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MAPPING OF ELEMENTAL COAL CONTENT FOR EXPLORATION AND MINING

Jane Hodgkinson and Micaela Grigorescu
CSIRO

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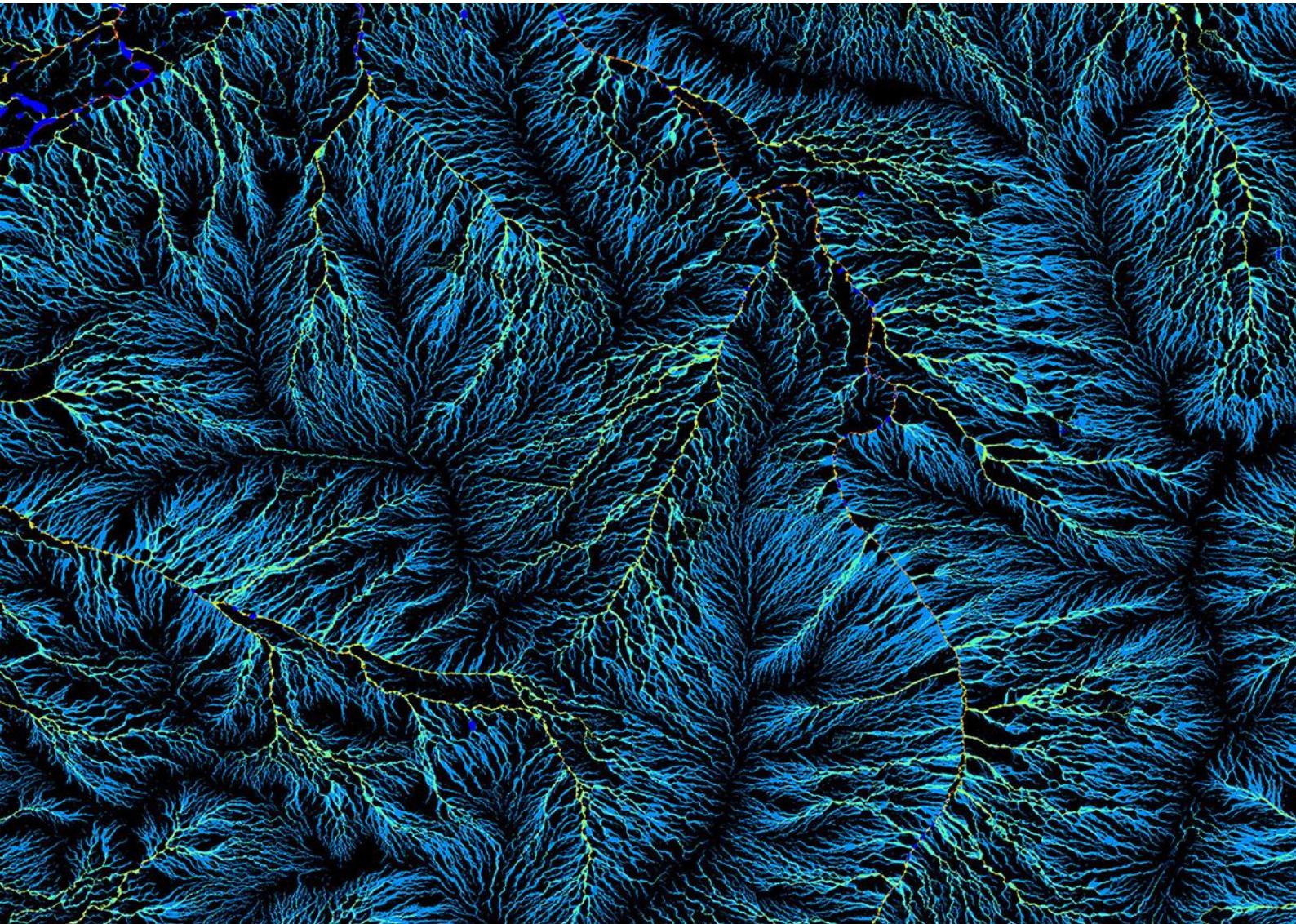
C29030 ACARP - Mapping of Elemental Coal Content for Exploration and Mining

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Dedication

This work is dedicated in memory of our dear colleague, Dr Oswald “Ossie” Marinoni who worked in CSIRO Land and Water, for which we are very grateful. Oswald played a vital role in this project’s preparation but sadly, was unable to join us in its completion.

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Executive summary

This project has analysed the concentrations of 50 elements not typically measured in coal in nearly 90 Australian coal samples from Queensland and New South Wales. Many of the samples are found to host critical elements above Australian crustal averages. The project provides the first dataset and map of its kind for Australian coal. Further work is required to extend the dataset, and examine mineral association and the fate of elements to develop extraction methods that maximise value of our precious coal resources.

Internationally, alternative coal use is actively sought to protect jobs and revenue as traditional coal use declines. In particular, the use of coal to source critical minerals including rare earth elements (REE) is an area of heavy investment at present in USA. Coal-content knowledge of Australian coals is sparse so predictive mapping to match coal with alternative uses has not been possible until now.

The work performed in this project (C29030) intends to provide data that can be used to clarify potential targets that may improve the industry's long-term potential. Eighteen contributors (coal mines and power plants) donated more than 150 samples for analysis. The project plan allowed 89 samples to be analysed, carefully selected to represent 6 basins, covering a range of coal measures and seams of varying ages. **Results indicate a high incidence of above crustal average concentrations of many of the 50 elements analysed.** Rare earth elements (REE) in particular, are elevated by up to 6 times more than average crustal concentrations in some samples.

Following a CSIRO proof-of-concept project that explored the same elements in Late Permian coal from the northern Bowen Basin, this ACARP project is the largest of its kind in Australia, presenting the first map and elemental coal content dataset for ACARP members.

The results were combined with pre-existing data of the elemental signatures of other rocks and coals in eastern Australia, mapped spatially, and compared graphically to determine potential sources of elements.

The objectives and aims of this project, have been met, which were to:

- Deliver the first coal content map of its kind for Australian coal
- Present elemental composition as a database of the samples assessed and a report interpreting the results including geological provenance of the elemental matter

Key findings are:

- Element concentrations (i.e. rare earth elements and yttrium - REY) appear to be directly correlated with the amount of mineral matter present in coal (ash)
- Lithium, rare earth elements, gold and bismuth tend to be concentrated above average crustal abundance and have to be assessed further in coal products in Queensland

Significantly, this project has sought a solution towards the Open Cut and Underground committees' focus for 'Innovative methods for the acquisition, capture and modelling for exploration'.

This may inform decision making for matching coal to alternative markets. Nevertheless, we recommend a broader study in addition to some more detailed case studies to better understand the fate of elements in an end-to-end study to inform processing for avoiding loss of value.

While concentrations of elements in the samples found to be above crustal averages may not be equal to those of typical ore grades, such concentrations may warrant further investigation. Further, mineral association of each element must be determined prior to evaluating economic opportunities and whether suitable extraction techniques can be identified.

In this report, we provide a detailed literature review of the locations from a geological perspective and the methods used, including selected treatment of data for interpretation. We lay out the results in chart and map forms, providing the full dataset in Appendix A (Excel format) and more detailed maps in Appendix B .

Appendix C consists of summary reports that were provided to each of the sample contributors and Appendix D provides a short resume of the project team.

1 Introduction

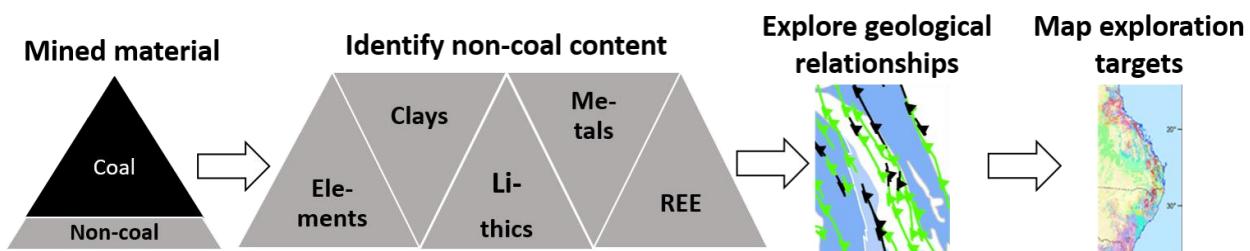
This project investigates the elemental content of Australian coal, providing strategic mapping to address the need for innovative exploration. The aim is to clarify potential targets of value to further improve the industry's long-term potential.

The objective of this project is to present elemental composition and geological provenance of the non-coal fraction of a range of Queensland and New South Wales coals.

The aim is to develop a better understanding of coal content and elemental provenance to inform decision making for exploring new economic resources and alternative markets. A further aim is to encourage additional research and stimulate interest for more detailed mapping and analysis.

Problem: Alternative coal use is actively sought in India, USA and China to develop new coal markets as the thermal market declines. One growing coal use is as a source of elements such as rare earth elements (REE), making coal a dual product. Australian coal exploration currently focusses on products suited to steel and energy markets, which drives coal mining, processing and marketing, but makes it difficult for other black-coal users such as those in chemicals and materials markets, to source their needs. With more comprehensive coal-content knowledge and predictive mapping, the coal industry can encourage growth in such markets. 'Innovative methods for the acquisition, capture and modelling for exploration' are sought by the Open Cut and Underground committees.

Solution: For new markets to select Australian coals for elemental extraction, a geological examination of coal-content will provide early indications of their potential. To improve exploration success, interpretation and interpolation between known geology and examined coals are needed to form an elemental coal map.



Research and new technology: Elements of potential industrial interest, including lithium, uranium, REE and gold have been found in coal in Russia, China and the USA. To understand and predict the abundance and variation of these elements, knowledge of the geological history of the coal is important. Elements may have been deposited during peat development and concentrated during coalification or emplaced later by mineral-enriched fluids. An internally funded CSIRO project (2017-19) explored alternative coal use, identifying that current knowledge of abundance of trace elements in Australian coals is limited. In the CSIRO project we analysed 38 Fort Cooper Coal Measure samples and found that several contained above crustal-average lithium and REE. In this project we examined more samples from various formations and coal basins to expand the dataset and provide an overview of coal element content. Through geological interpretation, we will identify potential targets where elemental content exceeds average crustal levels.

Benefit and transfer to industry: Connecting the elemental analysis with the depositional geology will improve the understanding of the coal for all coal-users. The preliminary knowledge-base and

draft map may assist exploration and introduce additional economic drivers for coal mining, by providing a framework for investors to identify potential targets to obtain secondary products from their operation. It may encourage small or niche mining operations and drive exploration to seek relevant deposits.

Approach: We aimed to analyse up to 60 samples (budgeted ~\$25,000) from supporting Australian mines and liaised with coal-fired power stations to discuss fly-ash availability. Elemental content analysed and mapped. Laboratory techniques included ICP, ICPMS, slow-ashing and aqua regia digestion. Using pre-existing geological maps, results are plotted and analysed spatially using 3D ArcGIS and further analysed using multiple criteria analysis. **This provides the first coal-content map of its kind for Australia.**

Outcome: This project provides a prototype map with early indications that may encourage exploration for element-rich multiple-product coal resources. We expect the base data to improve knowledge on the potential elements present in a range of Australian coals that may be of interest to some ‘alternative use’ markets. Ultimately, it may stimulate niche or alternative coal mining and processing and motivate future coal investment.

This project has been supported by CSIRO funded internal proof of concept project (2017-19: ~\$158k), the results of which are now published (Hodgkinson and Grigorescu, 2020). At the time of project acceptance by ACARP, several mining companies, including Glencore, had offered their support to provide coal samples. Further mines provided kind assistance throughout the duration of the project in addition to assistance by the ADAA.

2 Project History

In 2017-19, CSIRO funded a strategic project (~\$158k) that explored potential future coal utilisation to ensure R&D alignment with future needs. Results identified a growing international interest in the extended value of coal through direct use of the coal, coal waste and elements and minerals found in coal. Specifically, research in USA, Europe, Russia and China has identified economic concentrations of elements or metals in the non-combustible portion (commonly referred to as coal ‘ash’ or mineral matter) of some coals including uranium, rare earth elements, gold, lithium, calcium and magnesium. High levels of germanium are sourced from coal-bearing strata in China and Russia. Recovery of uranium, aluminium and REE from coal is an expanding area of research (Zou, Tian and Li, 2016). Whilst some of the material would have been emplaced in swamp conditions and concentrated through extreme compression during coalification, other elements have been emplaced at a later stage from percolating mineral-rich fluids. In 2017-19 CSIRO examined ~38 samples from the Fort Cooper Coal Measures (Bowen Basin) to explore, as proof of concept, potential element concentrations and suitable methods of analysis (Hodgkinson and Grigorescu (2020). Several samples contained above crustal-average elements such as lithium and REE. Past ACARP projects have acknowledged elemental content in coal such as C25044 (QCC Resources, 2018). C17003 (Dale, 2003) and C3096 (CSIRO, 1995) that considered elements of environmental concern; however, they did not assess elements that may be of economic interest.

Elements in coal may become a product *via* a range of scenarios. For example, high element-coal might be purchased by a new market specifically for processing, producing cleaned coal as a secondary product; a mine’s processing plant may be adapted to produce both cleaned coal and elements of value; or ash collected after coal-use (or tailings from a processing plant) may be sold to a processor. In any of these scenarios, legislative requirements relating to the mine’s ability to benefit from the sale of other minerals would need to be considered. Nevertheless, the presence of valuable elements and minerals may affect coal price at some mines, potentially increasing profits.

Future markets may seek coal with content and characteristics specific to their needs, but with current knowledge of what is in our coal, these needs cannot easily be met by the Australian coal industry. One of the requirements will be to identify what is in un-mined coal, that could be available to an end-user prior to processing, as well as what remains after combustion, and use that information to map geological provenance and inform future mining and uses.

2.1 State of the art

Elemental recovery from coal is not uncommon when resources run low, such as when uranium was needed post WWII or when there was an increased surge in demand, such as in the 1950s, when the commercial extraction of germanium from coal commenced. Some elements listed by various countries as ‘critical’, such as rare earth elements (REE) and lithium are now being sought from coal in USA and China. The presence of rare earth elements and yttrium (REY) in coal waste in economic concentrations was reported over 80 years ago. Factors that control the presence of such anomalies in coal deposits include hydrothermal fluid circulation and percolating water, volcanic ash and marine influences during peat formation. In some cases, the anomalies may be a result of more than two processes and would be indicators of different source regions and history of the coal during and after deposition. Despite their name, REEs are not rare in the earth’s crust with around 180-200

ppm (equivalent to $\mu\text{g/g}$, mg/kg or g/t) in average upper crust but are so called because they are rarely found in economically-exploitable concentrations. Coal enriched in REE, in addition to germanium, gallium and yttrium is found in USA, Russia and China due to local volcanic activity during coal development. REE have been found to be approaching commercially viable levels in some coal fly ashes from the UK, as well as Russia's far-east and Siberia, Inner Mongolia and southern and southwestern China and eastern USA. Estimates are that global concentration of REE in coal fly ash is on average 445 ppm (Ketris and Yudovich, 2009). In experiments, up to 99% of the REEs in coal fly ash samples (of 200-700 ppm concentrations) was extracted (Ketris and Yudovich, 2009). Fly ash currently being produced in the USA is estimated to potentially provide more than three times the REE mass per kilogram of total REE extracted from conventional ores. In a study to determine commercial viability of extracting REE from the Powder River Basin coal (USA), 70% of REE content in fly ash was recovered using an existing heated nitric acid digestion process. REE have been extracted from poor coal waste using an environmentally friendly, inexpensive solvent such as ammonium sulphate (Rozelle et al., 2016). Stoy et al. (2021) recently developed a method for preferential recovery of REE from coal fly ash using a recyclable agent.

While some other elements such as gold are rarely found in coal in anomalously high concentrations, their potential presence remains worth exploring simply because of their high value. Gold has been found in coal in high concentrations in Western-Siberia and India. Coal is a major source of germanium in Inner Mongolia, in Yunnan Province in China, and at Novosjaktinskoye Mine in Russia. Coal tailings and coal fly ash, often considered to be waste, may be sold for use in construction material but may also represent a potential source of rare earth- and other strategic elements.

Full elemental content is presently unknown for many coals that are routinely mined, despite availability of laboratory standards and capabilities. Analysis of strategic elements and minerals of economic interest in coal waste is not currently performed as a matter of course and thus valuable elements may have been disregarded or discarded with waste material. Australian Standard 'AS 1038.10.0-2002 - Coal and coke - Analysis and testing - Determination of trace elements - Guide to the determination of trace elements' (Dale, 2003) was developed by CSIRO and the Australian Coal Association Research Program (ACARP), primarily to identify concentrations of elements that would be detrimental to health and the environment. Further, proximate, ultimate and ash analyses are routinely performed to determine the presence of elements that may impact on coal combustion and coking properties or those that may be corrosive, abrasive or impact on health and the environment through emissions or leaching to waterways, but elements of economic interest are rarely examined. For this reason, CSIRO investigated, as proof of concept (2017-19), elemental content of Fort Cooper Coal Measure samples from Queensland, identifying concentrations of elements in the coal, some of which are greater than average crustal levels (Table 1) that currently have market demand.

Table 1. A selection of elements with elevated concentrations (relative to crustal averages) in CSIRO-analysed samples (2017-19) of the Fort Cooper Coal Measures. Typical use of such elements also described. Indication of critical minerals provided (Commonwealth of Australia, 2019)

Element	Use	On USA Critical Minerals list	On E.U.'s Critical Minerals list	On Japan's Critical Mineral list
Lithium	batteries, pharmaceuticals	Y		Y
Zinc	batteries, pharmaceuticals, electrical equipment			
Thorium	electronics, nuclear fuel			
Bismuth	alloys, fire alarms, sprinkler systems	Y	Y	
Cerium	polishing agent and in glass	Y	Y	Y
Lanthanum	batteries, camera lenses	Y	Y	Y
Praseodymium	magnets, lasers and glass	Y	Y	Y
Neodymium	magnets, lasers, electric motors	Y	Y	Y
Samarium	magnets, lasers	Y	Y	Y

Comparing cut-off values of potentially economic concentrations of elements in coal and its waste, with those of traditionally mined ores and sources is not straightforward. A relevant cut-off grade of an element from coal-waste may be much lower than from traditional ores because it has already been excavated, crushed and transported to a repository, providing cost benefits that will allow for lower concentrations to become economically viable. Conventional REE ore-mining scenarios, for example, require concentrations of between 1000 and 5000 ppm. A cut-off grade for rare earth oxides from coal has been suggested as around 800 ppm (Seredin and Dai, 2012). Even lower concentrations may be economic given improved beneficiation techniques.

Improved methods for extracting elements from coal waste are also a focus of interest. Elements and metals in coal that are considered to have the best chance for economic recovery are: REE, silver (Ag), gold (Au), platinum group elements (PGE), beryllium (Be), selenium (Se), vanadium (V), gallium (Ga), antimony (Sb), scandium (Sc), molybdenum (Mo), tungsten (W), rhenium (Re), germanium (Ge), uranium (U), yttrium (Y), niobium (Nb), zirconium (Zr) and aluminium (Al). The process of combustion liberates the non-combustibles and concentrates the elements, although some elements may volatilize and be lost in the process of heating. High temperatures can cause some glassy ash particulates that entrap elements causing them to be unresponsive to extraction processes. Low-temperature ashing can preserve some of the combustible elements and avoid the vitrification process but may not be possible in industrial boilers/furnaces. Recognising what is present in coal before washing or combusting provide an opportunity to adjust wash-plant activities to ensure value from the mined coal can be optimised. Coal tailings from coal preparation plants on the other hand, have not been heated and may be more amenable to element extraction. Peterson et al. (2019) analysed coal mineral content to validate economic viability using a closed loop acid digestion process for samples with REE concentrations above 300 ppm. ANSTO Minerals have continuous piloting and demonstration plants for processing rare earths, lithium, gold and other metals, developing new and more efficient methods to obtain trace elements. ACARP Project C27015 (UNSW) is currently exploring elemental content of coal from the perspective of toxicity to human health. Fluorine and phosphorous distributions are being examined by project C26029 (UQ) and they have also reported examining REE trends. Emerging technologies will provide evolving chemical extraction methods that may improve economic feasibility of even lower concentrations.

Market potential of any element or metal that could be in coal may grow if new resources become available making supply more stable. For example, some heavy REE (HREE) are relatively scarce and their uncertain long-term availability may control demand as manufacturers seek alternative options, but if availability can be more guaranteed, their demand may increase. Some light REE (LREE) such as La and Ce are widely available and critical to existing and developing technologies, but their demand is growing as new uses are also being developed. China is currently the single largest REE supplier producing approximately 80% for world markets. The tuffaceous-rich samples analysed by CSIRO (2017-19) display higher than crustal-average concentration elements and one of the samples had more than three times (>600ppm) average crustal concentrations. Some of the elements found in elevated concentrations in the samples examined by CSIRO, including REE and lithium are on the Critical Minerals lists of Australia, USA and Japan (Table 1).

Given that both industrial and technological resources and needs for extraction will change over time, cataloguing and documenting the elemental composition of coal in Queensland and New South Wales may assist future development of coal and strategic element products to benefit both the coal and mineral industries. Importantly, once it is ascertained that an element is present, the next step is to explore its association with the coal, such as being part of a clay structure, to determine its liberation potential both before washing, or after combustion that in turn may identify opportunities for alternative washing and combustion techniques.

Low-ash coal is commonly considered to be a preferred resource, as the non-coal portion is not currently considered to be of value. However, should ash be found to host some elements of value, the higher-ash coal might be considered an economically mineable option, although new processing techniques might be required to ensure as much of the mineral fraction as possible can be captured. Under such circumstances, production outputs may be ‘coal + mineral matter’ rather than ‘coal + waste’.

3 Project Objectives and Aims

The objectives of this project are to:

- Determine the elemental composition of coals from a range of geological formations and basins
- Provide a better understanding of elemental geological provenance
- Inform where such elements may be found in similar formations and geological settings
- Develop a map of elemental coal content to assess spatial distribution and trends

The aims are:

- to help provide a knowledge base that can inform decision making for exploring further economic coal resources for alternative markets, and
- to encourage further research and stimulate interest for further, more detailed mapping and analysis.

We present here:

1. data and analytical results on geochemical composition of a range of coals from Queensland and New South Wales and connect it with depositional geology
2. results on spatial analysis findings that may determine potential for new exploration sites and improve understanding of the coal for all users. The map will be the first coal-content map of its kind for Australia
3. a report and, map and dataset for ACARP member and other potential end-users

4 Project Work Plan and Progress

4.1 Plan

The proposed Project Plan was as follows:

- The project initially aimed to access up to 60 samples from supporting mines, and geological surveys, and data or samples from coal-fired power stations
- We have mapping and database development capabilities and analytical expertise and software required to perform this work
- A sampling strategy will be developed to ensure access to a good spatial representation of Queensland and NSW coals, although availability of coals from supporting mines will be understood and honoured. Sample analysis in the laboratory, digital mapping and GIS data and Excel data collation will be performed to CSIRO research standards
- Field work will not be required, and this will allow for timely completion of each stage through to final desk top assessments and reporting
- A presentation will be prepared after results have been prepared, a map has been completed, and a prototype database has been developed
- A report and presentation piece (poster, abstract or paper) will also be prepared and presented to industry through MetSIgnited and ACARP

The planned timeline is provided in Table 2.

INTENDED WORK PROGRAM

Task 1: Preparation, literature review, detailed planning (months 1-2)

- Desktop based literature review to provide background and understand known conditions
- Plan sampling strategy and laboratory work
- Liaise with coal fired power stations for potential for additional data on fly-ash

Task 2: Sampling, laboratory work and data collection (months 3-6)

- Samples will be prepared as per plan
- Samples will be processed in laboratory and data collected and collated for analysis
- ArcGIS mapping will begin

Task 3: Data analysis and mapping (months 5-7)

- Data will be prepared for analysis using multiple criteria analysis, charting and techniques deemed appropriate at the time
- Preliminary maps will be prepared for spatial analysis
- Presentation of preliminary findings to monitors

Task 4: Data interpretation, reporting and presentation (months 8-12)

- Results may be grouped or clustered into specific conditions, maps will be updated with findings
- Interpretation, discussion and presentation to monitors. Report will be drafted as work progresses
- Presentation will be made to supporting mine

Management and reporting included throughout each task (months 1-12)

Table 2. Proposed project plan

Tasks	Assigned	Start	MONTH: 1 2 3 4 5 6 7 8 9 10 11 12											
			June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	March	April	May
Project management	JH	1/06/2020												
Task 1 PREP, LIT REVIEW, PLANNING (MONTHS 1-2)		1/06/2020												
Lit review	OM, JH	1/06/2020	■											
Sampling strategy	OM, JH	21/06/2020		■										
Explore for data	JH	31/07/2020												
Task 2 SAMPLING, LAB WORK, DATA COLLECTION (MONTHS 3-6)		1/08/2020												
Sample collection and prep	JH	1/08/2020			■									
Sample analysis at Lab	JH, Lab	5/08/2020			■									
ArcGIS Mapping	OM	29/08/2020				■								
Half way report to monitors	OM, JH	15/11/2020							MILESTONE					
Task 3 ANALYSIS AND MAPPING (MONTHS 5-7)		14/10/2020												
Data collation and prep	JH	14/10/2020				■								
Data analysis	OM, JH	5/11/2020					■							
Spatial analysis	OM	15/12/2020						■						
Presenting to monitors	JH	15/01/2020								MILESTONE				
Task 4 INTERP, REPORTING, PRESENTING (MONTHS 8-12)		1/01/2021												
Grouping and clustering analysis	OM, JH	1/01/2021								■				
Interp, discussion	OM, JH	28/02/2021									■			
Present to monitors/mines	JH	1/05/2021												
Draft report for ACARP review	OM, JH	1/06/2020	■	■	■	■	■	■	■	■	■	■	■	MILESTONE

4.2 Progress

Due to team-member unavailability at the beginning of the project, there was minimal project activity from July to September. A replacement team member, Dr Micaela Grigorescu was employed as an independent researcher from October 2020. Other delays were experienced due to difficulties obtaining some of the samples during the intended time frame caused by staff changes at mines, COVID effecting mining activities and commercial interruptions to teams. Time was made up over the November to February period but the project was kindly granted an extension by three months to allow for sample return and interpretation from the laboratory. An updated timeline is provided in Table 3.

Table 3. Updated timeline

Tasks	Assigned	Start	MONTH: 1 2 3 4 5 6 7 8 9 10 11 12 13 14												
			July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July
Project management	JH	1/07/2020													
Task 1 PREP, LIT REVIEW, PLANNING (MONTHS 1-2)		1/07/2020													
Lit review	MP, JH	1/07/2020													
Sampling strategy	MP, JH	1/09/2020													
Explore for data	JH	1/11/2020													
Task 2 SAMPLING, LAB WORK, DATA COLLECTION (MONTHS 3-6)		1/10/2020													
Sample collection and prep	JH	1/10/2020													
Sample analysis at Lab	JH, Lab	5/10/2020													
ArcGIS Mapping	MP, JH	1/10/2020													
Half way report to monitors	MP, JH	15/12/2020								MILESTONE					
Task 3 ANALYSIS AND MAPPING (MONTHS 5-7)		14/11/2020													
Data collation and prep	JH	14/11/2020													
Data analysis	MP, JH	5/12/2020													
Spatial analysis	MP, JH	15/01/2021													
Presenting to monitors	JH	12/02/2021								MILESTONE					
Task 4 INTERP, REPORTING, PRESENTING (MONTHS 8-12)		1/02/2021													
Grouping and clustering analysis	MP, JH	1/02/2021													
Interp, discussion	MP, JH	1/04/2021													
Present to monitors/mines	JH	15/08/2021													
Draft report for ACARP review	MP, JH	31/08/2020											MILESTONE	MILESTONE	

4.3 Mine site access

Project personnel did not require mine site access. Samples have been provided by mines and power stations and transported by courier or post.

4.4 Safety implications

Potential research hazards

Samples were collected by mining companies supporting this project. Normal CSIRO site training and protocol were followed. Laboratory work was undertaken by laboratory experts, in accordance with laboratory HSE requirements having followed stringent training. Other work was completed at the desk-top with low HSE exposure. HSE training for the work-place was completed and complied with. COVID restrictions were followed throughout.

5 Literature Review

5.1 Minerals and elements in coal

Most of the chemical elements found in the Earth's crust can be detected in coal deposits, although their concentrations may vary depending on the primary source of sediments and the depositional and post-depositional history of the coal basin (Raask, 1985; Swaine, 1990; Saxby, 2000; Hower *et al.*, 2016). Here we review the sources of elements that may be found, their affinities, availability and extraction.

5.1.1 Element source

Elements and mineral matter found within coal measures may have originated from organic material and/or clastic or pyroclastic minerals such as zircon, monazite, apatite and xenotime (Finkelman, Dai and French, 2019; Dai *et al.*, 2020). Detrital minerals (delivered from a pre-existing source), including clays, phosphates, sulphates, carbonates and oxides may have been transported by wind or water to the basin during peat accumulation and can continue to accumulate, modify or enrich while the peat becomes buried, compressed and heated (coalified). The accumulations of mineral matter can lead to concentrations that may be greater than normal background expectations in the upper crust (Raask, 1985; Ward, 2016; Dai *et al.*, 2020) often due to compression of the peat.

Seredin and Dai (2012) consider **ash falls, hydrothermal activity and water movement within a coal basin as primary processes of syn- and post-depositional enrichment**. They classified the main sources of detrital elements as follows:

- **terrigenous** material, which is transported by surface waters and controls the element input and accumulation
- **tuffaceous** material, which is derived from weathering and leaching of volcanic ash
- groundwater-driven (**infiltration**) material, and
- material enriched during **hydrothermal** activity, which facilitates the ascending of potentially metal-rich deep fluids

Regardless of the way in which the detrital material reaches the coal basin, the surrounding igneous and volcanic rocks represent the main mineral matter supplier. **Primary rocks may imprint a particular elemental signature on the coal deposits and their seams**. For example, carbonatite deposits with abundant bastnaesite [(La, Ce)CO₃F or (Y, Ce)CO₃F] or syenites containing loparite [(Ce,Na,Ca)(Ti,Nb)O₃] may be enriched in light REE (LREE). Peralkaline intrusions and xenotime-monazite [YPO₄ - (Ce,La,Th)PO₄] accumulations in mafic rocks are enriched in heavy REE (HREE). All the clay deposits proximal to such rocks may present a similar REE pattern and contain metals or REE resources (Van Gosen *et al.*, 2017).

The abundance of REE has been found to decrease in magmatic rocks in the following order:
carbonatites > ultramafic and alkaline rocks > calc-alkaline rocks > alkali basalt > continental tholeiites.

The REE content of metamorphic rocks is similar to their protoliths; however, it has been reported that accessory minerals (zircon, monazite, xenotime, allanite, sphene and apatite) tend to concentrate REE much more than the original rock (Randive *et al.* 2014 and references therein).

Field studies that were aimed at determining the REE behaviour in sedimentary systems found that **REE are mobilised and recycled during the weathering of primary rocks** but they are not transported far from their source. **Most REE are found in fine-grained sediments, especially bound within clays** that can readily adsorb trivalent REEs (Randive *et al.* 2014 and references therein).

5.1.2 Element affinities

Coal is composed of a mixture of organic and inorganic compounds, most of the latter being authigenic although some are detrital. The inorganic phases include:

- quartz
- clays (kaolinite, illite, montmorillonite)
- chlorite
- pyrite
- calcite
- siderite, and
- to a lesser extent apatite species and heavy minerals

All these minerals may contain or adsorb trace elements or REE (Schweinfurth, 2016), depending on chemical affinities.

Raask (1985) reviewed the mode of occurrence and concentration of trace elements in bituminous and sub-bituminous coals in terms of mineral matter characteristics. The reactive and porous matrix of lignites and sub-bituminous coals can incorporate a large number of light elements and transition metals in organo-metal complexes. The bituminous coal trace elements are present mainly in the mineral matter fraction, in particular pyrite and marcasite, which can host chalcophile elements.

Regional depositional conditions can also control chemical behaviour: for example, trace elements such as chromium (Cr), copper (Cu), nickel (Ni), rubidium (Rb) and vanadium (V) show some enhanced concentrations in marine sediments in some parts of the world, while elsewhere, high-sulphur coals are relatively rich in cadmium (Cd) and zinc (Zn) (Raask, 1985).

It is commonly reported worldwide that **low-rank, high-ash coal contains higher concentrations of organically-bound elements**, such as HREE. The process of HREE-humic acid chelation occurs during the early stages of coalification, resulting in highly stable humic complexes (Dai *et al.*, 2020; Gollakota *et al.*, 2019; Hower *et al.*, 2016; Qin *et al.*, 2018).

5.1.3 Element availability

Total concentration of REE in average bulk continental crust is around 125 parts per million (ppm) (Rudnick and Gao, 2013). As previously stated, these elements are commonly found in coals associated with clay structures, although variable amounts may be attached to the organic phase.

Element availability for extraction is highly dependent on the nature of chemical bonding and the stability of complexation.

Finkelman et al. (2019) concluded that modes of occurrence within clays, silicates and carbonates need deeper understanding but, as “a number of interesting and rare phases have been found in coal”, more detailed investigations of coal mineralogy are justified.

Some elements in coal are strongly bound and require extreme resource (energy, water, chemicals) input for partitioning and extraction, while others may be more feasible for economic extraction. Although the elemental concentrations in the coal itself are typically low, the concentration of valuable elements as a portion of the material that is not coal (i.e., sediment that will be washed out or become fly/bottom ash) becomes greater.

Methodologies for extraction have evolved over time and economic feasibility changes as demand grows for certain elements and minerals.

5.1.4 Element extraction

Numerous studies have been carried out to explore element content in coal in recent years, in the attempt to determine economically feasible methods of extraction.

Until recently, it was considered costly to extract such elements from coal and demand was relatively low. However, as easily accessible sources of some elements and minerals have become exhausted combined with increase in demand, methods have been developed that reduce cost and the environmental impact of their extraction. Some research of extraction methods has been driven by the fact that REE are vital for a range of products needed in electronics, transport, health care, computers, rechargeable batteries, electric vehicles and chemical catalysts, (US Department of Energy, 2017).

There are challenges to extract REE from the complex mineral matter, which may increase extraction costs, but they may be offset by the fact the material has already been processed and stored. US Department of Energy (DOE) (2017) estimated an economic cut-off concentration of 500 ppm in coal mineral matter. The US DOE and the National Energy Technology Laboratory's (NETL) 'Feasibility and Recovering of Rare Earth Elements' program is developing extraction, separation and recovery technologies to produce REE and critical minerals from coal-based resources without generating unwanted products. They state that co-production of REEs with other useful materials may make recovery more economically favourable (US Department of Energy, 2019).

Until 2002, the Mountain Pass mine in California supplied most of the world's REEs; since then, however, China has become the main producer of REE (approx. 75% of world's production in 2018). REE ores are mainly mined in Jiangxi Province, south China, but the resources are expected to be exhausted within the next 20 years (Mancheri, 2012; Goodenough, Wall and Merriman, 2018). The main deposits are associated with carbonatites and provide the vast majority of world's LREE reserves. Minor occurrences include REE-bearing clay deposits, monazite and xenotime placers, pegmatites and hydrothermal veins (Xie *et al.*, 2016).

In this context, China's recent export restrictions have led to a 'global hunt' for new REE sources and coal has been identified as a potential target. While REE are not particularly rare, concentrations that make extraction economic are, and methods for extracting them that are environmentally friendly, are a challenge. (Stoy, L., Diaz, V. and Huang, 2021) have demonstrated REE recovery from coal fly ash using a recyclable agent. Estimates from America expect 10.9 million tonnes of REE

resources may be available in coal deposits located across nine states (US Department of Energy, 2017) (US Department of Energy, 2019).

The challenges with REE recovery from coal and coal products are related to the:

- large volume of material that requires processing
- economic recovery of REE from low-concentration sources
- recovery and separation technologies that need tailoring to the coal product (US Department of Energy, 2017) (US Department of Energy, 2019)

Finkelman *et al.* (2018) subjected bituminous and subbituminous coals to sequential leaching with ammonium acetate, hydrochloric acid, hydrofluoric acid and nitric acid to quantify the modes of occurrence of about 40 elements, including REE. Although the results indicated that, within this coal rank range, the leaching behaviour of many elements were broadly similar, the chemical behaviour varied with the rank. In bituminous coals, the REE were predominantly in the phosphate minerals (70% for the LREE and 50% for the HREE), while in the low rank coals, about 50–60% of REE were associated with the clays. Many of the rank differences were controlled by the detrital input or pyritization of the coal.

Further discussion on elemental recovery is continued in Section 5.1.6.

5.1.5 Coal products potential

US Department of Energy (2017) completed an assessment of the feasibility of economic recovery of REE from coal and by-product streams such as fly ash, coal refuse and aqueous effluents. Over 1800 samples, representing approximately 30,000 individual REE analyses, were taken from various sources to investigate the potential for commercial separation of REE from coal-associated materials.

The report identified **several areas of recovery opportunities in the coal value chain** (Figure 1):

- mining (overburden and co-mining of REE-rich layers if present)
- separation (coarse and middlings refuse, and fine coal by-products)
- energy conversion (fly ash and bottom ash)

In addition, the extraction of REE from coal might open alternative or niche markets for:

- currently uneconomic coal deposits (e.g., high-ash or low-rank), and
- smaller mine operators

The report concluded that mining of REEs present in coal materials that are currently mined for other coal needs, as a dual or by- product, may represent potential savings when compared to production in a mine dedicated solely to extraction for REE. Although extraction from a coal source may be challenging due to the large volume of material that must be processed to recover economic REE concentrations, the **costs may be offset by the fact that the material has already been mined, crushed, washed and transported** to an area with well-established infrastructure (i.e., mine tailings or power plant ash dams).

