive clay free, sand-sized particles. The resulting sample was put through heavy mineral separation using tetrabromoethane with a density of 2.96g/cc and then methylene iodide with a density of 3.3g/cc in order to separate zircons and other heavy minerals from the sample. The resultant heavy mineral sample was then used to select zircon grains for CA-TIMS. Zircons with complete crystal boundaries and free from any impurities are selected using light microscopy, to avoid any resorbed and reworked grains.

For the purpose of CA-TIMS dating, 4 to 10 or more grains from each sample were selected, chemically abraded to remove any exterior alteration or contamination (see Mattinson (2005)), then processed with a known tracer solution and mounted on a metal filament sample holder for insertion into the TIMS. The TIMS process thermally ionized the grain droplet at about 8000-10000V under high vacuum to ionize the elements for detection by the mass spectrometer. More detail on the process of CA-IDTIMS can be found in Crowley *et al.* (2007), Schoene *et al.* (2013) and in Metcalfe *et al.* (2015). Two different laboratories were used for the analyses at the: Australian National University (Ayaz *et al.* 2016a); and Boise State University (Metcalfe *et al.* (2015) and this study).

Geochemical analysis

All analysed samples presented here are from the YTB. The samples were processed for major elements using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and for trace and rare earth elements Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the University of Queensland. Approximately 20g of each whole rock sample was ground to a fine powder using an agate ball mill in a clean room to reduce cross contamination prior to analysis. Major oxide analyses were recalculated to dry weight percentage, accounting for moisture and Loss on Ignition (LOI). Rare Earth Elements (REE) analyses were normalised to chondrite (McDonough & Sun 1995).

6.3 Results

U-Pb Geochronology Results

CA-TIMS results for samples from this study had high equivalence within and between samples across the northern Bowen Basin from Newlands to Dawson mines some 450 km distance, with an average ^{206}Pb/^{238}U age estimated at 252.88 ± 0.07 Ma. Details of the dating results for individual zircon grains are shown in Table 6 and in Appendix B: Table 7, and on the map and cross sections in Figure 60.

Table 6 Location data for samples and resulting dates interpreted from CA-TIMS analysis of zircons (from Jim Crowley, Boise State University). Detailed descriptions of data are found in Appendix B: Table 7 and Figure 67.

Mine site	Tag	Sample type	Depth from	Depth to	East	North	MGA Zone	Date (Boise)	±
Newlands	NEW-1	core	171.65	171.8	593995	7654645	94-55	252.869	0.066
Poitrel	POI-1	core	50.68	51.1	629263.8	7558024	94-55	252.847	0.074
Poitrel	POI-4	core	51.5	51.68	629263.8	7558024	94-55	252.872	0.070
Foxleigh	FOX-1	pit	95.39	~96	683225.77	7464039.17	94-55	252.924	0.068
Dawson	Daw-2	pit	pit 3-5m below E-seam		~200696	~7275357	94-55	252.905	0.069

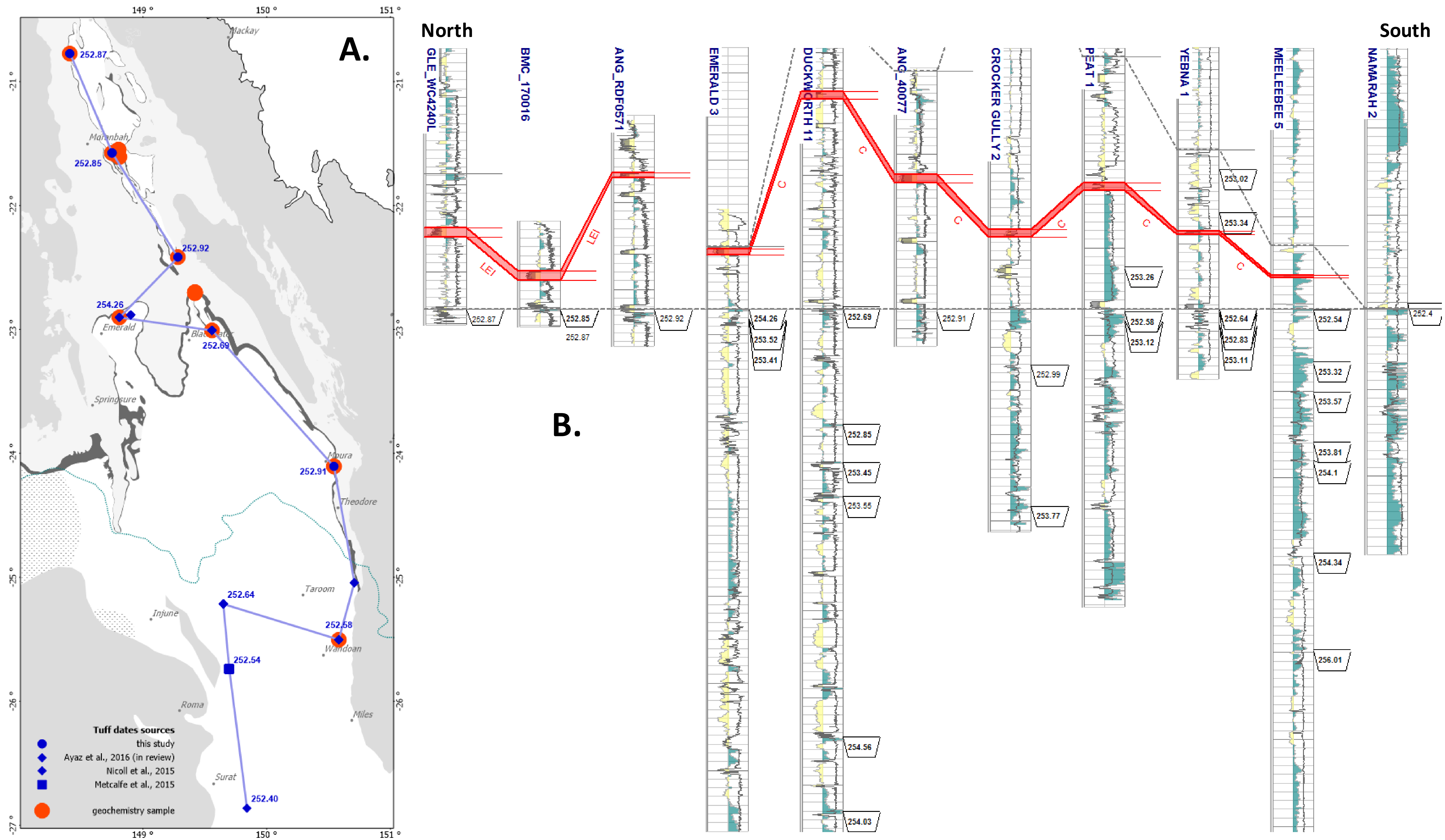


Figure 60 Map (a) and cross section (b) locations for tuff samples with CA-IDTIMS age dates and geochemical analyses discussed in this report.

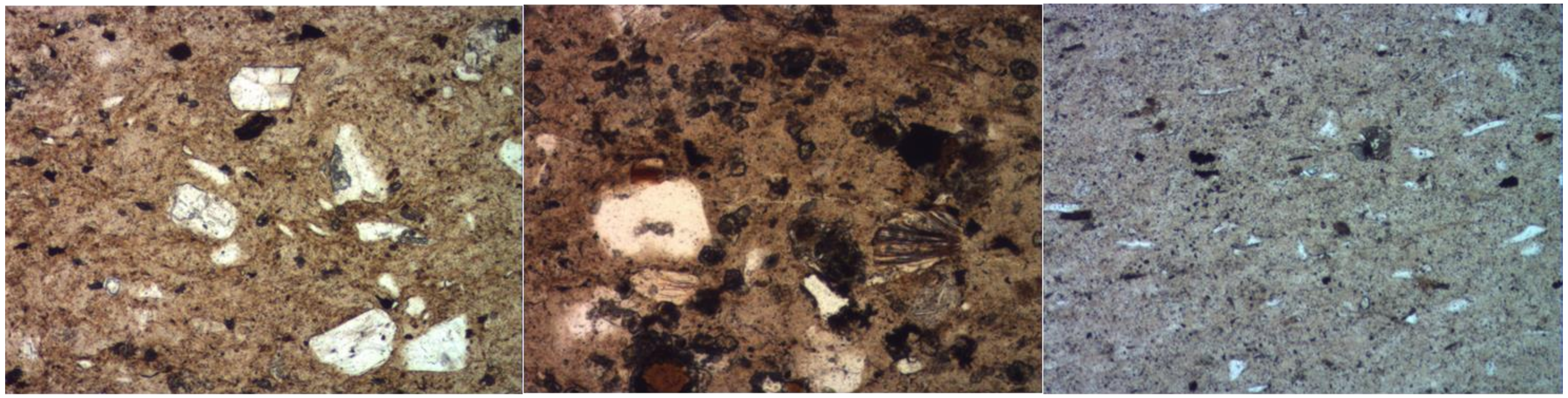
Dates obtained for the YTB in this study compare favourably with those measured for the YTB from the southern part of the basin (Metcalfe *et al.* 2015, Nicoll *et al.* 2015, Ayaz *et al.* 2016a) although the latter show a greater range from 252.58 ± 0.23 to 253.07 ± 0.22 Ma. Some of this variation could be due to uncertainty in correlation within what is commonly termed the Kaloola Member. The date acquired from the Galilee Basin (Phillips *et al.* in review) is also in line with YTB dates from this study. Nevertheless, the age correspondence suggests a widespread eruption, or series of episodic eruptions over a geologically short time period that deposited the YTB, blanketing the landscape in which the lower Vermont Seam and its southern and Galilee Basin equivalents accumulated. At Poitrel Mine, two samples taken 40cm apart within the 1m thick YTB, returned dates of 252.85 ±0.07 and 252.87 ± 0.07 suggesting the YTB deposition could span from repeated episodes over 25,000 years.

