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Application of high-resolution borehole image analysis in conjunction with wellbore geophysical log data to improve coal characterisation in Permian coal measures, Bowen Basin, Australia

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Abstract

Coal reservoirs are unconventional in the sense that the scale of vertical and lateral variability is high when compared to conventional sandstone reservoirs. This requires higher resolution data (metres to decimetres to sub-microns levels) for calculation of reservoir properties. Rock core is the best, but it's expensive to obtain and destroyed during analysis. Recent advances in geophysical imaging of the wellbore provide "pseudo-core" from which to characterise the reservoir, but require advanced processing techniques coupled with ground-truthing to make them a reliable alternative. This project sought to develop methods for advanced coal seam gas reservoir characterisation using wellbore geophysical data and image logs, and to use this information to interpret coal seam gas reservoir properties, in particular coal lithotype, in the context of geological development of the Bowen Basin.

The first problem solved during the research was a conversion of borehole electrical images into a microresistivity curve. This procedure allowed the researcher to make a step from qualitative analysis of borehole images to the quantitative one. The resulting microresistivity curve was added to the wireline suite for geostatistical cluster analysis and the development of electrofacies. Thus, the resulting wireline suite consisted of gamma ray, bulk density, photo-electric factor, image-based microresistivity and deep laterolog wireline data.

Electrofacies analysis produced a coal lithotype profile which was validated by the results of other studies such as mm scale brightness profile logging and maceral content analysis. Implementation of the microresistivity curve method enhanced the resolution of coal profiling to decimetres level, while photo-electric curve allowed distinguishing between vitrinite- and inertinite-rich low density coal.

The results of electrofacies analysis were obtained for 26 wells spread over the Northern Bowen Basin area and the distribution of the coal electrofacies were analysed for both stratigraphical and geographical trends. It was observed that the inertinite-rich coal interpreted from electrofacies analysis increases towards the top of Late Permian coal and towards the north of the Northern Bowen Basin area. These results were consistent with previously observed trends defined by petrographic analysis.

Overall, this research project has resulted in the development of a new method for coal characterisation which goes beyond simple cut off values for density, and allows coal lithotype advanced characterisation based on high-resolution wireline borehole data. This method was tested in a case study where stratigraphical and geographical distributions of coal lithotypes were generated over the Northern Bowen Basin area.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

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Roslin, A., Esterle, J.S., under review. Electrofacies analysis using high-resolution wireline geophysical data as a proxy for inertinite-rich coal distribution in Late Permian coal seams, Bowen Basin. International Journal of Coal Geology.

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Paper 1

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Incorporated as Chapter 3

A. Roslin (MPhil candidate) performed the study, established the method which is described in the paper, prepared figures and tables, wrote manuscript.

Paper 2

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Incorporated as Chapter 4

A.Roslin (MPhil candidate) performed the study, established the method which is described in the paper, prepared figures and tables, wrote manuscript; J.S. Esterle (Principal MPhil supervisor) reviewed, discussed and edited manuscript.

Paper 3

Roslin, A., Esterle, J.S., accepted for publication. **Electrofacies analysis using high-resolution wireline geophysical data as a proxy for inertinite-rich coal distribution in Late Permian coal seams, Bowen Basin**. International Journal of Coal Geology.

Incorporated as Chapter 5

A.Roslin (MPhil candidate) performed the study, performed the analysis of data distribution, prepared maps, figures and tables, wrote manuscript; J.S. Esterle (Principal MPhil supervisor) reviewed, discussed and edited manuscript.

Contributions by others to the thesis

Aside from the inputs made by J.S. Esterle to the above papers, the following contributions are also acknowledged:

Professor Joan Esterle (Principal MPhil supervisor) contributed towards the conception and design of the study, obtained additional scholarship funds from ACARP Program, liaised with Arrow Energy for access to data and samples, and reviewed and edited the thesis.

Professors Stephen Tyson and Jim Underschultz (Associate MPhil supervisors) contributed towards the presentation of the thesis and editorial reviews.