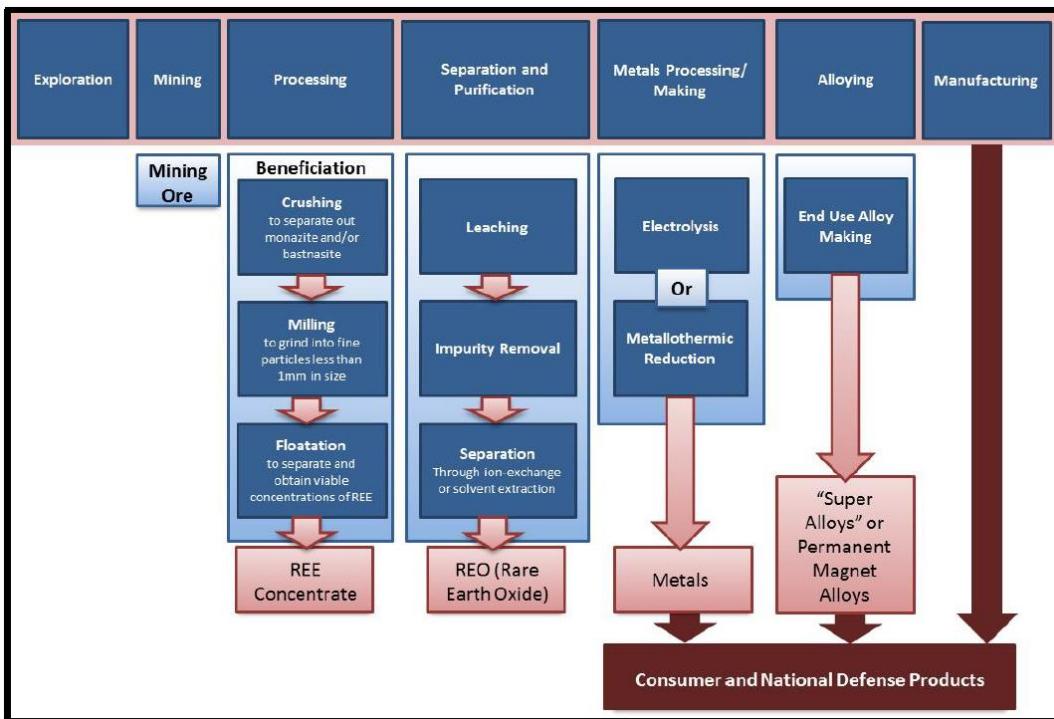


Figure 1. REE recovery opportunities across the coal value chain (Source: US Department of Energy, 2017)

5.1.6 Research relevant to the current project

The international interest in coal-related elements has resulted in extensive research for more than a decade; the following are the main topics:

- **origin** of elements in coal (Seredin and Dai, 2012; Dai, Graham and Ward, 2016; Finkelman, Palmer and Wang, 2018; Finkelman, Dai and French, 2019)
- mechanisms of element **enrichment** (Qin *et al.*, 2018; Arbuzov *et al.*, 2019)
- regional characteristics and significance of **geological setting** (Seredin and Dai, 2012; Taggart *et al.*, 2016; Yan *et al.*, 2019; Zhao *et al.*, 2019; Lefticariu, Klitzing and Kolker, 2020)
- **combustion products** potential as a source of trace elements and REE (Taggart *et al.*, 2016; Kolker *et al.*, 2017; US Department of Energy, 2017; Gollakota, Volli and Shu, 2019; Wang *et al.*, 2019)
- **extraction** methods with a focus on combustion products (University of Kentucky, no date; Franus, Wiatros-Motyka and Wdowin, 2015; Sahoo *et al.*, 2016; Judge and Azimi, 2020)

Notable is a study by Seredin and Dai (2012) who analysed accumulations of REE and yttrium (REY) in many coal deposits and coal ashes worldwide. They developed the following classification of enrichment patterns (N for normalised concentrations):

- LREY-enrichment - $\text{LaN}/\text{LuN} > 1$
- MREY-enrichment - $\text{LaN}/\text{SmN} < 1$, $\text{GdN}/\text{LuN} > 1$, and
- HREY-enrichment - $\text{LaN}/\text{LuN} < 1$

Particularly relevant to the current project is the **geological setting of coal deposits**, which may indicate potential content of value, including post-depositional process that may cause enrichment such as intrusions, volcanic activity or heat alteration.

Goodarzi and Cameron (1990) identified that coal adjacent to an intruded dyke was enriched with REE, As, Ca, Cu, Mg, Mn, Sr and Th. Thermally altered coal found close to basalts is typically avoided and left unmined due to coking and thermal alteration of the coal. However, preferential mining of such coals as element reserves, may provide an alternative use of that coal and a valuable source of much needed products.

REY enrichments have been reported in low rank coal due to acidic groundwaters mobilising trace elements and REE from surrounding volcanic rocks (Yan *et al.*, 2019). Some coals may contain REE from syn-depositional input of felsic or alkali volcanic ash, hydrothermal solutions or material redistributed from local carbonatites and alkaline granites (Dai and Finkelman, 2018; Arbuzov *et al.*, 2019). Dai *et al.* (2011, 2012, 2017) identified four types of volcanic ashes, each with its own elemental signature:

- mafic (moderately enriched in Sc, V, Cr, Co, and Ni and having positive Eu anomalies)
- felsic (lower REE, less pronounced negative Eu anomalies but greater fractionation between LREE and HREE)
- alkali (high Nb, Ta, Zr, Hf, REE, Y, and Ga, and distinct negative Eu anomalies)

REE may also be concentrated in coal mine drainage locations, which could be a source of recovery (Dai and Finkelman, 2018; Lefticariu, Klitzing and Kolker, 2020; Zhang *et al.*, 2020).

Cost-effective, environmentally friendly methods to extract REE and metals from coal by-products are being developed (Rozelle *et al.*, 2016). Low-quality, discarded coal from the Northern Appalachian coal fields (USA) for example, were treated with ammonium sulphate, an environmentally friendly and inexpensive solvent (lixiviant) to release the REEs. It was estimated that just 2% of REE extraction would make the process economic. During that study, 0.5% of the REE were extracted and the research team was confident that 2% can be achieved using an advanced ion exchange method. Importantly, the highest concentrations of REEs have often been found in the poorest quality coal, such as in the top layer of a coal seam (Rozelle *et al.*, 2016). In the case of open cut mining, where there may be zones of high REE content in overburden, REE could be extracted prior to the coal of interest. As the cost of the overburden removal is typically borne by the cost of mining coal, the overburden may become a cheap feedstock for producing a REE co-product.

Virginia Polytechnic Institute and State University (Virginia Tech) are working with industry partners on a pilot project to recover REE from coal using a hydrophobic-hydrophilic, water-repellent, water-friendly (HHS) method (Gupta and Li, 2016). The method has also shown to be effective at dewatering ultrafine coal. The researchers aim to develop a mobile facility to test different coal cleaning facilities throughout the Appalachian coal field.

Ultrafine coal is widely discarded due to a lack of suitable separation techniques. A commercial plant is using HHS to simultaneously separate water and mineral matter at ambient temperature and pressure from coal particles, with no lower particle size limit. The process can also separate REE and minerals containing REE from coal by-products (Yoon *et al.*, 2016; Biviano, 2017).

5.1.7 Fly ash

While fly ash already has economic and environmental value in inclusion in cement and concrete, fly ash is also being considered as a source of transition metals and REE (Franus, Wiatros-Motyka and Wdowin, 2015; Sahoo *et al.*, 2016; Taggart *et al.*, 2016; Kolker *et al.*, 2017; Li *et al.*, 2017; Gollakota, Volli and Shu, 2019; Scott and Kolker, 2019).

Massive quantities of coal fly ash are generated worldwide, which pose management challenges in terms of disposal and storage but may offer economic opportunities (Gollakota, Volli and Shu, 2019).

The recovery of valuable elements from fly ash presents several advantages as the material is:

- readily available not requiring excavation or physical beneficiation, and
- a fine powder, making it ideal for chemical processing (Taggart *et al.*, 2016)

Given the potential of fly ash, efforts are being made to develop methods for extracting strategic elements. A comprehensive review of methods and their recovery efficiencies is presented by Sahoo *et al.* (2016); overall, the methods typically involve one of the following processes:

- high-temperature chlorination
- magnetic separation
- alkaline leaching
- acid leaching
- combustion followed by acid leaching
- bioleaching
- sublimation

Taggart *et al.* (2016) tested acid leaching on fly ashes from the Illinois and Powder River basins and concluded that the **efficiency of the extraction may be more important than the initial concentration** of REE. They found that although the Illinois ash was richer in total REE (average REE+Y+Sc = 403 ppm) than the Powder River ash (average REE+Y+Sc = 337 ppm), the acid extraction recovered a higher concentration of REE from the Powder River ash (~70%).

Following up on Taggart *et al.* (2016) work, Kolker *et al.* (2017) analysed 19 samples of American ashes, including some from the Illinois and Powder River basins. They showed that Ca- and/or Fe-rich aluminosilicate glasses are more enriched in REE than aluminosilicate glasses not enriched with Ca and Fe. It was concluded that extraction methods have to be tailored to the origin and composition of the feed coal for the ash (Taggart *et al.*, 2016; Kolker *et al.*, 2017).

5.2 Data interpretation methods

- Post-Archaean Australian Shales (PAAS) are a standard suitable for normalisation of elemental concentrations in Australian rocks
- A series of indices can be used to analyse ratios and anomalies of elemental concentrations
- Discrimination diagrams are routinely used to determine tectonic settings and unravel the geological evolution of a multitude of rock systems

5.2.1 Normalisation

The chemical composition of the upper crust is considered an important constraint when assessing geochemical data. Consequently, there is a large number of papers assessing datasets and summarising findings published by researchers over many decades (see examples in Table 4).

One of the most cited publications for PAAS values (post-Archean Australian Shale), which are suitable for the normalisation of elemental concentrations in sedimentary rocks, was published by

Taylor and McLennan (1985); it was later revised by McLennan (2001), based on additional sedimentary datasets. The post-Archean shales are very similar throughout the world, hence the assumption that they are representative of the average upper crust composition. However, the shales are LREE-enriched, with a negative Eu anomaly and flat HREE (Rudnick and Gao, 2013). Condie (1993) argued that age, sediment texture and mixing also play a role in compositional variations and have to be considered in the interpretation of normalised data (Table 4). Most recently, Rudnick and Gao (2013) reviewed hundreds of publications on the subject and published a revised upper crust average composition (Table 4).

In this present work, the averages published by McLennan (2001) have been used for the normalisation of all elements analysed in this study, referred to as PAAS.

Table 4. Examples of crustal averages

Element (ppm)	Taylor and McLennan (1985)	McLennan (2001)	Condie (1993) by age (Ga)							Rudnick and Gao (2003)
			>3.5	3.5- 2.5	2.5- 1.8	1.8- 1.6	1.6- 0.8	0.8- 0.2	<0.2	
La	38	30	29	29	31	30	31	27	27	31
Ce	80	64	55	56	65	64	65	60	59	63
Pr	8.9	7.1	Nr	nr	nr	nr	nr	nr	nr	7
Nd	32	26	25	25	30	29	30	28	27	27
Sm	5.6	4.5	4.1	4.2	5.6	5.6	5.7	5.4	5.4	5
Eu	1.1	0.88	1.0	1.0	1.2	1.2	1.1	1.0	1.0	1
Gd	4.7	3.8	3.6	3.7	5.2	5.2	5.2	5.0	5.1	4
Tb	0.77	0.64	0.55	0.58	0.82	0.81	0.82	0.79	0.8	1
Dy	4.4	3.5	nr	nr	nr	nr	nr	nr	nr	4
Ho	1	0.8	nr	nr	nr	nr	nr	nr	nr	1
Er	2.9	2.3	nr	nr	nr	nr	nr	nr	nr	2
Tm	0.4	0.33	nr	nr	nr	nr	nr	nr	nr	0.3
Yb	2.8	2.2	1.6	1.7	2.3	2.3	2.4	2.3	2.4	2
Lu	0.43	0.32	0.27	0.28	0.38	0.37	0.39	0.39	0.43	0.3
Sc		13.6	13.1	12.5	14.5	14.1	14.1	14.2	14.2	14
Y		22	18	20	32	32	31	31	30	21

nr – not reported

5.2.2 Ratios and anomalies

Most researchers classify REE in LREE (La-Eu) and HREE (Gd-Lu), although a more refined classification separates the middle REE (MREE), resulting in the following elemental categories:

- LREE = La + Ce + Pr + Nd + Pm + Sm
- MREE = Eu + Gd + Tb + Dy (+ Y)
- HREE = Ho + Er + Tm + Yb + Lu

Seredin and Dai (2012) introduced the following ratios, which enable a rapid assessment of element enrichment of the light, middle and heavy elements in the REE series, where N represents the normalised concentrations:

- LREE-enrichment - $\text{LaN}/\text{LuN} > 1$
- MREE-enrichment - $\text{LaN}/\text{SmN} < 1$, $\text{GdN}/\text{LuN} > 1$, and
- HREE-enrichment - $\text{LaN}/\text{LuN} < 1$

Elemental anomalies, such as cerium (Ce) and europium (Eu) are often calculated to infer mineral source and chemical behaviour or conditions. **Cerium is an indicator of redox conditions, with positive anomalies occurring in oxidising conditions.** In coal deposits, the Ce anomaly is weakly negative or non-existent, reflecting the typical reducing conditions of coal depositional systems (Eq 1, after Dai *et al.* 2016).

$$\text{Ce anomaly} = \text{CeN}/\text{CeN}^*, \text{ where } \text{CeN}^* = (\text{LaN} \times 0.5) + (\text{PrN} \times 0.5)$$

1

Europium is also redox-sensitive; however, the redox transformation requires both reducing conditions and high temperatures. In coal deposits, the Eu anomaly can vary, largely depending on the primary source rocks that contributed detrital material to the coal deposit.

Felsic rocks present large negative Eu anomalies, as Eu is depleted during plagioclase crystallisation, while **mafic rocks present strong positive anomalies.** Such patterns are often observed in coal seams, although some of the **positive anomalies may be post-depositional** and caused by hydrothermal fluids. **High-apatite concentrations may also induce positive Eu anomalies.**

Interference with Ba may occur during ICP-MS analysis; therefore, **high Ba samples should be interpreted with caution** (Eq 2, Dai *et al.* 2016 and references therein).

$$\text{Eu anomaly} = \text{EuN}/\text{EuN}^*, \text{ where } \text{EuN}^* = (\text{SmN} \times 0.5) + (\text{GdN} \times 0.5)$$

2

Gadolinium (Gd) anomalies are largely overlooked, although positive values may be indicative of seawater intrusions or hydrothermal influences in the coal deposits (Eq 3, Dai *et al.* 2016).

$$\text{Gd anomaly} = \text{GdN}/\text{GdN}^*, \text{ where } \text{GdN}^* = (\text{SmN} \times 0.33) + (\text{TbN} \times 0.67)$$

3

To assess the economic value of REE deposits, Seredin (2010) developed an **outlook coefficient**, which is the **relative amount of critical REE to the relative excess of REE**. Subsequently, Seredin and Dai (2012) modified the ratio to include Y (Eq 4). The authors stated that **the higher the ratio, the higher the economic value** of the deposit being evaluated.

$$C = (\text{Nd} + \text{Eu} + \text{Tb} + \text{Dy} + \text{Er} + \text{Y})/\sum \text{REY} / (\text{Ce} + \text{Ho} + \text{Tm} + \text{Yb} + \text{Lu})/\sum \text{REY}$$

4

All of these ratios and indices have been calculated for the samples analysed as part of this project.

5.2.3 Sediment source discrimination

Discrimination diagrams are routinely used to determine tectonic settings and **unravel the geological evolution of a multitude of rock systems**, but mostly mafic igneous.

From early work by Shervais (1982), through to recent reviews and reassessments by Zhou *et al.* (2004), Snow (2006), Hastie *et al.* (2007), Pearce (2008), Saccani (2015) and Li *et al.* (2015) and references therein, the diagrams have been modified and improved based on hundreds of samples collected from around the world.

The difficulty in employing such diagrams to ascertain the origin of mineral matter in coal is related to the fact that sampling programs are not usually designed to allow for geochemical discrimination. **Many coal analytical suites** focus only on elements **necessary for traditional coal characterisation or include elements that may represent an environmental or health hazard** during mining or coal use. In addition, syn- and post-coalification processes, such as hydrothermal influences, diagenesis or weathering may alter the primary rock signatures and cause erroneous interpretation. Therefore, sediment sources and their tectonic setting that may be inferred from such diagrams must be considered with caution and used for orientation only.

We present a few examples of discrimination diagrams employed in this study to assess mineral sources and thus the potential of other coal measures that may have been influenced by similar tectonic settings and primary source material to contain elements of interest. The following diagrams (Figures 2, 3, 4, 5 and 6) display the chemical analyses of coal and tuff samples (Fort Cooper Coal Measures (CM), Bowen Basin) analysed by CSIRO as part of the proof-of-concept project previously conducted (Hodgkinson and Grigorescu, 2020).

Pearce *et al.* (1984) assessed over 600 samples of granites from different settings such as ocean ridge, volcanic arc, intraplate and collision granites and tested the relationships between Rb, Y, Nb, Yb and Ta, and some of their sums. The results showed that **granites exhibit distinctive trace element characteristics**. The example in Figure 2 shows that the provenance of the Fort Cooper CM coal and the associated tuffs is similar, volcanic arc and collision granites; in addition, the diagram shows that the tuffs are enriched in Y when compared to the coal samples.

Element ratios have been used by Hollocher *et al.* (2012) to discriminate the tectonic settings of basalts. The diagram in Figure 3 suggests that the Fort Cooper coal and tuff may have included detrital material of basaltic origin from an arc setting, which is consistent with the provenance of granites (Figure 2). However, this diagram provides a clearer separation between the coal (largely oceanic arc) and the tuff (predominantly continental arc).

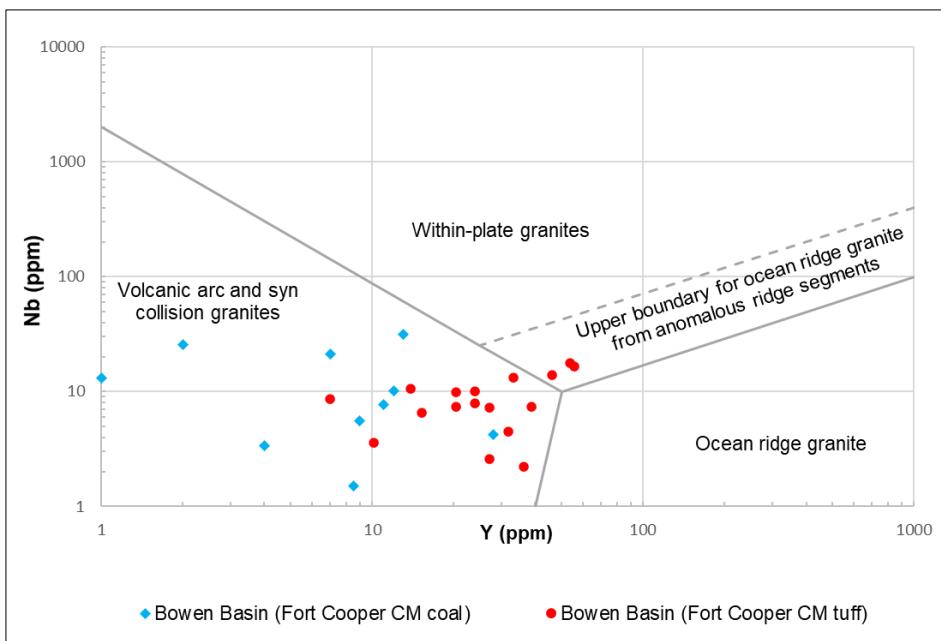


Figure 2. Tectonic interpretation of granitic rocks (after Pearce et al. 1984)

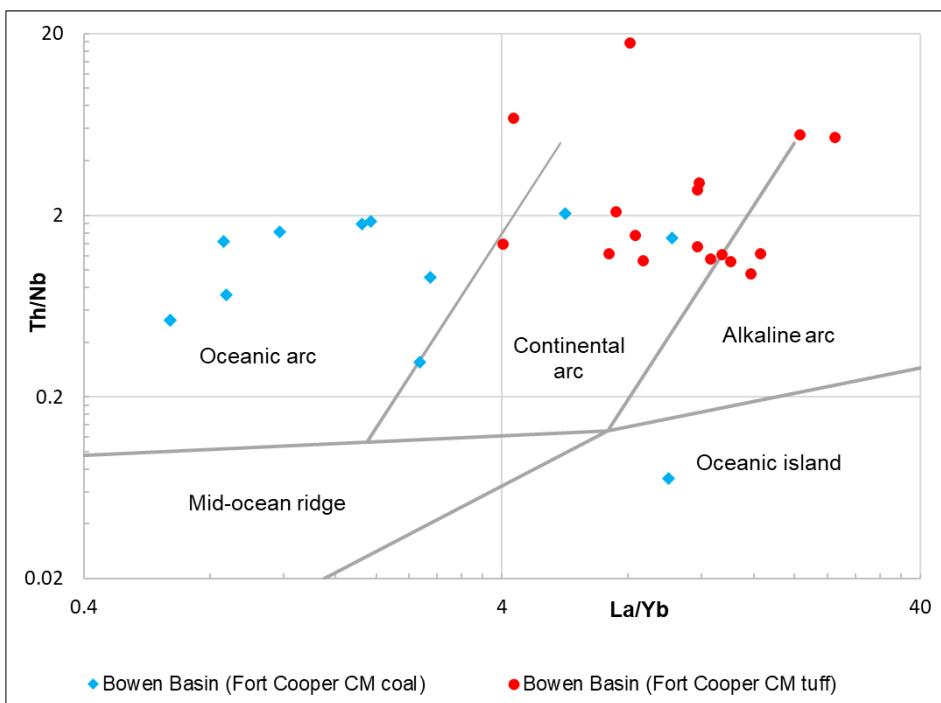


Figure 3. Tectonic interpretation of basaltic rocks (after Hollocher et al. 2012)

Hastie *et al.* (2007) assessed more than 130 basalt samples and introduced a Th-Co diagram as a proxy for K₂O-Si₂O diagrams. They argued that immobile elements like Th and Co would be suitable for the classification of weathered basalts, which will preserve only resistant and immobile elements. In addition, the Th-Co diagram can also discriminate between types of volcanic rocks (Figure 4). This Th-Co discrimination diagram suggests that the mineral material included in the Fort

Cooper coal and tuffs originated from calc-alkaline and high K andesite, dacite and rhyolite, which is consistent with previously reported interpretations (Ayaz, 2015; Fricker, 2019).

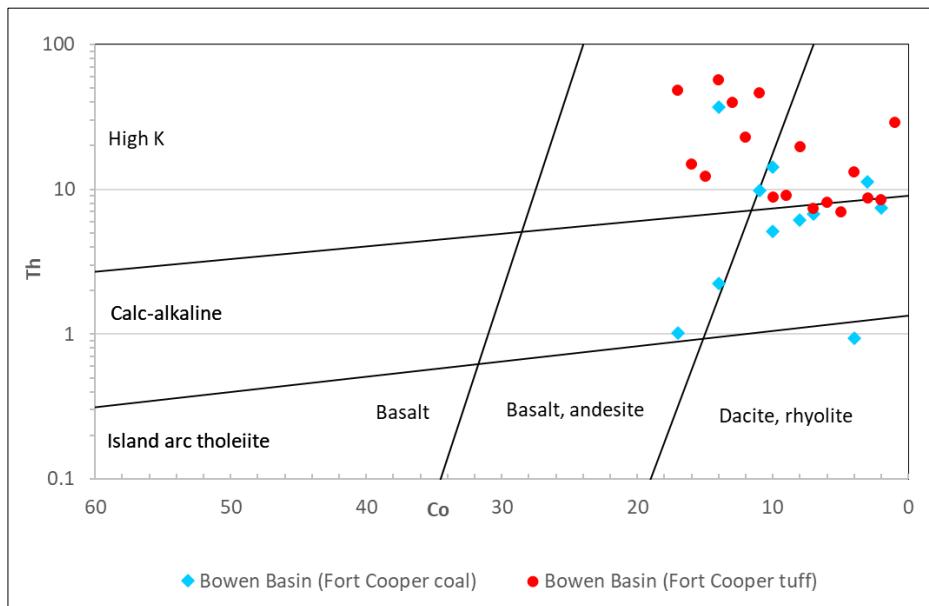


Figure 4. Tectonic and rock discrimination for arc volcanics (after Hastie et al. 2007)

As most of the diagrams have been designed and used for mafic igneous rocks, Gorton and Schandl (2000) revised the Th/Yb – Ta/Yb diagram published by Pearce (1983) and modified it to interpret felsic and intermediate rocks. The new diagram contains three zones for these rocks, based on the progressive enrichment in Th. As seen in Figure 5, some of the Fort Cooper coal and tuff samples plot in different felsic domains (see Figure 3 for comparison).

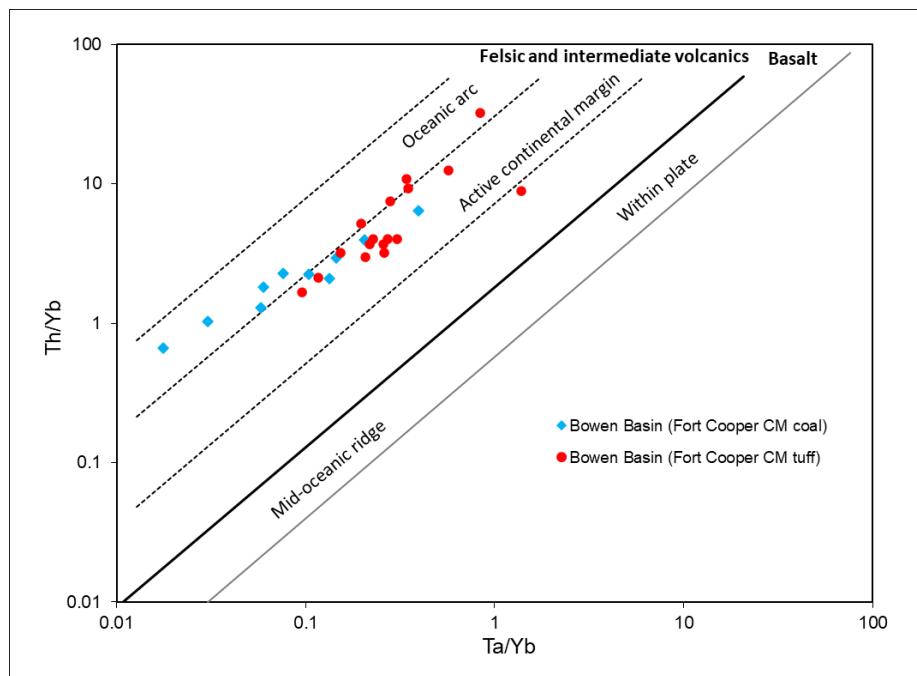


Figure 5. Tectonic discrimination of felsic and mafic rocks (after Gorton and Schandl 2000)

One of the most cited ternary diagrams for the discrimination of basalts has been published by Cabanis and Lecolle (1989). The basalt classification shown in this diagram (Figure 6) is similar to previously presented interpretations (Figure 3 and Figure 4) and confirms the provenance of minerals in the Fort Cooper CM.

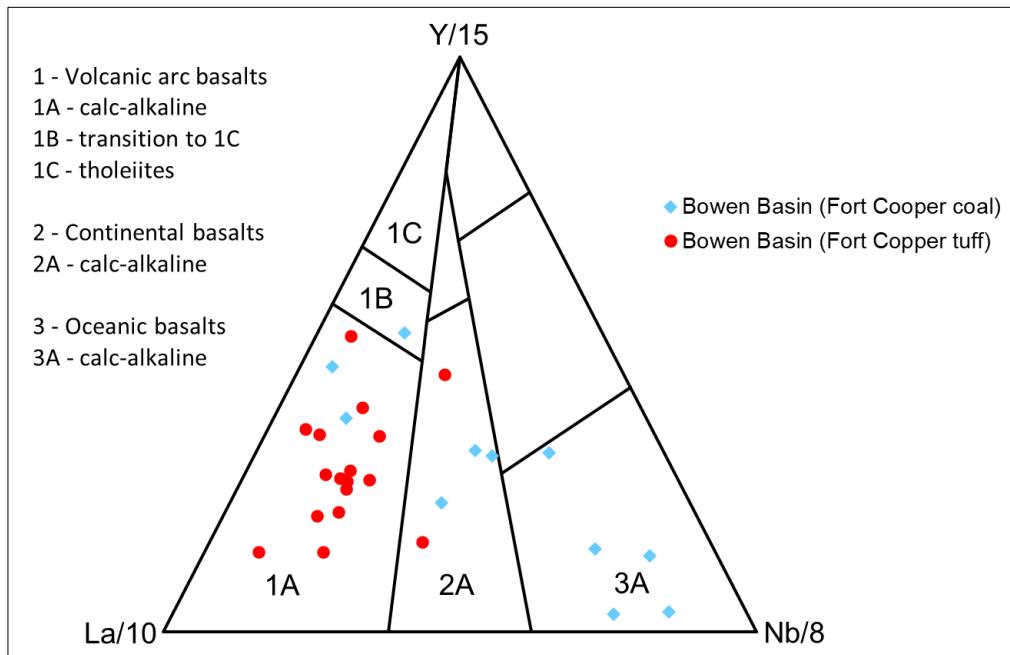


Figure 6 Ternary diagram for basalt classification (after Cabanis and Lecolle (1989))

5.3 Australian research

Assessments of elemental composition in Australian coal waste are not uncommon but relatively little has been done to explore coal waste content as potential resources. CSIRO research, funded by the Australian Coal Association Research Program (ACARP), has made significant contributions in this space, including the development of the Australian standard: ‘AS 1038.10.0-2002 - Coal and coke - Analysis and testing - Determination of trace elements - Guide to the determination of trace elements’. The main purpose of that research was for environmental purposes, concluding that exported Australian coals contain smaller concentrations of hazardous elements than international coals (Dale, 1995, 2003, 2006); however, very few analytical results are publicly available on a regional scale.

Despite its multi-tiered significance (scientific, commercial and environmental), the elemental composition of coal is rarely determined during coal exploration and, when investigated, it is largely focused on major element concentrations. According to international research, tuffaceous coal seams have the potential to host various strategic elements (Seredin and Dai, 2012; Dai *et al.*, 2017), which implies that many coal basins in Australia may be enriched in such elements.

5.3.1 Queensland

5.3.1.1. Relevant geochemical studies

The main objective of recent geochemical investigations of the upper Permian Yarrabee Tuff by Fricker (2019) and (Ayaz, 2015) was to establish the type of magmatic source and compare it with other Permian tuff compositions. The magma composition was found to be within the rhyodacite-dacite and trachyandesite fields, which is a known source of elements (Dai *et al.*, 2012, 2017). The maximum total REE concentration was 340 ppm, with an average of 142 ± 64 . Notable are some elements with concentrations above continental crust averages such as tantalum (Ta), molybdenum (Mo), silver (Ag), bismuth (Bi) and MREE (Ayaz, 2015; Fricker, 2019). Although the focus of that work was geochemical fingerprinting, the concentrations of elements detected in Permian tuffaceous sediments provided an estimate of their potential as a source of elements in the Bowen Basin coal (Figure 7).

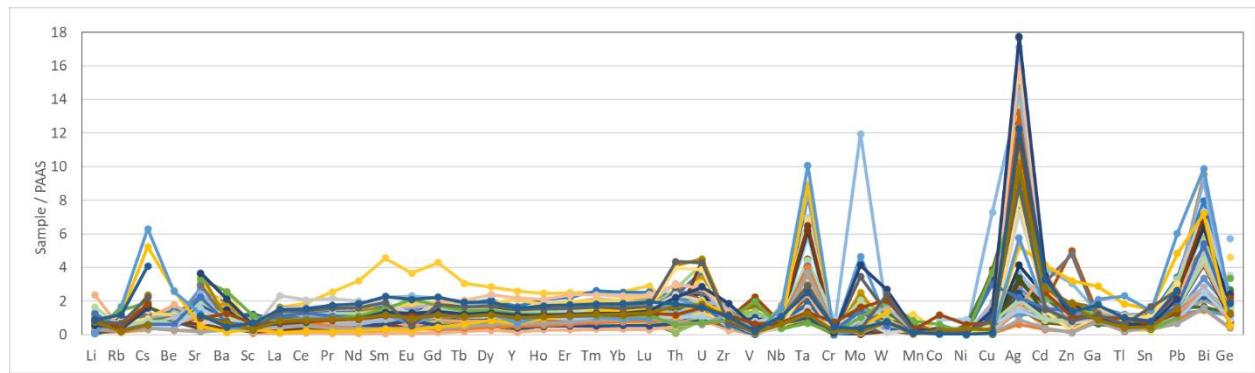


Figure 7. Element concentrations normalised against PAAS (Pre-Archean Australian Shale) in upper Permian tuffs (Ayaz, 2015; Fricker, 2019)

As part of an internal CSIRO project, the current authors investigated concentrations of elements including REE in the tuffaceous Fort Cooper CM. This formation is also upper Permian and stratigraphically located below the Yarrabee Tuff. The coal measures were deposited under foreland conditions and during intense volcanic activity with significant ash falls. **Higher than average crustal concentrations of REEs were found in many of the samples** analysed (primarily coal and tuffaceous layers), with the highest value being 440 ppm (Hodgkinson and Grigorescu, 2020). A detailed review of the Fort Cooper CM is provided by Grigorescu and Coffey (2018). The normalised concentrations revealed enrichments in REE and a few metals (Figure 8), although the absolute concentrations are very low (i.e., less than 1 ppm Ag and up to 3 ppm Bi).

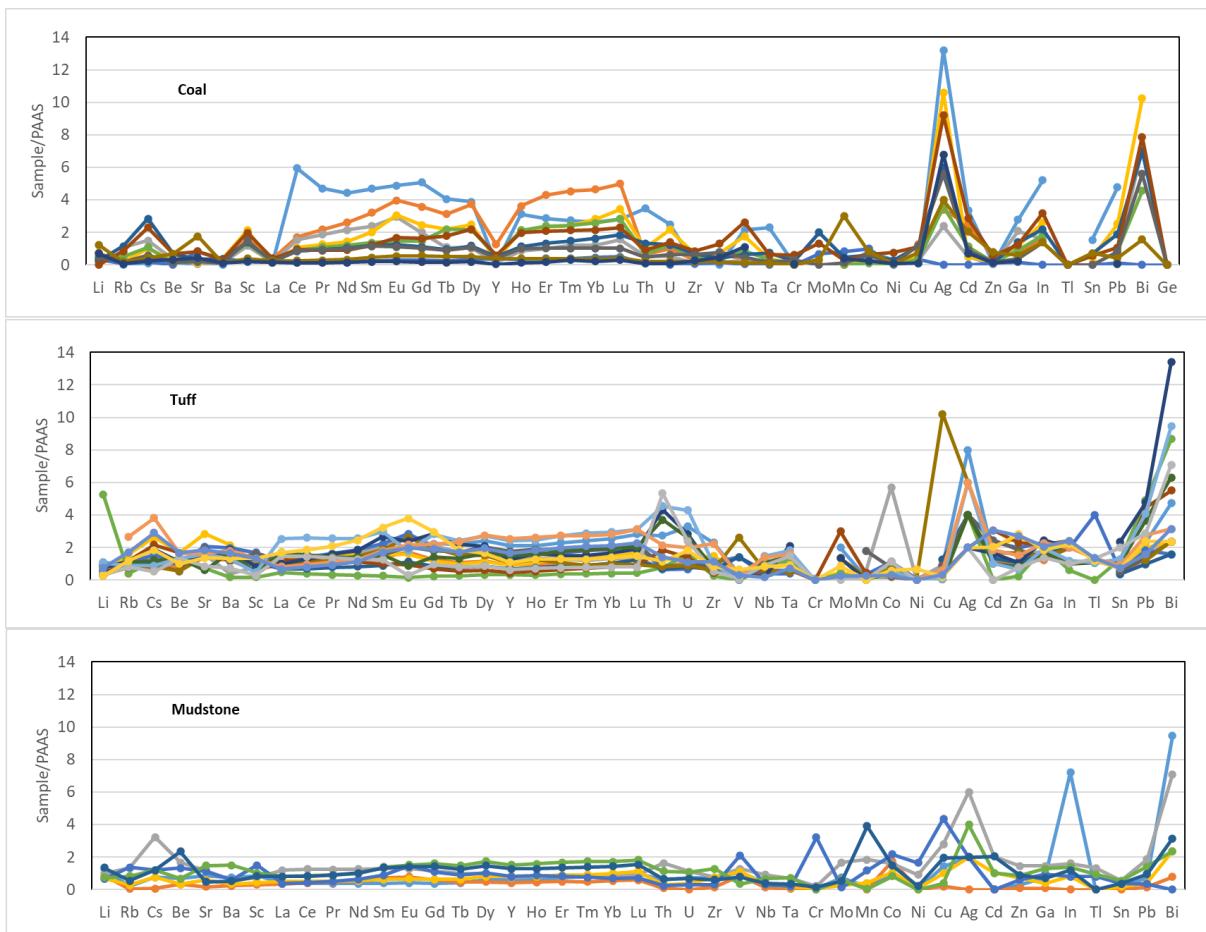


Figure 8. Normalised element concentrations in Fort Cooper CM coal, tuff and mudstones, Bowen Basin (Hodgkinson and Grigorescu, 2020)

Coal from three economically significant seams in the Collinsville Coal Measures were analysed for heavy and rare earth elements (Boyd, 2004). The coal measures occur in the northern-most Bowen Basin, on the western flank, and were **deposited in the thermal subsidence phase of the Bowen Basin evolution**. They are predominantly fluvial grading into paralic at the top, with high vitrinite and low liptinite content (Draper 2013 and references therein).

Coal from the highwalls of the Blake Central, Blake West and Bowen No.2 seams were analysed by Boyd (2004) to determine the likely environmental impact of coal mining and coal use. Heat-affected samples from the roof of the Blake Central, floor of the Bowen No.2 and the intrusion-affected Blake West seam were also analysed and compared with the unaffected coal.

Although the concentration of individual samples or their locations have not been made public, the weighted average concentrations provided by Boyd (2004) showed that most of the concentrations were similar to the average crustal concentrations (Figure 9), with the exception of **Au which is around 1 ppm, about 500 times average crustal composition**. Of note is that the LREE are highly dominant over the heavy elements, although the HREE present a slight enrichment. Overall, heat alteration results in loss of REE, which is more prevalent in the Blake Central seam.

Graphical correlations and sequential leach extractions showed that all the REE are associated with monazite or xenotime, with some presenting a minor affinity for illite or kaolinite. Weak association with apatite was determined for Eu, Sm and Tb, while Sc and Yb also associated with organic phases (Boyd, 2004).

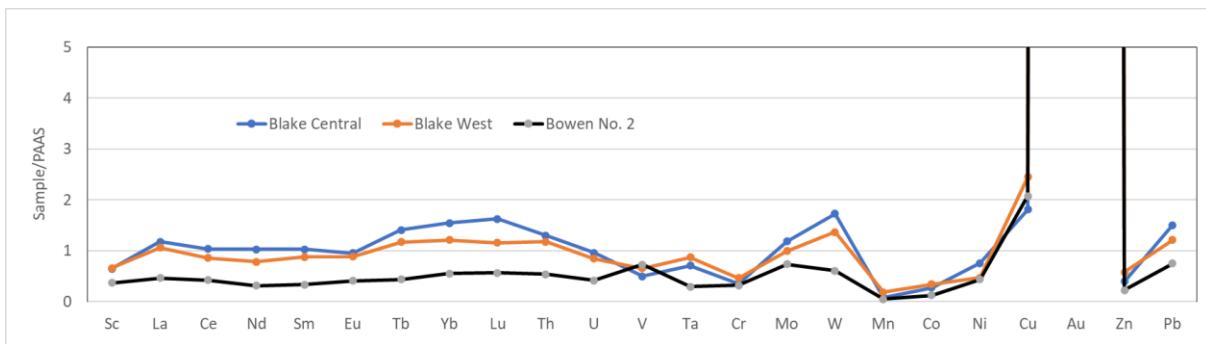


Figure 9. Normalised elemental concentrations of Collinsville CM seams, Bowen Basin (Boyd, 2004); note the enrichment in Au.

5.3.1.2. The Geological Survey of Queensland geochemical database

A large repository of geochemical analyses is held by the Geological Survey of Queensland (GSQ). The database includes analyses undertaken by GSQ over several decades and data collated from reports and research theses.

The following presents several examples of normalised elemental concentrations in sedimentary rocks that are relevant to the current study:

- a) Back Creek Group, lower Permian, Bowen Basin (Figure 10). Slight enrichments in lanthanum (La), yttrium (Y), vanadium (V), chromium (Cr) and nickel (Ni) have been found in the mudstones, sandstones and siltstones of the group. The REE data is incomplete with only LREE concentrations reported.