The nature of the YTB, its vertical variability and degree of reworking were out of scope for this study, but a simple isochore map (Figure 9) illustrates its regional distribution and lateral variation from <0.6 m in the north of the basin to areas reaching 2 m centrally around Poitrel and then variable but thinner south of the Comet Ridge where it is less confidently correlated. The isochore map did not show any thickening trends that help to pinpoint a vector to the source. Dates from the youngest Kaloola Member tuff suggest that the YTB event can be extended even further south in the Taroom Trough beneath the Surat Basin, for a total distance exceeding 450 km.

A simplistic calculation of tuff volume (450 km x ~100 km x 1 m uncompacted and ~5 m uncompacted as an arbitrary number) for the YTB in the Bowen Basin alone is around 45 km^3 compacted and 225 km^3 uncompacted. By comparison to recent volcanic ash falls of 1 cm, the eruptions at Pinatubo (Luzon, Phillipines) in 1991 measured ~ 2 km^3 whereas the super eruption from Toba (Sumatra, Indonesia) ~74,000 years ago is estimated at ~1000 km^3 (Self & Blake 2008). Ash fall from the Toba eruption, a Plinian type, was > 10 m thick near the source, but thinned to a few centimetres or less, hundreds to thousands of kilometres away. Creech (2002) and (Creech 2007) correlated and mapped the Late Permian Awaba Tuff in the Newcastle Coal Measures (between the Fassifern and Great Northern Seams) with the Naleen Tuff Member in the Wollombi Coal Measures (between the Hobden Gull and Hillsdale Coal Measures) over an area greater than 100,000^2 km in the Sydney Basin. The Awaba tuff averages 7.4 m thick across the coalfield, but in places attains 30 m, where it can be subdivided by its grain size and composition. The lower few metres were interpreted as a blanketing ash fall across the Hunter Coalfield. Above this a thick laminated sequence up to 12 m thick was interpreted to have been deposited subaqueously (in open bodies of water within the subsiding mires or adjacent water courses), with continued deposition of reworked tuff with associated plant debris and clastic sediments in the upper unit up to 17 m. The thickness distribution was interpreted to result from episodic volcanism over time that infilled low lying areas of peat mires and channels developed above or therein. It was postulated that the Awaba Tuff is the equivalent of the YTB, although the recent CA-TIMS date suggest that it is slightly older, at 253.21 ±0.06 Ma (Metcalfe *et al.* 2015).

Geochemistry of the Yarrabee Tuff

The geochemistry of the YTB was analysed to investigate whether there was variability across such a blanketing deposit. Based on hand sample description and thin section petrography, the Yarrabee Tuff Bed is strongly altered evident by the high amount of clays and lack of primary minerals. The samples varied from very light to dark grey in colour, with clay size grains and the classic soapy texture. Minor lithic fragments were observed but no pumice or residual glass fragments were observed. In some samples the tuff was bioturbated by Vertebraria, indicating relatively shallow (<1 m) acidic water or open mires similar to that envisaged by Creech (2002). Petrographically, the tuffs are extremely altered, and the matrix was interpreted as devitrified glass altered to kaolinite and illite (Figure 61). Phenocrysts of primary quartz and biotite, with lithic and organic fragments were common, as was siderite and pyrite as secondary alteration minerals.


10 x mag primary quartz fragments

10 x mag biotite altering to clays

5 x mag siderite blob, devitrified glass matrix

Figure 62 Photomicrographs of samples from the YTB, illustrating the altered nature of the tuff. From Fricker (2016).

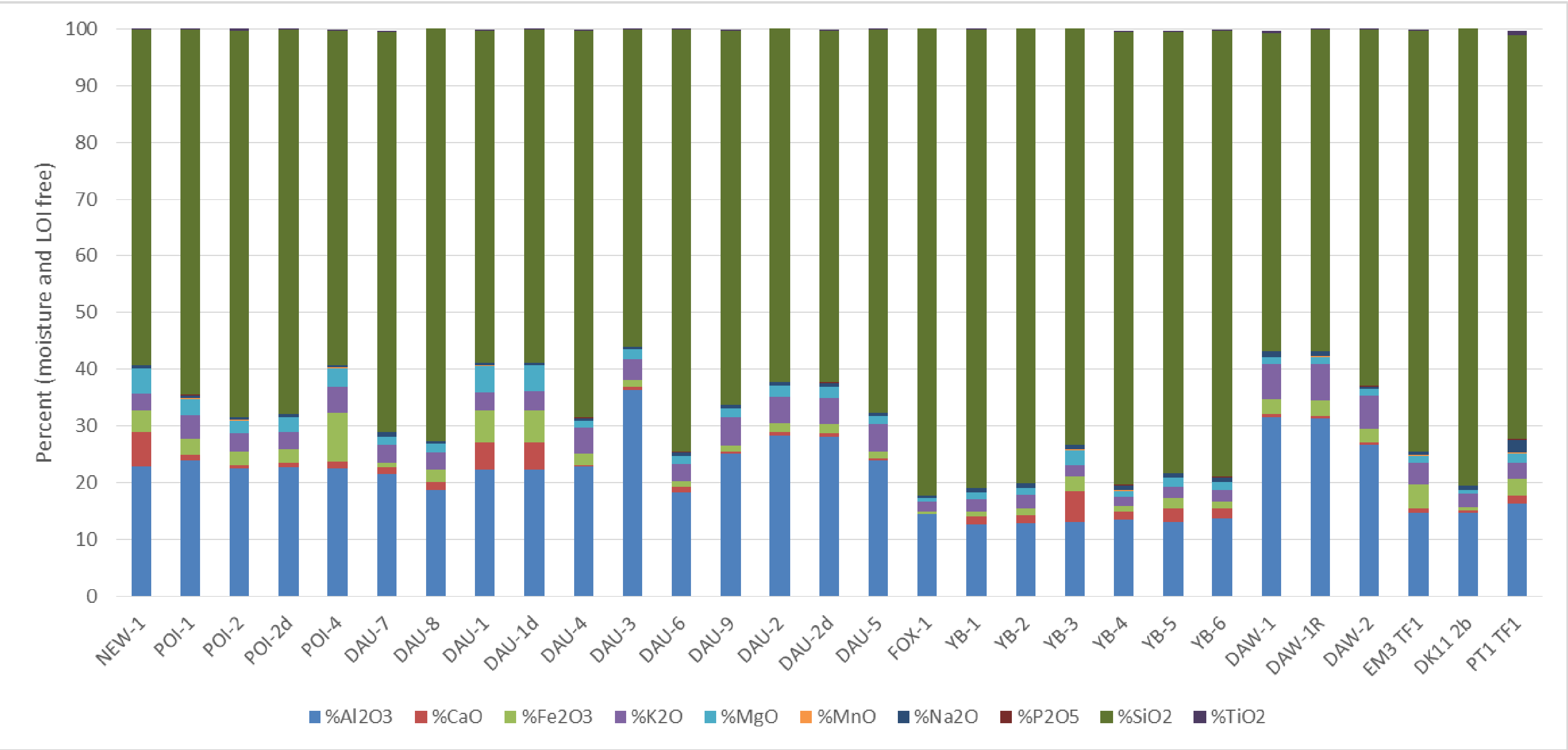


Figure 61 Variation in major oxides for tuff sample, corrected for moisture and LOI.

Alteration was also borne out in the major element data (Fricker 2016). The Loss on Ignition (LOI) across all samples was high (3 to 13%) indicating a large proportion of hydrous minerals. The oxides were normalised for LOI (moisture) and moisture (Figure 62). No distinctive pattern could be discerned between the areas, although the metal oxides (Fe_2O_3, MgO, MnO) and calcium contents were slightly higher in the northern sites, possibly reflecting the presence of iron rich lithic fragments, or secondary cements of dolomite. The alkali averages are low, with CaO, K_2O and Na_2O signifying leaching of mobile elements. SiO_2 and Al_2O_3 averages are both high, reflecting a predominantly clay mineral composition.

Cross plots of the total alkali vs SiO_2 (Le Maitre 2002), so called TAS diagram plots are a common way to investigate variation and provide a chemical classification for igneous rocks samples (Figure 63). The tuff samples lie predominantly in the andesite to rhyolite area of the basalt-rhyolite magma series. However, there is as much variation across the diagram within a single borehole core (Poitrel sample set) and across a single mine site (Daunia sample set) as there is across the entire basin. Comparison of the YTB with the roughly age equivalent Awaba Tuff and older Platypus Tuff showed a similar spread in the data. These results corroborate earlier work from Michaelsen (1999), that suggest a felsic composition with quartz contributing to the crystal composition of the tuff.