Statement of parts of the thesis submitted to qualify for the award of another degree

None

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Keywords

Bowen Basin, Rangal Coal Measures, Fort Cooper Coal Measures, Moranbah Coal Measures, wireline logs, borehole electrical images, electrofacies analysis, inertinite-rich coal

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 040309, Petroleum and Coal Geology, 50%
ANZSRC code: 040499, Geophysics not elsewhere classified, 25%
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1. INTRODUCTION

This thesis is focused on the application of Petrophysics to characterise and map changes in coal quality, in particular type or composition, for the Late Permian coal measures of the northern part of Australian Bowen Basin. Coal organic composition, defined megascopically by lithotype and microscopically by maceral analysis, will control the physical and chemical properties of coal for a given rank and grade that influence its utilisation and coal seam gas reservoir behaviour. Accordingly, geologists use the distribution of lithotypes to characterise the coal seams for correlation and sampling for further laboratory analysis. If the method which will be able to perform automatic coal characterisation based on wireline logs responses is established and validated, it might help geologists to execute coal lithotype characterisation in the absence of coal core samples.

Stratigraphic and regional variability in coal type in the Bowen Basin has been addressed by a number of authors (e.g. Beeston, 1986; Hunt, 1989; Hunt & Smyth, 1989) and in the Sydney Basin (summarised in Diessel, 1986; 2010). They found that duller inertinite-rich coal types were more common towards the end of the Late Permian and/or in areas of relatively low accommodation. Variation of inertinite was observed to closely follow temporal and spatial patterns of subsidence in the Permian basins. It was explained by the fact that subaerial and probably subaqueous oxidation took place due to water table fluctuation (Hunt and Smyth, 1989). The influence of climate is postulated in some areas and the global variations of inertinite in coal are related to the variable oxygen content of the Earth's atmosphere as a part of the wider pattern of global climate changes.

These authors (Beeston, 1986; Hunt, 1989; Hunt & Smyth, 1989; Diessel, 1986; 2010) used a traditional approach of manual core logging complemented by petrographic analysis of maceral and mineral composition and rank reflectance. Conventional wireline data (gamma ray and density data) are used exclusively for correlation of coal seams, although some authors have promoted their use for coal quality (Johnston, 1991; Scholes and Johnston, 1993; Zhou et al, 2007) and maceral composition analysis (Ahmed et al, 1991; Johnston et al, 1991). One can easily point out the main disadvantage of a "core only" approach: core data are not available for all wells drilled, as core is more expensive than rotary drilling, which means that results are sparse relative to all available borehole for a given mine site or coal seam gas field. In some cases, not all cored coals are samples and analysed, so the only record available are wireline logs. These geophysical data are underutilised, commonly only used to determine the coal seam thickness, and correlation, but can provide information on coal quality, and potentially coal type composition and rank. However, these data sometimes require advanced processing techniques coupled with a new approach towards the data analysis to extract coal character information.

The aim of this thesis was to develop methods for advanced coal reservoir characterisation using borehole geophysical logs and wellbore images, and apply these methods to the northern Bowen Basin Late Permian coal measures in order to map the stratigraphic and regional variation in coal type. Thus, the thesis was divided into two interrelated components, each of which converges to the objective of the research:

- The development of a method for coal analysis based on wellbore geophysical logs and borehole electrical images, its application to determining coal lithotype, and validation of the obtained results by comparison to those gathered by other methods (coal proximate analysis, manual lithotype profiling, and maceral content analysis).

- The application of the above developed methodologies to investigate stratigraphical and spatial distribution of different coal lithotypes over the northern part of Bowen Basin.

The following research questions were proposed to be answered during the course of the study in order to reach the main aim of the thesis:

- What is the most suitable approach for coal analysis based on wellbore geophysical logs and borehole electrical images?
- Is it possible to create a robust method for automatic coal lithotype identification using this approach?
- How are the results of the study correlated to those obtained by other methods (coal proximate analysis, manual lithotype profiling, maceral content analysis)?