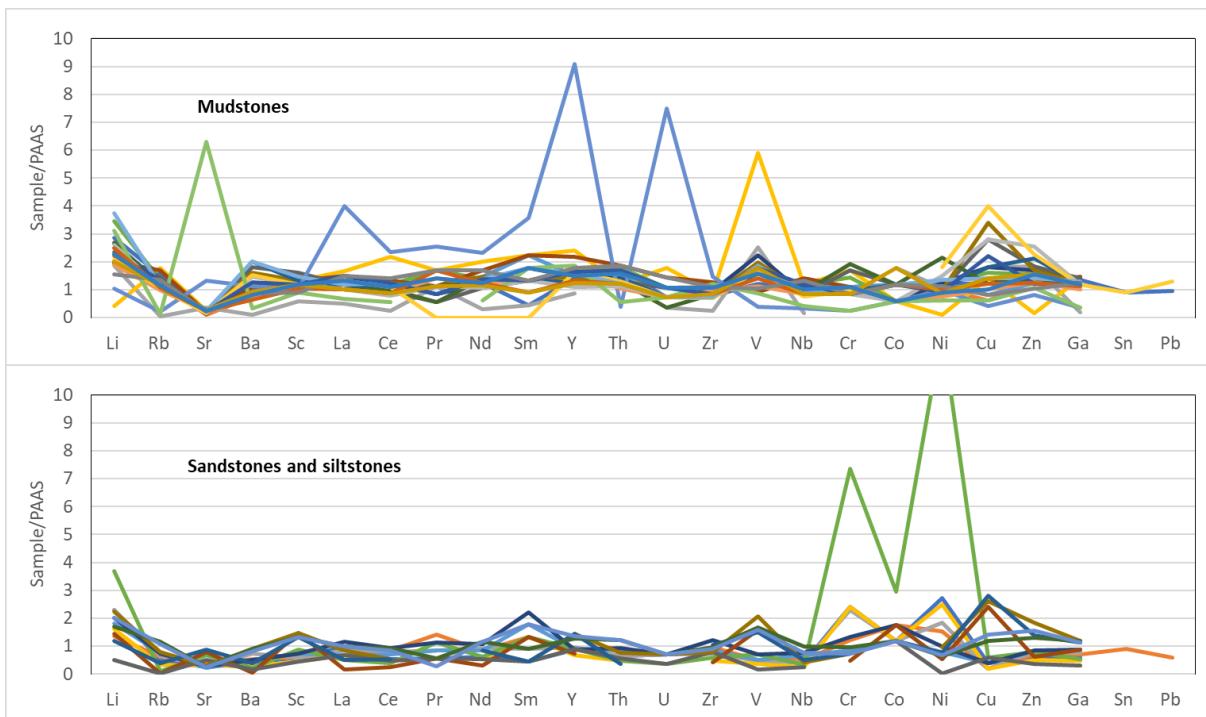


Figure 10. Normalised elemental concentrations in Back Creek Group, Bowen Basin (GSQ database)

- b) Black Alley Shale and Kaloola Member tuffs, upper Permian, Bowen Basin (Figure 11). Slight enrichments in thorium (Th), uranium (U), niobium (Nb), Ta, gallium (Ga), thallium (Tl) and Bi are apparent. Similarly, the MREE present a slight enrichment, while the Eu anomaly is negative in all the samples, indicating a felsic origin of minerals.

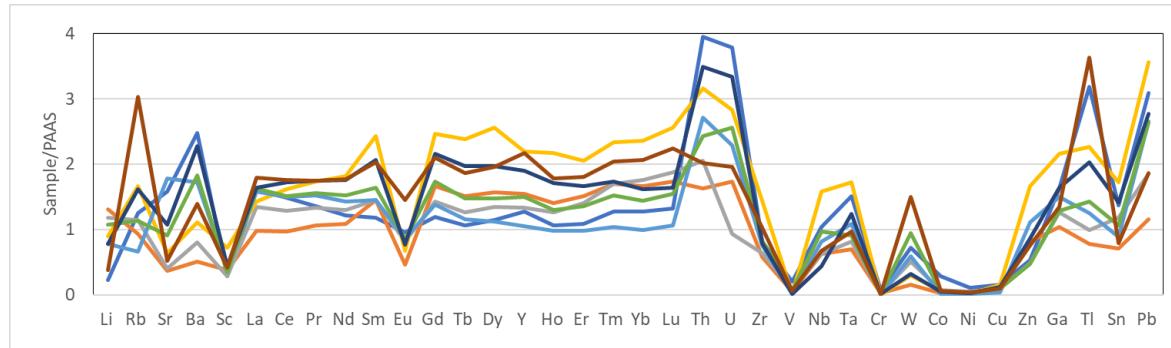


Figure 11. Normalised elemental composition of mudstones, Bowen Basin (GSQ database - Kaye 2014)

- c) Brisbane Tuff, upper Triassic, Ipswich Basin (Figure 12). These rhyolitic tuffs present a strong enrichment in Y, which varies between 95 and 150 ppm and Yb, between 11 and 17 ppm. Vanadium and Nb are also slightly elevated above the average crustal concentrations.

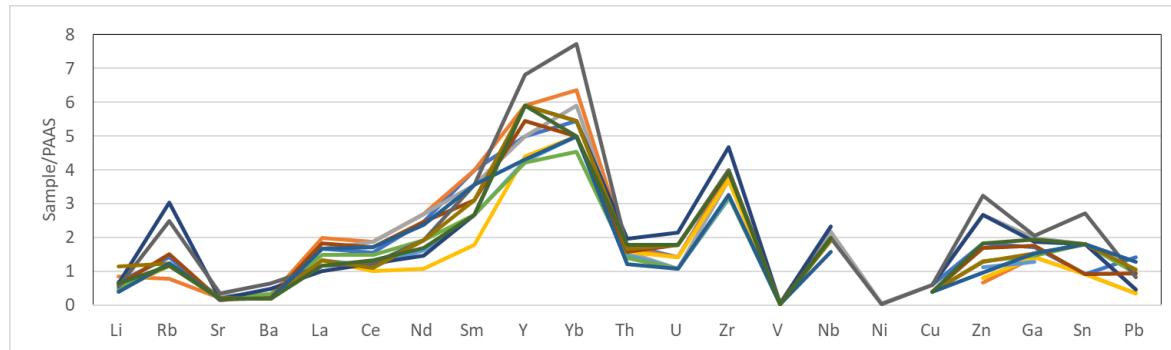


Figure 12. Normalised elemental composition of rhyolitic tuffs, Ipswich Basin (GSQ database).

- d) Walloon CM mudstones, upper Jurassic, Surat Basin (Figure 13). The character of mudstones units analysed below and above the Tangalooma Sandstone is very consistent, with no significant enrichments except terbium (Tb), which is highly elevated with concentrations ranging 3.5 to 7.8 ppm.

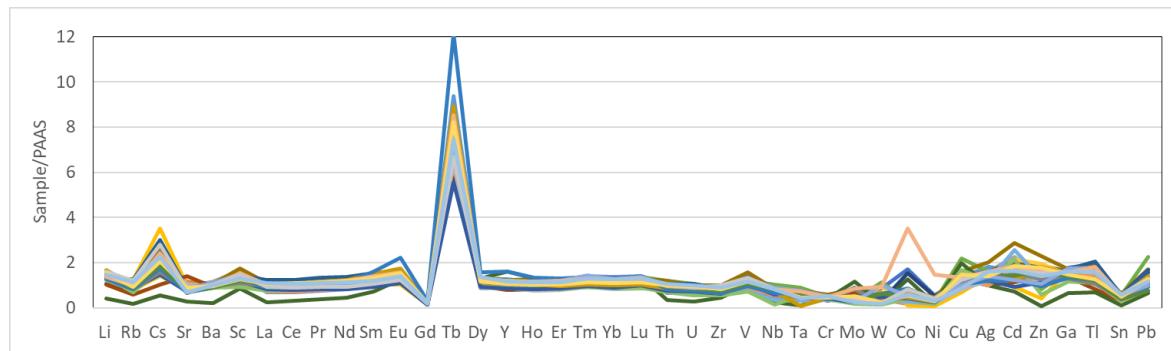


Figure 13. Normalised elemental composition of mudstones, Walloon CM, Surat Basin (GSQ database - Anderson 2014)

5.3.1.3. Geological background pertinent to element sources

Although not referring to the elemental composition of coal seams, the research conducted by Michaelsen and Henderson (2000) is highly relevant to the current study.

More than 200 sandstone samples from the Permian-Triassic succession of the northern Bowen Basin were analysed petrographically to identify the sediment source. The authors found two distinct petrofacies: a quartz-rich assemblage characteristic of the Back Creek Group (middle to upper Permian) and a volcanolithic-rich assemblage in the Blackwater Group (upper Permian), which includes several coal-bearing formations (Moranbah, Fort Cooper and Rangal coal measures).

The abundance of lithic fragments, overwhelmingly volcanic grains, increased upwards, with:

- 30% in the Moranbah CM
- 66% in the Fort Cooper CM, and
- 99% in the Rangal CM

Based on the abundance of volcanoclastics, the authors hypothesised that the dominant sediment source was the Middle Devonian to Early Carboniferous volcanic rocks, largely from the New England Orogen (Michaelsen and Henderson, 2000).

The Late Triassic basins (i.e. Ipswich and Tarong basins) are considered post-orogenic although they developed and started receiving sediments during the last compressional phase of the Hunter-Bowen Orogeny (Withnall *et al.*, 2013); **in terms of sediment source, these basins and their coal measures were most likely influenced by contemporaneous magmatism.**

Following the end of the Hunter-Bowen Orogeny in Middle-Late Triassic, the Great Australian Superbasin, including the Surat Basin, developed during the stabilisation of the eastern Australian continental margin and the New England Orogen. However, significant volcanoclastic input is apparent across the entire superbasin. The extrabasinal volcanism occurred in two pulses, related to rifting events along the eastern margin of the superbasin. The first pulse was in Middle Jurassic and the second occurred in Early Cretaceous (Bryan, 2013). Recent research showed that the tuff layers within the Walloon Coal Measures were produced by volcanoes with intermediate to felsic magma. It was inferred that the tuffs were related to a late Palaeozoic to Cretaceous continental arc caused by the westward subduction of the Pacific plate (Wainman, McCabe and Reynolds, 2021).

The **volcanic influence** determined by previous research (i.e., Michaelsen and Henderson 2000; Wainman *et al.* 2021) **demonstrates the potential of coal measures throughout eastern Australia to host trace and rare earth elements.**

5.3.2 New South Wales

Various coal seams from the Sydney Basin were analysed by Zhao (2012) to establish and discuss the relationship between mineral matter and the associated trace elements and REE. The samples included seam sections, outcrop and borehole core from the Bulli, Great Northern and Greta seams. The Great Northern and Greta coals are high-volatile bituminous in rank, while Bulli is classified as medium-volatile; of note is that the Great Northern coal contains a high proportion of liptinite and pyrite at the top, indicating the marine influence during its deposition.

The concentrations of most trace elements in the Great Northern, Bulli and the low-ash Greta coals were lower than the averages for worldwide coals. The vast majority of samples contained REE concentrations below the average crustal values, with total REE ranging from 11 ppm to 139 ppm. All seams were enriched in HREE and presented a positive Eu anomaly. Zhao (2012) reported some highly elevated concentrations of germanium (Ge) in the Greta seam, Bi in the Great Northern and lithium (Li) in Bulli coals (Figure 14) but such anomalous concentrations, in the order of tens of ppm, cannot be checked or confirmed by the authors of this report. The New England Fold Belt was considered the main source of elements (Zhao, 2012).

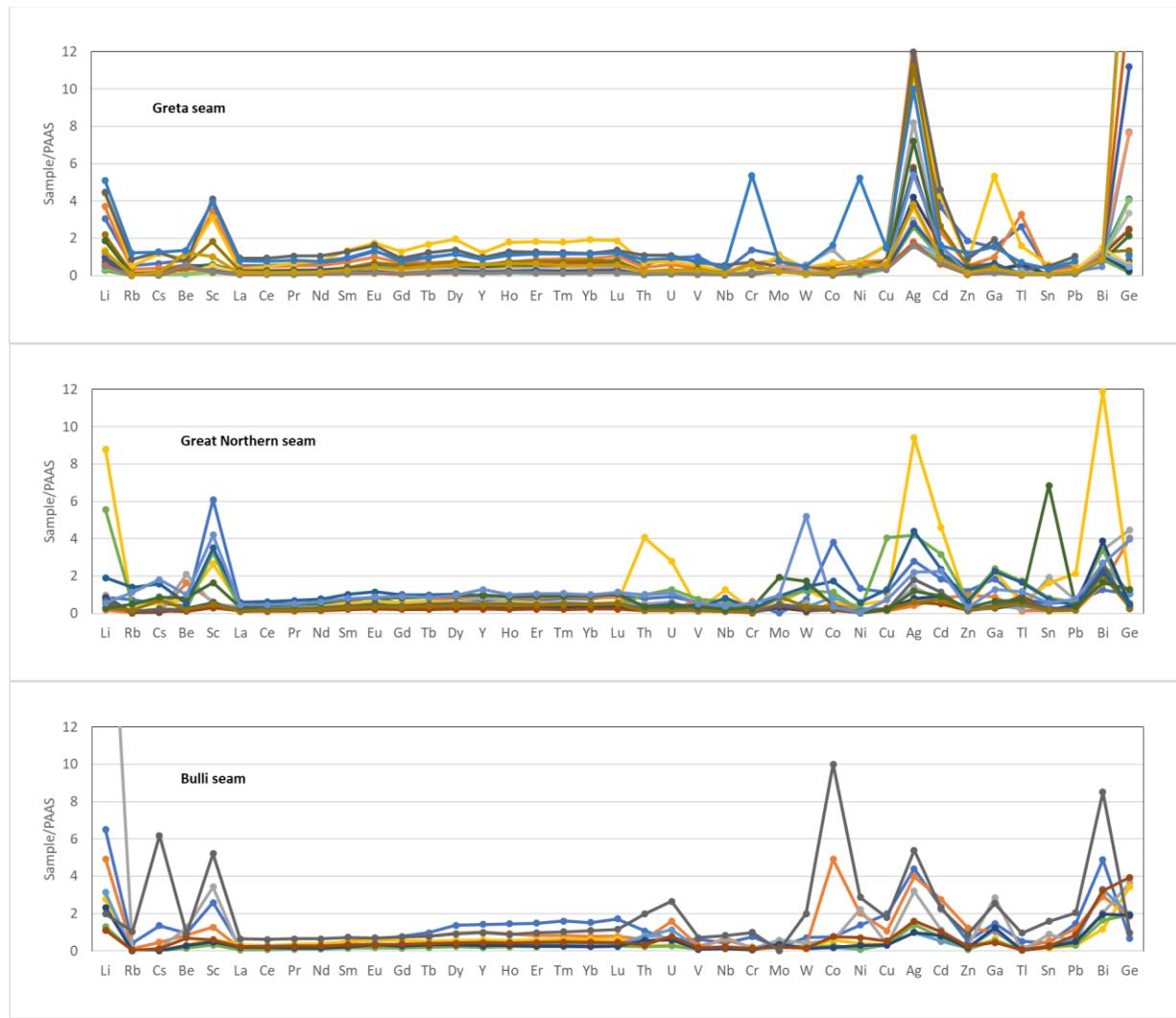


Figure 14. Normalised concentrations of elements in selected coal seams, Sydney Basin (Zhao, 2012).

The association of elements with the mineral matter in Permian coals from the Gunnedah Basin was investigated by Ward *et al.* (1999). Lanthanum, Ce and neodymium (Nd) were the only REE analysed; the majority of the samples had total REE concentrations below 50 ppm and no clear correlation with organic or mineral phases was reported. The potassium-bearing minerals contained high concentrations of rubidium (Rb) and the authigenic kaolinite had relatively high proportions of titanium (Ti). Zirconium (Zr) was also abundant and it was found to be associated with phosphorus (P) and hafnium (Hf). Based on the relationships exhibited by Ti, Zr, neodymium (Nd) and Y, Ward *et al.* (1999) concluded that an acid volcanic source contributed mineral matter to the coal seams analysed. Pyrite contained high concentrations of arsenic (As) and minor proportions of Tl, while Ge and gallium (Ga) appeared to be associated with the organic components. Chromium and V were

also related to each other, as were Ce, La, Nd and praseodymium (Pr), but none of these showed a relationship with organic or inorganic phases.

Geochemical correlation of the tuffs of the Illawarra CM with similar units in the stratigraphically equivalent Newcastle CM was undertaken to determine spatial relations during the deposition of coal-bearing units in the Sydney Basin (Grevenitz, Carr and Hutton, 2003). Three different claystone members (Huntley, Farmborough and Burragorang) were analysed for trace elements and REE to enable the characterisation of magma. The data showed that the magma was calc-alkaline, rhyodacitic to rhyolitic in composition and derived from a continental volcanic-arc tectonic setting (Grevenitz, Carr and Hutton, 2003). The study also provided some information on the concentrations of REE. Most samples contained up to two times the average REE crustal concentrations. There was no dominance of either the LREE or HREE, while the Eu anomaly was slightly negative. The normalised data showed enrichment in Mo and Bi (Figure 15).

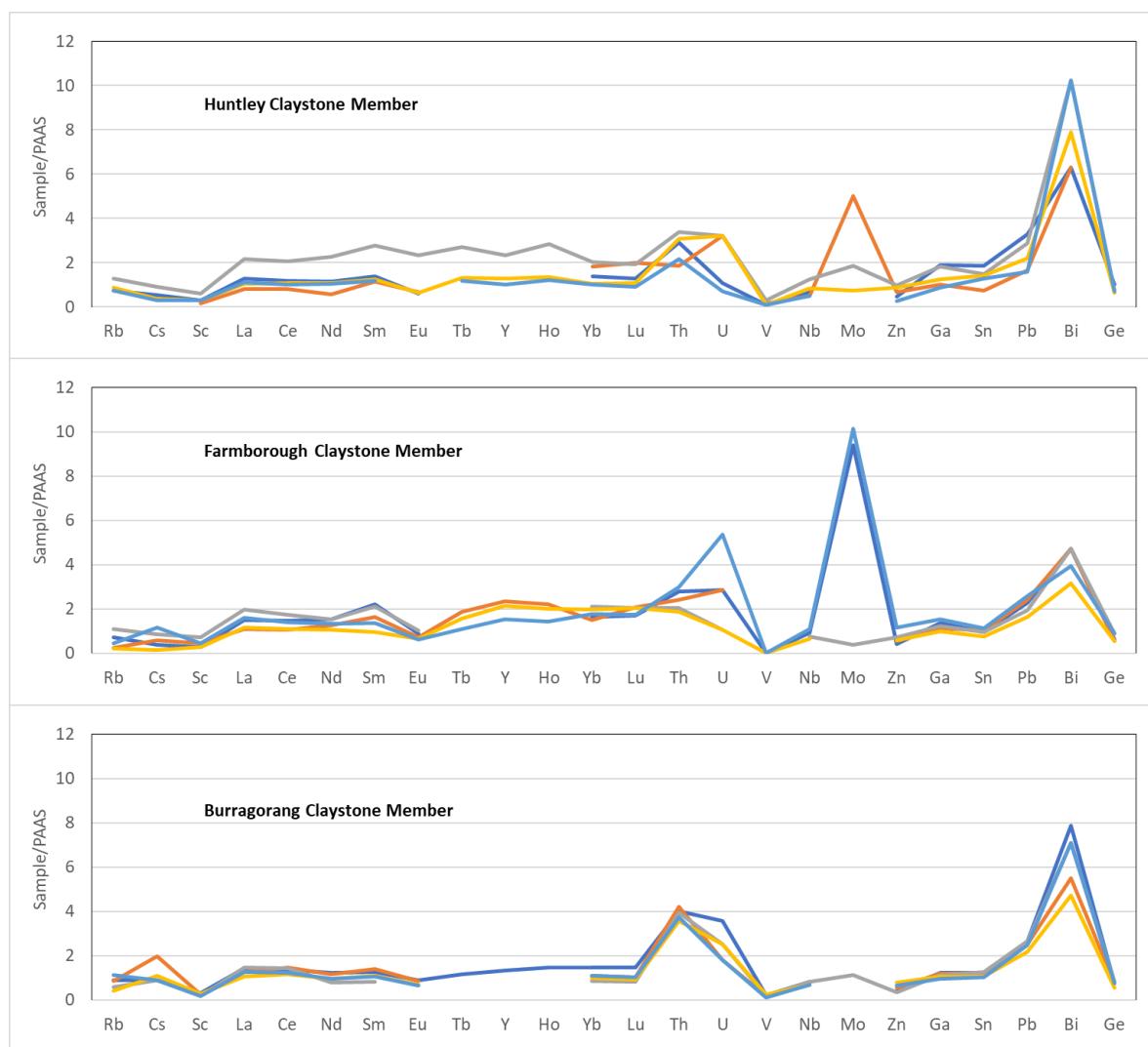


Figure 15. Normalised concentrations of elements in tuffs, Sydney Basin (Grevenitz, Carr and Hutton, 2003).

5.4 Target coal basins

Here we present geological background and history on the following basins that are represented by the samples analysed in this project:

- Bowen Basin
- Tarong Basin
- Ipswich Basin
- Surat Basin
- Gunnedah Basin
- Sydney Basin

5.4.1 Queensland

5.4.1.1. Bowen Basin

The Bowen Basin is the Queensland section of the large intracontinental coal-bearing Bowen-Gunnedah-Sydney Basin System that extends south into New South Wales (Draper, 2013). During its tri-phase evolution, from the latest Carboniferous–Early Permian to the late Middle Triassic, the basin was shaped by transtension, thermal subsidence and finally by foreland loading. The deformation and thrusting events of the latter phase are referred to as the Hunter-Bowen Orogeny (Korsch and Totterdell, 2009; Korsch *et al.*, 2009; Draper, 2013). During extensional and compressional events, the formation of troughs and platforms controlled deposition by changing the location of sedimentation depocentres (Mallett *et al.*, 1995). The environment of deposition and the rate and continuity of sedimentation were influenced not only by tectonism and changing depocentres, but also by series of marine transgressions and regressions (Draper, 2013).

Sedimentation during the initial extensional phase was mainly non-marine (Fielding *et al.*, 2001) and lead to the deposition the Reids Dome beds (Group 1, Table 5, after Draper and Boreham 2006).

Table 5. Coal groups and their formations

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

The subsequent thermal subsidence phase was extensive and largely marine, and included the Collinsville CM in the Bowen Basin. The Blair Athol and Wolfgang CMs occur in small early Permian cratonic basins to the west of the Bowen Basin (Group 2, Table 5). The coal seams are thick and similar in quality and depositional regime; the coal is generally thermal or high-volatile bituminous rank (Draper, 2013).

The late Middle Permian to late Middle Triassic foreland loading phase caused subsidence and sedimentary deposition under a variety of conditions:

- a) Late Permian – shallow-marine delta, prodelta, fluvio-deltaic, lacustrine and alluvial-plain settings – with deposition of the Group 3, 4 and 5 coals, and
- b) Early and Middle Triassic - meandering-fluvial, paleosol, braided-fluvial, lacustrine and enclosed fluvial systems with marginal alluvial fans

Probable uplift and exhumation caused basin termination at the end of the Middle Triassic (Fielding *et al.*, 2001; Draper, 2013).

Due to the complex geological and tectonic history of the Bowen Basin, the coal seams exhibit large variations in rank and quality. With the exception of Group 1 and Group 4, all other coals of the Bowen Basin are economically mined as they represent a significant resource of thermal and coking coal.

Fort Cooper Coal Measure (Group 4) samples previously analysed have been considered in this work. The coal measures sampled as part of this investigation are:

- Collinsville CM (Group 2)
- German Creek Formation (Fm) (Group 3)
- Bandanna Fm (Group 5) and
- Rangal CM (Group 5)

The **Collinsville CM (Group 2)** formed during an early phase of extension of the basin and crop out in the northern-most section of the Bowen Basin. The formation is fluvial at the base and paralic at the top. The thickest seams (up to 12 m) are in the fluvial sequences, with the highest rank being recorded in the Blake Seam (Draper 2013 and references therein).

The **German Creek Fm is a lateral equivalent of the Moranbah CM (Group 3)**; they both contain high-grade, vitrinite-rich, hard coking coal. Although both deposited during the onset of the foreland phase, their environment of deposition changed, from a fluvial to delta plain environment in the Moranbah CM, to a distal delta and marginal marine setting in the German Creek Fm (Draper, 2013).

The last phase of coal deposition includes the **Rangal CM and the Bandanna Fm. Group 5** is highly diverse in terms of quality and conditions of sedimentation, which encompass fluvial, lacustrine and paludal settings of deposition. The Rangal CM cover most of the northern Bowen Basin and were deposited in alluvial plains. The Bandanna Fm is more restricted geographically and appears to be a deltaic system developed in a freshwater lake. The coal rank of the group is consequently highly variable and all types of coal (thermal, coking and pulverised coal injection - PCI) are produced from these formations. At depth, these coals represent source rocks and are targeted for coal seam gas (CSG) production (Draper 2013 and references therein).

As previously detailed in Section 5.3.1.3., Group 3, 4 and 5 coals contain abundant volcaniclastics (Michaelsen and Henderson, 2000) and may potentially present elemental enrichments.

5.4.1.2. Ipswich Basin

The Ipswich Basin is an intermontane transtensional basin, with the **formation of interest in this study, being the Ipswich CM**, representing a thermal relaxation phase. During this depositional phase and possibly after its termination, the coal measures were deformed, folded and faulted, resulting in north-northwest trending structures.

The West Ipswich Fault represents a major fault system controlling the extent of the basin and its coal measures. Based on seismic evidence, the Ipswich CM onlap this structure, which has been interpreted as a basement high. The succession in the Ipswich Basin consists of basal, undifferentiated volcanics and the upper Ipswich CM. The latter has been divided into the lower Kholo Subgroup, which contains predominantly volcanic-rich material as lava flows and ash falls, and minor coarse sediments with reworked volcanic clasts. The upper succession, the Brassall Subgroup, is fluvial, with the lower unit (Tivoli Formation) being deposited in a predominantly river channel environment. The upper unit (Blackstone Formation) was deposited in a structurally controlled floodplain environment. Both units of the Brassall Subgroup contain numerous coal seams, thinner and less consistent laterally in the Tivoli Formation and thicker in the upper Blackstone Formation (Purdy and Cranfield 2013 and references therein).

The Ipswich Basin coal has the potential of containing strategic elements due to the intense faulting of the basin and the presence of volcanic material in its sediments and coal seams.

5.4.1.3. Tarong Basin

The Tarong Basin is a small, **fault-bounded basin**, which has been dated as Late Triassic and correlated with the Tivoli Formation in the Ipswich CM. The initial fluvial depositional environment was suggested to be high-energy and rapid, which lead to the deposition of the basal conglomerates. This was followed by decreasing sedimentation and formation of swampy conditions in paludal or lacustrine environments. Intermittent volcanic activity continued throughout the deposition. Secondary faults created 20-400 m lateral displacements in the coal areas (Jell 2013 and references therein).

The coal measures contain three main seams that increase in ash content with depth ((Beamish, B., Edwards, D. and Theiler, 2018) and references therein):

- the Ace seam, which is the uppermost and has an average thickness of 5.7m (Proberts, 2016 and references therein)
- the King seam (up to 16m thick) and
- at the base, the Queen seam (34m thick), each with high ash content (25–45%, Mutton 2003)

5.4.1.4. Surat Basin

The Surat Basin is a large, intracratonic basin formed in a continental sag from Late Triassic to Early Cretaceous. It is contiguous with the Eromanga Basin to the west and the Clarence-Moreton Basin in the east. The structure of the basin has been controlled by basement topography and the underlying Bowen Basin and its depo-centres (Cook and Draper 2013 and references therein).

Economically significant due to its hydrocarbon, coal and water resources, the Surat Basin has been extensively investigated to determine basin architecture, stratigraphy and age (Hamilton, Esterle and Sliwa, 2014; Wainman *et al.*, 2015; Reilly *et al.*, 2019; Wainman and McCabe, 2019).

The focus for this investigation is the Walloon CM, which are Late Jurassic in age (Wainman *et al.*, 2015) and about 350-500 m thick. The formation comprises labile sandstone, siltstone and mudstone, and coal in the upper two-thirds of the unit. It was interpreted as having been deposited in a fluvio-lacustrine environment with peat-forming mires (Cook and Draper, 2013; Wainman and McCabe, 2019).

The stratigraphy of the formation has been long disputed with the latest model comprising the following units, from the oldest to the youngest:

- Durabilla Formation
- Taroom CM
- Tangalooma Sandstone and
- Juandah CM (including lower Juandah CM, Juandah Sandstone and upper Juandah CM)

Lithofacies analysis and isopach maps suggest deposition in a southerly, prograding fluvial system (Hamilton, Esterle and Sliwa, 2014).

More recently, Reilly *et al.* (2019) employed seismic data and sequence stratigraphic methods to correlate stratigraphic units for fluid flow modelling. The study also showed that the Walloon CM consisted of bright reflectors, with the Macalister Seam being the first strong reflector at the top of the formation; the seam splits several times and the age of the splits differ regionally.

Facies and palynological analyses revealed marine-influenced facies, with brackish palynomorphs and tidal structures in the upper part of the measures (Wainman and McCabe, 2019). Palaeogeographic maps suggested that the fluvial system drained south/south west with the marine influence coming from the north and east.

The Walloon CM comprise thermal coals with high vitrinite and liptinite (Cook and Draper 2013). The overall **high detrital input to the mires and the numerous tuff layers** (Wainman *et al.*, 2015) **make the Walloon coal seams a target for trace element and REE determination.**

5.4.2 New South Wales

5.4.2.1. Gunnedah and Sydney basins

The tri-phase evolution (transtension, thermal subsidence and foreland loading) that shaped the Bowen Basin (Section 5.4.1.1.) has been inferred for the Gunnedah and Sydney basins (Fielding *et al.*, 2001). Relevant to the current study is the lateral correlation of Late Permian coal-bearing formations: Rangal CM (Bowen Basin), Upper Black Jack Group (Gunnedah Basin) and Illawarra CM (Sydney Basin), all of which have been sampled and analysed to perform a regional comparison of coal composition within the Bowen-Gunnedah-Sydney Basin.

The Black Jack Group consists of distinct sub-groups with several units of sandstones, shales, tuffs, conglomerates and coal. The thickness of the group varies from about 50 m in the west to more than 450 m in the south-east, but is mostly around 200 m. Several thick intrusions (tens of metres) are present near- and south of- the township of Gunnedah.

The lower section is deltaic with abundant coal, while the upper section is largely fluvial-lacustrine with marine influences (Tadros, 1995). Significant to this project is the presence of tuffs and intrusions, which may represent a source of elements in the Black Jack coal.

The Illawarra CM occur along the western margin of the Sydney Basin and consist of two major sub-groups. The lower unit represents the transition from marine deposition to a deltaic environment, with coal units. The upper unit is fluvial with point bars and floodplain environments, which also contains coal units. The Bulli Coal is the upper-most coal sequence, which marks the end of coal deposition in the Illawarra CM (Herbert and Helby, 1980).

6 Methodology and data

- 79 coal mine samples and 10 power plant ash samples have been analysed
- Previously published data from several authors has also been used
- The PAAS averages published by McLennan (2001) have been used for the normalisation of all elements analysed
- A series of ratios and indices have been calculated for the samples
- Discrimination diagrams to determine tectonic settings and geological evolution of a related rock systems have been interpreted
- Results have been mapped in ArcGIS

6.1 Samples analysed

The samples analysed and discussed in this study have been kindly provided by participating mines (Table 6, Figure 16 and Figure 17) and power plants (Table 7, Figure 18), the latter via the Ash Development Association of Australia (ADAA). Samples were ‘grab samples’ typically collected from larger samples provided by the mines or from bore core as available.

Table 6. Mine sample details

Mine	Coal formation	Age	Basin	Type (number)
Collinsville	Collinsville CM	Early Permian	Bowen	Coal from 2 pits (6)
Newlands	Rangal CM	Late Permian	Bowen	Coal (2), raw feed (2)
Coppabella	Rangal CM	Late Permian	Bowen	Coal (7)
Moorvale	Rangal CM	Late Permian	Bowen	Coal (5)
Lake Vermont	Rangal CM	Late Permian	Bowen	Coal, shale, tuff (12)
Oaky Creek	German Ck Fm	Late Permian	Bowen	Raw feed (1)
Rolleston	Bandanna Fm	Late Permian	Bowen	Coal (3)
Meandu	Tarong beds	Late Triassic	Tarong	Coal (6)
Collingwood Park	Ipswich CM	Late Triassic	Ipswich	Coal (2)
Wandoan	Walloon CM	Late Jurassic	Surat	Coal, mudstone (27)
Unnamed contribution	Black Jack Group	Late Permian	Gunnedah	Coal (2)
Metropolitan	Illawarra CM (Bulli seam)	Late Permian	Sydney	Coal (4)

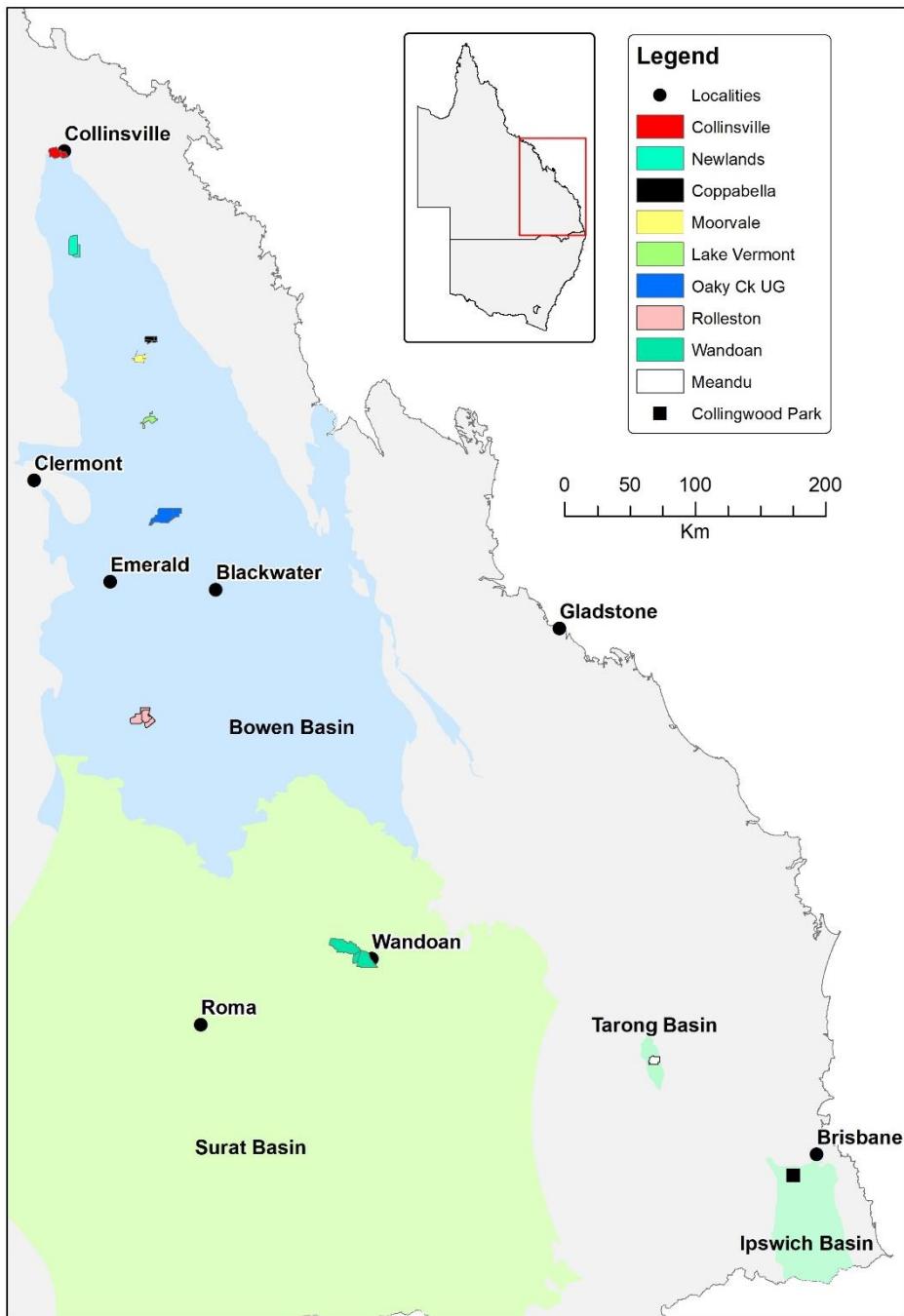


Figure 16. Location of participating Queensland mines in relation to coal-bearing sedimentary basins

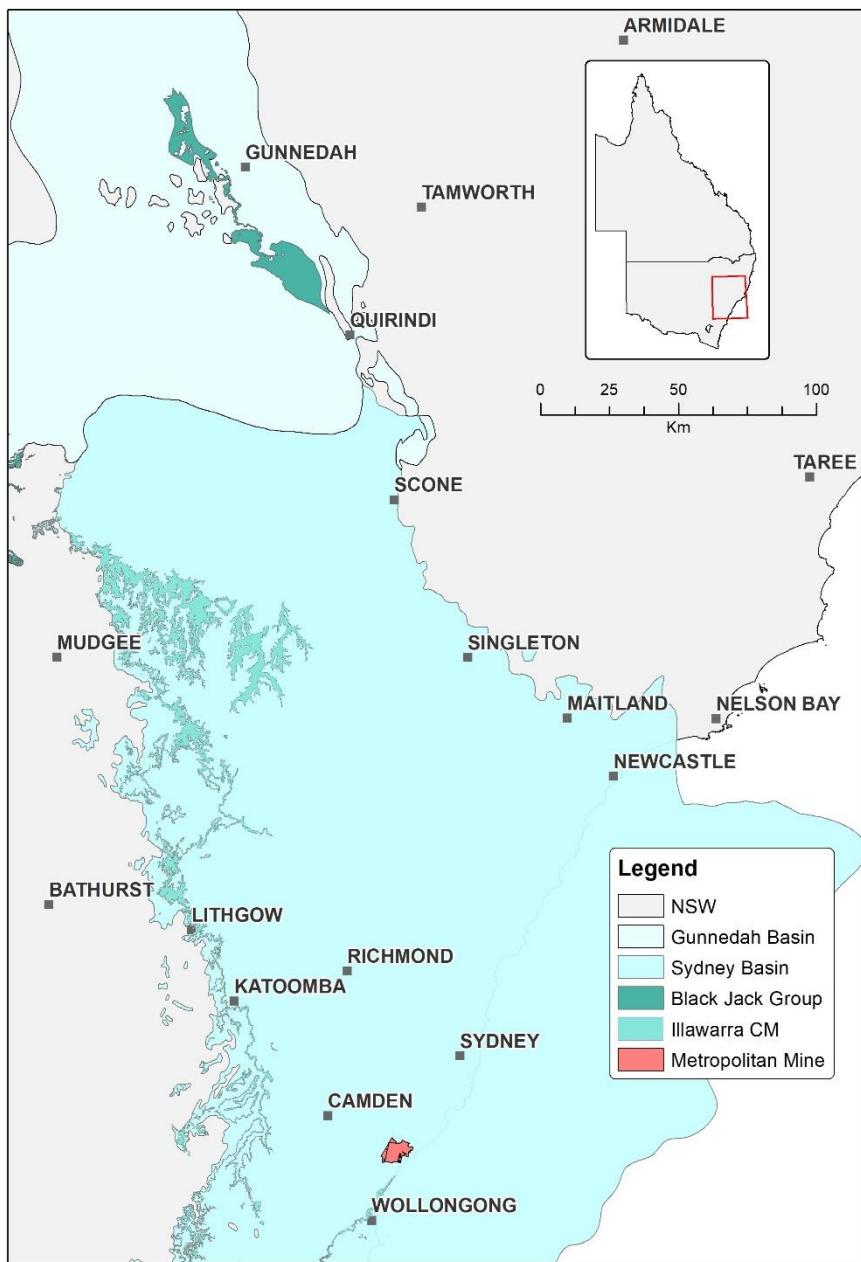
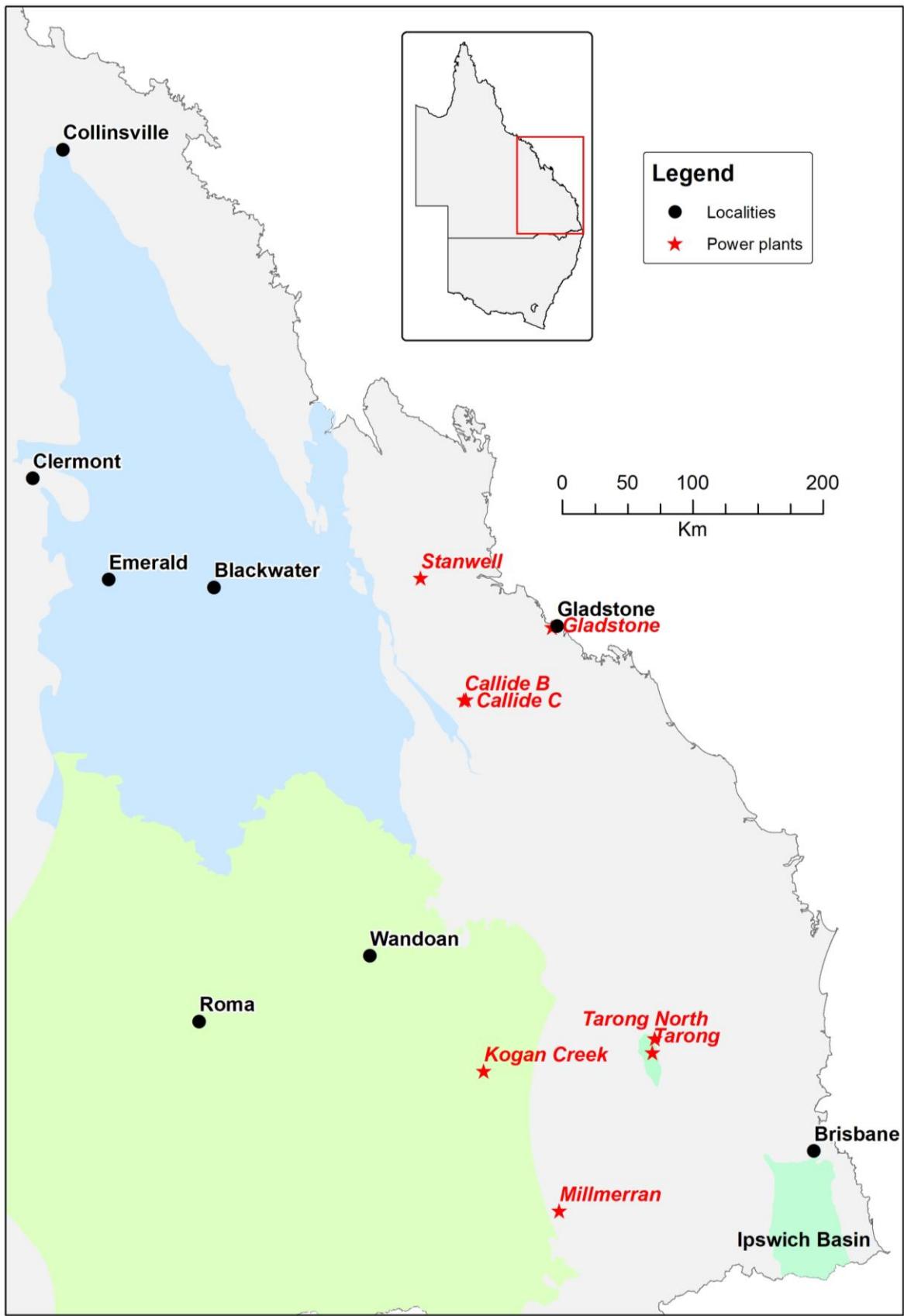


Figure 17. Participating New South Wales mines include an unnamed mine in the Gunnedah Basin and Metropolitan mine in the Sydney Basin

Table 7. Power plant samples

Power plant*	Mine and coal feed	Age	Type (number analysed)
Stanwell	Coronado Curragh mine – Rangal CM	Late Permian	Fly ash (1), bottom ash (1)
Gladstone	Rolleston and Ensham – Rangal CM	Late Permian	Fly ash (1), bottom ash (1)
Callide	Callide mine – Callide CM	Late Triassic	Fly ash (1), bottom ash (1)
Kogan Creek	Kogan Creek mine – Walloon CM	Late Jurassic	Fly ash (1), bottom ash (1)
Millmerran	Commodore mine – Walloon CM	Late Jurassic	Fly ash (1), bottom ash (1)

*Power Plant samples were kindly provided by the ADAA



Figure

18. Participating Queensland power plants

6.2 Sample and mine details

The samples analysed provide a good regional coverage for characterisation of a large range of formations, depths, seam compositions and coal rank (Table 8).