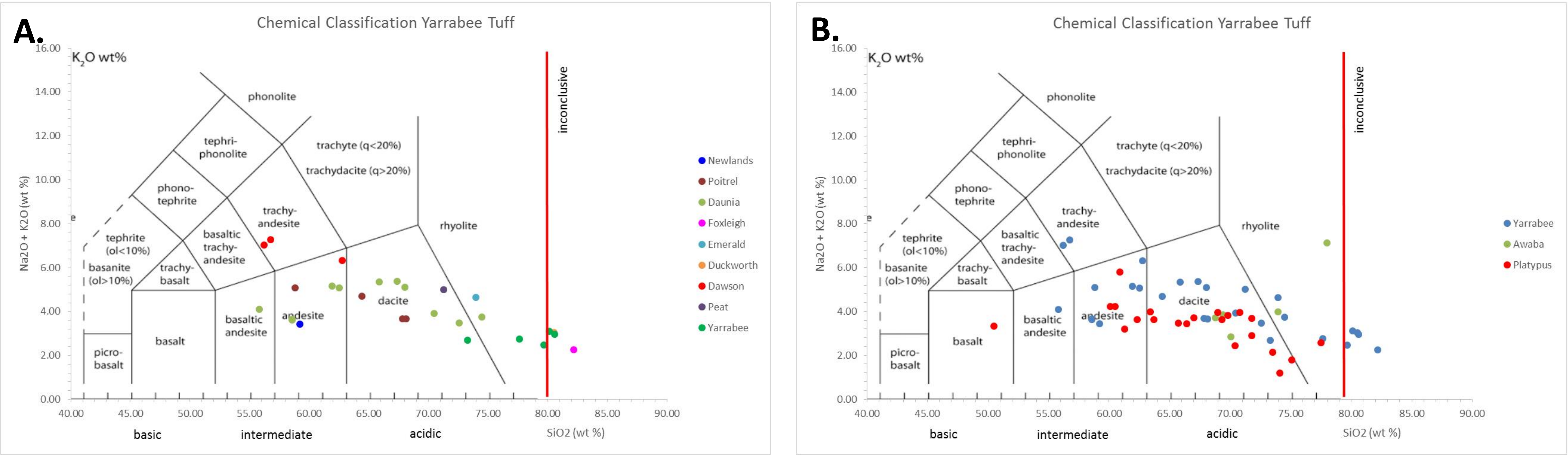


Figure 63 TAS diagram displaying chemical classification of the tuffs based on the proportion of alkalis and silica for A. samples from the different minesite and B. YTB samples compared to similar data for the Awaba and Platypus Tuff. Data from Fricker (2016), Grevenitz et al. (2003) and Michaelsen (2001); discrimination fields after Le Bas and Streckeisen (1991) and Le Maitre (2002) .

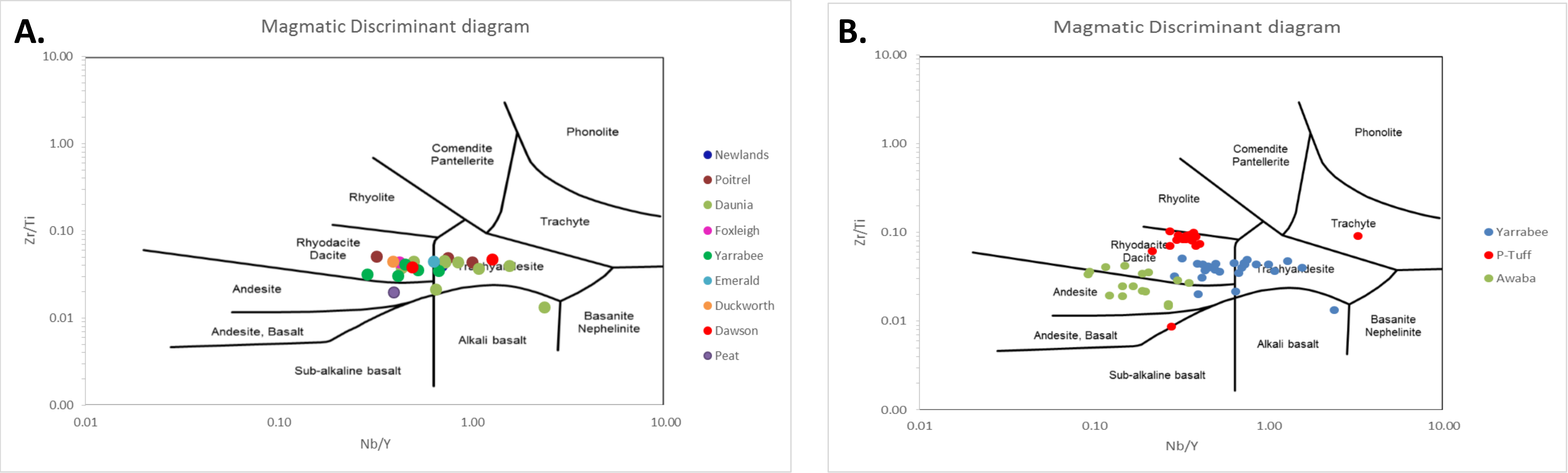


Figure 64 Cross plot of the ratios Zr/Ti against Nb/Y as a discriminator for potential sources. A. samples from the different minesites and B. comparison of YTB to the Awaba and Platypus tuffs. Data from Fricker (2016). Fricker (2016)

The trace element distribution of the samples was used to further classify the chemical character of the YTB, acknowledging that the samples are altered and most mobile elements would be leached. The immobile trace elements used for very altered tuffs are Ti, Zr, Y, Nb, Sc, V and Th. They are not usually transported in an aqueous medium and they are mostly unaffected by hydrothermal alterations. Plotting Zr/Ti vs Nb/Y on the magmatic discrimation diagram (Winchester & Floyd 1977) (Figure 64) gives an indication of the magmatic composition that corroborates that obtained from the major elements. The YTB samples are situated predominantly along the intermediate trachyandesite to felsic rhyodacite-dacite fields. These results are corroborated by the mineral composition of feldspars and biotite from a more intermediate composition to quartz phenocrysts in fine grain matrix of a more felsic composition. A comparison of the YTB to the Awaba and Platypus tuffs show some segregation. The Awaba Tuff is more intermediate in composition lying predominantly in the andesite field with overlap into the rhyodacite-dacite field. The Platypus Tuff by comparison is more felsic than the YTB.

A comparison of the uranium and thorium between the different tuffs was plotted in Figure 66. Mafic rocks have an average concentration of 4 and 1 ppm for Uranium (U) and Thorium (Th), respectively, while silicic rocks have respective concentrations of 17 and 3 ppm. The YTB has average concentrations of 20.79 and 6.26 ppm, respectively. Uranium is more soluble than Thorium in oxidising conditions which creates a larger Th/U ratio in silicic rocks especially in peat environments where U is readily leached from the volcanic ash. The YTB and Awaba tuff show a similar trend (with Th/U ratios of 3.98 and 3.51 respectively), but the Platypus Tuff is higher in both elements

The Rare Earth Elements (REE) are plotted for the YTB in Figure 65, normalised for Chondrite (McDonough & Sun 1995). These features are strong characteristics of silicic rocks. The enrichment of the DAW-1 within the HREE is attributed to mixing with sediments in the area. The YTB rare earth element composition is consistent with a felsic magmatic source of high LREE and low HREE with a distinct negative Eu anomaly. Eu has a distinct negative anomaly caused from the crystallisation of plagioclase from the melt. Else, there was not much discrimination between sites based on the REE.

6.4 Discussion

The YTB and Kaloola Member tuff is a blanketing tuff of great extent. If it is the equivalent of the Awaba Tuff in the Sydney Basin, then the event, or series of events leading to the deposition of the “final major tuff” before the Permo-Triassic boundary, approaches that of a super volcano. The similarity of geochemistry and age would suggest that this is a single event, or at least episodic events over a 70,000 to 100,000 year period exclusive of any other deposition from a similar source, although it is acknowledged that the tuffs are extremely altered from their deposition within the coal measures. The thickness distribution gives no clue as to the source area, and similar to the Awaba Tuff reflects the surface topography onto which is fell that was a relatively open canopied mire with open water bodies and sluggish river systems. The Awaba Tuff is substantially thicker, albeit reworked, and slightly less acidic. If it is older, it could be slightly less fractionated than the last gasps of the system for the silicic YTB. Michaelsen (2002) suggested that the general source of the pyroclastic units was “east” of the present coastline, and cited the occurrence of Late Permian (250-260 Ma) age granitoids distributed along the coastal sector of southern Queensland (Gust *et al.* 1993).

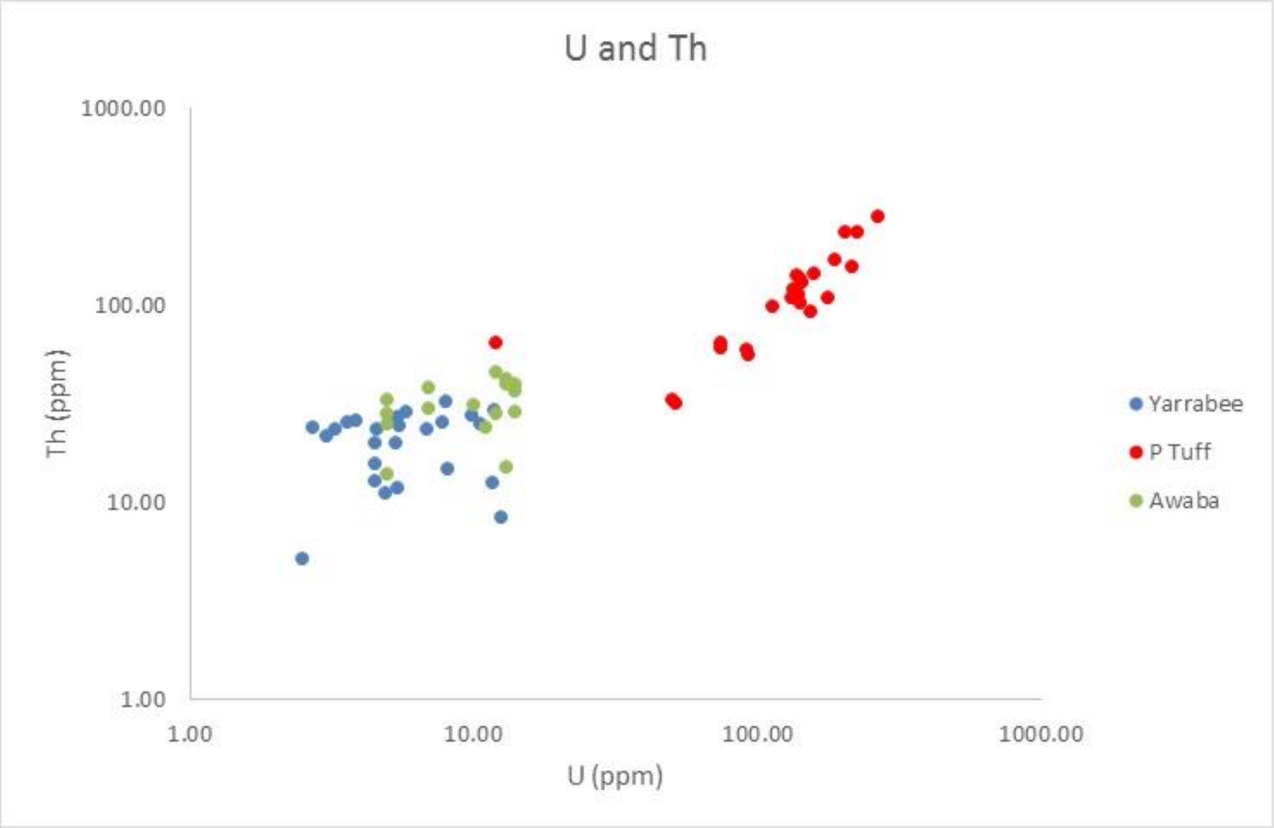


Figure 66 Cross plot of uranium and thorium for the different tuffs.