- Which log set is the best input dataset and why? What is the difference in the results obtained from using high-resolution and conventional data wireline log data? How can this difference be explained if there is any?
- Can this method be applied to other areas and which restrictions or limitations does this method have?
- How are different coal lithotypes distributed over the studied area? What processes might have caused such distribution?
- Does the coal lithotype vary vertically and laterally within specific seams across the basin? Which processes may have caused those variations if there were any observed?

The workflow, which was followed in order to accomplish the thesis main aim, consisted of three consecutive steps:

- Background literature review: includes analysis of the studied area and data which were available for the research; overview of previous studies about implementation of geophysical logs to determine coal quality; review of papers which describe exploitation of high-resolution wellbore geophysical data for different reservoir characterisation problems in order to find a suitable approach to solving the research problem; review of coal quality variations in the Bowen Basin and other foreland and cratonic coal basins.
- Establishing of methodology and results validation: involves procedures which result in creating a robust, automatic (or semi-automatic) algorithm of coal lithotype characterisation based on wireline log data and validation of the results obtained by this method by comparison them to those obtained by other methods (Paper 1 and 2).
- Regional analysis: the analysis of coal lithotypes stratigraphical and geographical distribution and discussion of possible interpretations of such distribution (Paper 3).

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2. BACKGROUND

2.1. GEOLOGICAL SETTINGS

The Bowen Basin is a part of a connected group of Permian coal basins in Eastern Australia which includes the Sydney and Gunnedah Basins (Figure 1). The Bowen Basin was an area of shallow-water or terrestrial sedimentation for most of the Permian (Fielding et al, 1993; Ward et al, 1995; Fielding et al, 2008; Birgenheier et al, 2010). Coal accumulated throughout almost all this period, initially around the margins and in isolated sites, but extending to cover virtually the whole basin in the latest Permian. The most favourable areas both for deposition and subsequent preservation of coals were on shelves and platforms, where very extensive areas of peat could be maintained in stable conditions over long time intervals. Humid conditions allowed these peats to extend hundreds of kilometres inland from the marine margin.