Table 8. Samples analysed in this study

Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Collinsville	Blake (BUB)	Coal	CBLA-01	63
	Bowen upper (BUB)	Coal	CBLN-02	59
	Bowen lower (BUB)	Volatile coal	CBLN-O1	67
	Little Bowen (BUB)	Coal	CLBOW-1	51
	Potts (Blake North)	Coal	CPOTTS-1	64
	Scott/Denison (Blake North)	Coal	SCCDE-1	15.5
Newlands	Goonyella Middle Seam	Coke raw feed	NEW-1	260
	Goonyella Middle Seam	Coke raw Feed	NEW-2	260
	P67 Goonyella Middle Seam	Coal	NEW-3	230
	R3 BSB Goonyella Middle Seam	Coal	NEW-4	260
Coppabella	Leichhardt Lower 1	Coal	CQ3868C4-CQ-12-24	12-24
	Leichhardt Lower 2	Coal	CQ3868C4-CQ-40-46	40-46
	Vermont Upper	Coal	CQ3878C4-CQ-59-67	59-67
	Vermont Lower 2	Coal	CQ3878C4-CQ-76-80	76-80
	Vermont Lower 3	Coal	CQ3878C4-CQ-92-95	92-95
	Leichhardt Lower 1	Coal	CQ3878C4-CQ-24-37	24-37
	Leichhardt Lower 2	Coal	CQ3878C4-CQ-38-44	38-44
Moorvale	Leichardt Upper 2	Coal	MV4045C4_CQ_18_21	18-21
	Leichhardt Lower 1t	Coal	MV4045C4_CQ_029_033	29-33
	Leichhardt Lower 1B	Coal	MV4045C4_CQ_37_41	37-41
	Leichhardt Lower 2	Coal	MV4045C4_CQ_046	46
	Leichhardt Lower 2	Coal	MV4045C4_CQ_052	52
Lake Vermont	Leichhardt roof	Carbonaceous mudstone	2648CR01	46.5-46.6
	Leichhardt	Coal	2648CR02	46.6-49.4
	Leichhardt floor	Mudstone	2648CR03	49.4-49.5

	Vermont upper	Coal 86% tonstein 14%	2700C02	24.6-24.8
	Vermont upper floor	Carb mudstone	2700C05	26.2-26.3
	Vermont	Coal	2676C02	37.4-38.2
	Vermont floor	Coaly shale	2676C11	43.7-43.9
	Vermont lower floor	Coaly shale	2648C09	95.5-95.7
	Vermont	Coal, carb. shale	2644C07-C08	44.1-44.8
	Vermont lower	Coal	2648C06-C08	91.8-95.5
	Vermont	Igneous rock	2638C03_IR	94.3-94.9
	Vermont	Heat affected coal	2638C04_HA	94.9-95.0
Oaky Creek	German Creek Seam	Coal raw feed	OCN-GC	180-230
Rolleston	B Seam	Coal	ROL-B	50-60
	D Seam	Coal	ROL-D	50-70
	D- low aft	Coal	ROL-D-AFT	50-70
Meandu	Ace seam roof ply	Coal	K4SST6_ACE1A	462.5
	Ace seam roof ply	Coal	K4SST6_ACE1B	462.5
	Lower King seam ply	Coal	RAMP5ST12_KING4 A	475
	Lower King seam ply	Coal	RAMP5ST12_KING4 B	475
	Upper Queen Seam A ply	Coal	CENTST11_QA1	454
	Upper Queen Seam A ply	Coal	CENTST11_QA2	455
Collingwood Park	Blackstone Formation	Coal	CP-013	127
	Blackstone Formation	Coal	CP-014	131.1
Wandoan	Uncorrelated	Coal	C9326-85.5	85.5
	Uncorrelated	Coal	C9367-74.8	74.8
	C6B	Coal	C9367-84.1	84.1
	C1A	Coal	C9368-58	58.0
	Uncorrelated	Coal	C9368-83.2	83.2
	C9A	Coal	C9368-112	112.0
	BL3A	Coal	C9365-37	37.0
	C3A to C4B	Coal	C9365-48	48.0
	Uncorrelated	Coal	C9365-57.7	57.7
	Uncorrelated	Coal	C9365-79.8	79.8
	BU1A	Coal	C9279-30.6	30.6
	C4E	Coal	C9279-53.1	53.1
	Uncorrelated	Coal	C9279-63.5	63.5
	IA roof	Coal	C9360-59	59.0
	Uncorrelated	Coal	C9360-61.6	61.6
	Uncorrelated	Coal	C9360-102.2	102.2
	Uncorrelated	Coal	C9358-45.5	45.5
	Uncorrelated	Coal	C9358-79.5	79.5
	Uncorrelated	Coal	C9359-80.3	80.3
	Uncorrelated	Coal	C9349-114.8	114.8

	Uncorrelated	Coal	C9354-132.4	132.4
	Uncorrelated	Coal	C9357-90.2	90.2
	Uncorrelated	Coal	C9357-100.3	100.3
	Uncorrelated	Coal	C9357-122.8	122.8
	Uncorrelated	Coal	C9369-41.4	41.4
	Uncorrelated	Coal	C9369-56.8	56.8
	Uncorrelated	Coal	C9369-135.3	135.3
Unnamed contribution	Black Jack Group	Coal	2572506	168
	Black Jack Group	Coal	2574133	220
	Bulli	Metropolitan	MG306A18CT	480
	Bulli	Metropolitan	MG306A13CT	425
	Bulli	Metropolitan	MG306A10CT	43
	Bulli	Metropolitan	MG306A15CT	440
Power plant	Dominant coal feed	Sample type	Sample name	Not applicable
Stanwell	Rangal CM	Fly ash	STFA-1	
Stanwell		Bottom ash	STBA-1	
Gladstone		Fly ash	GLFA-1	
Gladstone		Bottom ash	GLBA-1	
Callide	Callide CM	Fly ash	CALFA-1	
Callide		Bottom ash	CALBA-1	
Kogan	Walloon CM	Fly ash	KCBA-1	
Kogan		Bottom ash	KCFA-1	
Millmerran		Fly ash	MMFA-1	
Millmerran		Bottom ash	MMBA-1	

6.3 Other data

To perform comparison and a comprehensive regional interpretation of analytical data, other published datasets have been compiled and used in this study (Table 9, Figure 19). Conclusive summaries are presented in Section 5.3. Australian Research.

Table 9. Previous studies and data collated

Formation	Sample type (number)	Age (basin)	Reference
Yarrabee Tuff	Tuff (65)	Late Permian (Bowen)	Ayaz 2015; Fricker 2019
Fort Cooper CM	Coal, mudstone, carb mudstone, siderite, tuff (38)	Late Permian (Bowen)	Hodgkinson and Grigorescu 2020 (23 samples) and unpublished data (15 samples)
Collinsville CM	Coal (6 weighted averages)	Early Permian (Bowen)	Boyd 2004
Back Creek Group	Mudstone, siltstone (36)	Late Permian (Bowen)	Geological Survey of Queensland 2021
Black Alley Shale	Tuff (10)	Late Permian (Bowen)	Kaye 2014

Brisbane Tuff	Tuff (12)	Late Triassic (Ipswich)	Geological Survey of Queensland 2021
Walloon CM	Mudstone (29)	Late Jurassic (Surat)	Anderson 2014

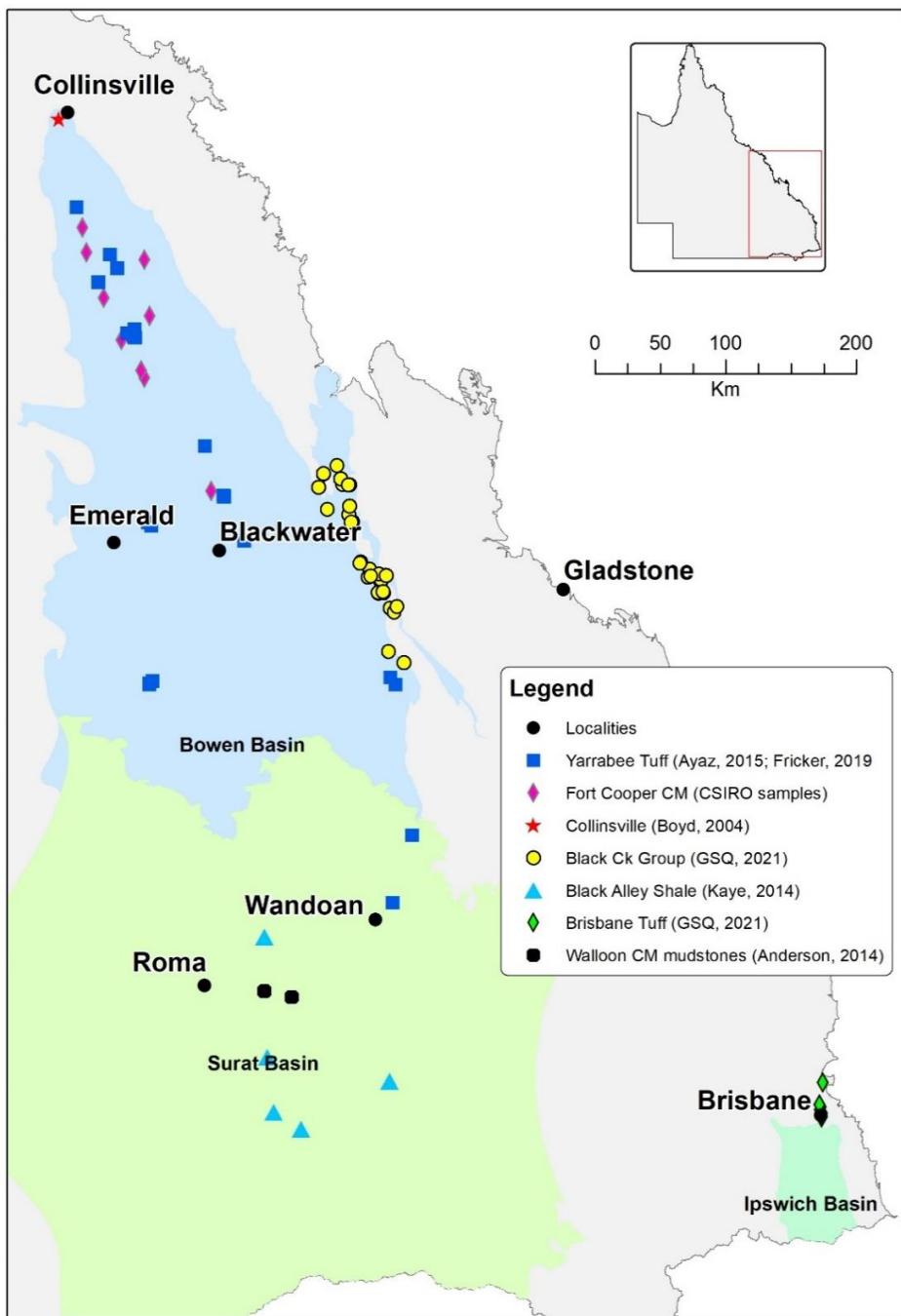


Figure 19. Other elemental data relevant to the project (tuffs and mudstones in or proximal to coal-bearing formations)

6.4 Laboratory analyses

The samples were prepared and analysed for elemental content by Bureau Veritas, New South Wales, following Australian Standards for analytical methods appropriate the material types (coal or non-coal): AS1038.10.0-2002. Methods used and elements identified for each are summarised in Table 10. Coal samples were gradually heated at 450°C and slow-ashed to remove organic matter but to retain elemental content. Power plant ash samples were also slow-ashed to ensure residual or contaminant organic matter was removed. The samples were then digested, and the results were converted back to the coal content using ash%. A portion of each sample was analysed for gold by fire assay and ICP-AES.

Table 10. Analyses performed for elemental identification in non-coal and coal samples under Australian Standard 'AS 1038.10.0-2002'

Material	Method	Elemental assessment
Non-coal pulps	IC3E Mixed acid digest – ICP-AES	Al (aluminium), Be (beryllium), Fe (iron), Li (lithium), Zn (zinc)
	IC3E Mixed acid digest – ICP-MS	Ag (silver), Ba (barium), Bi (bismuth), Cd (cadmium), Ce (cerium), Cs (caesium), Dy (dysprosium), Er (erbium), Eu (europium), Ga (gallium), Gd (gadolinium), Ge (germanium), Ho (holmium), In (indium), La (lanthanum), Lu (lutetium), Nb (niobium), Nd (neodymium), Pb (lead), Pr (praseodymium), Rb (rubidium), Re (rhenium), Sc (scandium), Sm (samarium), Sn (tin), Sr (strontium), Ta (tantalum), Tb (terbium), Te (tellurium), Th (thorium), Tl (thallium), Tm (thulium), U (uranium), W (tungsten), Y (yttrium), Yb (ytterbium)
	IC3E Mixed acid digest – ICP-MS	Co (cobalt), Cr (chromium), Cu (copper), Mn (manganese), Mo (molybdenum), Ni (nickel), V (vanadium), Zr (zirconium)
Coal pulps and power plant ash samples, slow ashed	AS1038.10.0 – Trace elements Fusion/Acid/ICP	Ba, Be, Co, Cr, Cu, La, Li, Mn, Mo, Ni, Sr, V, Y, Zn, Zr
	AS1038.10.0 – Trace elements by Acid Digest/ICP-MS	Ba, Ce, Cs, Ga, In, Nb, Pb, Rb, Sc, Ag, Sn, Ta, Te, Th, Tl, U, W
	IC3E Mixed acid digest – ICP-MS	Dy, Er, Eu, Gd, Ho, Lu, Nd, Pr, Re, Sm, Tb, Tm, Yb
	IC3E Mixed acid digest – ICP-AES	Fe
	Fire assay ICP-AES	Au

ICP-AES = inductively coupled plasma-atomic emission spectrometry; ICP-MS = inductively coupled plasma-mass spectrometry

Samples were prepared at the laboratory using a tungsten carbide mill. Yamasaki (2018) identified that samples can become contaminated with Co and W using such a mill. Most samples had high W spikes and we have therefore excluded W from the results. The Co results should be interpreted with caution.

6.5 Mapping

All the data with spatial representation (i.e., sample sites and geological information) have been plotted using ArcGIS Desktop Basic Single Use v 10.8.1.

Most of the participating mines provided sample locations. Although the coordinates were supplied in various projections, they were all reprojected in GDA2020. A complete list is presented in Appendix A . The Lake Vermont mine provided samples without coordinates; therefore, the sample locations were randomly placed in the mining lease.

The participating mine in the Gunnedah Basin opted to remain unidentified and provided only approximate sample locations to maintain anonymity.

The geological GIS layers were obtained from several public sources of digital data as follows:

- Geoscience Australia – Australian Geological Provinces (Raymond *et al.*, 2018)
- Mining, Exploration and Geoscience NSW – Surface Geology and Coal Basins (Colquhuon *et al.*, 2020)
- QSpatial QLD – Geological Framework (State of Queensland - Department of Resources 2021), Surface Geology (State of Queensland - Department of Resources 2021b) and Mining Leases (State of Queensland - Department of Resources 2021c).

7 Results and interpretation

7.1 Summary of sampling results

Table 11 presents a summary of analytical results and comments on all the samples provided by the participating mines and power plants. The complete dataset is provided in Appendix A.

Table 11. Summary of analytical results

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Collinsville	Blake (BUB)	Coal	107.0	0.8	Li, Sc, V, Cr, Cu, Mo, Bi
	Bowen upper (BUB)	Coal	64.5	0.7	
	Bowen lower (BUB)	Volatile coal	103.7	1.5	
	Little Bowen (BUB)	Coal	74.8	0.7	
	Potts (Blake North)	Coal	91.7	1.1	
	Scott/Denison (Blake North)	Coal	207.9	0.6	
Newlands	Goonyella Middle Seam	Coke raw feed	105.1	1.0	Li, Mo, Bi
	Goonyella Middle Seam	Coke raw feed	104.3	1.0	
	P67 Goonyella Middle Seam	Coal	67.6	1.0	
	R3 BSB Goonyella Middle Seam	Coal	146.7	0.7	
Coppabella	Leichhardt Lower 1	Coal	47.6	1.1	Li, Au, Bi
	Leichhardt Lower 2	Coal	37		
	Vermont Upper	Coal	68.2	1.0	
	Vermont Lower 2	Coal	89.5	0.9	
	Vermont Lower 3	Coal	67.2	1.4	
	Leichhardt Lower 1	Coal	45.3	1.0	
	Leichhardt Lower 2	Coal	32.9		
Moorvale	Leichhardt Upper 2	Coal	49.0	0.7	Au, Bi
	Leichhardt Lower 1t	Coal	43.9		
	Leichhardt Lower 1B	Coal	44.0		
	Leichhardt Lower 2	Coal	47.6	0.7	
	Leichhardt Lower 2	Coal	19.6		
Lake Vermont	Leichhardt roof	Carbonaceous mudstone	193.7	0.9	Li, V, Cu, Mo, Ag, Cs, Bi
	Leichhardt	Coal	115.9	0.9	
	Leichhardt floor	Mudstone	44.0	1.1	
	Vermont upper	Coal 86% tonstein 14%	67.0	0.7	
	Vermont upper floor	Carb mudstone	130.2	0.9	
	Vermont	Coal	51.3	1.0	

	Vermont floor	Coaly shale	103.3	0.9	
	Vermont lower floor	Coaly shale	102.6	1.0	
	Vermont	Coal, carb. shale	66.9	1.0	
	Vermont lower	Coal	54.5	1.1	
	Vermont	Igneous intrusion	210.1	0.9	
	Vermont	Heat affected coal	127.0	0.6	
Oaky Creek	German Creek Seam	Coal raw feed	71.5	1.1	Li, Bi, Au
Rolleston	B Seam	Coal	45.7	1	Li, Bi, Au
	D Seam	Coal	15.4		
	D- low aft	Coal	16.7		
Meandu	Ace seam roof ply	Coal	47.4	2.4	Y, MREE, Au, Bi
	Ace seam roof ply	Coal	73.2	1.1	
	Lower King seam ply	Coal	124.1	1.1	
	Lower King seam ply	Coal	172.5	2.4	
	Upper Queen Seam A ply	Coal	51.5	2.8	
	Upper Queen Seam A ply	Coal	30.6	2.4	
Collingwood Park	Blackstone Formation	Coal	80.6	2.6	Li, Sc, V, Ga, Mo, Ag, Cd, In, Bi
	Blackstone Formation	Coal	58.2	2.8	
Wandoan	Uncorrelated C9326-85.5	Coal	73.7	3.3	Be, V, Mo, MREE, HREE, Bi
	Uncorrelated C9367-74.8	Coal	78.4	1.5	
	C6B C9367-84.1	Coal	95.4	3.7	
	C1A C9368-58	Coal	37.8	2.7	
	Uncorrelated C9368-83.2	Coal	82.4	1.7	
	C9A C9368-112	Coal	301.5	2.1	
	BL3A C9365-37	Coal	61.0	2.3	
	C3A to C4B C9365-48	Coal	23.6	1.1	
	Uncorrelated C9365-57.7	Coal	161.6	3.0	
	Uncorrelated C9365-79.8	Coal	87.7	2.0	
	BU1A C9279-30.6	Coal	41.5	1.0	
	C4E C9279-53.1	Coal	80.5	3.0	
	Uncorrelated C9279-63.5	Coal	166.0	2.8	
	IA ROOF C9360-59	Coal	63.4	1.9	
	Uncorrelated C9360-61.6	Coal	51.7	2.5	
	Uncorrelated C9360-102.2	Coal	108.6	1.9	
	Uncorrelated C9358-45.5	Coal	184.6	1.1	
	Uncorrelated C9358-79.5	Coal	83.4	3.6	
	Uncorrelated C9359-80.3	Coal	219.6	1.0	
	Uncorrelated C9349-114.8	Coal	143.5	1.5	
	Uncorrelated C9354-132.4	Coal	116.6	2.7	

	Uncorrelated C9357-90.2	Coal	250.0	3.1	
	Uncorrelated C9357-100.3	Coal	97.9	3.0	
	Uncorrelated C9357-122.8	Coal	168.3	1.0	
	Uncorrelated C9369-41.4	Coal	149.1	1.1	
	Uncorrelated C9369-56.8	Coal	124.1	3.6	
	Uncorrelated C9369-135.3	Coal	184.3	1.1	
Un-named contribution	2572506	Coal	10.7		
	2574133	Coal	9.7		
Metropolitan	Bulli	Metropolitan	64.9	1.2	Li, Au, Bi
	Bulli	Metropolitan	56.5	1.1	
	Bulli	Metropolitan	55.3	1.4	
	Bulli	Metropolitan	67.2	1.2	
Power plant	Formation	Sample type	Total REY (ppm)	Outlook coefficient REY	Other above background elements
Stanwell	Rangal CM	Fly ash	403	1.5	Li, Mo, Bi
		Bottom ash	339	1.4	
Gladstone	Rangal CM	Fly ash	312	1.1	Li, Mo, Bi
		Bottom ash	272	1.1	
Callide	Callide CM	Fly ash	224	1.1	
		Bottom ash	201	1.1	
Kogan Creek	Walloon CM	Fly ash	304	1.0	Mo, Ag, In, Au only in bottom ash, Bi
		Bottom ash	309	1.1	
Millmerran	Walloon CM	Fly ash	357	1.2	Cu, Ga, Y, Mo, Ag, MREE, HREE, Bi
		Bottom ash	362	1.2	

Note: Never detected are Ge, Re and Tl; rarely detected are Mo and Ag.

7.2 Results by basins

7.2.1 Bowen Basin

The Bowen Basin coal measures have been analysed at 7 mines:

- Collinsville
- Newlands
- Coppabella
- Moorvale
- Lake Vermont
- Oaky Creek and
- Rolleston

With the exception of Collinsville where the Early Permian coal was analysed, the mine sites were sampled to determine the characteristics of Late Permian correlatives:

- Rangal CM (Newlands, Coppabella, Moorvale, Lake Vermont)
- German Creek Fm (Oaky Creek, which is also the only underground sample of the dataset), and
- Bandanna Fm (Rolleston)

Consistently higher than background levels of Li, Au and Bi, are found in all the Bowen Basin samples, with occasional enrichments of V, Cu, Cr and Mo. **Collinsville is the only site found to have elevated Sc** (Appendix A).

Noteworthy is Au, which is generally 4-5 times the background (~ 6-9 ppb) concentrations, with much higher concentrations of 19 and 28 ppb at Lake Vermont and Rolleston, respectively.

A strong correlation with Al (as a surrogate for clay minerals) has been detected for most elements, except Au, which demonstrates that **adsorption by clay minerals is the main control over the distribution of chemical elements in the coal measures**.

The total REE concentrations are generally low, around 100 ppm (Table 11 and Appendix A), with a couple of exceptions in the Potts pit at Collinsville (total REE = 208 ppm) and in the Leichhardt roof at Lake Vermont (total REE = 194 ppm). Particularly low (total REE < 50 ppm) are the concentrations determined at Coppabella, Moorvale and Rolleston.

Notable are two samples from Lake Vermont: an igneous intrusion in the Vermont seam and the associated heat-affected coal (Table 11 and Appendix A). The igneous intrusion has a very different chemical signature than the coal samples at Lake Vermont with Cr, Ni, Nb, Cs and Ta concentrations exceeding background levels. The strong positive Eu anomaly suggests a mafic origin. The heat-affected coal is also dissimilar with respect to the intrusion and the other Vermont seam samples as it contains Sc, Ga and Cs above background levels.

The outlook coefficient (Table 11) is also low in all the Bowen Basin samples, suggesting limited commercial value, due to the low concentrations of HREE.

The Ce anomaly is generally 0.9-1, which suggests that oxidation (anomaly > 1) may have occurred during coal deposition (Appendix A). The Eu anomaly is much more variable, ranging from 0.8 to 1.4, with a high value of 2.5 at Lake Vermont (Appendix A), which also associates with high Ba. Each mine site has some values equal to, or above, 1, suggesting that the **REEs may be primarily sourced from mafic rocks or through hydrothermal activity**.

A few positive Gd anomalies (>1) are determined, supporting the **influence of hydrothermal fluids**, on deposits at Newlands and Lake Vermont (Appendix A).

7.2.2 Tarong Basin

The Tarong CM were sampled only at the Meandu mine. The six analysed samples represent two plies of each of the Ace seam, lower King seam and upper Queen seam.

The three seams have slightly different trace and REE signatures (Table 11 and Appendix A):

- The Ace seam has elevated Y, no Bi and the highest REE concentrations of all the Meandu seams (total REE = 124-172 ppm), with a MREE and HREE dominance
- The King seam has no La or Bi, low REE total
- The Queen seam has elevated Au and Bi, low REE total but a strong HREE dominance in one of the plies

Most of the outlook coefficients are higher than those determined for the Bowen Basin samples (Table 11) due to **elevated MREE and HREE in four of the six plies analysed. Remarkable is one of the Ace plies with total REE = 172 ppm and outlook coefficient = 2.4.**

The Ce anomaly is generally positive, presumably due to coal oxidation during its deposition (Appendix A). The Eu anomaly is marginally positive suggesting a mafic source of elements. The negative Gd anomalies in all the samples indicate the absence of any hydrothermal influence.

7.2.3 Ipswich Basin

The Ipswich Basin is represented by only two samples making it difficult to draw a conclusion. As stated in (5.4.1.2), **the Ipswich Basin coal has the potential of containing strategic elements** due to the intense faulting of the basin and the presence of volcanic material. Elevated elements are Li, V and Bi (as observed in Late Permian coal samples) and Sc (similar to Collingsville). **Unique to the Blackstone Fm are elevated Ga, Cd and In**, which are not remarkable in the Bowen Basin samples.

The total REE concentration is far below 100 ppm, although the outlook coefficient is higher than for the Bowen Basin samples, due to the dominance of HREEs over the LREEs. The Ce and Gd anomalies are negative (<1) suggesting no oxidation or hydrothermal impact. The Eu anomaly is positive, presumably indicating the mafic source of REE.

7.2.4 Surat Basin

The Surat Basin samples are exclusively from the Walloon CM and only from **Wandoan Mine**. However, the **large number of samples enabled a comprehensive spatial characterisation of these Jurassic coal measures**.

Based on their location and geological setting, the samples were divided into a northern cluster, associated with the local Walloon CM outcrop and a southern cluster where all the samples were under cover, beneath either Springbok Sandstone or Tertiary basalts (Figure 20).

The samples of the **northern cluster present significant enrichments** (Table 11), **compared to the Bowen Basin samples**. The REEs are elevated and show a clear dominance of HREEs over the other rare earths in the series (see PAAS graphs in Appendix A). Remarkable samples with concentrations greater than the PAAS background (146 ppm) (Appendix A) are:

- C9368-112 (seam C1A), REY totals of 301 ppm
- C9365-57.7, REY totals of 162 ppm and
- C9279-63.5 (uncorrelated seams), REY totals of 166 ppm

The samples in the southern cluster are similar to the northern cluster in terms of elemental enrichments, although the REY pattern **shows that the MREEs and the HREEs are equally dominant over the LREE** (Appendix A). The highest REE totals both samples are from uncorrelated seams, are:

- C9357-90.2, under basalt cover, 250 ppm and
- C9359-80.3, under the Springbok Sandstone, 220 ppm

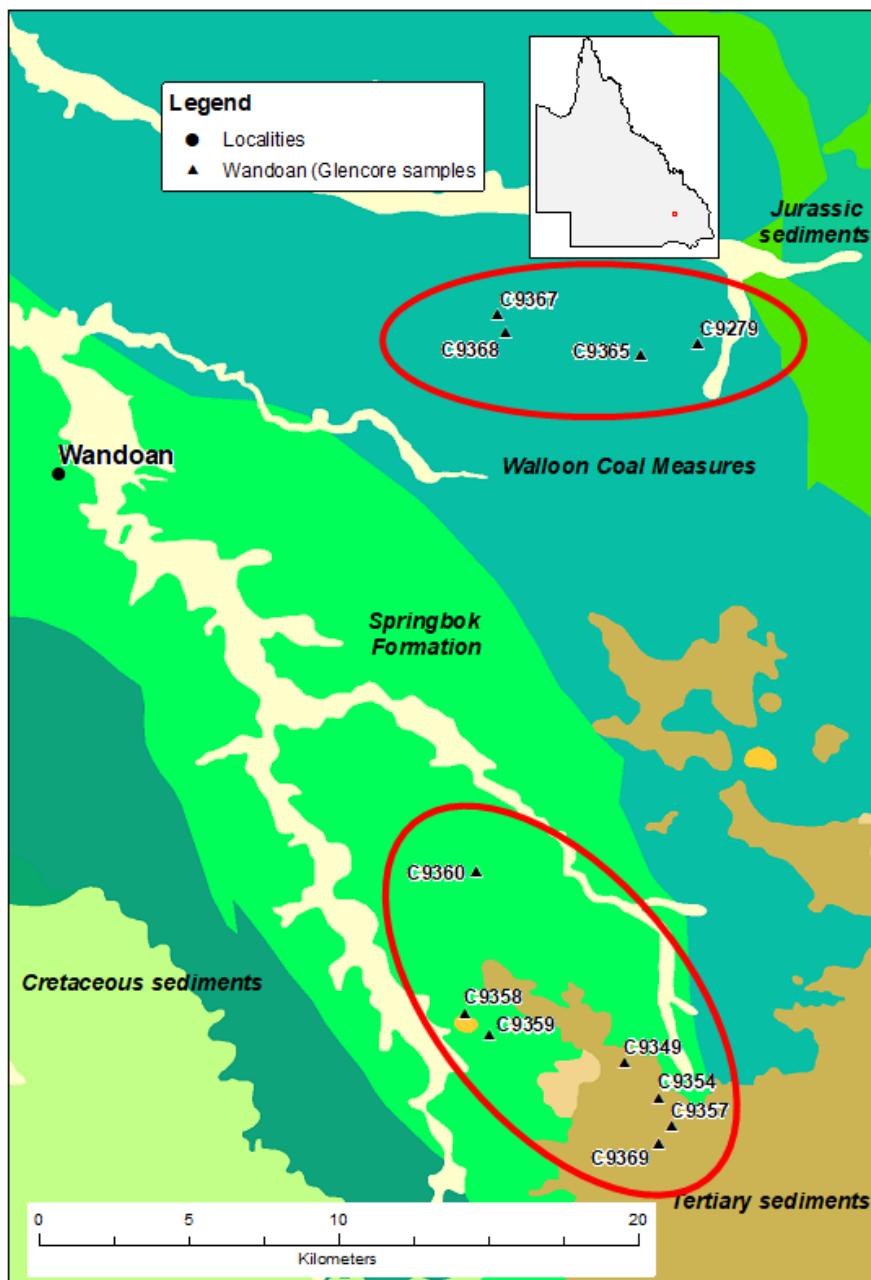


Figure 20. Spatial distribution of Walloon CM samples in the Wandoan area; red circles highlight the northern and southern sample clusters

Another difference between the northern and southern clusters is the vertical variation of element concentrations. In the examples displayed in Figure 21, the **REE concentrations increase with depth in the northern cluster and decrease with depth in the southern cluster**. Sediment cover (derived from the Springbok Sandstone or Tertiary basalt) may play a role in **providing a local source of elements leached from the overlying rocks and/or by preventing transport of elements out of the system by rainwater**.

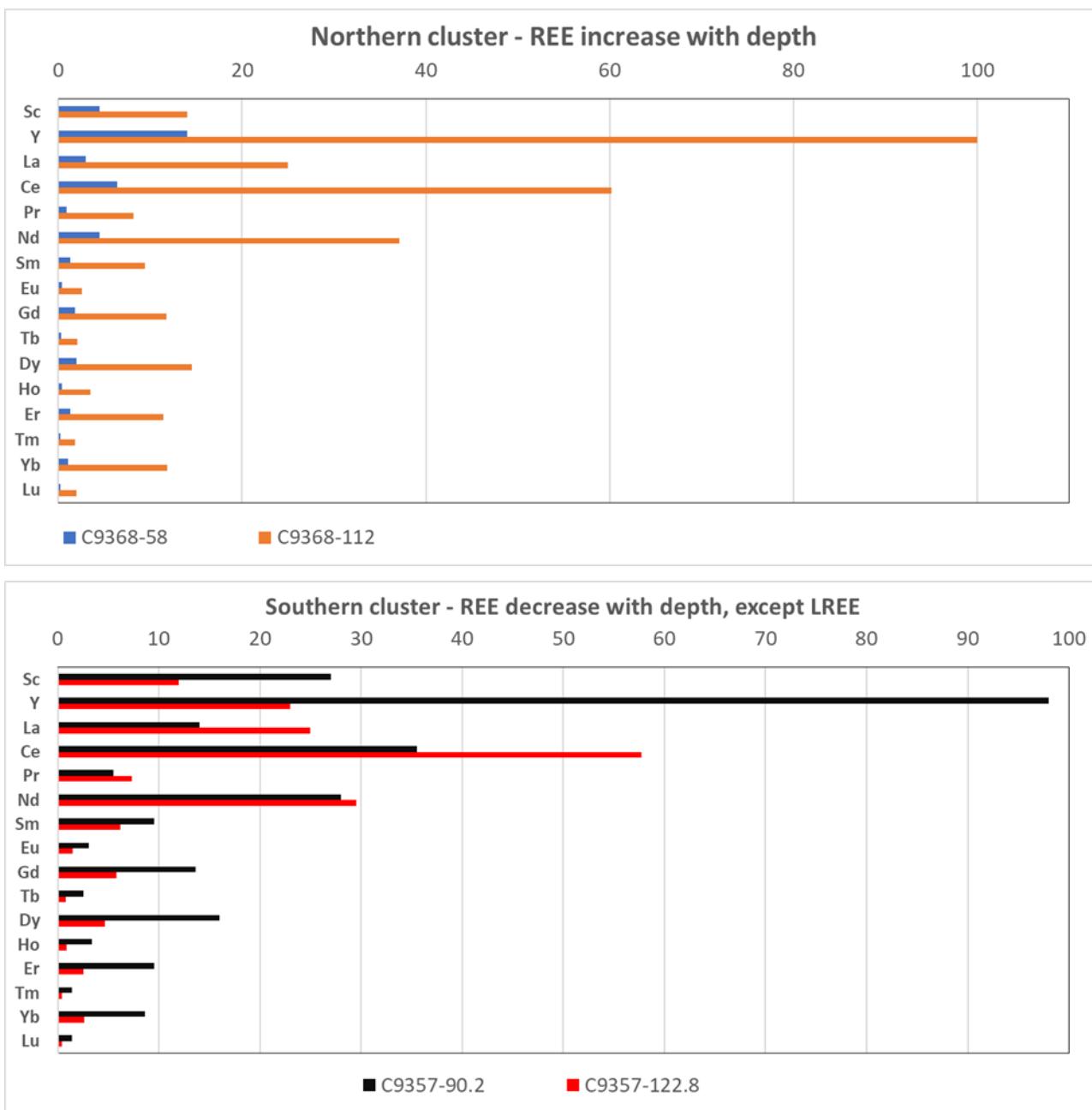


Figure 21. Examples of vertical variations of REE within the northern and southern clusters

The relationship between depth and REE concentrations was also assessed for all the Wandoan samples as a whole, regardless of their location. A few REEs displayed a bimodal variation with depth (Figure 22). The overall correlation is weak because the REE are split into two populations, from depths greater than 60 m. In some samples, the selected REE increase in concentration with depth, while others exhibit low REE totals regardless of depth (see red arrows in Figure 22). Figure 23 shows the strong correlation of the same elements with Y, which suggests that **some of the MREE and HREE are controlled by the same factors as Y**. Aluminium was not analysed in these samples but considering the strong correlation with Al that was determined in the Bowen Basin samples, **it can be assumed that clay minerals are the main factor controlling the occurrence and adsorption of Y and other REE**.