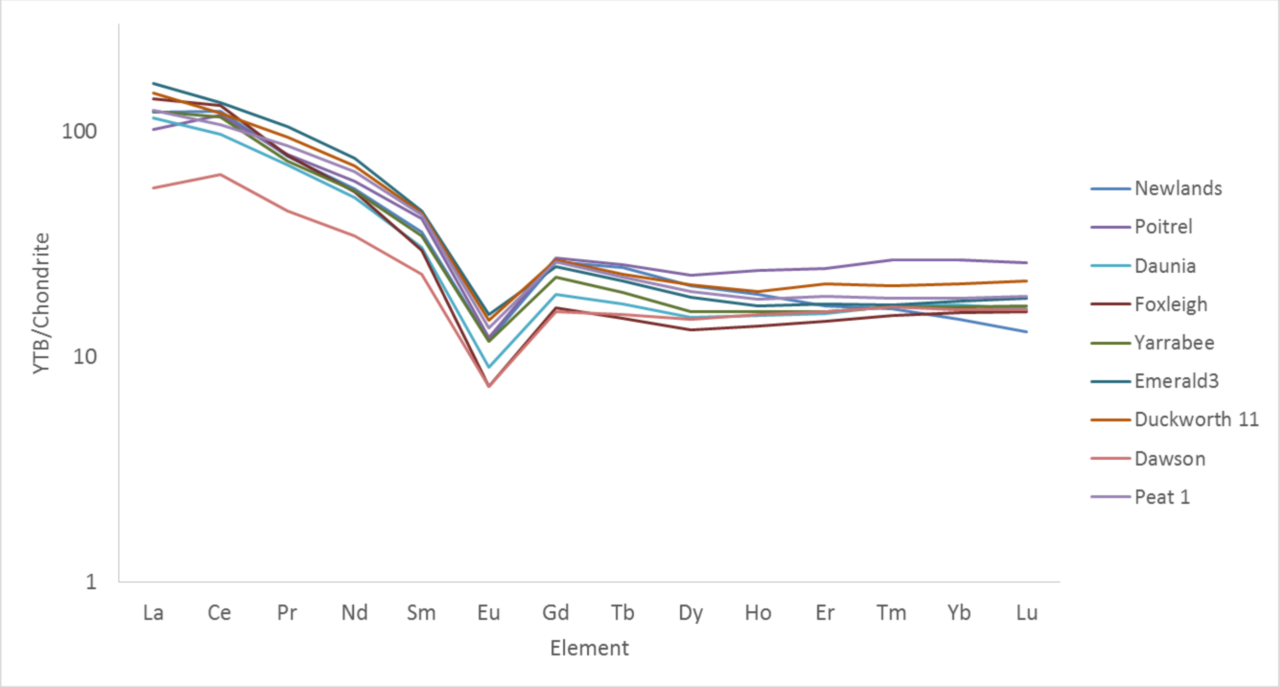


Figure 65 Chondrite-normalised values of the YTB across different minesites.

7 CONCLUSIONS

Supermodel 2015 provides an industry wide reference to the correlation and lateral variability in coal seam thickness, splitting patterns and interburden character for the Rangal-Baralaba-Bandanna Coal Measures in the Bowen Basin, and correlatives of these and older coal measures in the Betts Creek beds of the Galilee Basin. Data came from proprietary and open file drilling information selected in key cross sections through the basins. More detailed spatial models of the interburden variability were provided for the Rangal Coal Measures across mines in the Nebo Synclinorium by Wilson and for the Baralaba Coal Measures at Dawson mine by Caldwell, utilising more closely spaced drilling data and highwall studies. Regional correlations were corroborated by absolute age dating of tuffs which also gave insight into peat accumulation and sedimentation rates within an actively subsiding foreland basin.

Brakel *et al.* (2009) subdivided the Late Permian to Early Triassic strata into five Supersequences that record the progressive infilling of the basin, and the shifting depocentres from west to east in response to foreland loading. The uppermost Supersequence F2, the Rangal-Baralaba-Bandanna Coal Measures and the overlying G Rewan Group, record rapid southerly progradation of continental alluvial sedimentation in response to uplift on the New England Orogen. The active thrust system that divided the subsiding foreland from the eroding highland during the deposition of the F2 and G Supersequences was a >1000km long, north-south trending fault system that linked the Marlborough Nappe with the Moonie-Goondiwindi Fault and the Hunter Thrust. The character of this major structure varied along strike with sections dominated by strike-slip deformation, and others by steep thrust faults (e.g. Babaahmadi (submitted)). Both sequences thicken towards the fault system in the east and towards the north where they are truncated by erosion. It is likely that the foreland basin depocentre continued to the north past the core of the Marlborough Nappe. One consequence of the proposed north-south trending depocentre of the foreland basin is that the Nebo Synclinorium, Comet Ridge and Denison Trough are all located distally with respect to the main thrust front. This variation in subsidence controlled the distribution of thick merged and thin split coals.

The base of the Rangal sequence is the Yarrabee Tuff and the upper bound the last significant coal seam, the Leichhardt or Leichhardt Rider or equivalent. Confidence in correlations was supported by the consistent age returned by the high precision CA-IDTIMS method of 252.88 ±Ma for Yarrabee Tuff samples supplied by different mine sites around the basin. These were supplemented by samples in parallel projects (Metcalfe *et al.* 2015, Nicoll *et al.* 2015, Ayaz *et al.* 2016a). As the Triassic is dated at 252 Ma, the deposition of the coal measures occurred in less than a million years. Distal to the thrust front, the Rangal and equivalent coal measures are less than 100m and contain thicker and fewer coal seams; proximal to the front the measures are thicker than 200m and contain thinner but more numerous seams resulting in higher net coal. Although not a component of this study, the vitrinite content of these thinner seams can also be higher as subsidence promotes preservation, assuming that it is in balance with peat accumulation.

Correlation of individual seams across the different coal measures corroborated early work from Matheson (1990a). The Yarrabee Tuff was used as the datum and it is overlain by the Vermont,-Pisces-or E Seam. The Leichhardt Seam correlates to the Pollux Seam in the Bandana and the C Seam in the Baralaba measures. In the Nebo Synclinorium, seams are relatively thick and laterally continuous with the three basic seams-Vermont, Leichhardt and Phillips. To both the southwest and the southeast, these superseams split into numerous plies, responding to the increased subsidence and flooding and reoccupation of the mire by predominantly fluvial systems. In the Rangal Coal Measures, splitting is less complex and offset stacking of thick, stacked sandstone channels in the interburden is common. In the Taroom Trough splitting is more complex, reflecting variable rates of subsidence particularly proximal to the front. Although the depositional setting of the Late Permian coal measures is continental, evidence for rising base level and estuarine conditions has been noted at Blackwater (Fielding 2015) and also at Dawson (Caldwell 2016) mines. This would also explain the presence of a regionally persistent carbonaceous mudstone above the Leichhardt Seam that floors the base of the Rewan transition. This interpretation differs to the Rewan representing a rapid progradation during a low stand systems tract, at least in early in its deposition. Brakel *et al.* (2009) pondered why there was no regional marine incursion at the end of the Permian, considering the rapid subsidence rates in the foreland, and this could suggest there was, even across the Anakie Inlier into the Galilee Basin.

The Late Permian coal measures in the Galilee Basin, the Betts Creek beds, are commonly thought of as a condensed sequence in a low accommodation setting relative to the Bowen Basin. Coal seams within the Galilee Basin are laterally extensive and can occur for more than 300km. Comparatively very little splitting of coal seams occurs within the basin, compared to some areas of the Bowen Basin. The Betts Creek beds split southward by marine incursions (the Black Alley Shale, Mantuan Productus Beds, Peawaddy Formation) into the Bandanna Formation and Colinlea Sandstone, both of which can contain coals. A revised seam stratigraphy (Phillips *et al.* 2017) was confirmed by age dates of the Yarrabee Tuff (Phillips et al, in review). The tuffaceous “C seam” below the marine-deltaic sequence and the interpreted Yarrabee Tuff at the top of the B seam above it, suggest that only the uppermost A seam is the equivalent of the Bandanna Coal Measures. Coal seams are merged to the north, approximately in line with the thick merged seams of the Moranbah, Fort Cooper and Rangal Coal Measures in the Bowen Basin, and split and thin southward. This and the presence of the carbonaceous marker mudstone above the last coal, suggests that the Anakie Inlier may not have been a prominent feature during the Late Permian and Triassic periods.