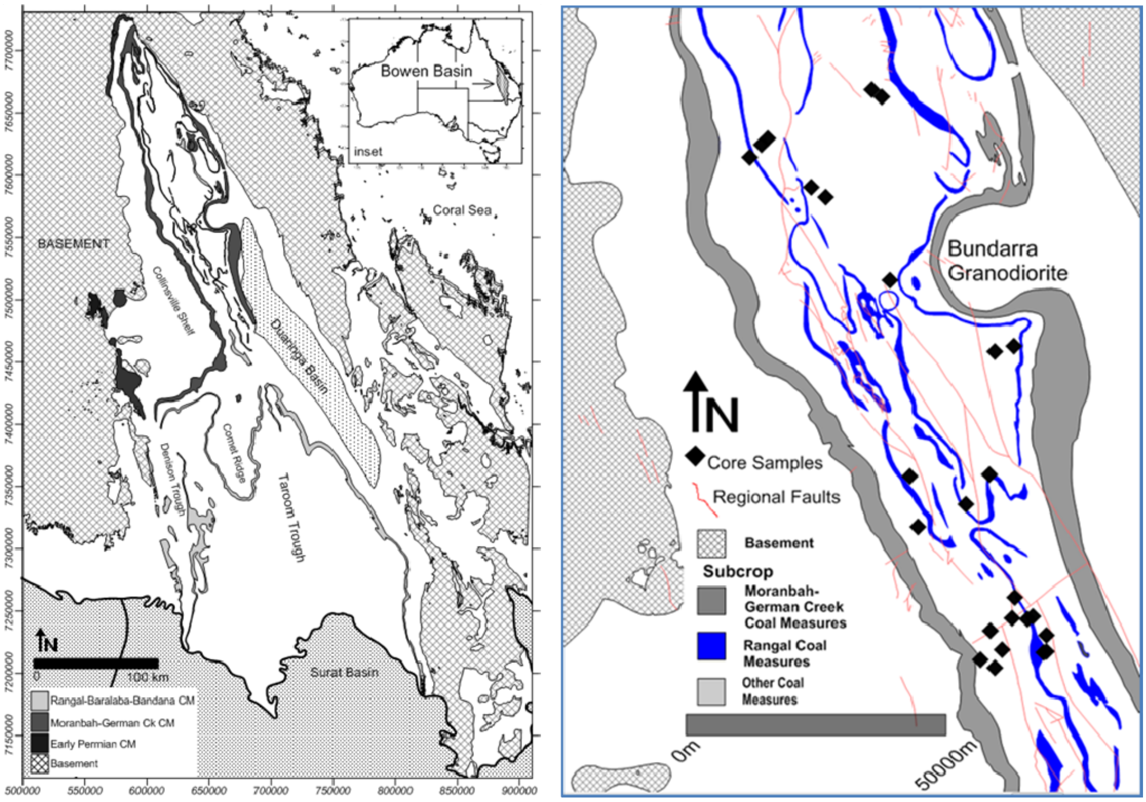

Figure 1 Location map of the study area within a) simplified map of economic coal measures in the Bowen Basin, with inset of location within Australia and b) close up showing location of core samples with wireline logs. Note that the Fort Cooper Coal Measures are not shown. Compiled from IRTM shape files **www.irtm.qld.gov.au**

The basin's complex structure has resulted in a wide range of coal ranks, which, in association with the range of environments suitable for formation of coal, has resulted in a wide variety in coal type and quality. The Rangal (RCM), Fort Cooper (FCCM) and Moranbah (MCM) Coal Measures (Figure 2) are primary targets for coal seam gas exploration and production in the northern Bowen Basin (Draper, 1985; Jell et al, 2013).