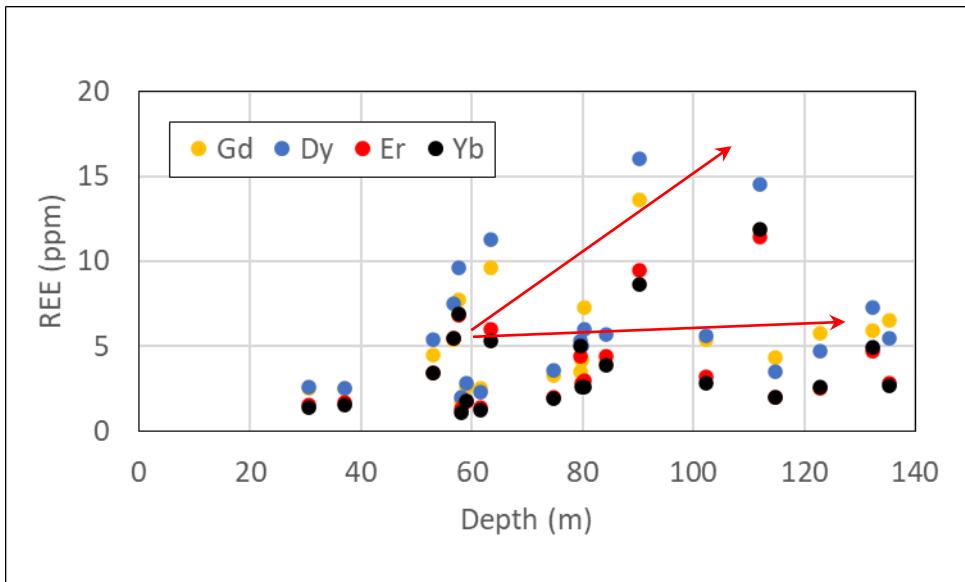


Figure 22. Selected REE variation with depth displaying two populations

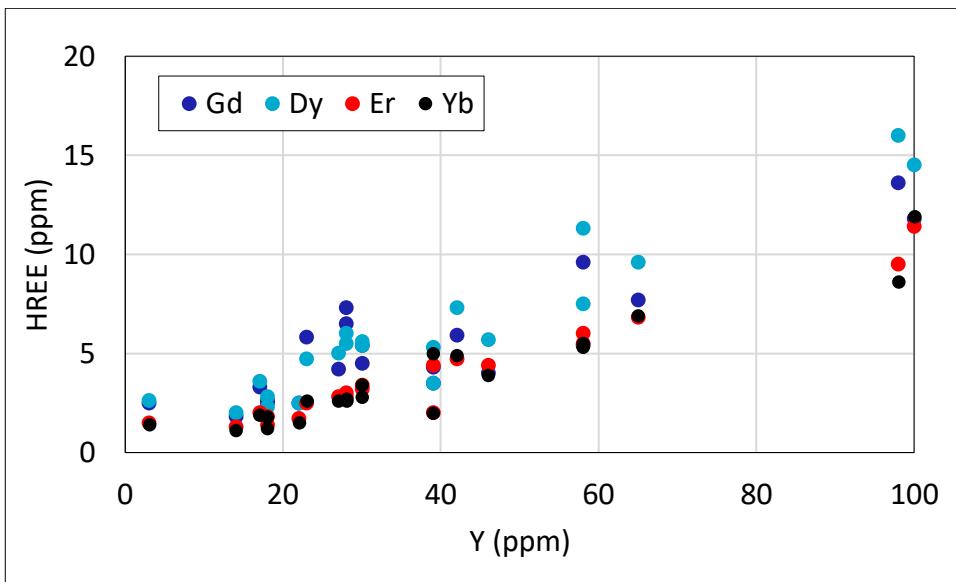


Figure 23. Selected REE relationship with Y

7.2.5 Gunnedah Basin

Two samples were provided by an unnamed mine that is extracting coal from the Black Jack Group in the Gunnedah Basin, NSW. The samples contain **the smallest concentration of elements in the entire dataset**.

All elemental concentrations **are below background levels and total REE is around 10 ppm**. The main controlling factor of the low concentrations can be assumed to be the low-ash content of the coal. The low element concentrations determined at this mine site are lower than those reported by Ward et al. (1999) (Section 5.3.2). **Further samples from the Gunnedah Basin should be examined** to draw a conclusion.

7.2.6 Sydney Basin

The coal samples from the Metropolitan Mine are poor in trace elements and REE (total REE < 70 ppm). Remarkable though are the concentrations of Li (100 ppm), Au (0.004 ppm) and Bi (0.53 ppm), which are a few times higher than the background concentration levels (20 ppm, 0.0018 ppm and 0.127 ppm, respectively). The generally low concentrations of elements and elevated Li and Bi in these low ash samples corresponds with findings by Zhao (2012) (see Section 5.3.2). Further samples from the Gunnedah Basin should be examined to draw more in-depth conclusions of potential concentration and distribution through the mined and unmined seams in the Sydney Basin.

7.3 Sediment sources by basin

7.3.1 Bowen Basin

Researchers such as Michaelsen and Henderson (2000), Zhao (2012), Bryan (2013), Withnall *et al.* (2013), Ayaz (2015) and Wainman *et al.* (2021) investigated the petrography of basinal sediments, their geochemical signatures or their tectonic settings, and concluded that **volcanoclastics dominate the sediments of:**

- the middle to upper Permian in the Bowen Basin
- the Ipswich Basin
- the Tarong Basin
- the Walloon CM in the Surat Basin and
- some tuffaceous coal measures in the Sydney Basin

The volcanic material originated primarily from the rocks of the New England Orogen (NEO, Queensland) and the New England Fold Belt (New South Wales).

The origin of NEO elements in the Queensland coals, analysed as part of this study, is confirmed when comparing the geochemical signatures of Permian, Triassic and Jurassic coals with the **existing GSQ geochemical data**, which consists of hundreds of samples collected from various NEO provinces (Geological Survey of Queensland, 2021b).

The following figures present discrimination diagrams showing the chemical signature of selected NEO provinces.

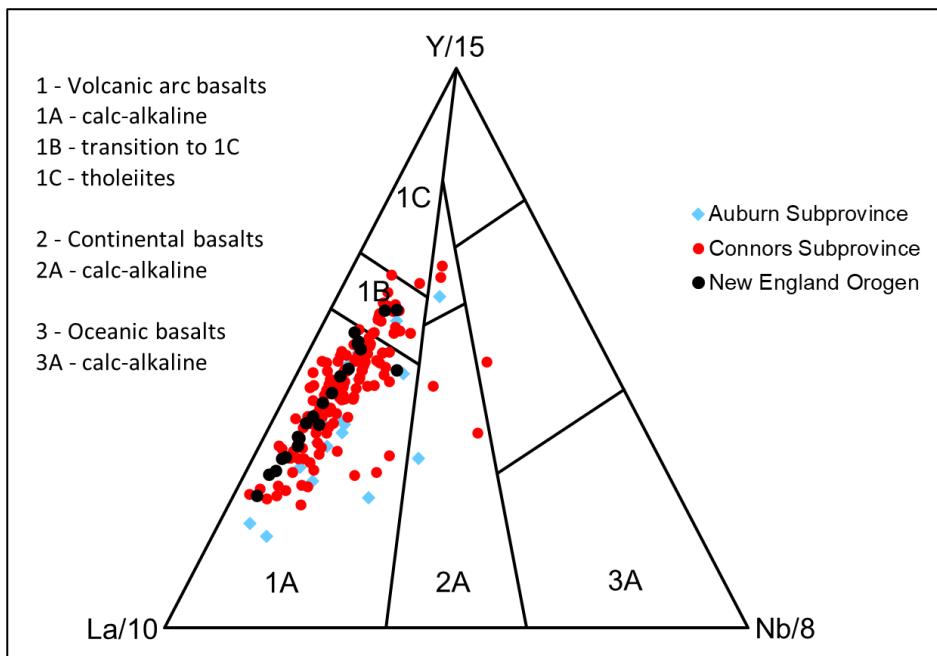


Figure 24. Basalt discrimination (after Cabanis and Lecolle 1989); the vast majority of samples are calc-alkaline arc basalts with a small proportion of continental basalts

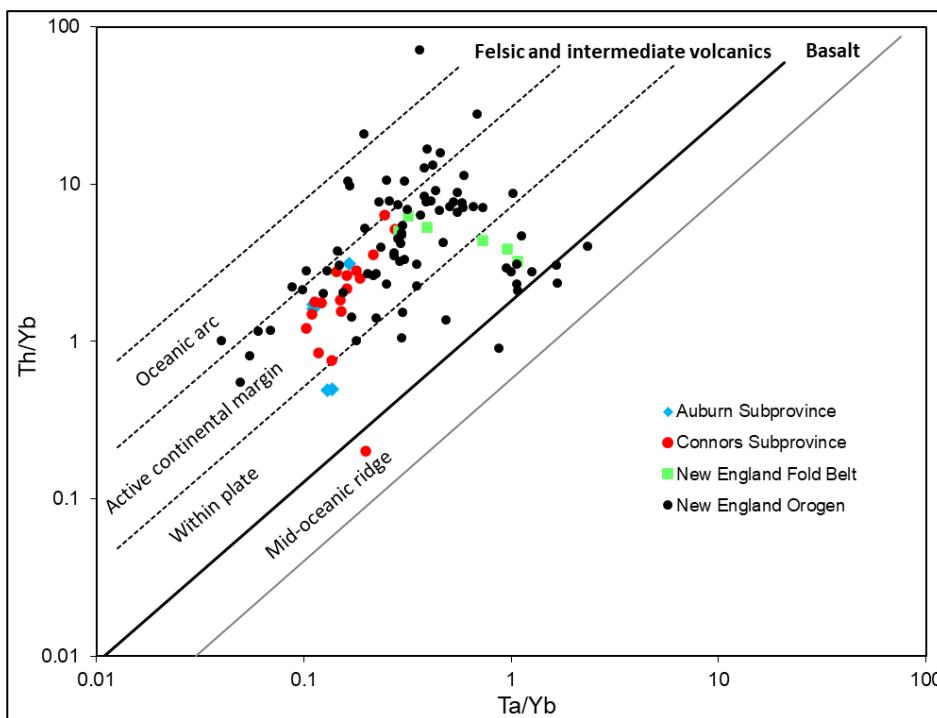


Figure 25. Volcanic arc rocks discrimination (after Gorton and Schandl 2000); the majority of arc volcanics are felsic or intermediate rocks

The signature of the volcanic arc rocks (Figure 24 and Figure 25) is very similar to the signature of elemental content of the coal samples from the Bowen Basin (Figure 26 and Figure 27).

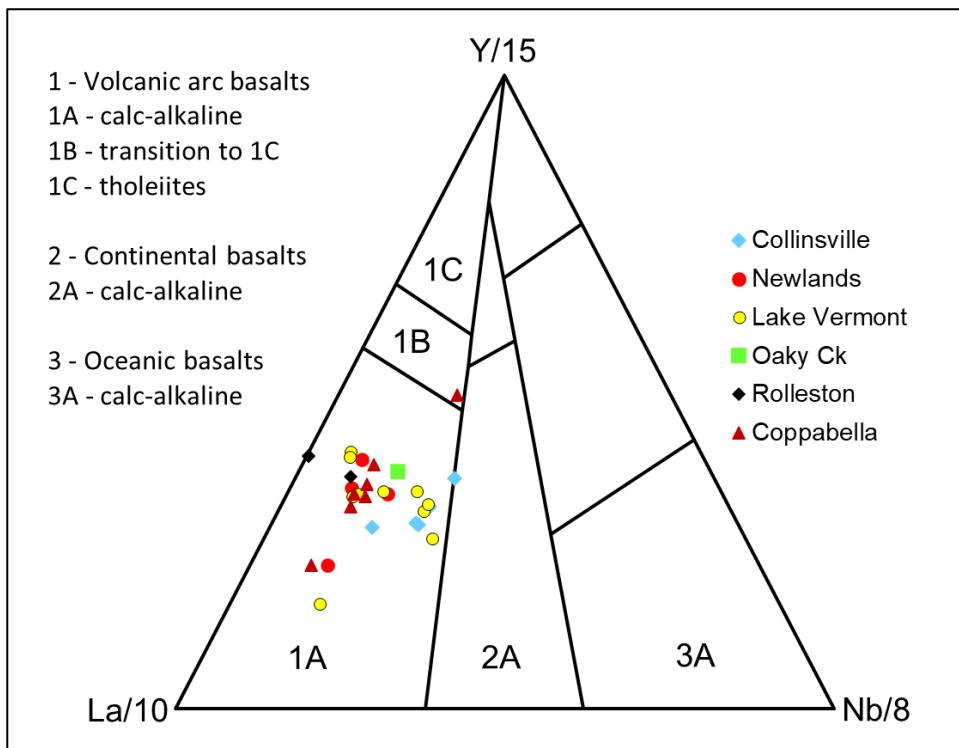


Figure 26. Basalt discrimination (after Cabanis and Lecolle 1989); the volcanoclastics in coal samples are derived from calc-alkaline arc basalts. The Moorvale samples could not be assessed as La was not detected.

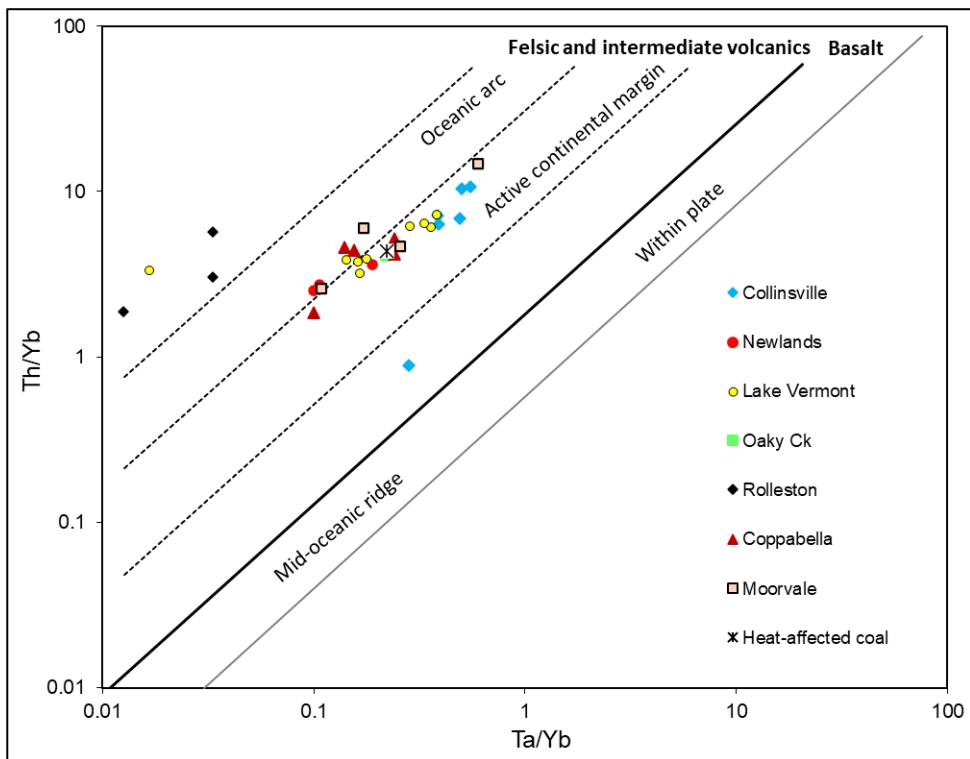


Figure 27. Volcanic arc rocks discrimination (after Gorton and Schandl 2000); the majority of coal samples contain arc-derived felsic or intermediate lithics. The heat-affected coal sample collected from Lake Vermont has a similar signature as most other samples.

Additional diagrams provide evidence to refine elemental origin by assessing other rocks (i.e., granites, Figure 28) or confirming previous findings (i.e., type of volcanic arc, Figure 29 or type of volcanic rock, Figure 30).

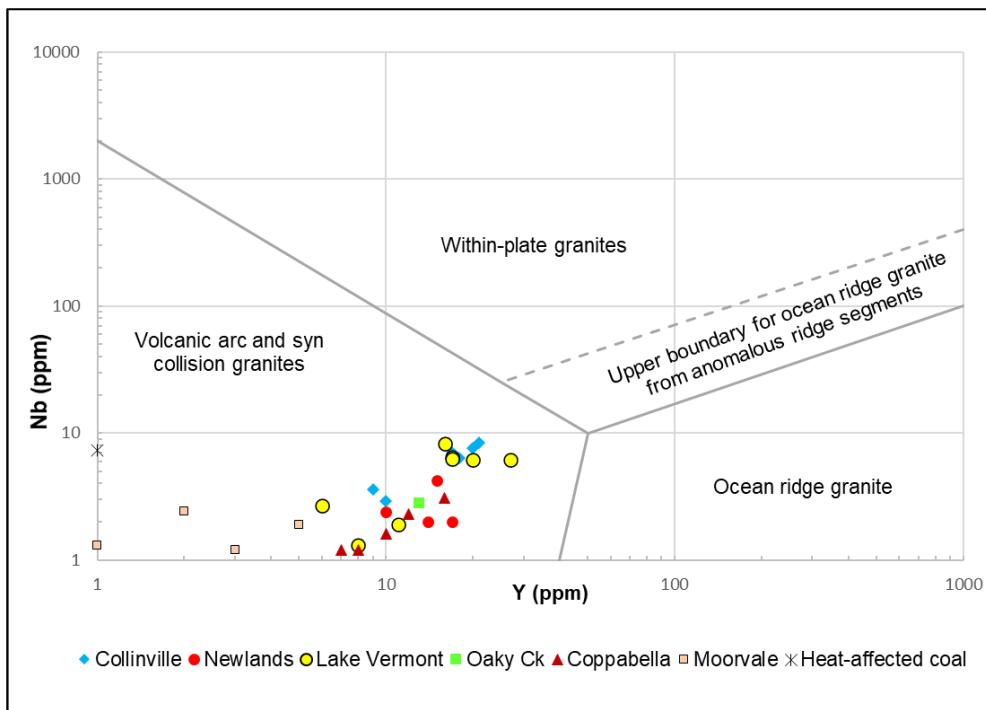


Figure 28. Discrimination of granites (after Pearce et al. 1984); all samples fall in the volcanic arc domain

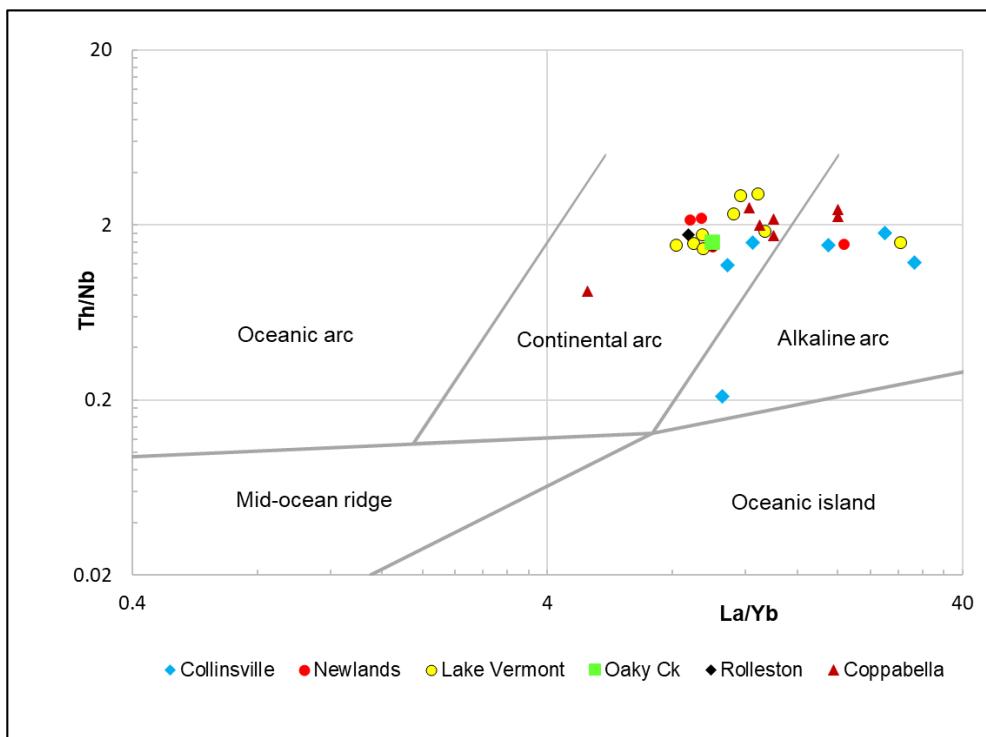


Figure 29. Discrimination of mafic volcanics and metamorphic rocks (after Hollocher et al. 2012)

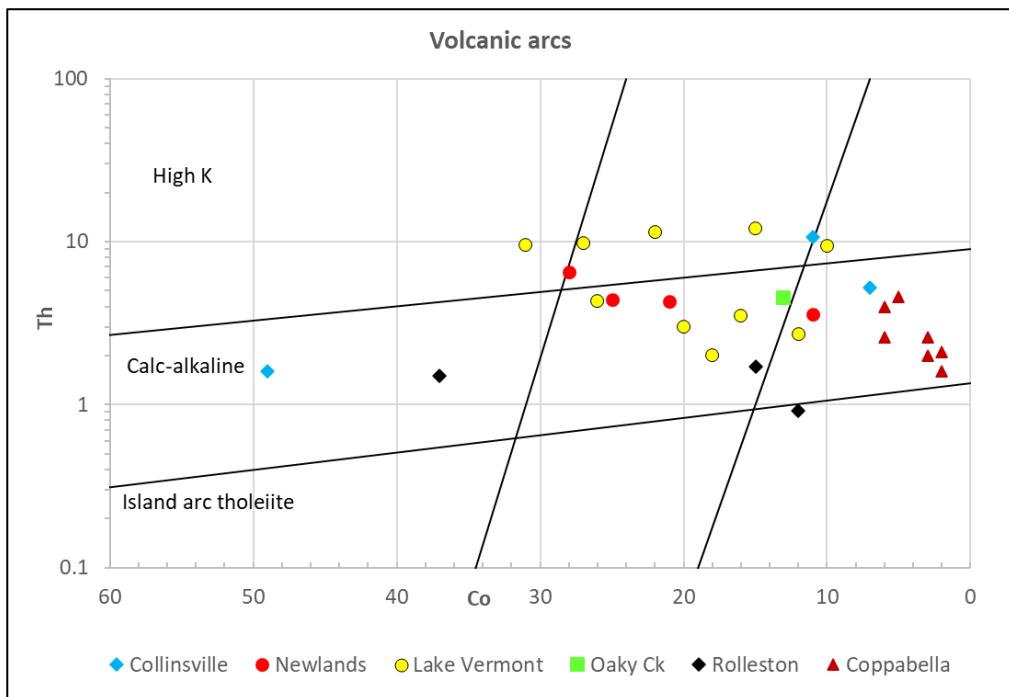


Figure 30. Types of volcanic arcs (after Hastie et al. 2007); the majority are basalts and andesites

7.3.2 Tarong, Ipswich and Surat basins

The following figures (Figure 31, Figure 32, Figure 33, Figure 34 and Figure 35) display the chemical character of Triassic and Jurassic coal samples and the likely tectonic setting of the element source.

The samples analysed are from the Meandu mine (Tarong Basin), Collingwood Park core (Ipswich Basin) and from the Wandoan mine (Surat Basin).

The sample chemical signature is similar in this subset but slightly different than what was determined in the Bowen Basin:

- the basalts are predominantly calc-alkaline (as in the Bowen Basin) but from volcanic arc, continental and oceanic settings (Figure 31), not only volcanic arcs as in the Bowen Basin (Figure 26)
- the strong oceanic influence is also shown in Figure 34
- the felsic and intermediate character of the volcanoclastics is similar to the Bowen Basin samples (Figure 32), and
- the intermediate rock character is also shown in Figure 35

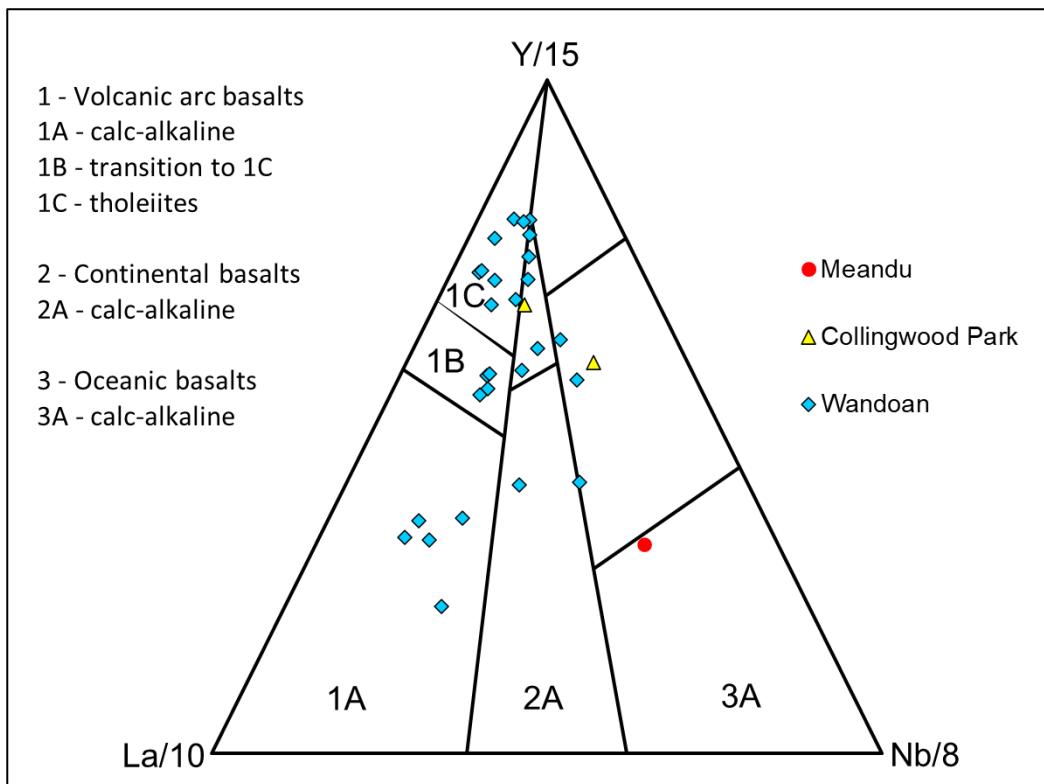


Figure 31. Basalt discrimination (after Cabanis and Lecolle 1989); the volcanoclastics in coal samples are derived from various calc-alkaline basalt settings.

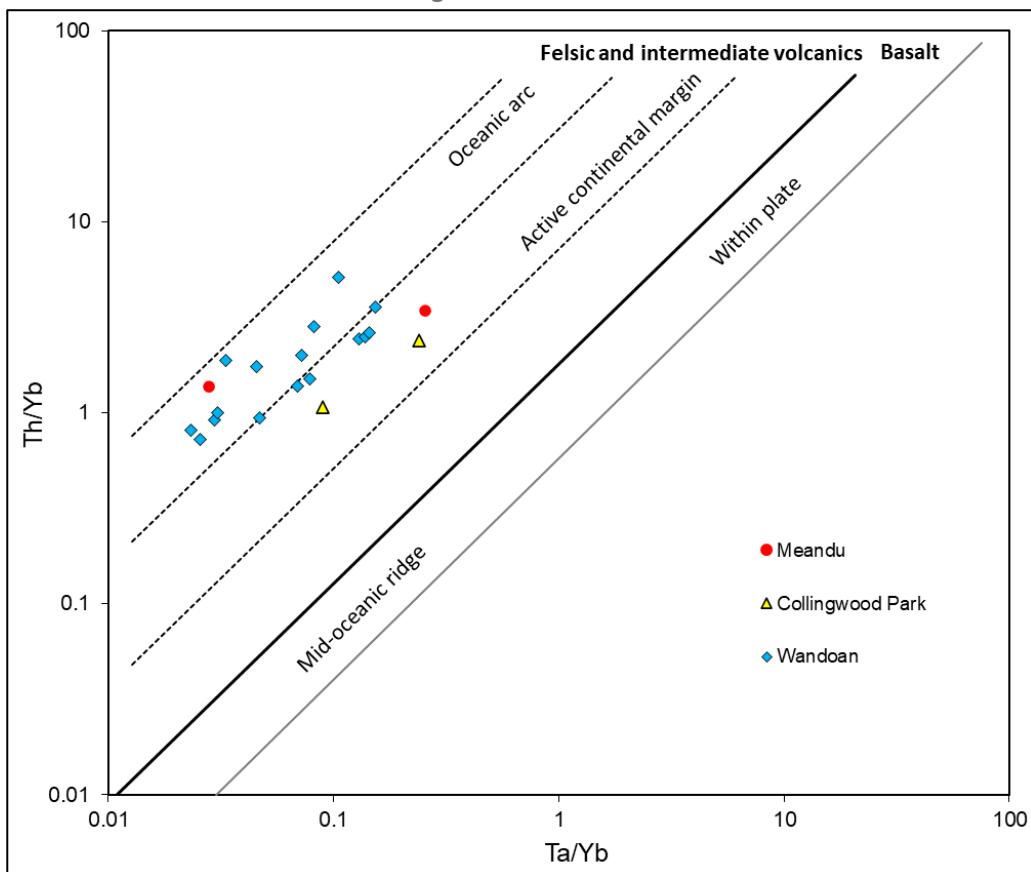


Figure 32. Volcanic arc rocks discrimination (after Gorton and Schandl 2000); the majority of coal samples contain arc-derived felsic or intermediate lithics.

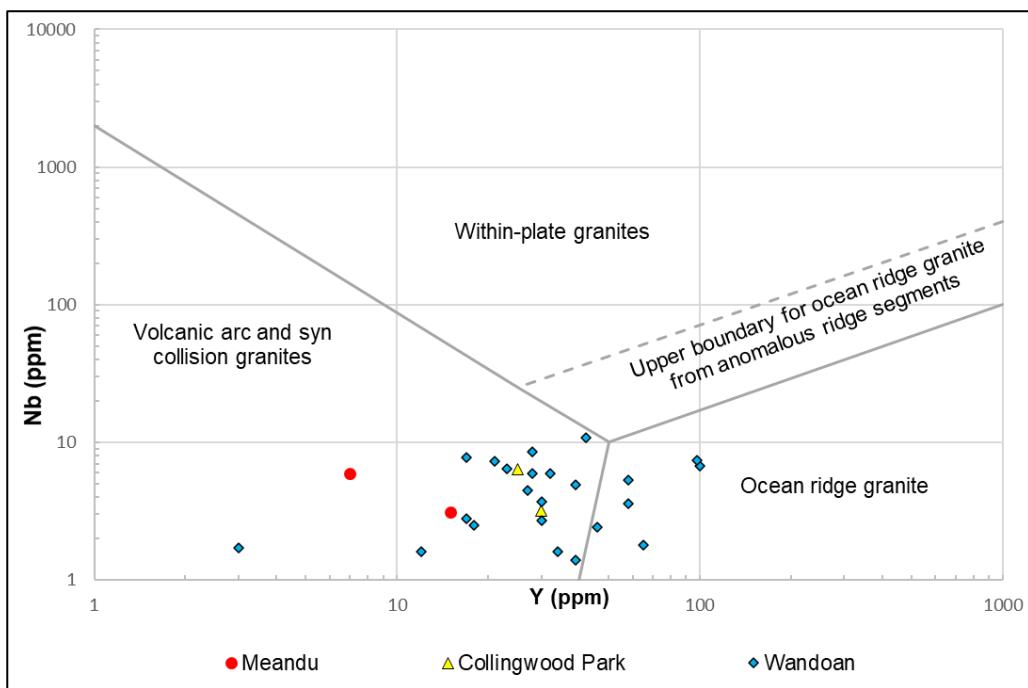


Figure 33. Discrimination of granites (after Pearce et al. 1984); most samples fall in the volcanic arc domain, with some Wandoan containing high Y and suggesting an ocean ridge setting.

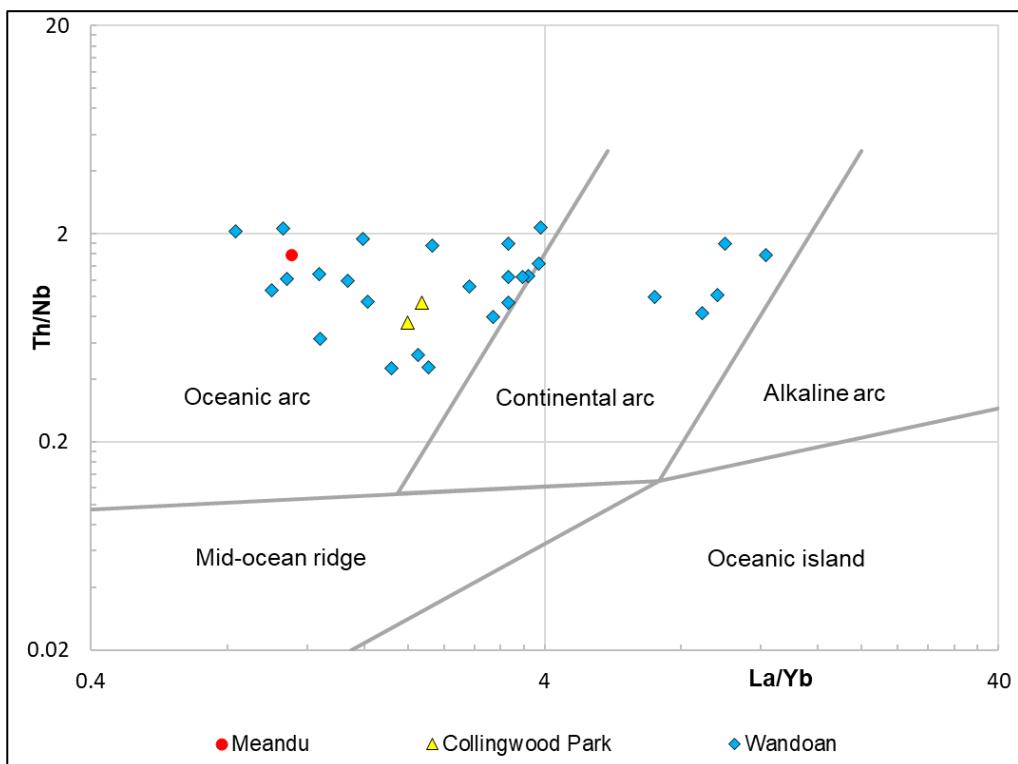


Figure 34. Discrimination of mafic volcanics and metamorphic rocks (after Hollocher et al. 2012); the oceanic arc setting is dominant.

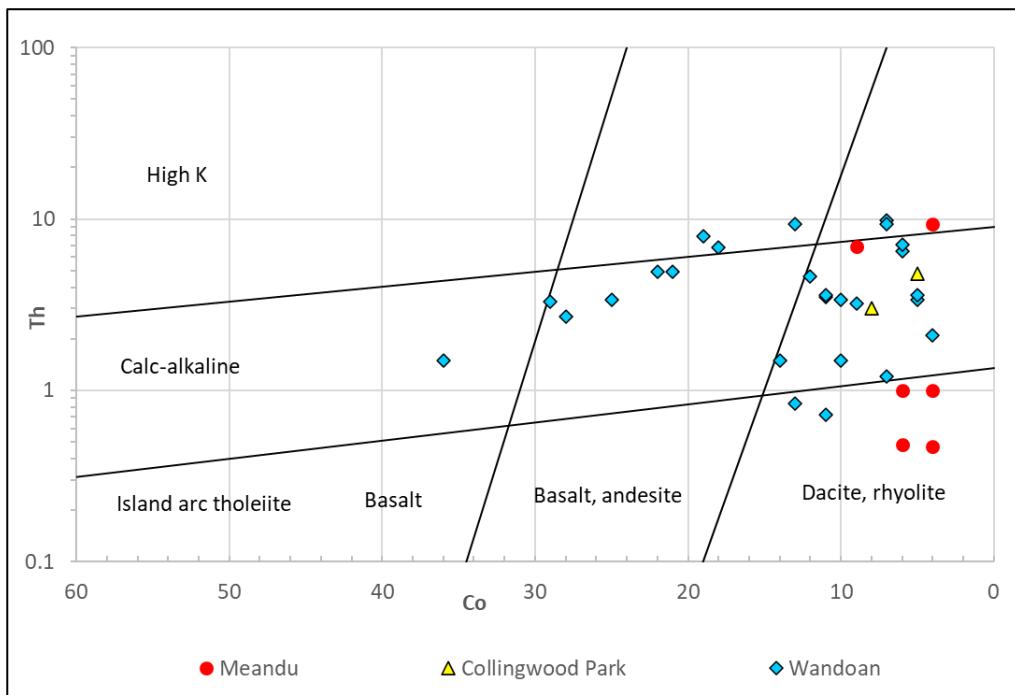


Figure 35. Types of volcanic arcs (after Hastie et al. 2007); the majority are intermediate rocks

7.3.3 Gunnedah and Sydney basins

The following figures (Figure 36 and Figure 37) display the chemical character of samples from New South Wales indicating the likely tectonic setting of the element source. They are plotted against New England Fold Belt rock samples (Geological Survey of Queensland, 2021a) for context.

The samples analysed are from the Metropolitan Mine (Sydney Basin) and an unnamed source in the Gunnedah Basin.