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APPENDIX A – CORRELATION TABLES FOR COMPANY COAL SEAM CODES

Correlation schemas were developed for each of the three regions (Rangal – Bandanna – Baralaba) separately, as seams could not be confidently correlated between the regions. Coal seam codes from each mine site were replaced by Supermodel codes as shown in the tables below.

Please note that:

- Some minor seams were omitted from the regional correlation.
- To keep the Supermodel schema simple, the same seam codes were used for split seams in unconnected areas, even though they may refer to different plys splitting off the main seam.

Reference for tables	
*	thrust repetitions occur
[]	ply codes were merged into single seam code
seam	minor seams that were not replaced by Supermodel codes
[	minor seam split not shown on maps
[	major seam split shown on maps

Rangal Coal Measures

	SUPERMODEL	FOXLEIGH			PICARDY		WINCHESTER	ISAAC PLAINS		POITREL		MILLENIUM		DAUNIA	CARBOROUGH DOWNS		MOORVALE	COPPABELLA		
		south		north	south	centre		north	south			west	east							
PHILLIPS	PHI	ROP1	ROP1	ROP1	PH1*		L1A1		(picked)			(picked)						PHLS	PHLS	PHI
		ROP2							(picked)			(picked)								
LEICHARDT	LEIU1																			
	LEIU2														LHU		PHI		LU2	LCU1
		MMTU																		*LCU2*
	LEIU3				LEIUS - PH2		L2AU												LL1A	
	LEI	**MMT1**	**MMT1**	**MMT1**	**LEI***	**LEI***	**L2A - L2AL**	**LHD-LHU**	**LEI - L2**	**L14**	**L4 - L12**	**LL**		**L3**	**LHL - LHM**	**LHD**	**LL1**	**MC**	**LCTL - ML**	**LL3**
	LEIL1			TRA1																
	LEIL2	MMTL	TRA1	TRA2	*LL1-LL2-LL3*	LL1-LL2-LL3		LHL				MU-MM		L4	L1	L1	LL2			
	LEIL3						L2B, L2BC													
VERMONT			TRA2A									*RVU*		*VT*	*L2*	*L2*				
	VERU1	PI1B & PI1A	TRA2B	PI1B	VER1*	VER1*					V1 & V2	VU1	VU1	V1*	VX	VX	VU1		*HT2*	
	VERU2	PI2A	PI2A	PI2A	VER2*	VER2*	VA3	V1	V1	V23	V3	VU1B	VU2	V3*	(picked)	(picked)	VU2		VRMN	
	YT	**YT**	**YT**	**YT**	**YT***	**YT***	**YT**	**(picked)**	**(picked)**	**YT**	**YT**	**YT**	**YT**	**YT***	**VU**	**VU**	**YTB**		**YTFB**	
	VERL	PI2B & PI2C	PI2B	PI2B	VER3*	VER3*	VB	V2	V2	VL	VL	VL	VL	VL*	VER - VL	VER - VL				
						↑	↑	↑	↑			↑		↑						
GIRRAH	GIRU						VH	V3	V3				*VLG*							
					V3T*	V3T*														
	GIR	GIR	GIR	GIR	VER4*	VER4*	VJ, VJ1			GIR		GIR	GIR	GIR*			GIR		GRAH	
					LEIL3 is a persistent carbonaceous shale. Some smaller LEIL seams were not correlated.					L13 & L4 are very close together (not really split) L12 in western 4 holes only	VERU1 & 2 are a package.	Upper Leichardt picks added			L2 is a thin rider above VERU1		The Phi is correlated with LEIU2 not PHI. Only 3 wells intersect YT.	No wells intersect below LEI.		No wells intersect below LEI.

Rangal Coal Measures (continued)

	SUPERMODEL	**SOUTH WALKER CREEK**				**RED HILL (BMA)**		**RED HILL (Vale)**		**BURTON**			**HAIL CREEK**			**BEE CREEK**	**NEWLANDS**	
										south		**north**	**Elphinstone**	**Hail Creek**	**Mt Roberts**			
PHILLIPS	PHI1	not coded (added for this project)													EU1		Rider 1 Seam	
	PHI2																Rider 2 Seam	
LEICHARDT	LEIU1					RL1		L1										
	LEIU2			MT1														UN (Ply C-F)
	LEIU3			MT- MT2														
	LEI	**MB2 (MR)**	**MB**	**MB**	**MA**	**RL2**	**RL0**	**L2**	**LHD**	**BL**	**BV3U**	**BV3U**	**E00**	**EEL**	**E00**	**EL**	**UN (A-F) & EB (1-3)**	**UN (Ply A-B)**
	LEIL1																	
	LEIL2	MF	MF			RL3	RL3	L3	L3	BV3U	BV3M2		H0U	*EL1*	*EL1*	MF		
	LEIL3																	
VERMONT	VERU1		HT1							BV3M1					H0U			
	VERU2	HT	HT2/HT3			RV11 & RV12	RV11 & RV12	VU	VU	BV3L	BV3L	BV3L	HL1U	HEU	HL1U	HT	LN Ply 1	
	YT	**YT**	**YT**	**YT**		**YTB**	**YTB**	**YT**	**YT**	**BV2**	**BV2**	**BV2**	**HYT**		**HYT**	**YT**	**Yarrabee Tuff**	
	VERL	HB1	HB2	HB	HY	RV2	RV2	VL	VL	BV1	BV3	BV3	HL1L	HEL	HL1L		LN Ply 2	
GIRRAH	GIRU					GIRU - RV3							HL2L	H0L1				
	GIR	GIR				GI1	GI1	GIR	GIR	GIR - GRH	GIR - GRH	GIR - GRH	FC1-FC2	H0L2	FC1-FC2	HY	Girrah	
				MT is a thick Z-split up to MT1	VERU2 shales out locally.	RV3 is poor, mostly only mudstone. Some was in Girrah and was recorrelated.				The VER1 split could also be a lower Leichardt split.	To create a working section, the LEI was taken at the base of BV3E where unsplit.		H0U is a Leichardt split	VERU2 is very thick	H0U is a Vermont split	VERU2 is thick	Girrah plies not correlated	

Baralaba Coal Measures

	SUPERMODEL	YARRABEE		BARALABA						BELVEDERE		DAWSON				SCOTIA
				north			south					north			south	
	AUU						REI*	REIUM	[REIU & REIM]							
								REIL								
	AU			MDY	[MDYL & MDYU]		DBT*	DBTU*	[DBTUB* & DBTUA*]						AU*	
								DBTL*	[DBTLB & DBTLA]							
	A	CAN*		BYD*	[BYDL & BYDU]		DAW*	[DAWL & DAWM & DAWU]		A1		A*-BA*		AU*	A*	C1 - C2U
	AL	ARS*		CAM	CAMU*		DUN*	DUNU*	[DUNUB & DUNUA]	A2-A22			AU*	A*	AL	
					*CAML**											
	ALL							DUNL*	[DUNLB & DUNLA]	A3						
CASTOR	B			REI*	REIUM	[REIU & REIM]				B-B1		BA*-BB*	A*	B*	B*	C2
					REIL											
	BX	CASU					SDN*	[SDNL & SDNU]			B21		B*			
	BL	CASL					WRI*	WRIML	[WRIU* & WRIM*]	B2	B22-[C11 & C12]	BB*	[CU*]			C2UL
								*WRIL**								
								*SWR**								
POLLUX	**C**	**POL**		**DBT***	**DBTU***	**[DBTUB* & DBTUA*]**	**DBL***	**DBLL (A&B) & DBLU (A&B)**		**C1**	**[C21 & C22]**	**C-CML-CL*-CU***	**C-CML-CL***	**BL**	**BL**	**C2-C2L-C2LL**
					DBTL*	[DBTLB & DBTLA]										
ORION	DU	ORN								D1			DU	C	C	C3
	D	PIS	PISL				COO*	[COOL* & COOU*]		D2		D*	D*	DU	DU	C4
	DL			DAW*	[DAWL & DAWM & DAWU]							DL*	DL*	D-DL*	D*	
PISCES	E			DUN*	DUNU*	[DUNUB & DUNUA]	DRT*	DRTL (A&B) & DRTU (A&B)		E1	[E11 & E12]	E*	E*	E*	DL*	C4L
					DUNL*	[DUNLB & DUNLA]										
VIRGO/ KOOLOOLA	I						*SDRU**	*SDRUB (A)*		F1-F2-F3	E2	*I**	*I**	*I**	*I**	
		VIR		*WRI**	WRIML	[WRIU* & WRIM*]	*SDRM**	*[SDRMB & SDRMA]*				*F*-FL*-G*-H**				
					WRIL*		*SDRL**	*[SDRLB & SDRLA]*								
				*SWR**			*K1*									
				DBL*	DBLL (A&B) & DBLU (A&B)											
				COO*	[COOL* & COOU*]											
				DRT*	DRTL (A&B) & DRTU (A&B)											
				SDRU*	SDRUB (A)											
				SDRM*	*[SDRMB & SDRMA]*											
				SDRL*	*[SDRLB & SDRLA]*											
				K1												
				Correlation with Baralaba 2C & 5C			Correlation with Banana 1			BWD004 recorrelated		Local recorrelations necessary			Local recorrelations necessary	