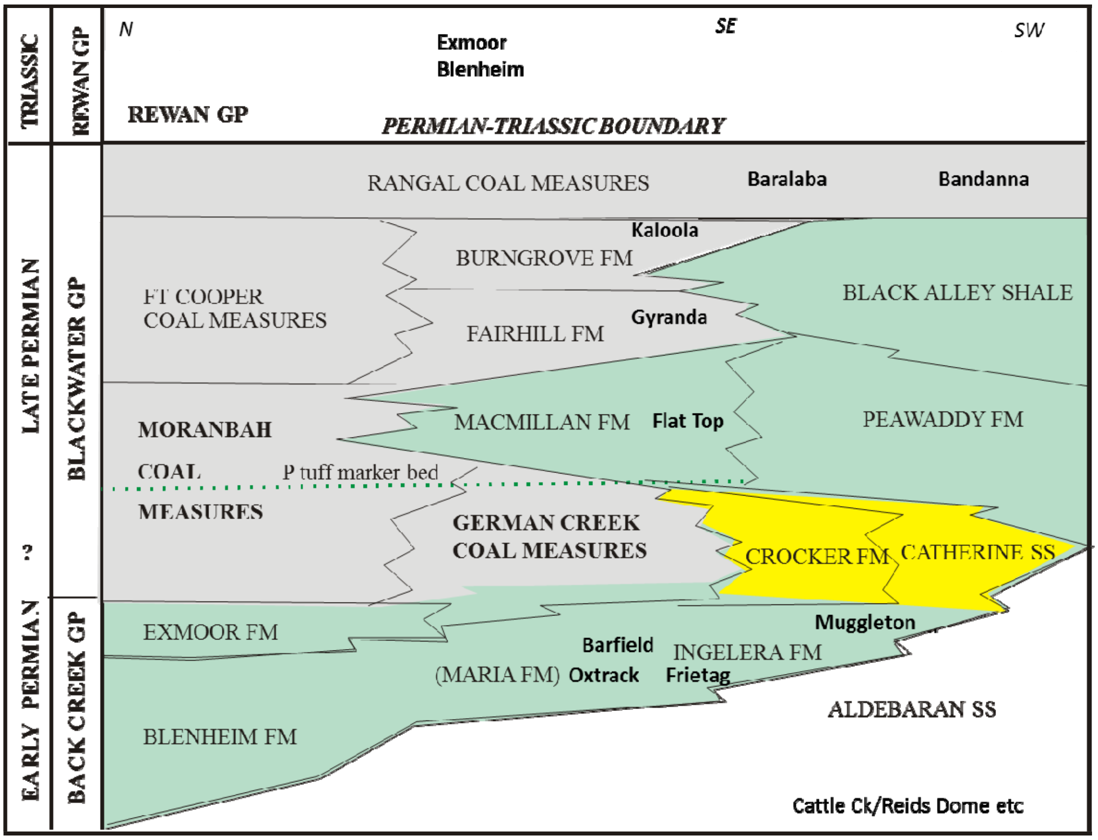

Figure 2 Stratigraphic framework for the Moranbah-German Creek Coal Measures. Modified after Esterle, 2002, Draper, 1990; Falkner & Fielding, 1993; Michaelsen, 1999

Coal organic composition is defined megascopically by lithotype and microscopically by maceral analysis. Coal lithotypes were first introduced by Stopes (1919) as a visual method for characterising the compositional differences within and between coal seams that, along with thermal maturity, reflect the chemical and physical properties of the coal. Different systems have since emerged (Stopes, 1919; Theissen, 1935; Cady, 1942; Schopf, 1960; Diessel, 1982; Stach et al. 1982), but all rely on some estimate of the proportion and thickness of end member components – vitrain (bright bands), durain (dull bands) and others (fusain, various types of stone bands) (Figure 3).

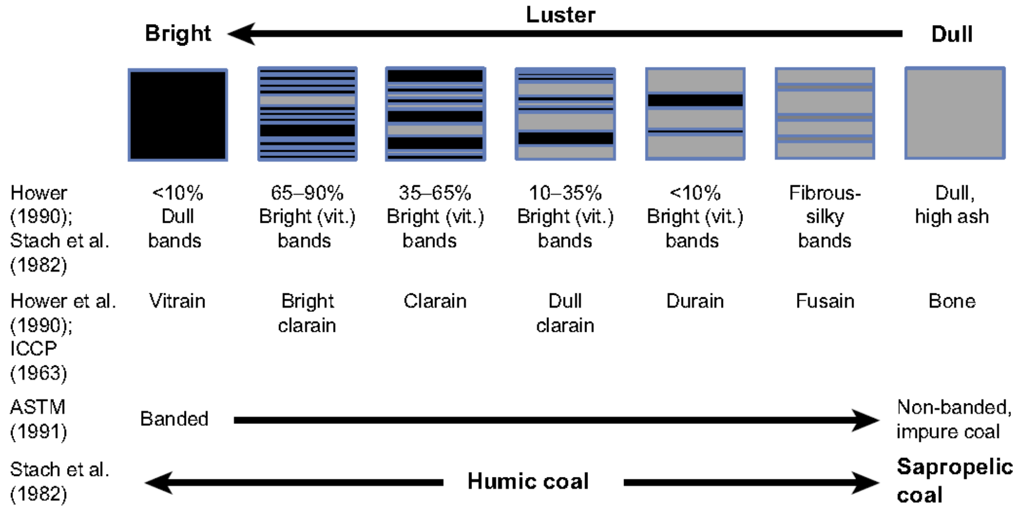

Figure 3 Different classification systems for coal lithotypes (from Flores, 2014 and references therein). Australian Standards use the following terms and proportions of bright or vitrain: Bright >90%, Bright Banded 60-90%, Banded 40-60%, Dull banded 10-40%, Dull with Minor Bright 1-10% and Dull <1%

The microscopic constituents of coal are called macerals and are analogous to minerals in other rocks. Macerals are divided into three groups, depending on the source of the organic matter. Vitrinite is derived from woody plant tissues; liptinite from resinous and waxy plant components and the source of inertinite is oxidized plant material (Teichmuller, 1989). The inorganic material is defined as mineral matter (Gary, 1972).