- The clastics in the Gunnedah and Sydney samples are of intermediate to rhyolitic compositions
- The samples from Gunnedah Basin plot as a source from a mid-ocean ridge setting
- The Sydney Basin samples are sourced from calc-alkaline volcanic arc and continental settings

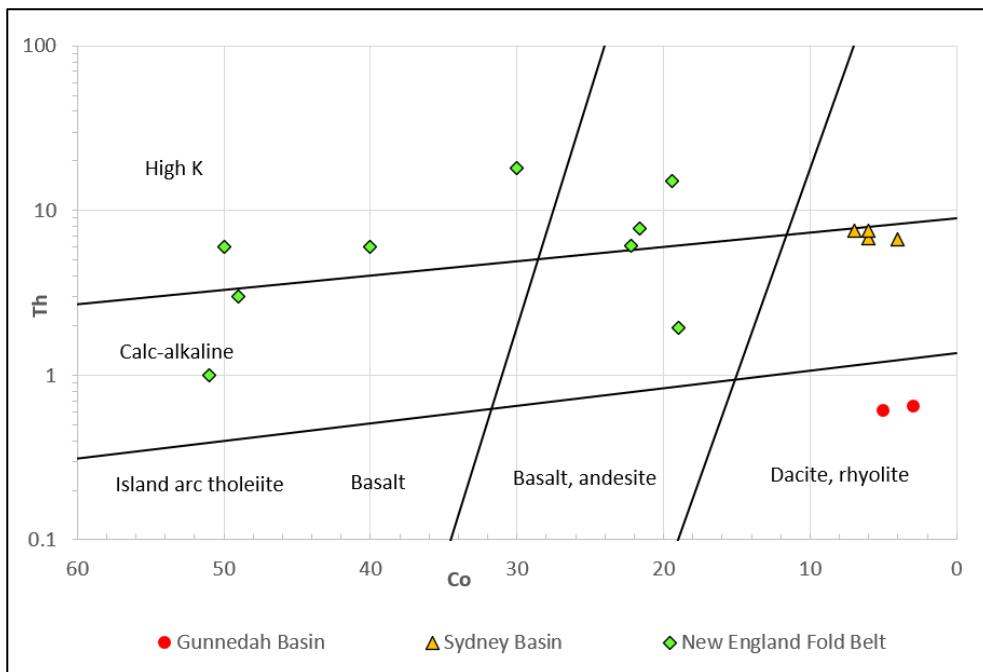


Figure 36 . Types of volcanic arcs (after Hastie et al. 2007) showing also New England Fold Belt rocks: the clastics in the Gunnedah and Sydney samples are intermediate to rhyolite compositions.

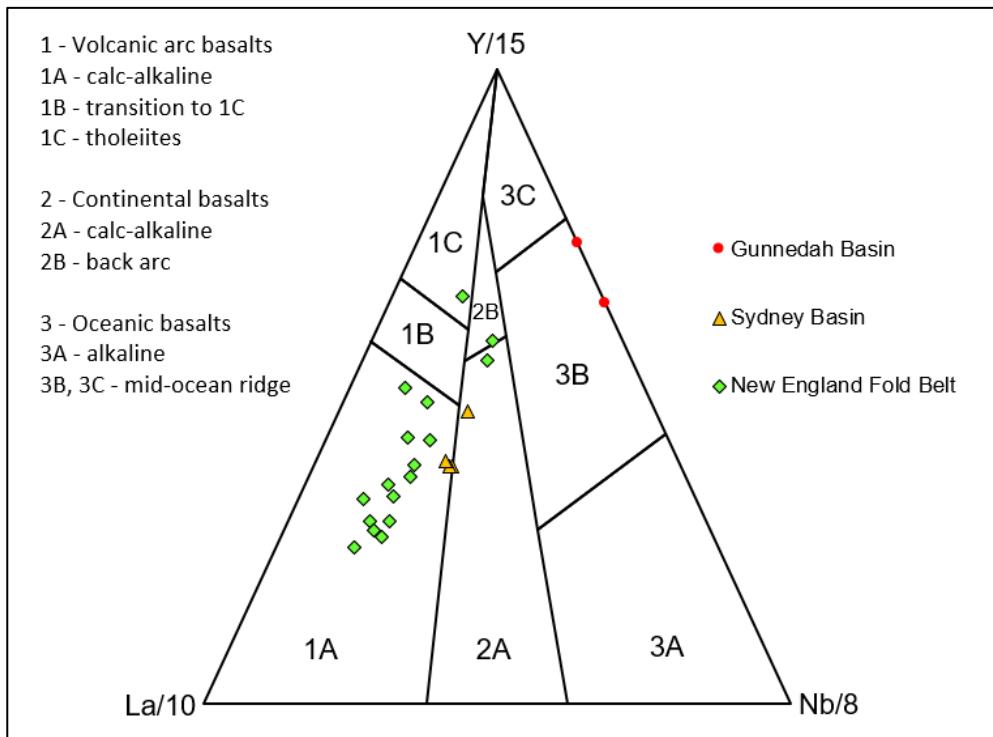


Figure 37 Basalt discrimination (after Cabanis and Lecolle 1989) showing New England Fold Belt rocks; the clastics in Gunnedah coal samples plot as mid-ocean ridge settings and the Sydney Basin clastics plot as calc-alkaline volcanic arc and continental settings.

7.4 A special note on power plant ash

Ash samples from five power plants (Figure 18) were analysed (Figure 38).

- The highest total REE concentration was determined in the Stanwell ash (Rangal CM), followed closely by the Millmerran ash (Walloon CM)
- The lowest REE content was found in the Callide ash (Callide CM)
- A large difference between the fly ash and bottom ash concentrations was observed in the Stanwell, Gladstone (both Rangals) and Callide ash samples, while at Kogan Creek and Millmerran (each of Walloon CM sources) the two types of ash are very similar in concentrations
- Each power plant has a different elemental signature with elevated concentrations (>2 times the PAAS background values) as follows:
 - Stanwell: Li, Sc, Y, Mo, Ag, Cd, In, MREE, HREE, Bi
 - Gladstone: Li (highest Li of all the power plant ashes), Cu, Mo, In, MREE, Bi
 - Callide: Mg, Fe, Zr, Mo, MREE
 - Kogan Creek: Ga, Mo, Ag, MREE, Au (in bottom ash only), Bi
 - Millmerran: Cu, Ga, Mo, Ag, In, MREE, HREE, Bi

It is notable that of the five power plants, only the Stanwell and Gladstone samples have high Li, consistent with other coals sourced from the Rangal CM (Section 7.2.1) and Gladstone levels being somewhat higher than the other Rangal coal samples (Appendix A).

The outlook coefficient is highest in the Stanwell and Millmerran ash and strictly related to their high concentrations of MREE and HREE, which are currently considered more valuable than the LREE.

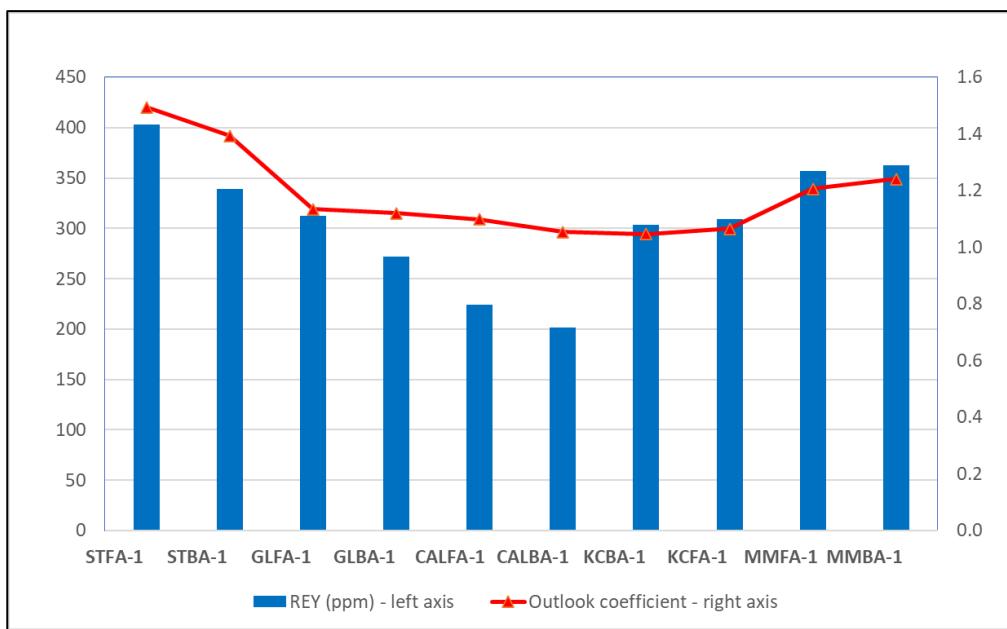


Figure 38. Total REY composition compared with the outlook coefficient, which relates to the commercial value of the product. Legend: ST - Stanwell, GL - Gladstone, CAL - Callide, KC - Kogan Creek, MM - Millmerran, FA – fly ash, BA – bottom ash

Rolleston coal is supplied to the Gladstone Power Plant (Greg Mills and Paul Van der List, pers. comm) although coal is also sourced from Ensham mine. It is notable (Figure 39 and Appendix A) that the Au, while relatively high (up to 9 times crustal average) in the Rolleston samples was not detected in the Gladstone ash. The signature of the elements evident from the Gladstone power plant ash is remarkably different to that of the Rolleston coal. Ensham coal may be represented in the sample and may be distorting the signature. Concentrations of many elements were much higher in the ash than in the coal, suggesting a **deeper investigation of elemental content and concentration from pit-to-ash may be of value.**

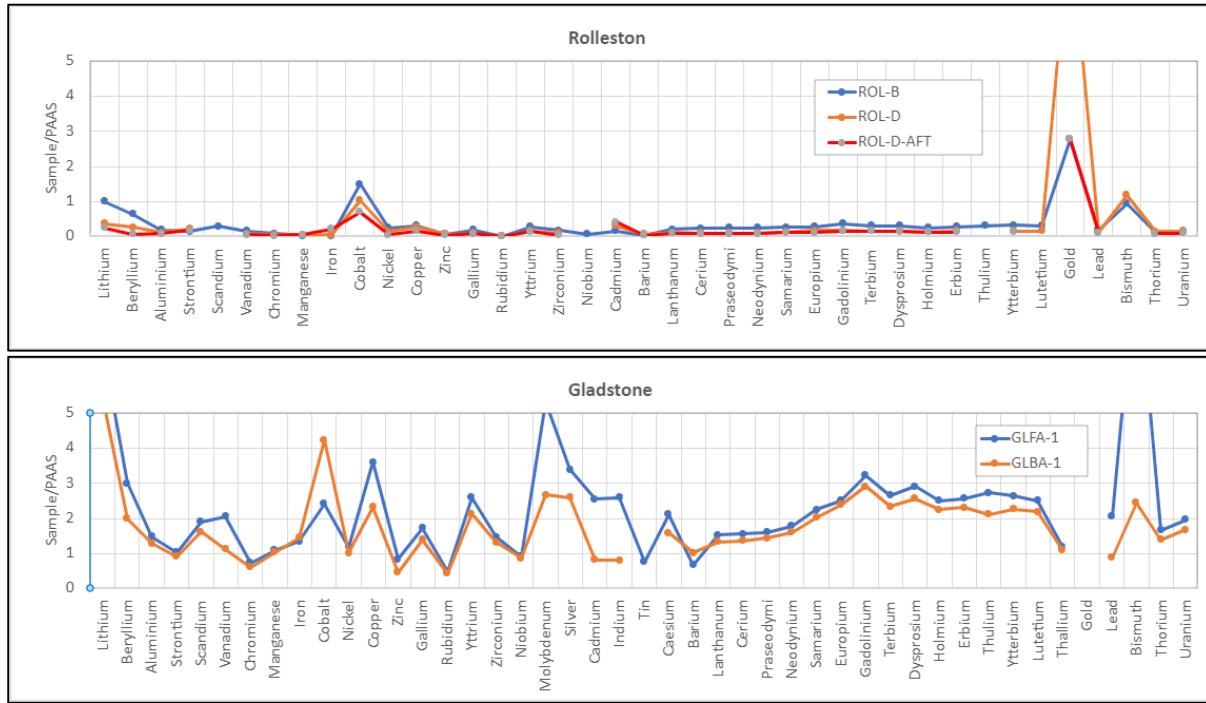


Figure 39. Rolleston Mine and Gladstone power plant samples, noting the difference

8 Discussion

This investigation of chemical elements in Australian Permian, Triassic and Jurassic coal measures is **the first attempt of its kind to determine and map the occurrence of elements, their concentrations and spatial distribution.**

For this spatial assessment of elements in coal, across two states, six basins and various coal measures and seams, nearly 90 samples were from contributing coal mines and power plants (Figure 40) were analysed.

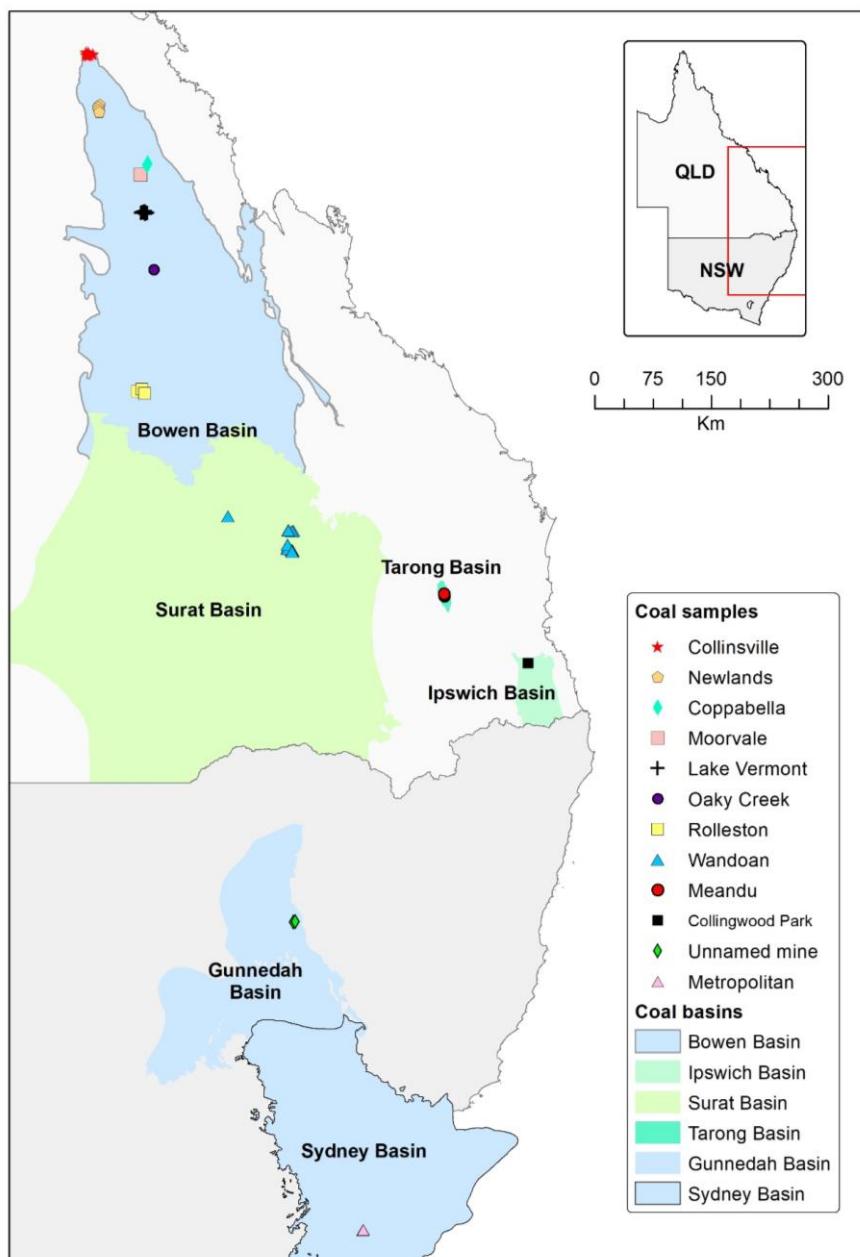


Figure 40. Coal sample spatial distribution

An additional 38 samples, previously analysed using the same methods (23 published by Hodgkinson and Grigorescu, 2020 and 15, CSIRO, unpublished), were included in this work (Figure 19 and Appendix A). For further comparison purposes, to determine possible provenance of elemental content, additional data (detailed in Section 5.3) were collated and assessed.

The elemental concentrations in each sample, were normalised against the widely used standard (PAAS) to assess local enrichments above the average continental crust composition, enabling us to perform sample comparisons regionally (Appendix A). Detailed spatial distribution patterns presented in Appendix B also show comparison where high, moderate and low concentrations persist. Noteworthy results from the comparisons include:

- **Consistently higher than background levels of Li, Au and Bi are found in all Bowen Basin samples** (Section 7.2.1)
- Collinsville is the only site found to have elevated Sc (Section 7.2.1)
- At Lake Vermont, Au is generally 4-5 times the background crustal average (~ 6-9 ppb) (Section 7.2.1)
- Concentrations in the deposits from Newlands and Lake Vermont indicate they have been influenced by hydrothermal fluids (Section 7.2.1)
- At Meandu Mine in the Tarong Basin, MREE and HREE are elevated in four of the six plies analysed; one of the Ace plies contains REE concentrations of 172 ppm and has an outlook coefficient of 2.4 (Section 7.2.2)
- Elevated elements in the Ipswich Basin (Late Triassic) coal are Li, V and Bi (also observed in Late Permian coal samples) and Sc (similar to Collinsville, Early Permian) are likely due to the intense faulting of the basin and the presence of volcanic material (Section 7.2.3)
- Unique to the Blackstone Fm (Ipswich Basin) are elevated Ga, Cd and In, elements that are unremarkable in the Bowen Basin samples (Section 7.2.3)
- Elemental concentrations of all Gunnedah Basin samples are below background levels and total REE is around 10 ppm - **further samples from the Gunnedah Basin should be examined** (Section 7.2.5)
- Metropolitan Mine samples are remarkable in concentrations of Li, Au and Bi, being a few times higher than the background concentration levels (Section 7.2.6)

Due to high availability of donated samples, we were able to select more than twenty from the Wandoan area (Section 7.2.4), divided into a northern and southern cluster, enabling a comprehensive spatial characterisation of these Jurassic coal measures. Results indicated that:

- there are **significant enrichments in the Wandoan northern cluster compared to the southern cluster and compared to the Bowen Basin samples** (Section 7.2.4)
- in the southern Wandoan cluster, MREEs and HREEs are equally dominant over the LREE (Section 7.2.4)
- REE concentrations increase with depth in the northern Walloon cluster and decrease with depth in the southern Walloon cluster (Section 7.2.4)

It is **likely that sediment cover is providing a local source of elements** leached from the overlying rocks and/or by preventing transport of elements out of the system by rainwater (Section 7.2.4). Further it can be assumed that **clay minerals are the main factor controlling the occurrence and adsorption of Y and REE** (Section 7.2.4). These results demonstrate that high detrital input and tuff in the Walloon coal seams should make them a target for trace elements and REE. Importantly, the variation between the northern and southern clusters of the Wandoan area indicates that even **local**

distinctions occur and that characterisation of the elemental content will require as much detailed mapping as any resource.

Further it can be suggested from the comparisons and the discrimination diagrams that:

- Elemental delivery may have been from volcanic material that originated primarily from the rocks of the New England Orogen (Queensland) and the New England Fold Belt (New South Wales) (Section 7.3.1)
- The main control over the distribution of chemical elements in the coal measures is their adsorption by clay minerals (Section 7.2.1); this is also supported by the direct correlation between ash (%ad) and REY (Table 12 – bold text highlights high-ash coals)
- REEs may be primarily sourced from mafic rocks or through hydrothermal activity (Section 7.2.1).

Table 12. Coal quality and selected element concentrations (bold text denotes high ash coal)

Mine/Parameter	Ash (%ad)	Volatile matter (%daf)	Carbon (%daf)	Total REY min (ppm)	Total REY max (ppm)	Li average (ppm)	Sc average (ppm)
Collinsville ¹	21.7	22.9	86.5	75	208	36.8	10.3
Newlands ¹	14.8	31.8	85.1	68	147	21.0	5.7
Coppabella ¹	11.8	13.5	90.5	37	90	67.7	3.5
Moorvale ¹	11.8	18.4	89.5	20	49	8.0	4.4
Lake Vermont ¹	10.5	22.9	88.5	44	210	45.5	11.0
Oaky Creek ¹	9.0	28.4	88.2	71.5	71.5	34.0	4.6
Rolleston ¹	7.5	37.3	80.3	19	42	10.8	4.0
Meandu²	30.1	41.9	80.5	31	173		13.7
Collingwood Park						11.1	11.3
Wandoan¹	23.5	52.6	75.9	27	302	85.5	5.5
Unnamed Contribution						36.8	10.3
Metropolitan ³	8.8	22.2	90.3	55	67	21.0	5.7

¹ Averages based on Mutton (2003) and Juniper (2010)

² Mutton (2003)

³ Juniper (2010)

The total REE concentrations look consistently promising in the Walloon and Tarong CMs, suggesting that younger Jurassic and Triassic thermal coals may contain a valuable secondary- or by-product. Unfortunately, these coal formations were sampled at one location only and no regional conclusion can be drawn. **We recommend greater detailed analysis of Walloon and Tarong CM samples.**

Regarding Late Permian coals, a regional assessment has been possible as most of the Bowen Basin mines provided samples from the Rangal CM and its correlative, the Bandanna Fm. Each mine's coal samples (Newlands, Coppabella, Moorvale, Lake Vermont and Rolleston) have their particular signature in terms of element content and REE enrichment pattern (Table 11 and Appendix A). The Lake Vermont samples are the most enriched in many strategic elements, while Moorvale and Rolleston contain the lowest concentrations. Nevertheless, **we recommend additional exploration**

of samples from these mines to validate the findings so far and further substantiate potential for a useful by-product.

Although consistent enrichments have been determined in many samples (Table 11), the current or future economic potential of such occurrences cannot be assessed without a thorough examination of mineral association to determine liberation and extraction techniques. Additionally, elemental opportunities may be enhanced with better understanding of element behaviour through the various stages of mining, processing, use and disposal. This will direct suitable research and development of methods that limit elemental destruction, loss or isolation.

Many coal samples in this study contained Au from a range of basins. The lack of Au detection in most power plant samples may be due to:

- a rare, low Au coal feed
- the Au having been washed out to tailings prior to combustion
- Au may be destroyed by the combustion process at the power plant
- A sampling issue: Au is heavy and may accumulate at the bottom of waste ponds, it would be impossible to sample without coring an ash pile.

Further research would be needed to draw a conclusion on this.

Boyd (2004) analysed elements in coal from three economic seams in the Collinsville CM (Section 5.3.1) and concluded they were similar to the average crustal concentrations (Figure 9), with the exception of Au at around 1 ppm and about 500 times the average crustal composition. LREE were found to be dominant over the heavy elements, although the HREE were slightly enriched. In comparison, our Collinsville CM samples identified that REEs are similar, MREE dominate in both datasets but our Au concentrations were lower. Additional Collinsville Coal samples would be required to draw any conclusions on this.

Ward et al. (1999) reported very low elemental concentrations (REE < 50 ppm) in Permian coals from the Gunnedah Basin, which are comparable with the samples analysed in this study (REE < 10 ppm).

Zhao (2012) reported up 140 ppm REE in the Sydney Basin coals, with elevated Li, Bi and Ge in some seams. The Metropolitan samples analysed in this study do not exceed 70 ppm REE and have elevated Li and Bi; Ge was not detected.

9 Conclusions and further work

- Nearly 90 samples were provided by contributing coal mines and power plants (Figure 40)
- They were analysed for 50 elements not typically measured in coal
- Results were interpreted in relation to their possible provenance (coal basin, age and primary source of elements)
- First map of its kind for Australia
- The elemental concentrations in each sample were normalised against a widely used standard (PAAS) to assess local enrichments (above the average continental crust composition)
- Samples were compared regionally (Appendix A)
- Detailed spatial distribution patterns are presented in Appendix B
- Results indicate a high incidence of above crustal average concentrations of many of the 50 elements analysed
- Further work will improve knowledge on distribution and elemental sources to inform prediction

In conclusion, this project has presented for the first time, a map and analysis that indicates a strong correlation exists between volcanic activity during and after coal deposition and elemental concentrations within coal. REE and Au, while not equal to that of typical ore concentrations, are concentrated greater than PAAS in many of the samples, which may warrant further investigation if suitable extraction techniques can be identified. Further, mineral association of each element must be determined for all elements prior to evaluating economic opportunities.

Limitations of this study are as follows:

- While target sampling was exceeded, the budget meant that not all donated samples could be analysed – further analysis could be possible of samples already donated
- Grab samples were utilised – more samples should be analysed from each site to determine representative results
- There were too few samples in some regions to draw preliminary conclusions on local conditions
- Limited validation was available for some of the areas
- Power plant coal feeds were not available for analysis to allow comparison with the resulting ash composition

Further work is recommended to do the following:

- Analysis of overburden such as Tertiary basalts, in addition to more wide sample selections of coal content – overburden may host valuable elements and itself may provide a resource opportunity
- Analysis of tailings and other waste streams to determine where concentrations are accumulating
- The destination of Au may be of specific interest – whether it is washed into tailings or is being destroyed on combustion. Methods may be developed that can prevent loss of Au
- Ash provenance reassessment and analysis of feed and end products
- Case studies for start to end (pit to product and all waste streams) to determine which processes may destroy, transfer or accumulate elemental resources.

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Appendix A The Dataset

Appendix A contains

- elemental concentrations in ppm (mg/kg) that are presented in Chapter 7
- descriptive statistics (range, min, max, average, standard deviation)
- total REE + Y
- outlook coefficient $C = (Nd + Eu + Tb + Dy + Er + Y)/\Sigma REY)/(Ce + Ho + Tm + Yb + Lu/\Sigma REY)$
- normalised concentration against PAAS values (post-Archean Australian shale), after McLennan, 2001, reflecting above background concentrations
- indices based on normalised REE concentrations

Note: Co should be viewed with caution, contamination from tungsten carbide crushing mills may be possible

Appendix B Spatial distribution of strategic elements

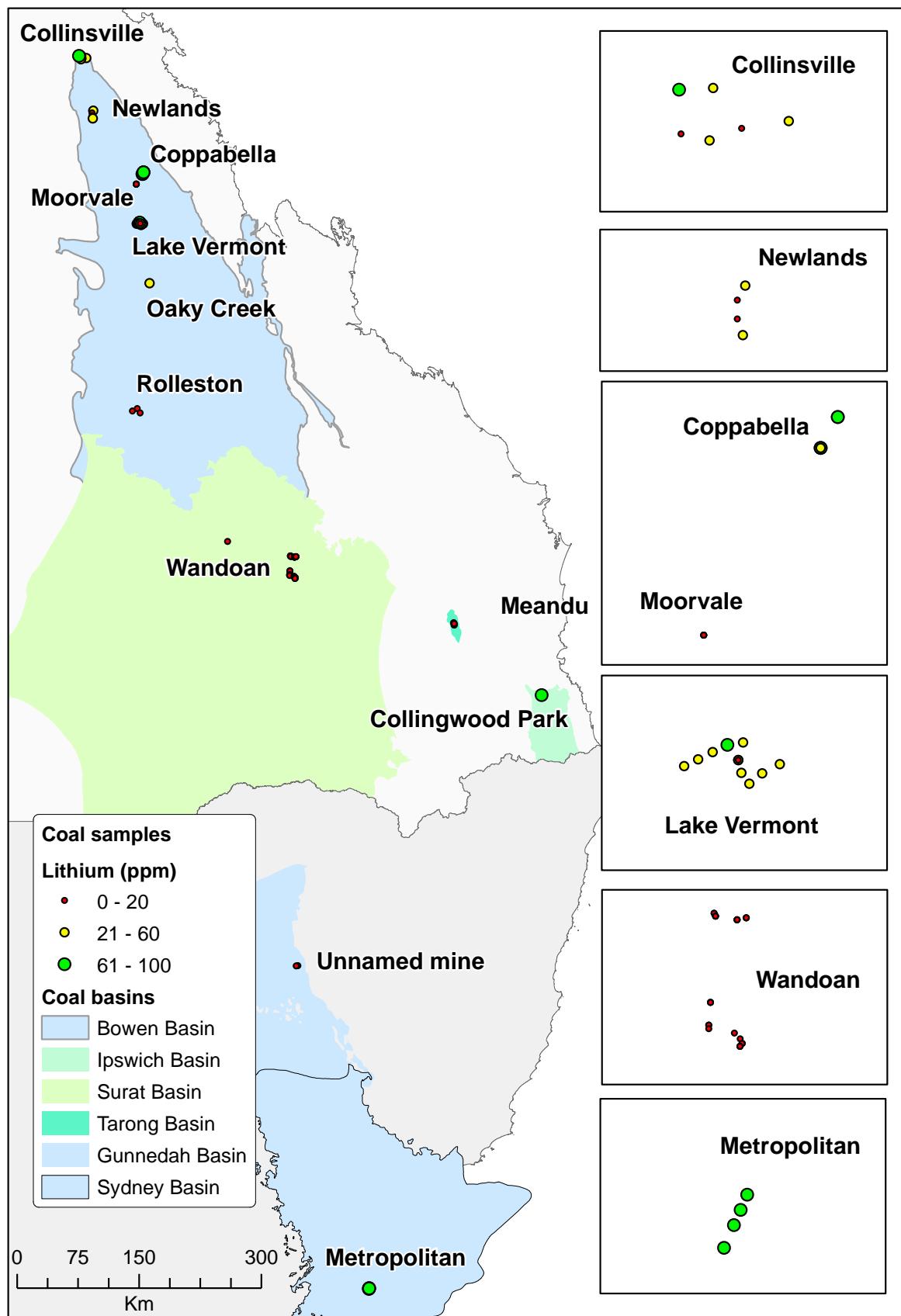
The following maps display the spatial distribution of key elements that have been determined to be above crustal abundance concentrations (Table B.1).

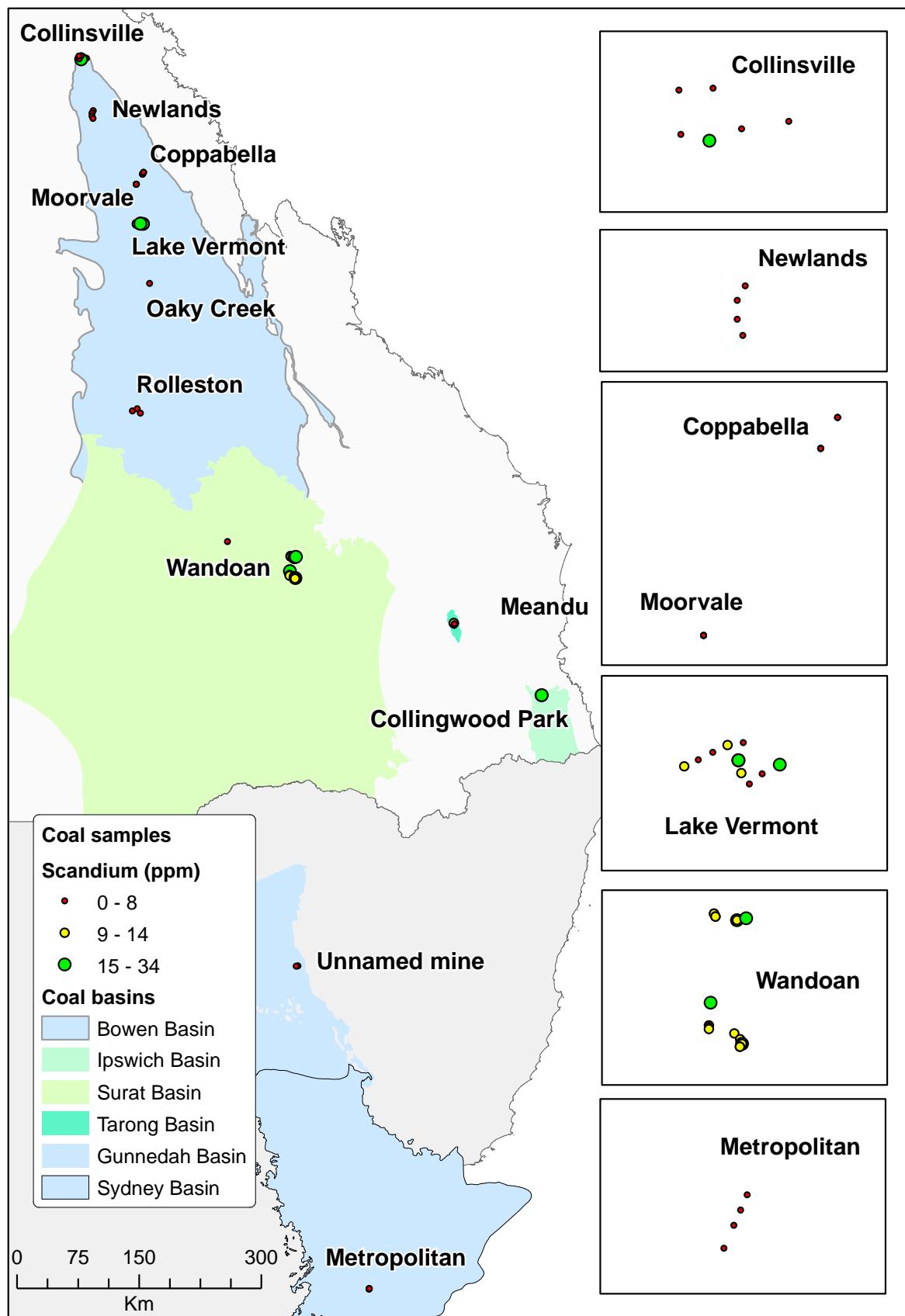
Apx Table B.1 Average crustal composition of selected elements and parameters

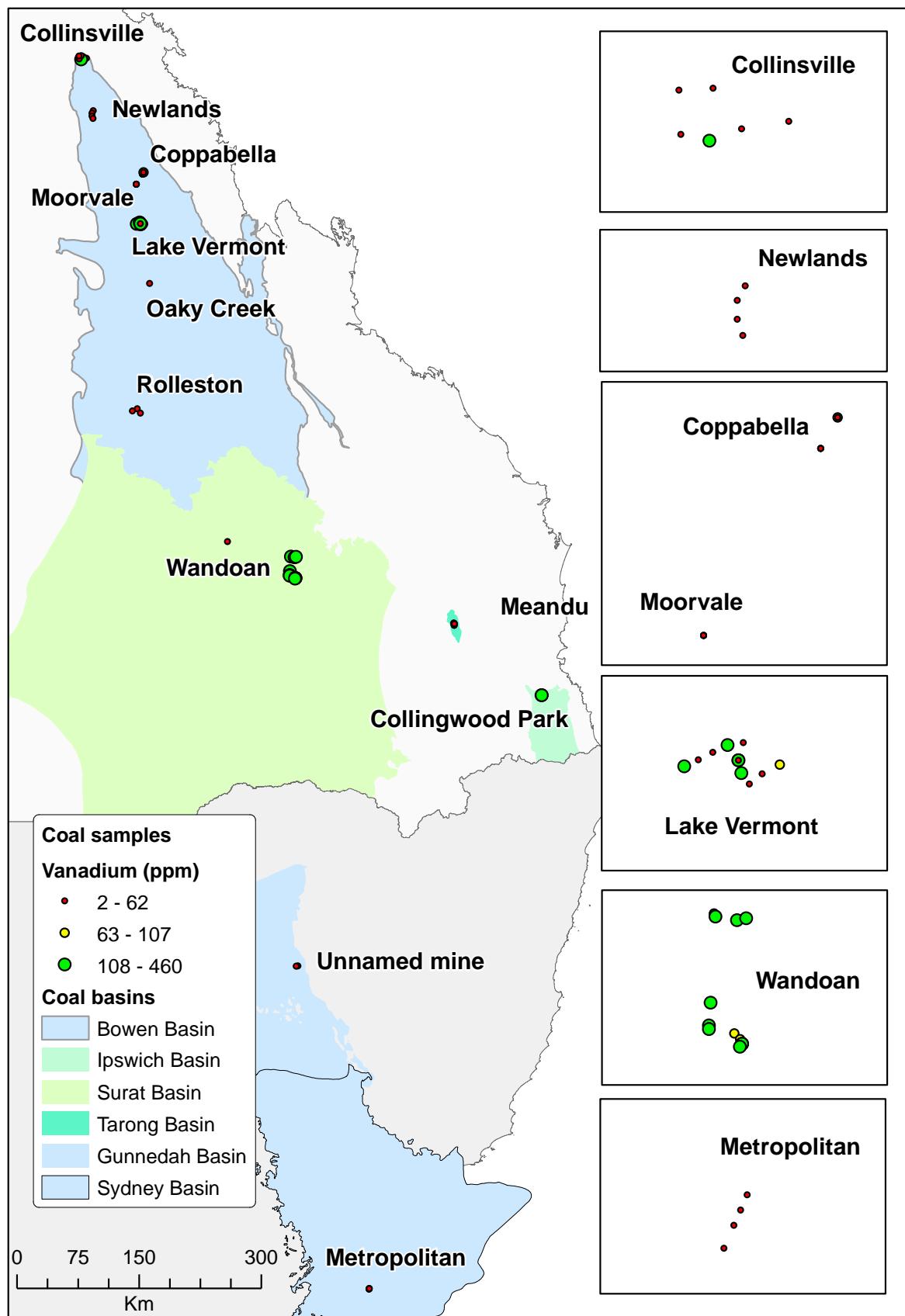
Element	Symbol	PAAS (ppm)
Lithium	Li	20
Scandium	Sc	13.6
Vanadium	V	107
Copper	Cu	25
Yttrium	Y	22
Gold	Au	0.0018
Bismuth	Bi	0.127
Totals	REE	145
	REY (REE+Y)	170
	LREE (La+Ce+Pr+Nd+Sm)	132
	MREE (Eu+Gd+Tb+Dy+Y)	30
	HREE (Ho+Er+Tm+Yb+Lu)	6

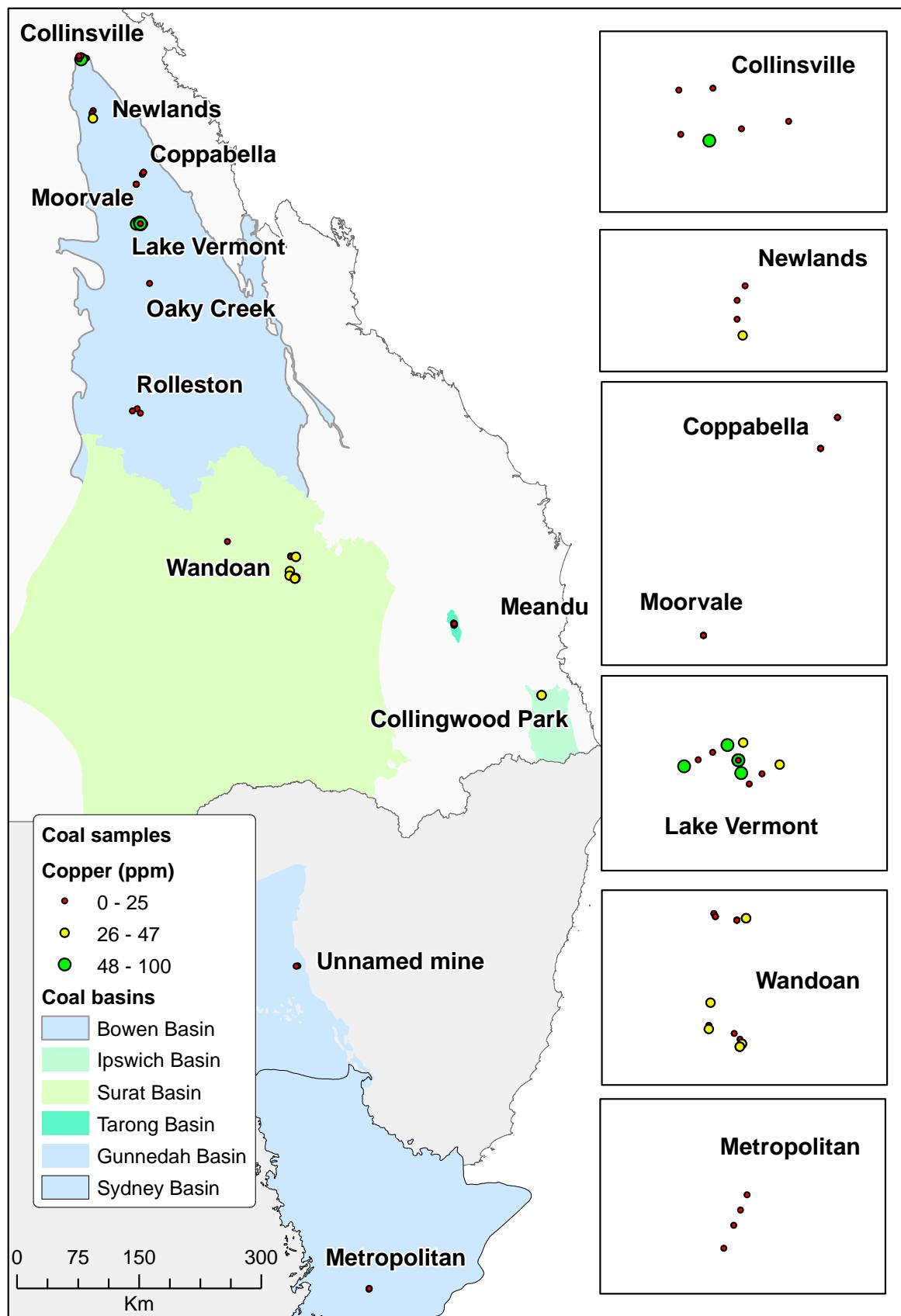
The range of elemental concentrations shown in the map legends are built around the PAAS values. For example, the ranges displayed for Li are:

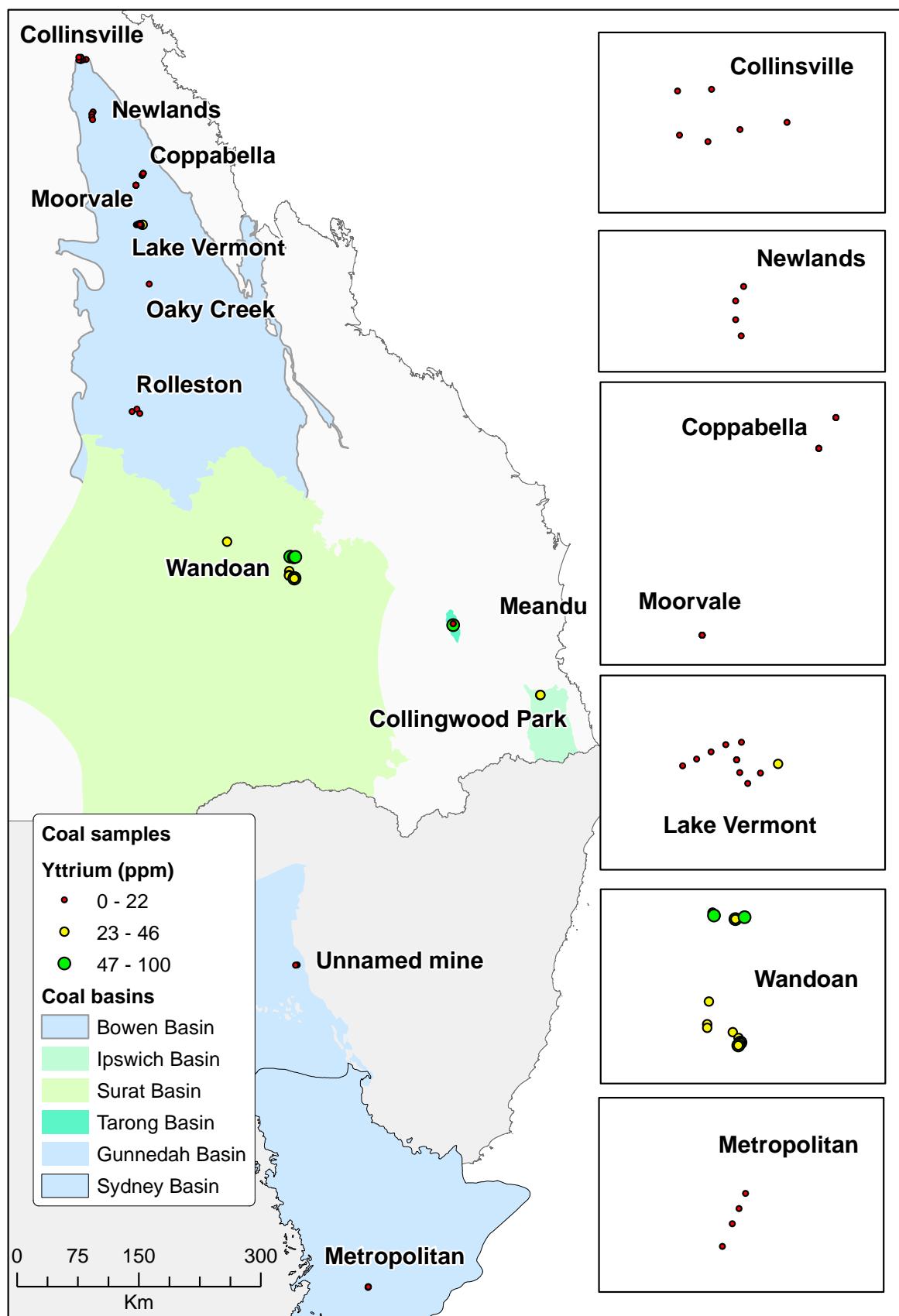
- 0 – 20 ppm (below background) – red symbol
- 21 – 60 ppm (above background) – yellow symbols – promising concentrations
- 61 – 100 ppm (3-4 times above background) – green symbols – notable concentrations

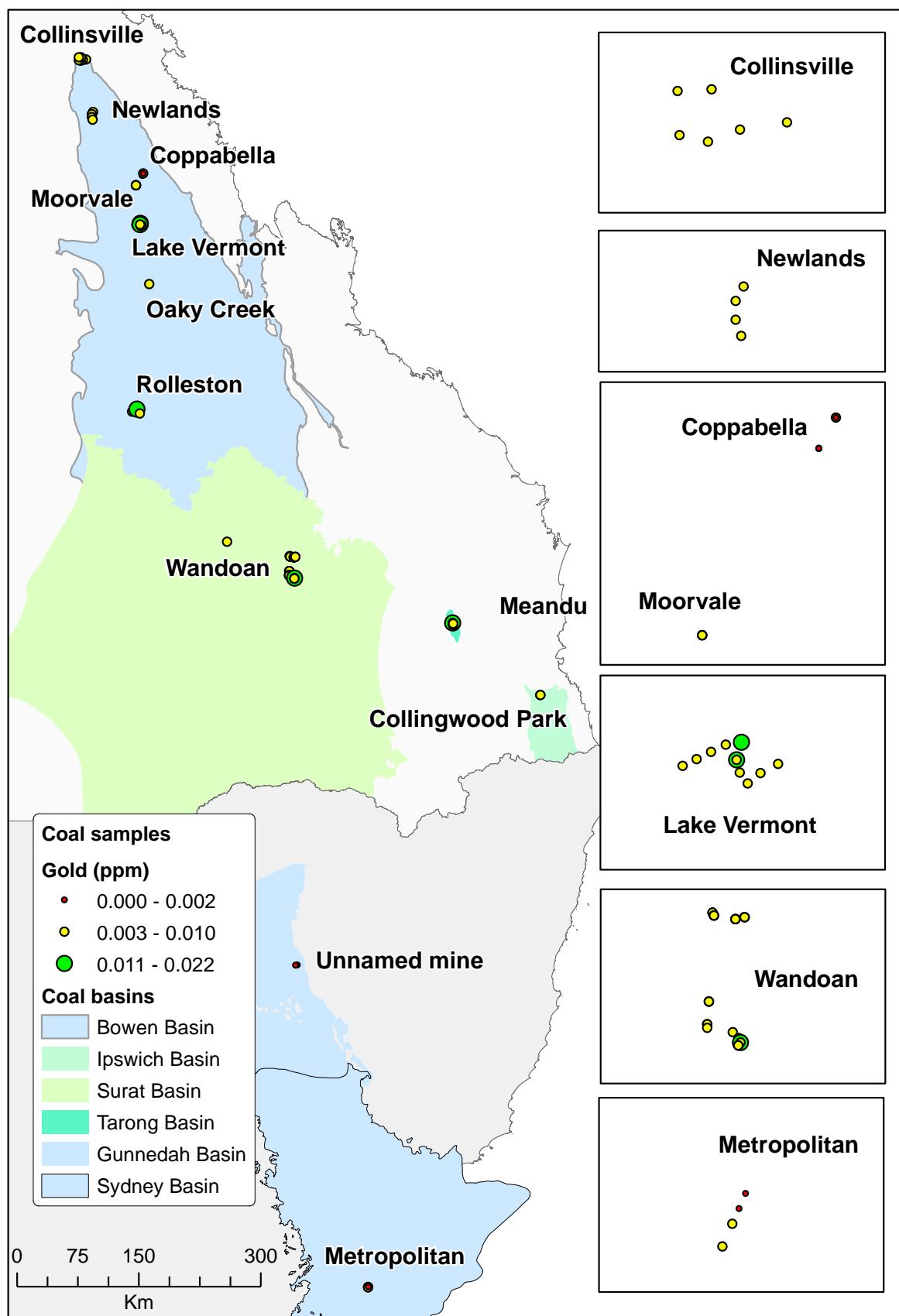


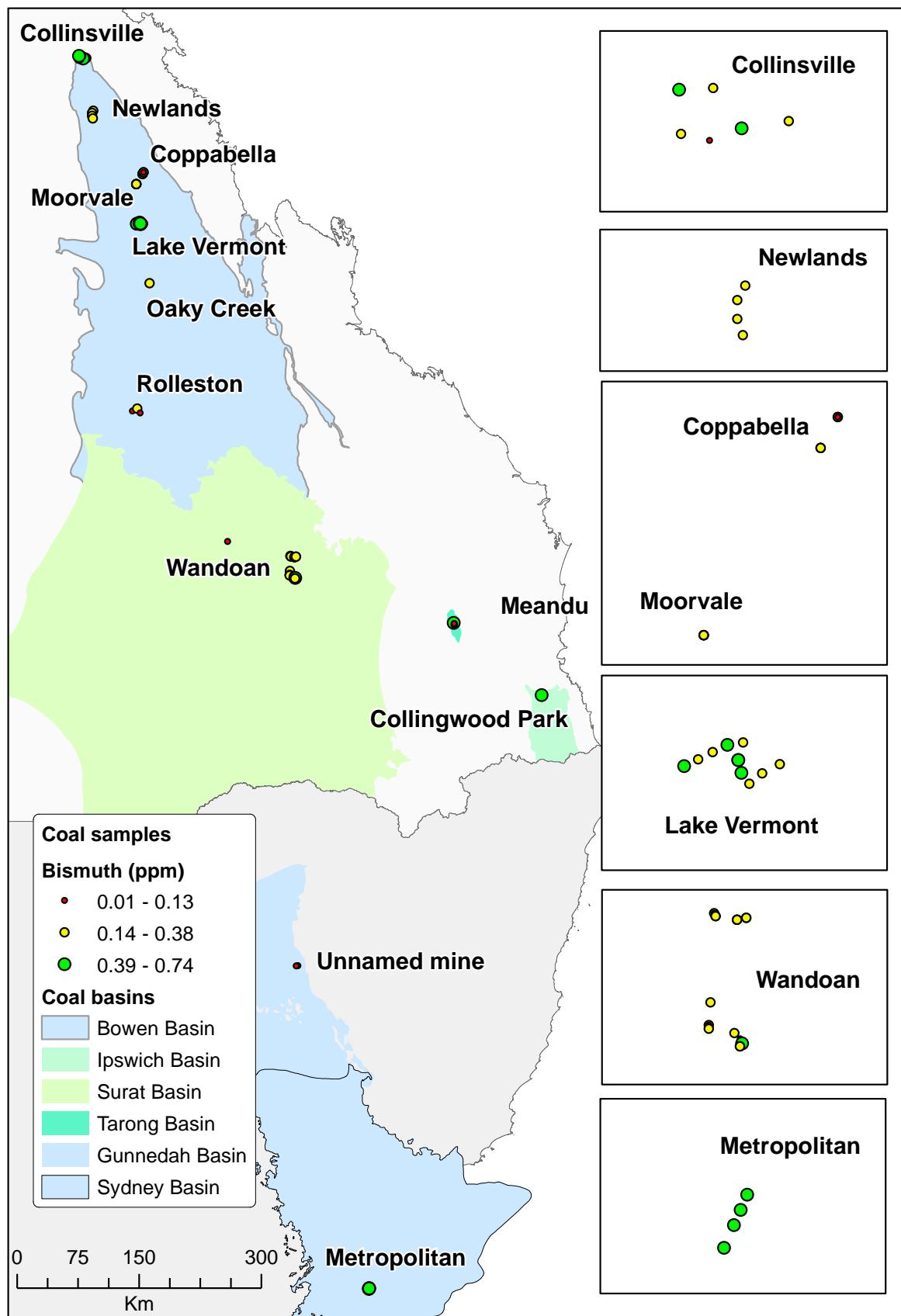


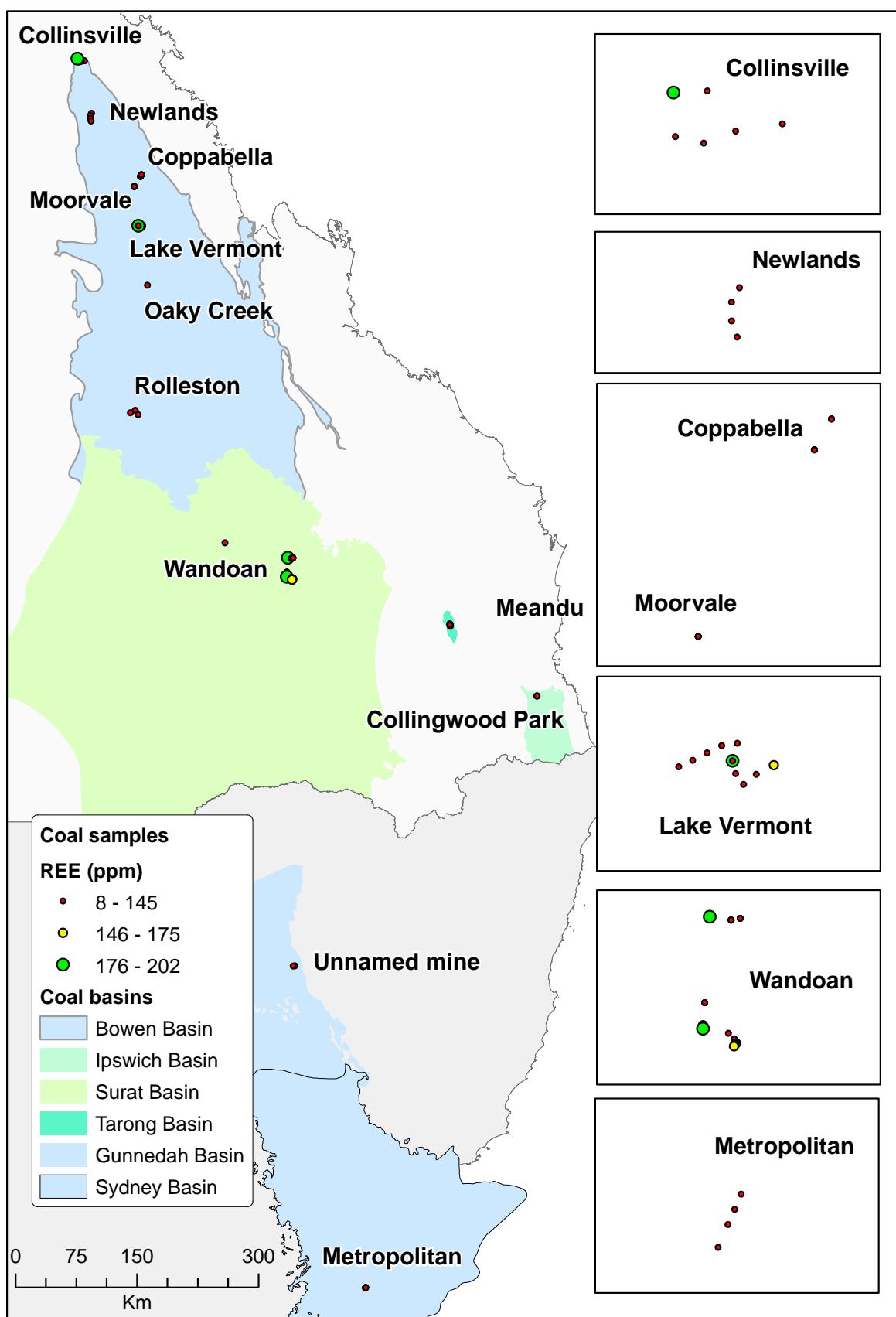


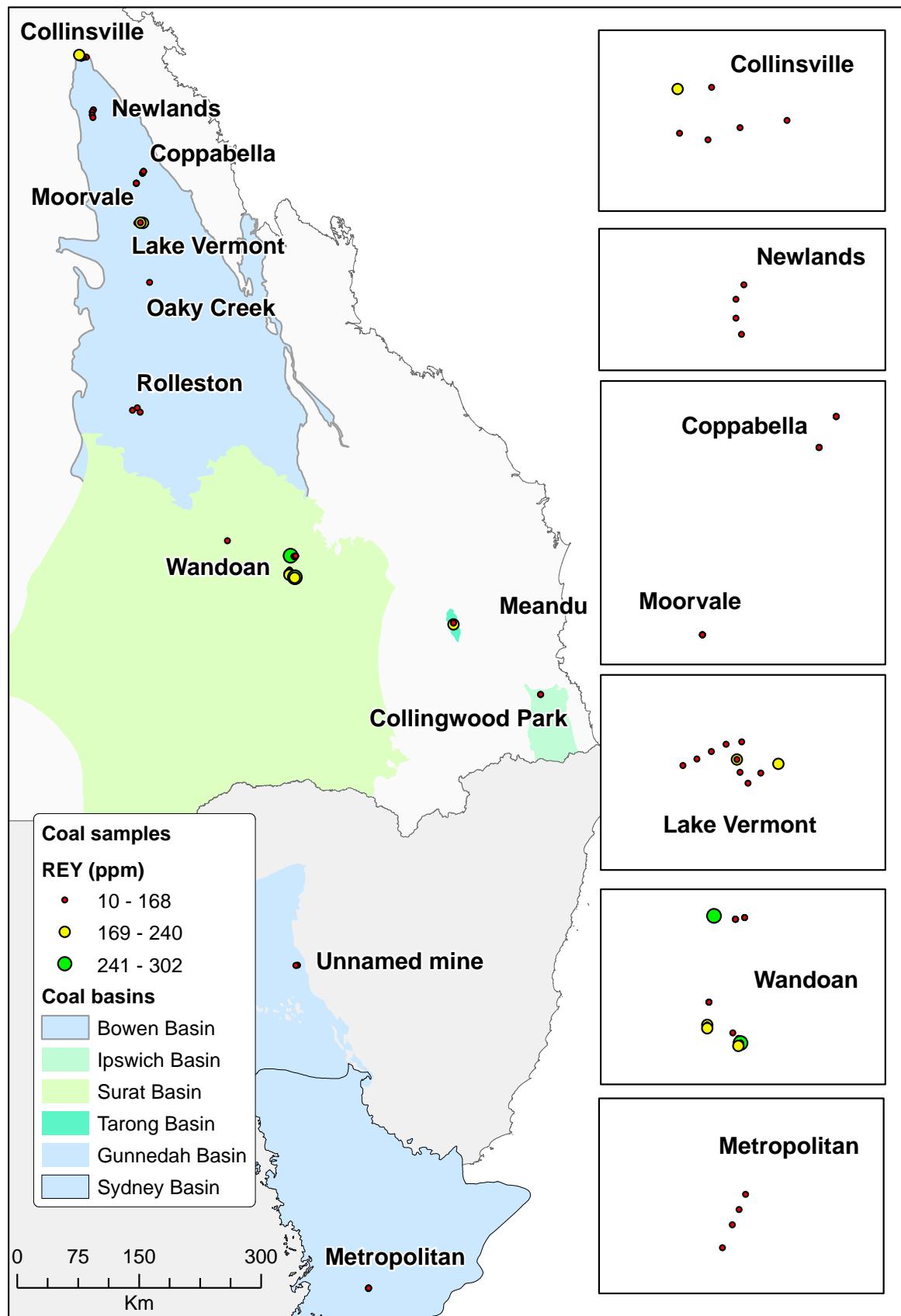


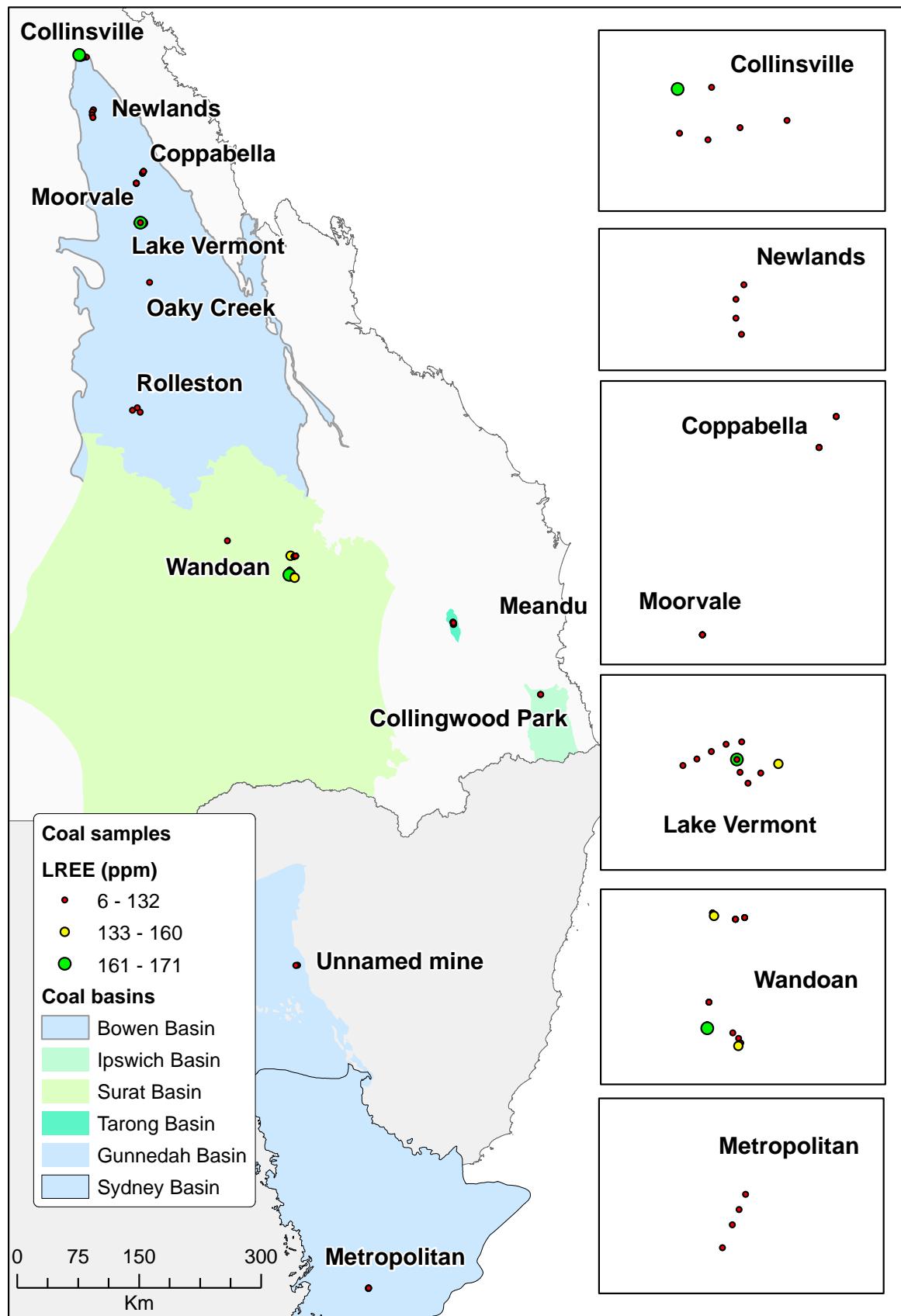


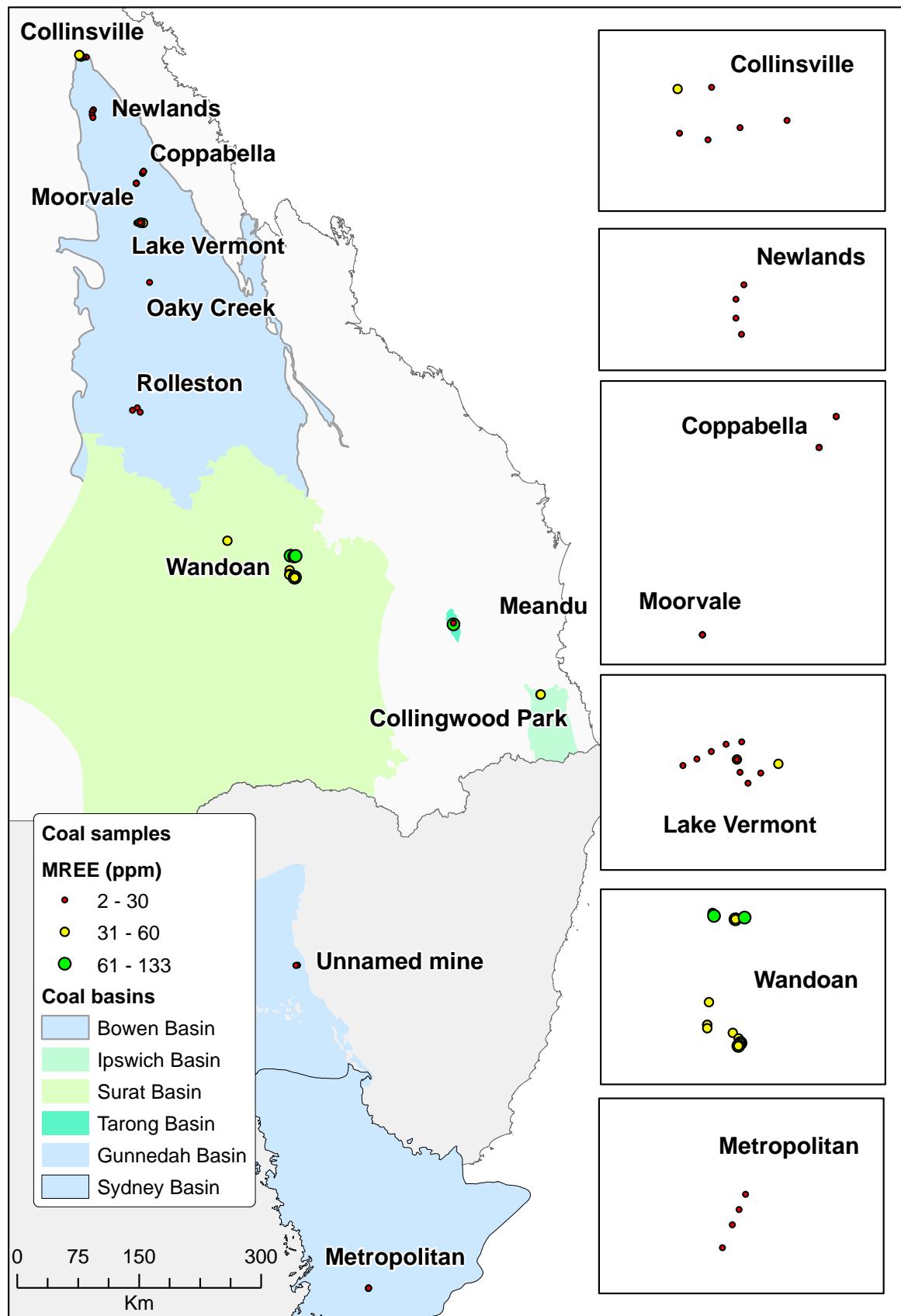


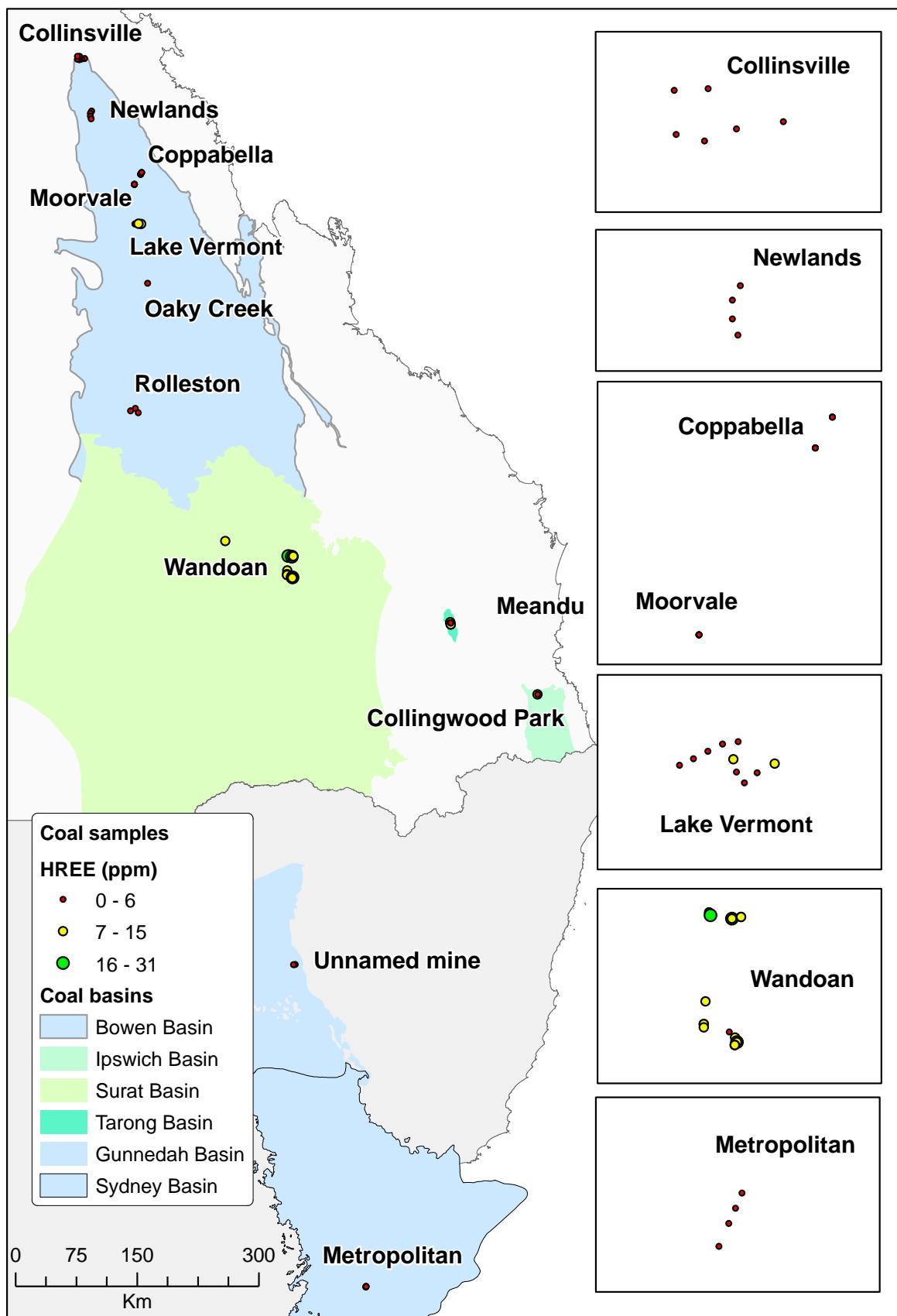












Appendix C Reports to contributors

The following reports were supplied to supporting mines.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

ADAA

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

Power Plant	Dominant coal feed	Sample type	Sample name
Stanwell	Rangal CM	Fly ash	STFA-1
Stanwell		Bottom ash	STBA-1
Gladstone		Fly ash	GLFA-1
Gladstone		Bottom ash	GLBA-1
Callide	Callide CM	Fly ash	CALFA-1
Callide		Bottom ash	CALBA-1
Kogan	Walloon CM	Fly ash	KCBA-1
Kogan		Bottom ash	KCFA-1
Millmerran		Fly ash	MMFA-1
Millmerran		Bottom ash	MMBA-1

Table 2: Summary of analytical results Table 11 in CSIRO Report

Power Plant	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Stanwell	Rangal CM	Fly ash	403	1.5	Li, Mo, Bi
		Bottom ash	339	1.4	
Gladstone	Rangal CM	Fly ash	312	1.1	Li, Mo, Bi
		Bottom ash	272	1.1	
Callide	Callide CM	Fly ash	224	1.1	
		Bottom ash	201	1.1	
Kogan Creek	Walloon CM	Fly ash	304	1.0	Mo, Ag, In, Au only in bottom ash, Bi
		Bottom ash	309	1.1	
Millmerran	Walloon CM	Fly ash	357	1.2	Cu, Ga, Y, Mo, Ag, MREE, HREE, Bi
		Bottom ash	362	1.2	

Sample elemental results

Appendix A of full CSIRO dataset



Key Notes

- The highest total REE concentration was determined in the Stanwell ash (Rangal CM), followed closely by the Millmerran ash (Walloon CM).
- The lowest REE content was found in the Callide ash (Callide CM).
- A large difference between the fly ash and bottom ash concentrations was observed in the Stanwell, Gladstone (both Rangals) and Callide ash samples, while at Kogan Creek and Millmerran (each of Walloon CM sources) the two types of ash are very similar in concentrations.
- Each power plant has a different elemental signature with elevated concentrations (>2 times the PAAS background values) as follows:
 - Stanwell: Li, Sc, Y, Mo, Ag, Cd, In, MREE, HREE, Bi
 - Gladstone: Li (highest Li of all the power plant ashes), Cu, Mo, In, MREE, Bi
 - Callide: Mg, Fe, Zr, Mo, MREE
 - Kogan Creek: Ga, Mo, Ag, MREE, Au (in bottom ash only), Bi
 - Millmerran: Cu, Ga, Mo, Ag, In, MREE, HREE, Bi

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Collingwood Park

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

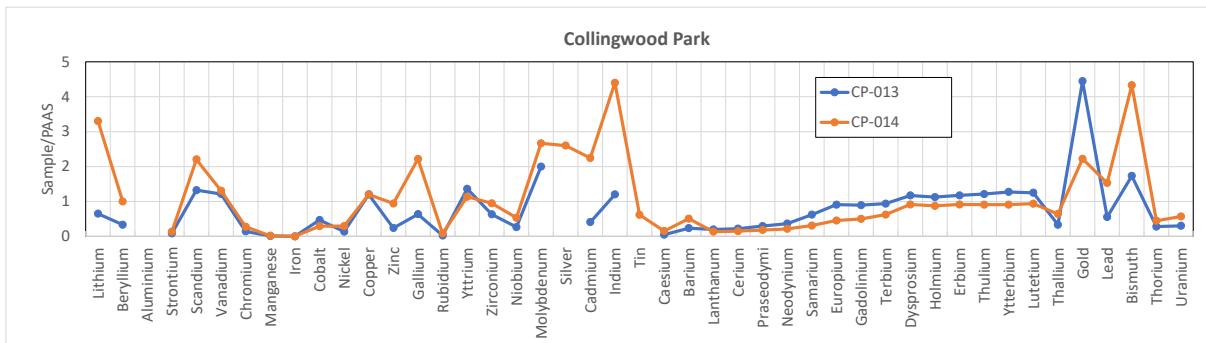
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Collingwood Park	Blackstone Formation	Coal	CP-013	127
	Blackstone Formation	Coal	CP-014	131.1

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Collingwood Park	Blackstone Formation	Coal	80.6	2.6	Li, Sc, V, Ga, Mo, Ag, Cd, In, Bi
	Blackstone Formation	Coal	58.2	2.8	

Sample elemental results

Appendix A of full CSIRO Report



Key Notes

- The Ipswich Basin coal has the potential of containing strategic elements due to the intense faulting of the basin and the presence of volcanic material in its sediments and coal seams.
- The Collingwood Park samples from the Blackstone Formation, were the only samples in this study that represented the Ipswich Basin
- The clastics are derived from active continental margin basalts
- Elevated elements are Li, V and Bi (as observed in Late Permian coal samples) and Sc (similar to Collinsville). Unique to the Blackstone Fm are elevated Ga, Cd and In, which are not remarkable in the Bowen Basin samples.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Collinsville

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

Rank (after Mutton, 2003): medium volatile hard coking coal or medium volatile thermal coal

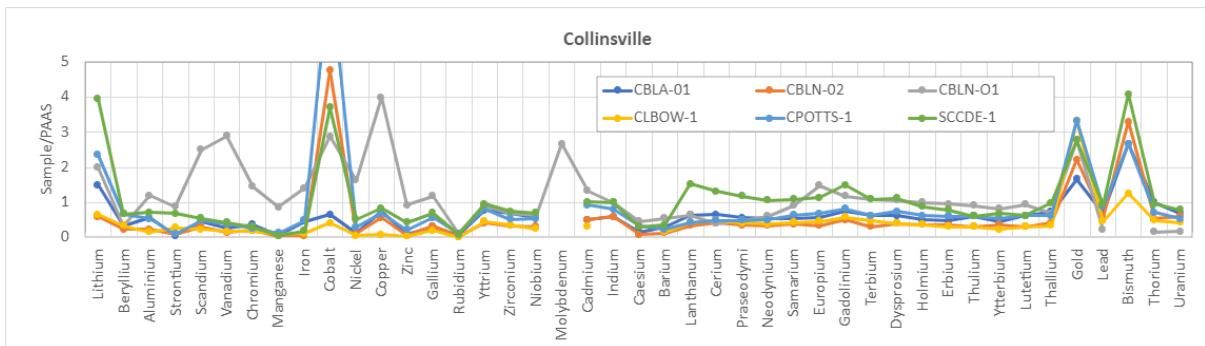
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Collinsville	Blake (BUB)	Coal	CBLA-01	63
	Bowen upper (BUB)	Coal	CBLN-02	59
	Bowen lower (BUB)	Volatile coal	CBLN-O1	67
	Little Bowen (BUB)	Coal	CLBOW-1	51
	Potts (Blake North)	Coal	CPOTTS-1	64
	Scott/Denison (Blake North)	Coal	SCCDE-1	15.5

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Collinsville	Blake (BUB)	Coal	107.0	0.8	Li, Sc, V, Cr, Cu, Mo, Bi
	Bowen upper (BUB)	Coal	64.5	0.7	
	Bowen lower (BUB)	Volatile coal	103.7	1.5	
	Little Bowen (BUB)	Coal	74.8	0.7	
	Potts (Blake North)	Coal	91.7	1.1	
	Scott/Denison (Blake North)	Coal	207.9	0.6	

Sample elemental results

Appendix A of full CSIRO dataset



Extract Key Notes

- Consistently higher than background levels of Li, Au and Bi, are found in all the Bowen Basin samples, with occasional enrichments of V, Cu, Cr and Mo. Collinsville is the only site found to have elevated Sc.
- The total REE concentrations are generally low, around 100 ppm, with a couple of exceptions in the Potts pit at Collinsville (total REE = 208 ppm)
- Boyd (2004) analysed elements in coal from three economic seams in the Collinsville CM and concluded they were similar to the average crustal concentrations, with the exception of Au at around 1 ppm and about 500 times the average crustal composition. LREE were found to be dominant over the heavy elements, although the HREE were slightly enriched. In comparison, our Collinsville CM samples identified that REEs are similar, MREE dominate in both datasets but our Au concentrations were lower. Additional Collinsville Coal samples would be required to draw any conclusions on this.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Coppabella