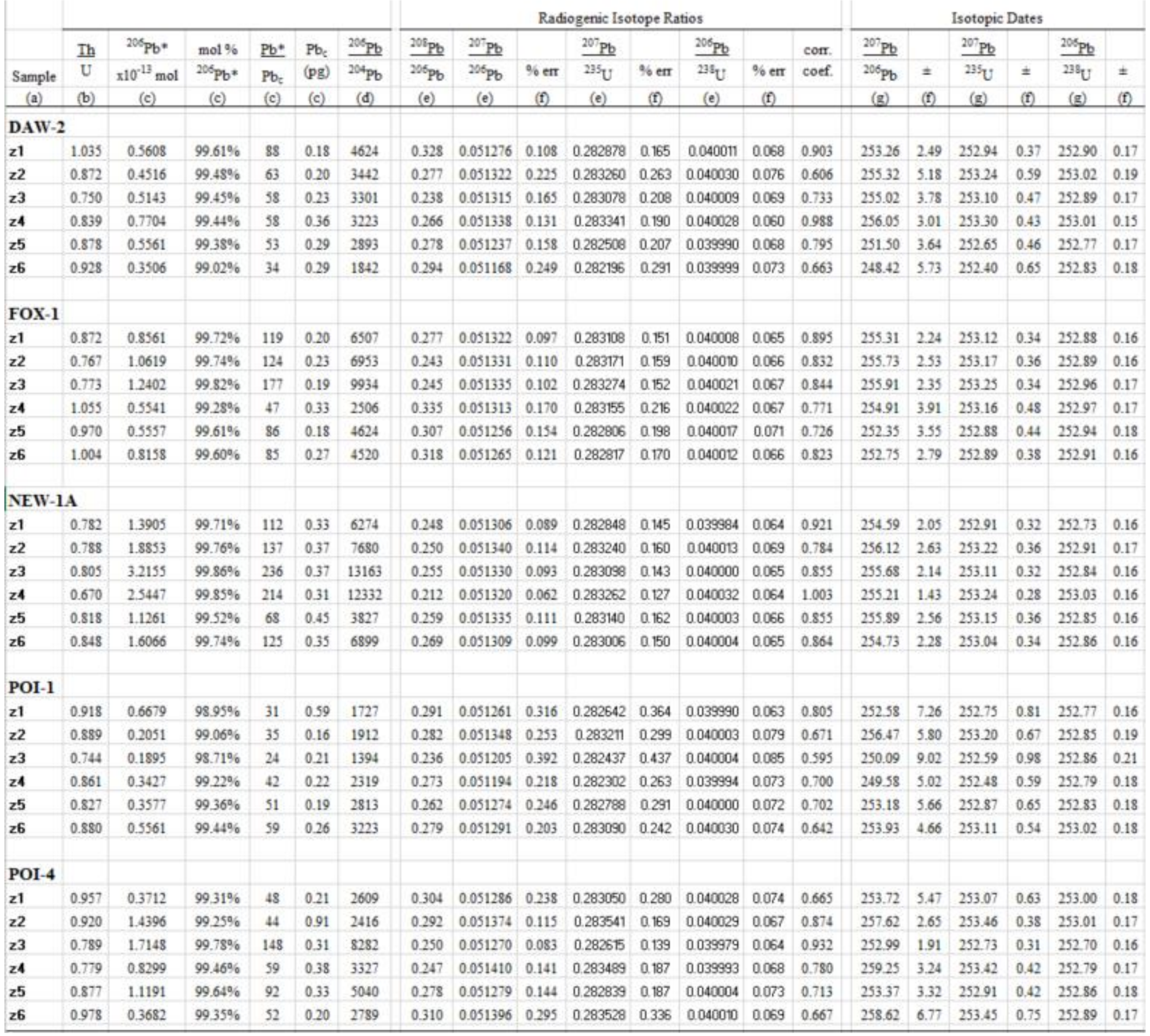
Bandanna Coal Measures

	SUPERMODEL		ROLLESTON	DURHAM		FAIRVIEW			ENSHAM									HUMBOLDT/SBW		
									west	south					north					
																	A11			
	ARS		X-X1			A				A1	A1	A1	A1	A1	A1	A1	A12	ARSU*	ARSU*	ARS*
ARIES																				
	ARSL		*X2*															ARSL*	ARSM	
		CASU				A1					A211	A211							CASU	
CASTOR	CAS	CAS	A-A1-A2			A2				A21	A212	A212	A211					CAS*	CASL	
	POLU		B-C		CRB3U			BU		A22	A22									
	POL				CRB3		B	B	A	C1 - A2 (& A21)	C (& A21)	A22C	A3C	A2C	A2C1	A2 (& C1)	A21	POLU	POL	ARG
POLLUX					*CRB2U*											*A22*	*A22*			
	POLL			CRB2	CRB2			C	C1	C1						C1	C1 [C11&C12]	*POLL*		
	POLLL				CRB2L			C1	*C22*	*C22*	*C22*				*C22*	*C22*	*C22*			
ORION	ORN	ORN	D-D1-D2	CRB1	CRB1	D	D	D	P	P3 (&1 &2)	P3 (&1 &2)	P3 (&1 &2)	P3 (&1 &2)	P3 (&1 &2)	P3 (&1 &2)	P3 (&1 &2)	P3	ORNU	ORN	
		ORNL			CRB1L	D1	D1	D1	Q1	Q	Q	Q	Q	Q	Q	Q	Q	ORNM		
		PSU																PIS	PIS	PIS
PISCES		YT							(picked)											
		PSL							V	V	V	V	V	V	V	V	V			
VIRGO	VIR					E-E1-F			(repicked using QDEX well constraints)									VIR	VIR	VIR

	SUPERMODEL		BLACKWATER											CURRAGH		
			Nth Ballambo	Blackdown/Wilpeena	Tannyfoil	Stewarton	Deep Creek	BesgroveAirstrip	Burngrove	Sagittarius	Mimosa	Bonniedoon	North	South		North
	ARS		TR75-TRT*	TRT*	TR	TR	TR	TR	TR	TRU	TRU	TRU	TRU			
ARIES										*TRL*	*TRL*	*TRL*	*TRL*			
	ARSL				T*	T*	TU	TU	TU	TU	TU	TU	TU			
							TL	*TL*	*TL*	*TL*	*TL*	*TL*	*TL*			
		CASU	P4U	MR	MR	MR										
CASTOR	CAS	CAS	P4L*	M54*	M54*	M54*	M54*				P04	P4L* [& U*]	P4L*[&U&R]	C00-P00	C00*	WPSR
	POLU															
	POL		L31*	L31*	L31*	L31*	L32* [& L01]	L41*	L41*	L31U*	L32*	P03 [&P02]	P3U [& L]	I00	WPS	WPS
POLLUX																
	POLL												P1U*			
	POLLL											P1L*	P1L*			
ORION	ORN	ORN	SG	SG	SG	SGU [&SGL]	SGU [&SGL]	SGU [&SGL]	SG	SG	SG	SG	SG			
		ORNL														
		PSU	PS	PSU	PSU	PSU	PSU	PSU	PSU	PSU	PSU	PSU	PSU	O00		
PISCES		YT		YT	YT	YT	YT	YT	YT	YT	YT	YT	YT	YT	YT	YT
		PSL		PSL	PSL	PSL	PSL	PSL	PSL	PSL	PSL	PSL	PSL	I2	PSCL	PSCL
VIRGO	VIR		VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	VIRGO	V00	V00	V00

APPENDIX B – ADDITIONAL TABLES AND FIGURES FOR YARABEE TUFF AGE DATES

Table 7 U-Pb isotopic data for minesite samples data for this study, from Jim Crowley, Boise State University.



							Radiogenic Isotope Ratios									Isotopic Dates					
Sample (a)	Th/U (b)	^{206}Pb* x10^{-13} mol (c)	mol % ^{206}Pb* (c)	Pb*/Pb$_c$ (c)	Pb$_c$ (pg) (c)	^{206}Pb/^{204}Pb (d)	^{208}Pb/^{206}Pb (e)	^{207}Pb/^{206}Pb (e)	% err (f)	^{207}Pb/^{235}U (e)	% err (f)	^{206}Pb/^{238}U (e)	% err (f)	corr. coef.	^{207}Pb/^{206}Pb (g)	± (f)	^{207}Pb/^{235}U (g)	± (f)	^{206}Pb/^{238}U (g)	± (f)
DAW-2																				
z1	1.035	0.5608	99.61%	88	0.18	4624	0.328	0.051276	0.108	0.282878	0.165	0.040011	0.068	0.903	253.26	2.49	252.94	0.37	252.90	0.17
z2	0.872	0.4516	99.48%	63	0.20	3442	0.277	0.051322	0.225	0.283260	0.263	0.040030	0.076	0.606	255.32	5.18	253.24	0.59	253.02	0.19
z3	0.750	0.5143	99.45%	58	0.23	3301	0.238	0.051315	0.165	0.283078	0.208	0.040009	0.069	0.733	255.02	3.78	253.10	0.47	252.89	0.17
z4	0.839	0.7704	99.44%	58	0.36	3223	0.266	0.051338	0.131	0.283341	0.190	0.040028	0.060	0.988	256.05	3.01	253.30	0.43	253.01	0.15
z5	0.878	0.5561	99.38%	53	0.29	2893	0.278	0.051237	0.158	0.282508	0.207	0.039990	0.068	0.795	251.50	3.64	252.65	0.46	252.77	0.17
z6	0.928	0.3506	99.02%	34	0.29	1842	0.294	0.051168	0.249	0.282196	0.291	0.039999	0.073	0.663	248.42	5.73	252.40	0.65	252.83	0.18
FOX-1																				
z1	0.872	0.8561	99.72%	119	0.20	6507	0.277	0.051322	0.097	0.283108	0.151	0.040008	0.065	0.895	255.31	2.24	253.12	0.34	252.88	0.16
z2	0.767	1.0619	99.74%	124	0.23	6953	0.243	0.051331	0.110	0.283171	0.159	0.040010	0.066	0.832	255.73	2.53	253.17	0.36	252.89	0.16
z3	0.773	1.2402	99.82%	177	0.19	9934	0.245	0.051335	0.102	0.283274	0.152	0.040021	0.067	0.844	255.91	2.35	253.25	0.34	252.96	0.17
z4	1.055	0.5541	99.28%	47	0.33	2506	0.335	0.051313	0.170	0.283155	0.216	0.040022	0.067	0.771	254.91	3.91	253.16	0.48	252.97	0.17
z5	0.970	0.5557	99.61%	86	0.18	4624	0.307	0.051256	0.154	0.282806	0.198	0.040017	0.071	0.726	252.35	3.55	252.88	0.44	252.94	0.18
z6	1.004	0.8158	99.60%	85	0.27	4520	0.318	0.051265	0.121	0.282817	0.170	0.040012	0.066	0.823	252.75	2.79	252.89	0.38	252.91	0.16
NEW-1A																				
z1	0.782	1.3905	99.71%	112	0.33	6274	0.248	0.051306	0.089	0.282848	0.145	0.039984	0.064	0.921	254.59	2.05	252.91	0.32	252.73	0.16
z2	0.788	1.8853	99.76%	137	0.37	7680	0.250	0.051340	0.114	0.283240	0.160	0.040013	0.069	0.784	256.12	2.63	253.22	0.36	252.91	0.17
z3	0.805	3.2155	99.86%	236	0.37	13163	0.255	0.051330	0.093	0.283098	0.143	0.040000	0.065	0.855	255.68	2.14	253.11	0.32	252.84	0.16
z4	0.670	2.5447	99.85%	214	0.31	12332	0.212	0.051320	0.062	0.283262	0.127	0.040032	0.064	1.003	255.21	1.43	253.24	0.28	253.03	0.16
z5	0.818	1.1261	99.52%	68	0.45	3827	0.259	0.051335	0.111	0.283140	0.162	0.040003	0.066	0.855	255.89	2.56	253.15	0.36	252.85	0.16
z6	0.848	1.6066	99.74%	125	0.35	6899	0.269	0.051309	0.099	0.283006	0.150	0.040004	0.065	0.864	254.73	2.28	253.04	0.34	252.86	0.16
POI-1																				
z1	0.918	0.6679	98.95%	31	0.59	1727	0.291	0.051261	0.316	0.282642	0.364	0.039990	0.063	0.805	252.58	7.26	252.75	0.81	252.77	0.16
z2	0.889	0.2051	99.06%	35	0.16	1912	0.282	0.051348	0.253	0.283211	0.299	0.040003	0.079	0.671	256.47	5.80	253.20	0.67	252.85	0.19
z3	0.744	0.1895	98.71%	24	0.21	1394	0.236	0.051205	0.392	0.282437	0.437	0.040004	0.085	0.595	250.09	9.02	252.59	0.98	252.86	0.21
z4	0.861	0.3427	99.22%	42	0.22	2319	0.273	0.051194	0.218	0.282302	0.263	0.039994	0.073	0.700	249.58	5.02	252.48	0.59	252.79	0.18
z5	0.827	0.3577	99.36%	51	0.19	2813	0.262	0.051274	0.246	0.282788	0.291	0.040000	0.072	0.702	253.18	5.66	252.87	0.65	252.83	0.18
z6	0.880	0.5561	99.44%	59	0.26	3223	0.279	0.051291	0.203	0.283090	0.242	0.040030	0.074	0.642	253.93	4.66	253.11	0.54	253.02	0.18
POI-4																				
z1	0.957	0.3712	99.31%	48	0.21	2609	0.304	0.051286	0.238	0.283050	0.280	0.040028	0.074	0.665	253.72	5.47	253.07	0.63	253.00	0.18
z2	0.920	1.4396	99.25%	44	0.91	2416	0.292	0.051374	0.115	0.283541	0.169	0.040029	0.067	0.874	257.62	2.65	253.46	0.38	253.01	0.17
z3	0.789	1.7148	99.78%	148	0.31	8282	0.250	0.051270	0.083	0.282615	0.139	0.039979	0.064	0.932	252.99	1.91	252.73	0.31	252.70	0.16
z4	0.779	0.8299	99.46%	59	0.38	3327	0.247	0.051410	0.141	0.283489	0.187	0.039993	0.068	0.780	259.25	3.24	253.42	0.42	252.79	0.17
z5	0.877	1.1191	99.64%	92	0.33	5040	0.278	0.051279	0.144	0.282839	0.187	0.040004	0.073	0.713	253.37	3.32	252.91	0.42	252.86	0.18
z6	0.978	0.3682	99.35%	52	0.20	2789	0.310	0.051396	0.295	0.283528	0.336	0.040010	0.069	0.667	258.62	6.77	253.45	0.75	252.89	0.17

(a) z1, z2, etc. are labels for analyses composed of single zircon grains that were annealed and chemically abraded (Mattinson, 2005). Labels in bold denote analyses used in weighted mean calculations.
(b) Model Th/U ratio calculated from radiogenic 208Pb/206Pb ratio and 207Pb/235U date.
(c) Pb* and Pbc are radiogenic and common Pb, respectively. mol % 206Pb* is with respect to radiogenic and blank Pb.
(d) Measured ratio corrected for spike and fractionation only. Fractionation correction is 0.16 ± 0.03 (1 sigma) %/amu (atomic mass unit) for single-collector Daly analyses, based on analysis of EARTHTIME 202Pb-205Pb tracer solution.
(e) Corrected for fractionation and spike. Common Pb in zircon analyses is assigned to procedural blank with composition of 206Pb/204Pb = 18.04 ± 0.61%; 207Pb/204Pb = 15.54 ± 0.52%; 208Pb/204Pb = 37.69 ± 0.63% (1 sigma). 206Pb/238U and 207Pb/206Pb ratios corrected for initial disequilibrium in 230Th/238U using Th/U [magma] = 3.0 ± 0.3 (1 sigma).
(f) Errors are 2 sigma, propagated using algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).
(g) Calculations based on the decay constants of Jaffey et al. (1971). 206Pb/238U and 207Pb/206Pb dates corrected for initial disequilibrium in 230Th/238U using Th/U [magma] = 3.0 ± 0.3 (1 sigma).

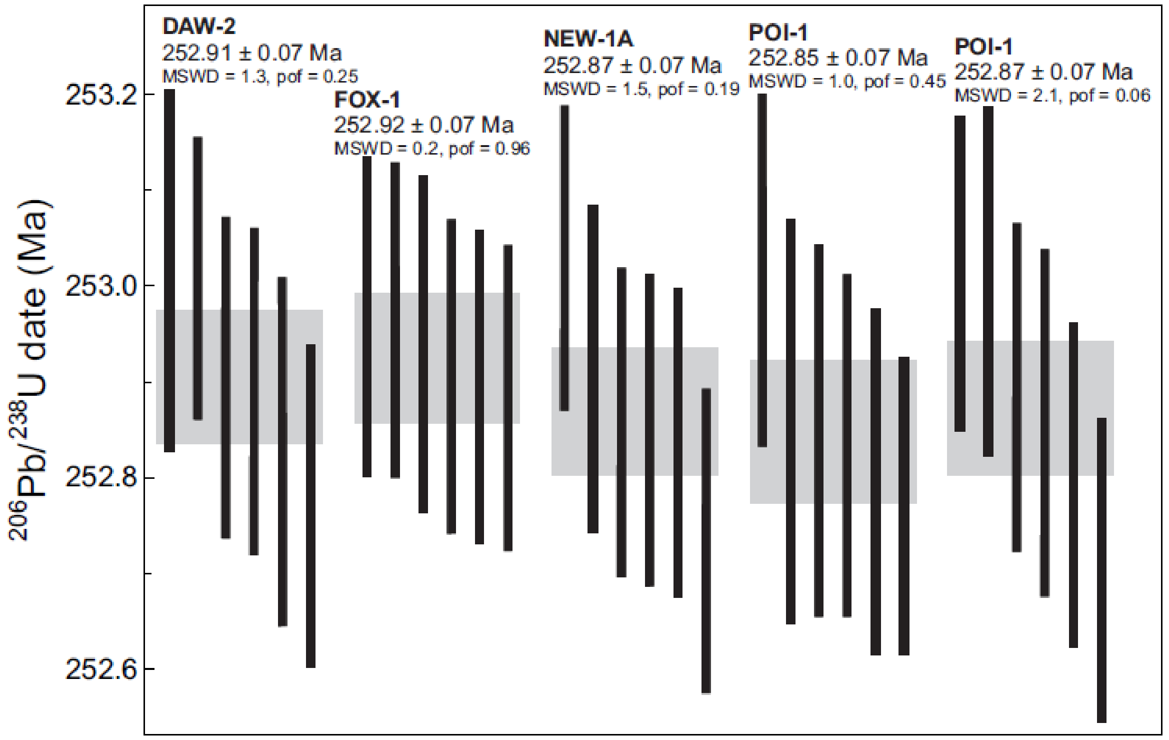
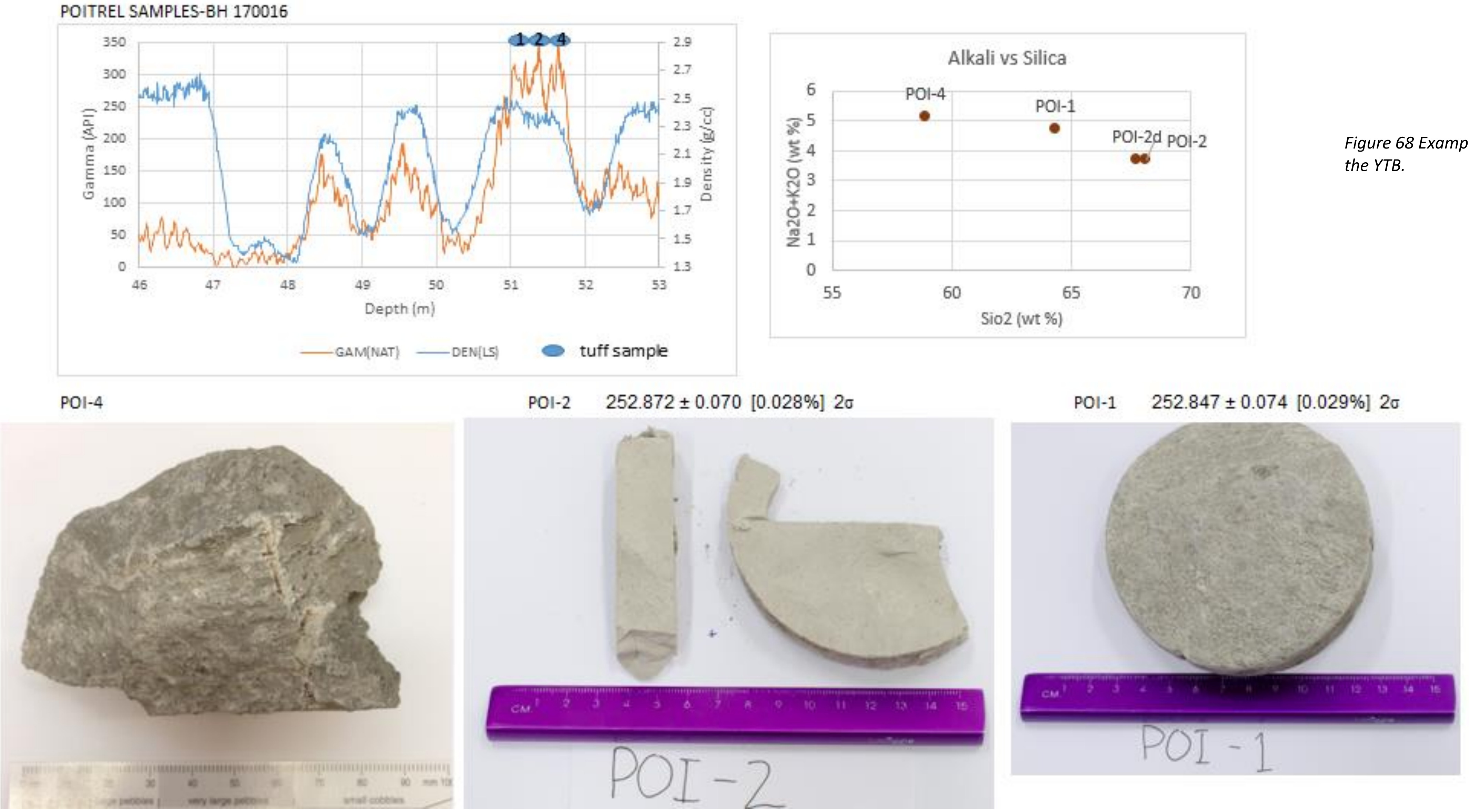