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

Rank (after Mutton, 2003): Low volatile, low ash and sulphur, high energy PCI coal or high energy thermal coal

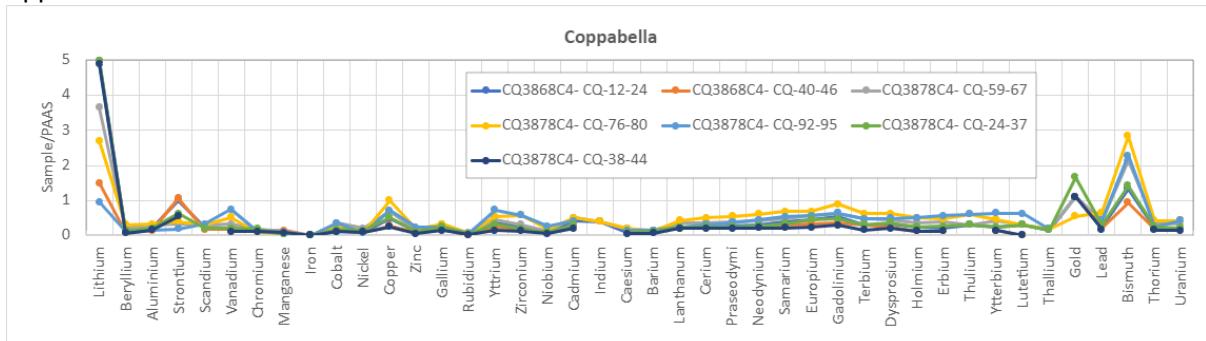
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Coppabella	Leichhardt Lower 1	Coal	CQ3868C4-CQ-12-24	12-24
	Leichhardt Lower 2	Coal	CQ3868C4-CQ-40-46	40-46
	Vermont Upper	Coal	CQ3878C4-CQ-59-67	59-67
	Vermont Lower 2	Coal	CQ3878C4-CQ-76-80	76-80
	Vermont Lower 3	Coal	CQ3878C4-CQ-92-95	92-95
	Leichhardt Lower 1	Coal	CQ3878C4-CQ-24-37	24-37
	Leichhardt Lower 2	Coal	CQ3878C4-CQ-38-44	38-44

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Coppabella	Leichhardt Lower 1	Coal	47.6	1.1	Li, Au, Bi
	Leichhardt Lower 2	Coal	37.0		
	Vermont Upper	Coal	68.2	1.0	
	Vermont Lower 2	Coal	89.5	0.9	
	Vermont Lower 3	Coal	67.2	1.4	
	Leichhardt Lower 1	Coal	45.3	1.0	
	Leichhardt Lower 2	Coal	32.9		

Sample elemental results

Appendix A of full CSIRO dataset



Extract Key Notes

- Lithium, gold, and bismuth were above average crustal concentrations in the Coppabella samples
- Regarding Late Permian coals, a regional assessment has been possible as most of the Bowen Basin mines provided samples from the Rangal CM and its correlative, the Bandanna Fm. Each mine's coal samples in the Rangals have their particular signature in terms of element content and REE enrichment pattern
- REE concentrations that are particularly low (total REE < 50 ppm) include samples from Coppabella.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Lake Vermont

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Lake Vermont	Leichhardt roof	Carbonaceous mudstone	2648CR01	46.5-46.6
	Leichhardt	Coal	2648CR02	46.6-49.4
	Leichhardt floor	Mudstone	2648CR03	49.4-49.5
	Vermont upper	Coal 86% tonstein 14%	2700C02	24.6-24.8
	Vermont upper floor	Carb mudstone	2700C05	26.2-26.3
	Vermont	Coal	2676C02	37.4-38.2
	Vermont floor	Coaly shale	2676C11	43.7-43.9
	Vermont lower floor	Coaly shale	2648C09	95.5-95.7
	Vermont	Coal, carb. shale	2644C07-C08	44.1-44.8
	Vermont lower	Coal	2648C06-C08	91.8-95.5
	Vermont	Igneous rock	2638C03_IR	94.3-94.9
	Vermont	Heat affected coal	2638C04_HA	94.9-95.0

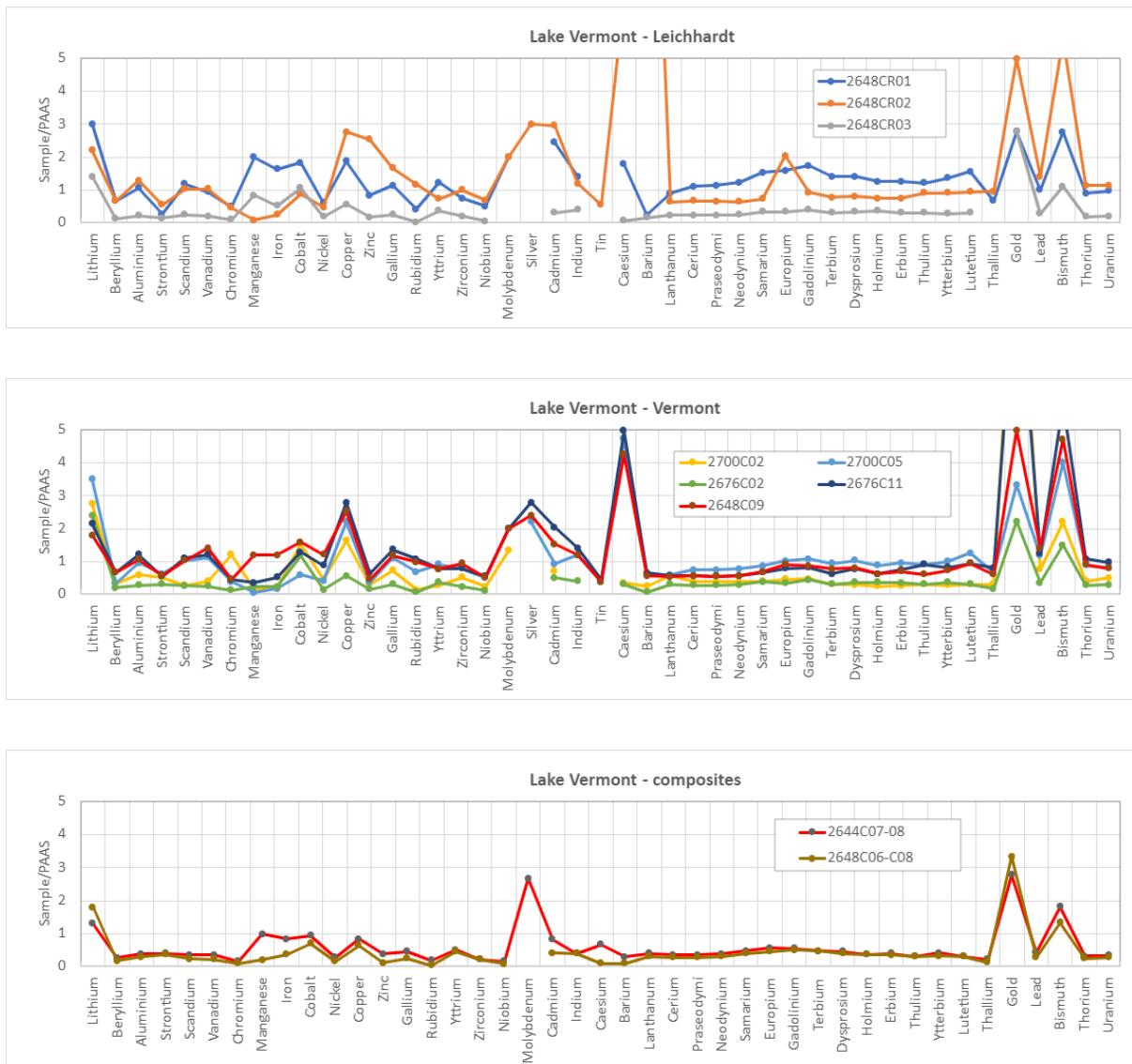
Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Lake Vermont	Leichhardt roof	Carbonaceous mudstone	193.7	0.9	Li, V, Cu, Mo, Ag, Cs, Bi
	Leichhardt	Coal	115.9	0.9	
	Leichhardt floor	Mudstone	44.0	1.1	
	Vermont upper	Coal 86% tonstein 14%	67.0	0.7	Li, V, Cu, Mo, Ag, Cs, Bi
	Vermont upper floor	Carb mudstone	130.2	0.9	
	Vermont	Coal	51.3	1.0	
	Vermont floor	Coaly shale	103.3	0.9	

	Vermont lower floor	Coaly shale	102.6	1.0	
	Vermont	Coal, carb. shale	66.9	1.0	
	Vermont lower	Coal	54.5	1.1	
	Vermont	Igneous intrusion	210.1	0.9	Cr, Ni, Nb, Cs, Eu, Ta
	Vermont	Heat affected coal	127.0	0.6	Sc, Ga, Cs, Au, Bi

Sample elemental results

Appendix A of full CSIRO dataset



Extract Key Notes

- Au is generally 4-5 times the background (~ 6-9 ppb)
- Leichhardt roof at Lake Vermont total REE = 194 ppm
- Notable samples from Lake Vermont: an igneous intrusion in the Vermont seam and the associated heat-affected coal. The igneous intrusion has a very different chemical signature than the coal samples at Lake Vermont with Cr, Ni, Nb, Cs and Ta concentrations exceeding background levels. The strong positive Eu anomaly suggests a mafic origin. The heat-affected coal is also dissimilar with respect to the intrusion and the other Vermont seam samples as it contains Sc, Ga and Cs above background levels.
- The Eu anomaly has a high value of 2.5 at Lake Vermont
- A few positive Gd anomalies (>1) are determined, supporting the influence of hydrothermal fluids, on deposits at Lake Vermont

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Meandu

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

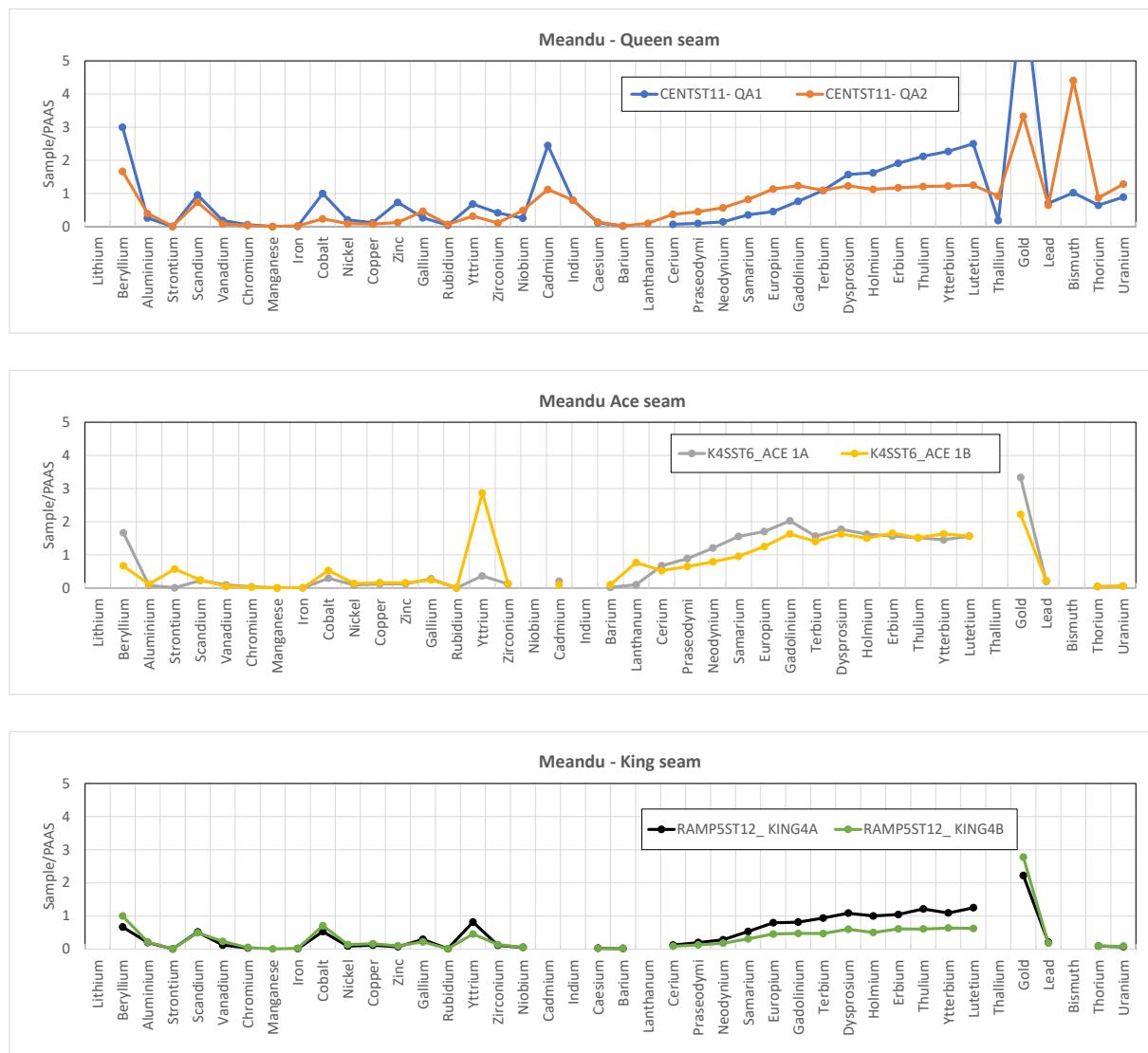
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Meandu	Ace seam roof ply	Coal	K4SST6_ACE1A	462.5
	Ace seam roof ply	Coal	K4SST6_ACE1B	462.5
	Lower King seam ply	Coal	RAMP5ST12_KING4 A	475
	Lower King seam ply	Coal	RAMP5ST12_KING4 B	475
	Upper Queen Seam A ply	Coal	CENTST11_QA1	454
	Upper Queen Seam A ply	Coal	CENTST11_QA2	455

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Meandu	Ace seam roof ply	Coal	47.4	2.4	Y, MREE, Au, Bi
	Ace seam roof ply	Coal	73.2	1.1	
	Lower King seam ply	Coal	124.1	1.1	
	Lower King seam ply	Coal	172.5	2.4	
	Upper Queen Seam A ply	Coal	51.5	2.8	
	Upper Queen Seam A ply	Coal	30.6	2.4	

Sample elemental results

Appendix A of full CSIRO dataset



Key Notes

- MREE and HREE are elevated in four of the six plies analysed; one of the Ace plies contains REE concentrations of 172 ppm and has an outlook coefficient of 2.4
- Samples from the three Meandu seams samples have slightly different trace and REE signatures:
 - The Ace seam has elevated Y, no Bi and the highest REE concentrations of all the Meandu seams (total REE = 124-172 ppm), with a MREE and HREE dominance
 - The King seam has no La or Bi, low REE total
 - The Queen seam has elevated Au and Bi, low REE total but a strong HREE dominance in one of the plies.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Metropolitan

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

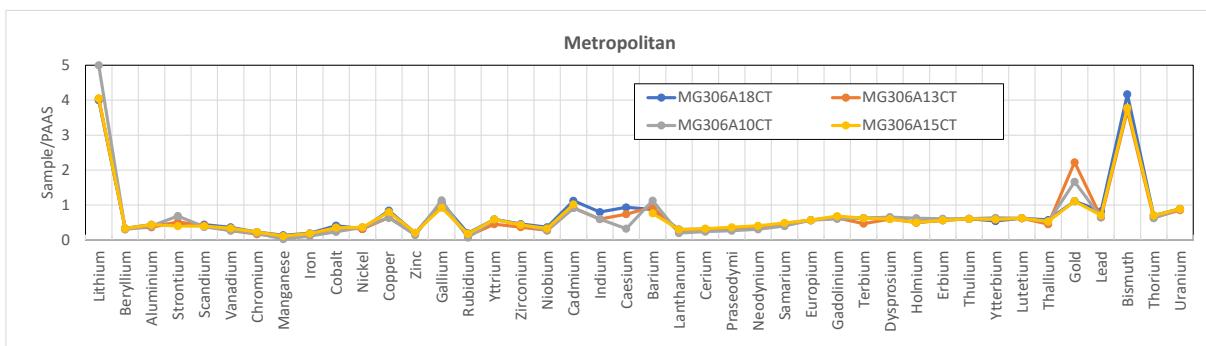
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Metropolitan	Bulli	Metropolitan	MG306A18CT	480
	Bulli	Metropolitan	MG306A13CT	425
	Bulli	Metropolitan	MG306A10CT	43
	Bulli	Metropolitan	MG306A15CT	440

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Metropolitan	Bulli	Metropolitan	64.9	1.2	Li, Au, Bi
	Bulli	Metropolitan	56.5	1.1	
	Bulli	Metropolitan	55.3	1.4	
	Bulli	Metropolitan	67.2	1.2	

Sample elemental results

Appendix A of full CSIRO dataset



Key Notes

- The coal samples from the Metropolitan Mine are poor in trace elements and REE (total REE < 70 ppm)
- Remarkable though, are the concentrations of Li (100 ppm), Au (0.004 ppm) and Bi (0.53 ppm), which are a few times higher than the background concentration levels (20 ppm, 0.0018 ppm and 0.127 ppm, respectively)
- The generally low concentrations of elements and elevated Li and Bi in these low ash samples corresponds with findings by Zhao (2012)
- The Metropolitan samples analysed in this study do not exceed 70 ppm REE and have elevated Li and Bi; Ge was not detected

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Moorvale

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

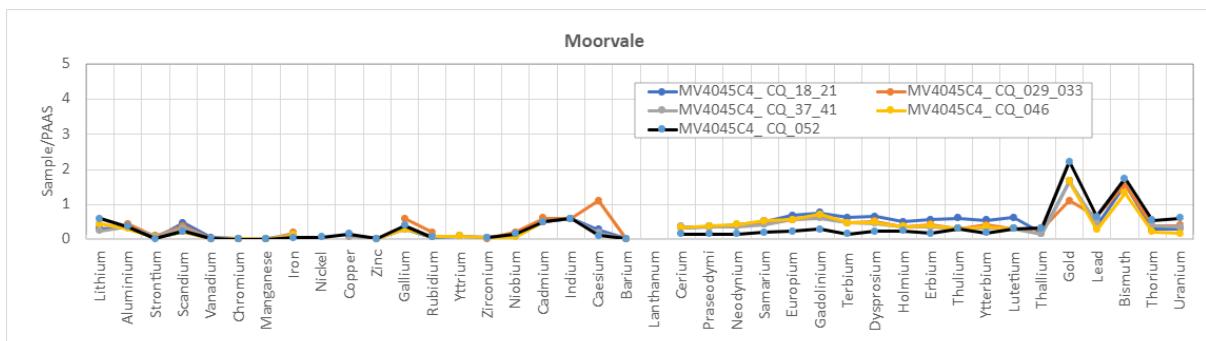
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Moorvale	Leichhardt Upper 2	Coal	MV4045C4_CQ_18_21	12-24
	Leichhardt Lower 1t	Coal	MV4045C4_CQ_029_033	40-46
	Leichhardt Lower 1B	Coal	MV4045C4_CQ_37_41	59-67
	Leichhardt Lower 2	Coal	MV4045C4_CQ_046	76-80
	Leichhardt Lower 2	Coal	MV4045C4_CQ_052	

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient	Other above background elements
Moorvale	Leichhardt Upper 2	Coal	49.0	0.7	Au, Bi
	Leichhardt Lower 1t	Coal	43.9		
	Leichhardt Lower 1B	Coal	44.0		
	Leichhardt Lower 2	Coal	47.6	0.7	
	Leichhardt Lower 2	Coal	19.6		

Sample elemental results

Appendix A of full CSIRO dataset



Extract Key Notes

- Samples with particularly low REE (total REE < 50 ppm) concentrations include samples from Moorvale.
- Gold and Bi were detected at above average crustal concentrations (PAAS).

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Newlands

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

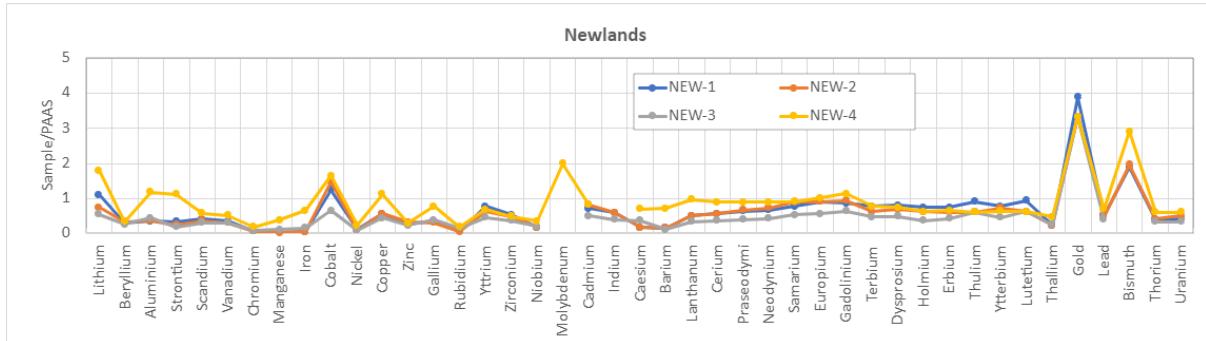
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Newlands	Goonyella Middle Seam	Coke raw feed	NEW-1	63
	Goonyella Middle Seam	Coke raw Feed	NEW-2	59
	P67 Goonyella Middle Seam	Coal	NEW-3	67
	R3 BSB Goonyella Middle Seam	Coal	NEW-4	51

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient REY	Other above background elements
Newlands	Goonyella Middle Seam	Coke raw feed	105.1	1.0	Li, Mo, Bi
	Goonyella Middle Seam	Coke raw feed	104.3	1.0	
	P67 Goonyella Middle Seam	Coal	67.6	1.0	
	R3 BSB Goonyella Middle Seam	Coal	146.7	0.7	

Sample elemental results

Appendix A of full CSIRO dataset



Extract Key Notes

- A few positive Gd anomalies (>1) are determined in deposits at Newlands.
- Concentrations in the deposits from Newlands indicate they have been influenced by hydrothermal fluids.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Oaky Creek

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

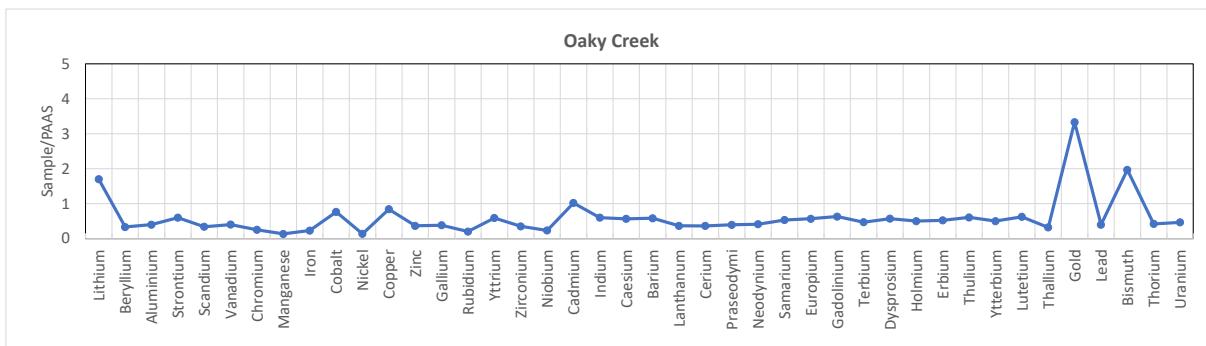
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Oaky Creek	German Creek Seam	Coal raw feed	OCN-GC	180-230

Table 2: Summary of analytical results (Table 11 in CSIRO Report)

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient REY	Other above background elements
Oaky Creek	German Creek Seam	Coal raw feed	71.5	1.1	Li, Bi

Sample elemental results

Appendix A of full CSIRO dataset



Key Notes

- The Oaky Creek sample was the only underground sample of the dataset
- Oaky Creek displayed higher than background crustal concentrations (PAAS) of Li, Au ad Bi
- Additional Oaky Creek samples would be required to better understand elemental sources and draw a conclusion on elemental potential.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Rolleston

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

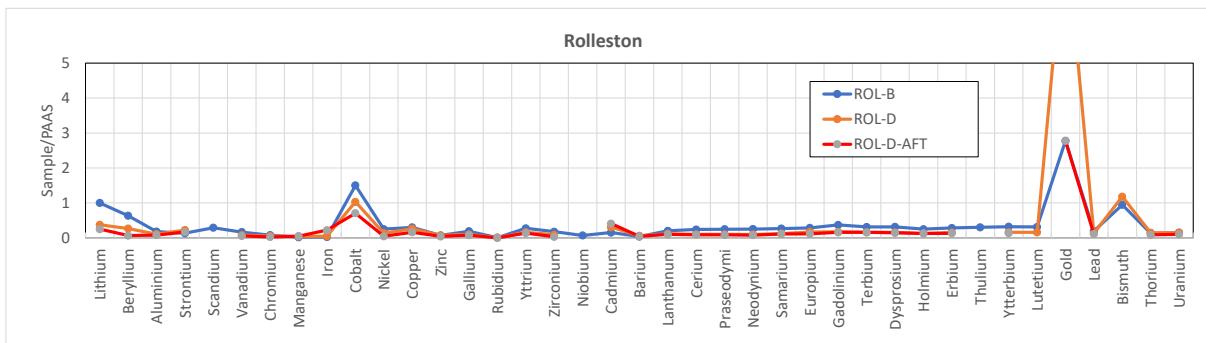
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Rolleston	B Seam	Coal	ROL-B	50-60m
	D Seam	Coal	ROL-D	50-70m
	D- low aft	Coal	ROL-D-AFT	50-70m

Table 2: Summary of analytical results (Table 11 in CSIRO Report)

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient REY	Other above background elements
Rolleston	B Seam	Coal	45.7	1	Li, Bi, Au
	D Seam	Coal	15.4		
	D- low aft	Coal	16.7		

Sample elemental results

Appendix A of full CSIRO dataset



Key Notes

- Au is generally 4-5 times the background (~ 6-9 ppb) concentration, with 28 ppb at Lake at Rolleston
- Particularly low REE (total < 50 ppm) concentrations are found at Rolleston
- Rolleston samples contained among the lowest concentrations of many strategic elements in this study, although we recommend additional analysis of samples to validate findings and substantiate potential for useful by-products
- Rolleston coal is supplied to the Gladstone Power Plant who kindly provided ash samples for analysis, results of which are discussed in the CSIRO report, but in summary
- Deeper investigation of elemental content and concentration from pit-to-ash may be of value.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Unnamed Mine – Black Jack Group

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

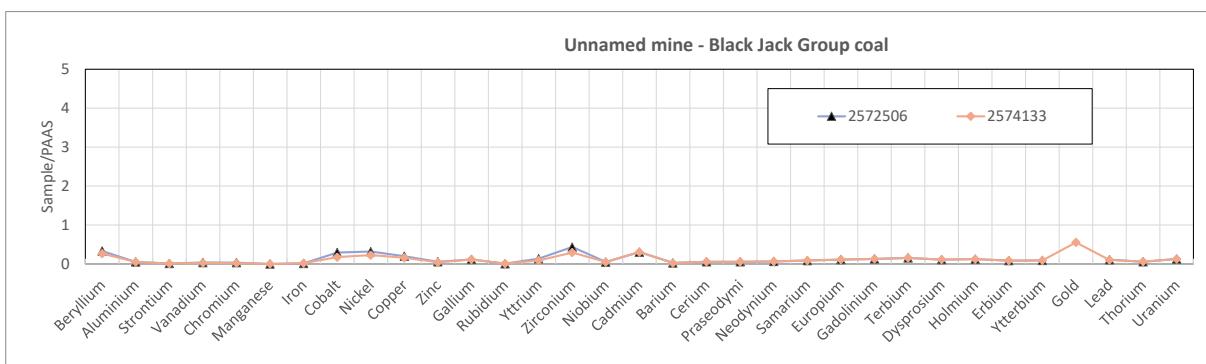
Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Unnamed Mine – Black Jack Group	Black Jack Group	Coal	2572506	168
	Black Jack Group	Coal	2574133	220

Table 2: Summary of analytical results Table 11 in CSIRO Report

Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient REY	Other above background elements
Unnamed Mine – Black Jack Group	2572506	Coal	10.7		
	2574133	Coal	9.7		

Sample elemental results

Appendix A of full CSIRO dataset



Key Notes

- Two samples were provided by an unnamed mine that is extracting coal from the Black Jack Group in the Gunnedah Basin, NSW.
- The samples contain the smallest concentration of elements in the entire dataset of samples analysed in this study.
- All elemental concentrations are below background levels and total REE is around 10 ppm.
- The main controlling factor of the low concentrations can be assumed to be low-ash content of the coal.
- The low element concentrations determined at this mine site are lower than those reported by Ward et al. (1999).
- Further samples from the Gunnedah Basin should be examined to draw a conclusion.

Contributor report for ACARP Project C29030

Hodgkinson and Grigorescu, CSIRO

August 2021

Mine: Wandoan

Table 1: Details of samples analysed (Table 8 in CSIRO Report)

Mine	Seam (pit) or formation	Sample type	Sample name	Depth (m)
Wandoan	Uncorrelated	Coal	C9326-85.5	85.5
	Uncorrelated	Coal	C9367-74.8	74.8
	C6B	Coal	C9367-84.1	84.1
	C1A	Coal	C9368-58	58.0
	Uncorrelated	Coal	C9368-83.2	83.2
	C9A	Coal	C9368-112	112.0
	BL3A	Coal	C9365-37	37.0
	C3A to C4B	Coal	C9365-48	48.0
	Uncorrelated	Coal	C9365-57.7	57.7
	Uncorrelated	Coal	C9365-79.8	79.8
	BU1A	Coal	C9279-30.6	30.6
	C4E	Coal	C9279-53.1	53.1
	Uncorrelated	Coal	C9279-63.5	63.5
	IA roof	Coal	C9360-59	59.0
	Uncorrelated	Coal	C9360-61.6	61.6
	Uncorrelated	Coal	C9360-102.2	102.2
	Uncorrelated	Coal	C9358-45.5	45.5
	Uncorrelated	Coal	C9358-79.5	79.5
	Uncorrelated	Coal	C9359-80.3	80.3
	Uncorrelated	Coal	C9349-114.8	114.8
	Uncorrelated	Coal	C9354-132.4	132.4
	Uncorrelated	Coal	C9357-90.2	90.2
	Uncorrelated	Coal	C9357-100.3	100.3
	Uncorrelated	Coal	C9357-122.8	122.8
	Uncorrelated	Coal	C9369-41.4	41.4
	Uncorrelated	Coal	C9369-56.8	56.8
	Uncorrelated	Coal	C9369-135.3	135.3

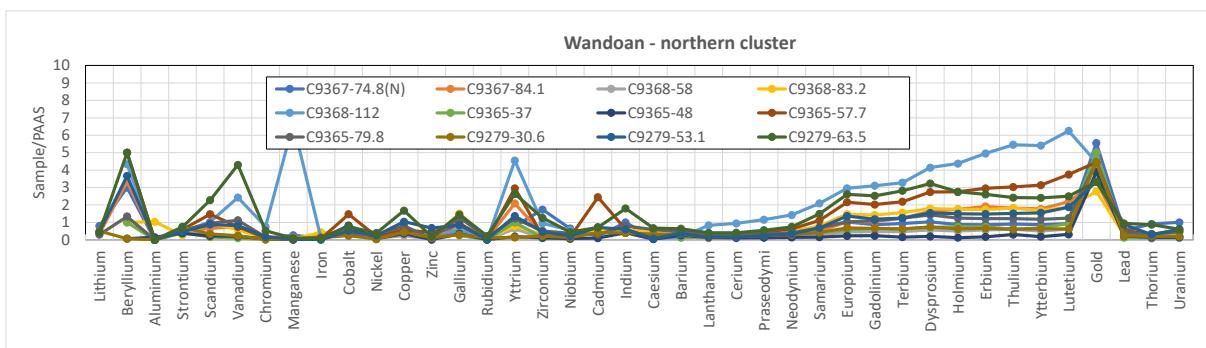
Table 2: Summary of analytical results (Table 11 in CSIRO Report)

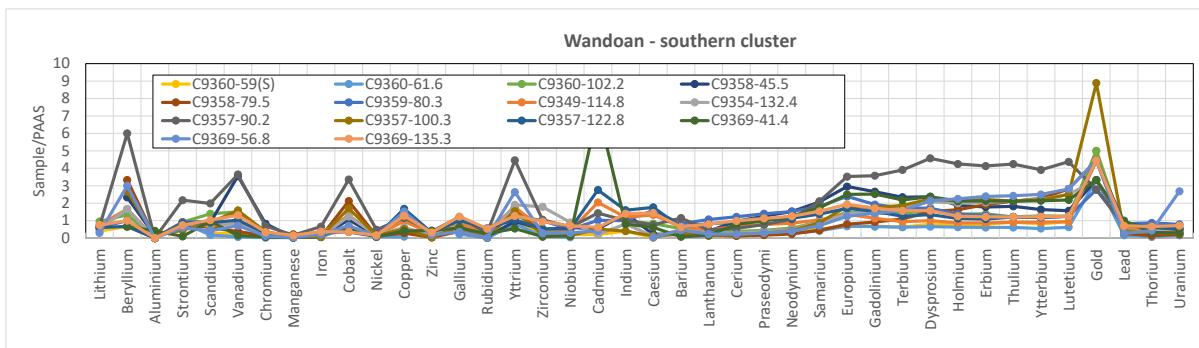
Mine	Seam (pit)	Sample type	Total REY (ppm)	Outlook coefficient REY	Other above background elements
Wandoan	Uncorrelated C9326-85.5	Coal	73.7	3.3	Be, V, Mo, MREE, HREE, Bi
	Uncorrelated C9367-74.8	Coal	78.4	1.5	
	C6B C9367-84.1	Coal	95.4	3.7	
	C1A C9368-58	Coal	37.8	2.7	
	Uncorrelated C9368-83.2	Coal	82.4	1.7	

C9A C9368-112	Coal	301.5	2.1
BL3A C9365-37	Coal	61.0	2.3
C3A to C4B C9365-48	Coal	23.6	1.1
Uncorrelated C9365-57.7	Coal	161.6	3.0
Uncorrelated C9365-79.8	Coal	87.7	2.0
BU1A C9279-30.6	Coal	41.5	1.0
C4E C9279-53.1	Coal	80.5	3.0
Uncorrelated C9279-63.5	Coal	166.0	2.8
IA ROOF C9360-59	Coal	63.4	1.9
Uncorrelated C9360-61.6	Coal	51.7	2.5
Uncorrelated C9360-102.2	Coal	108.6	1.9
Uncorrelated C9358-45.5	Coal	184.6	1.1
Uncorrelated C9358-79.5	Coal	83.4	3.6
Uncorrelated C9359-80.3	Coal	219.6	1.0
Uncorrelated C9349-114.8	Coal	143.5	1.5
Uncorrelated C9354-132.4	Coal	116.6	2.7
Uncorrelated C9357-90.2	Coal	250.0	3.1
Uncorrelated C9357-100.3	Coal	97.9	3.0
Uncorrelated C9357-122.8	Coal	168.3	1.0
Uncorrelated C9369-41.4	Coal	149.1	1.1
Uncorrelated C9369-56.8	Coal	124.1	3.6
Uncorrelated C9369-135.3	Coal	184.3	1.1

Sample elemental results

Appendix A of full CSIRO dataset





Key Notes

- Due to high availability of donated samples, we were able to select more than twenty from the Wandoan area, divided into a northern and southern cluster, enabling a comprehensive spatial characterisation of these Jurassic coal measures. Results indicated that:
 - there are significant enrichments in the north compared to the south and compared to the Bowen Basin samples,
 - in the southern Walloon cluster, MREEs and HREEs are equally dominant over the LREE.
 - REE concentrations increase with depth in the northern Walloon cluster, and decrease with depth in the southern Walloon cluster.
- Results demonstrate that high detrital input and tuff in the Walloon coal seams should make them a target for trace elements and REE
- Variation between the northern and southern Walloon clusters of the Wandoan area indicates that even local distinctions occur, and that characterisation of the elemental content will require as much detailed mapping as any resource.

Appendix D The Team

Jane Hodgkinson is a Research Scientist with 14 years' experience at CSIRO as a geologist, working in mining-related projects. She has experience in geological data analytics, multi-criteria analysis and project leadership. Jane successfully led and completed ACARP project C21041 and participated in numerous ACARP projects. She has a keen interest in improving value from mining. Jane initiated and led a 2-year project that explored coal use and potential coal content to extend and align interest in coal mining research and analysed ~30 coal samples, the results of which were published with Dr Micaela Grigorescu of the Geological Survey of Queensland. Jane has a BSc (Hons1) in Geology from Birkbeck College, London and a PhD in geology and geomorphology from Queensland University of Technology.

Micaela Grigorescu is a geoscientist with 20 years' experience in basin studies, environmental geochemistry and spatial analysis. She has worked with CSIRO both through the Geological Survey of Queensland and as an Independent Researcher for the ACARP Project C29030, where her expertise is utilised in areas of chemical data interpretation, source discrimination and mapping. Micaela has a degree in Geology and Geophysics from the University of Bucharest, Romania and a PhD in Environmental Geology from Queensland University of Technology.

Glossary

Ash – uncombusted portion of material, in the case of coal consists of lithics, metals, sometimes referred to by others as coal combustion residues

Authigenic – minerals and other materials formed in their present position such as carbonates, iron oxides, barite, pyrite and others

Bottom ash – coarse, angular particles, forms at bottom of coal furnace, too heavy to be lifted up smoke stack.

Chelation – where an organic agent extracts metallic ions from minerals or rocks forming complexes, assisting the mobilisation of metals

Coal Resources – are a ‘realistic estimate of coal that ... is more likely than not to become economically extractable’ (JORC, 2014, p17). It ‘should state the condition of the coal in the ground and the values for moisture and density’ (JORC, 2014, p6). Resources are defined by Inferred, Indicated and Measured (in order, reflecting levels of confidence in the resource estimate) (JORC, 2014, p8).

Coal Reserves – are defined as ‘economically mineable part of a Measured and/or Indicated Resource... that, at the time of reporting, extraction could reasonably be justified’. Reserves are subdivided based on order of increasing confidence from Probable Reserves to Proved Reserves (JORC 2012, p16) (or Proven in USA).

Detrital – particles of pre-existing, broken down rock, delivered by weathering and erosion processes (such as quartz, feldspar, ilmenite, rutile and others; some clays can form from these detrital materials in situ – strictly speaking making them authigenic, but from a detrital source).

Fly ash – fine, powdery uncombusted portion of coal, lightweight and easily carried up the smoke stack.

Inventory – for the purposes of this study and report, we refer to the term inventory as publicly reported resources and reserves reported by State and Federal Governments. See also footnote¹.

Rank – the degree of physical/chemical change that plant material has undergone (alteration from peat through to anthracite).

REE – Rare Earth Elements names for their relative rarity at which they occur in economic concentrations.

¹ Inventory Coal is defined by JORC Guidelines (for the estimation and classification of coal resources) (2014 ('the Code') http://www.jorc.org/docs/Coal_Guidelines_2014_-_Final_Ratified_Document.pdf) as: ‘an estimate of in situ coal that does not consider or does not pass the reasonable prospects test. It may include coal that currently has low prospectivity due to natural or cultural features that preclude mining’ (JORC, 2014, p6). An estimate of Inventory Coal is not publicly reported but it enables an estimate of unconstrained tonnages in situ to be reported for the purposes of strategic planning by Government and companies holding tenements.

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