Figure 67 Plot of 206Pb/238U dates from single grains and fragments of zircon analyzed by CA-TIMS. Plotted with Isoplot 3.0 (Ludwig 2003). Error bars are at the 2 sigma confidence interval. A weighted mean date is shown and represented by the grey boxes behind the error bars.

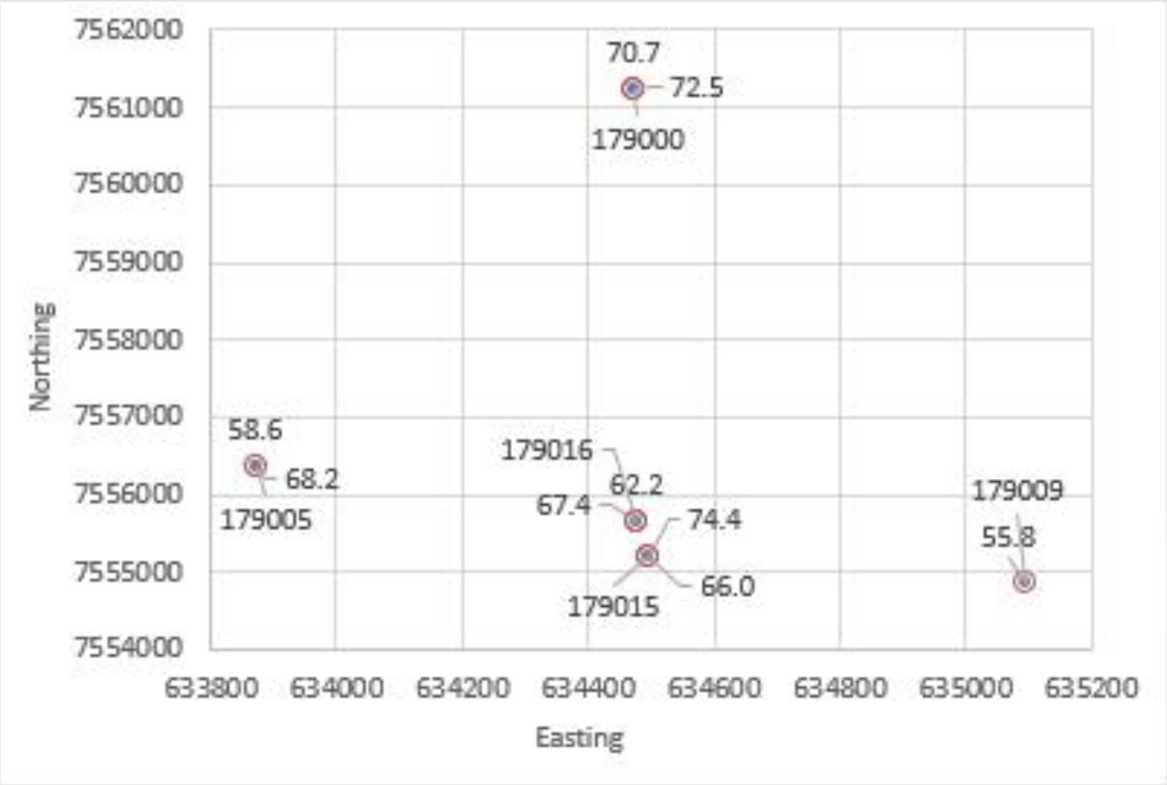


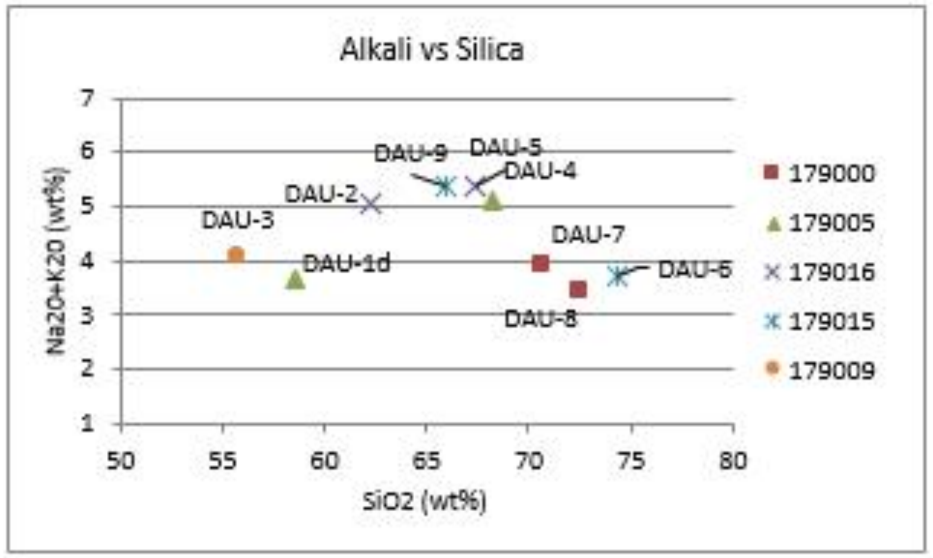
POI-4

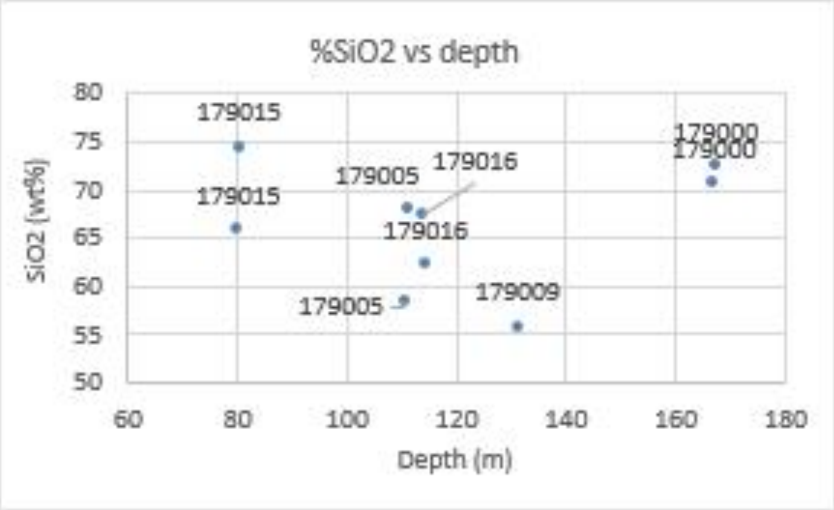
POI-2 252.872 ± 0.070 [0.028%] 2σ

POI-1 252.847 ± 0.074 [0.029%] 2σ

Figure 68 Examples of tuff samples from Poitrel Mine, showing their location within the YTB.







DAUNIA SAMPLES - MULTIPLE BOREHOLES

Figure 69 Examples of tuff samples from Daunia Mine, showing their location within different boreholes intersecting the YTB.