A number of studies were focused on Bowen Basin coal lithotype characterisation and analysis of coal distribution (Hunt, 1989; Hunt and Smyth, 1989; Diessel, 2010).

Hunt (Hunt, 1989) observed an increase of inertinite maceral content of coal towards the top of Late Permian coals of Bowen Basin. He analysed the spatial and stratigraphical distribution of coal of Eastern Australian cratonic and foreland basins and proposed some hypotheses about factors controlling observed petrographic variations (Hunt, 1989). Hunt stated that the variation of inertinite composition closely follows temporal and spatial patterns of subsidence in the Permian Basins and low subsidence rates led to extensive oxidation of the peat, while vitrinite content is, in places, independent of subsidence rate, which may reflect climatic control. He also pointed out that there is no evidence that inertinite-rich coals were formed from a unique flora of under climatic conditions different from vitrinite-rich Permian coals. In turn, Diessel investigated stratigraphic distribution of inertinite in coals on a global scale in the ranges from the Silurian to the Neogene periods (Diessel, 2010). Not only did he observe the global increase of inertinite-rich coal towards the top of Permian-Triassic boundary but also suggested some hypothesis explaining the potential origin of that trend. Diessel concluded that incomplete combustion was the main cause of inertinite formation. This infers that the most likely reasons for the changing frequency and efficacy of the peat fires responsible for the global variation of inertinite in coal have been the variable oxygen content of the Earth's atmosphere as part of the wider pattern of global climate changes.

2.2. METHODOLOGY OVERVIEW

The studies mentioned above relied on visual methods of coal characterisation and microscopic maceral analysis. These methods require physical presence of coal samples what is not always possible due to the fact that not all drilled wells are core-logged. Borehole wireline images might present "pseudo-core" alternative where real cores had not been sampled. Images can be produced from electrical, acoustic, density, photoelectric, gamma ray and caliper measurements (Rider and Kennedy, 2013). The highest resolution comes from the electrical borehole images in which the level of details is comparable to that of real cores. The specialist, high resolution, wireline electrical imaging tools use the detailed electrical response of a formation to create the image. These tools are mostly multi-pad (4-8) type devices with an array of small electrodes. The fine resistivity responses of all the electrodes are processed together, as a matrix, into an image. Images are widely used in petroleum industry and are becoming more common in the coal industry, usually from acoustic scanners. Although the acoustic images are more often used for coal characterisation, electrical images have also been utilised for cleat analysis (Artyom Sibgatullin, QGC; personal communication) and coal boundaries determination (Andrew Hall, Origin; personal communication) by visual analysis. These applications of borehole images involve visual analysis of images but their exploitation for coal lithotype characterisation might require advanced processing techniques.

Wireline logs have also been utilised for the purpose of coal lithotype characterisation (Zhou and Esterle, 2007) and the method which was used resembles a conventional cut-off method: predefined values of bulk density and natural gamma-ray logs are used to distinguish bright and dull coal. Although this research demonstrated quite good results for studied samples, the obvious disadvantage of this method is that it requires predetermined cut-offs which are not always accurate or known. Johnston (Johnston,

1991) studied the problem of wireline log data application for coal reservoir characterisation. He also mentioned that density and gamma ray are probably the most suitable logs for coal characterisation (Ahmed et al, 1991) but advanced coal reservoir characterisation requires to involve specific wireline data such as geochemical data for maceral composition and coal rank analysis (Johnston et al, 1991; Ahmed et al, 1991). The review of modern works demonstrate that the prevailing opinion is that the most useful wireline log for coal gas reservoir engineering is the bulk density log which is often used to identify coal, determine net coal thickness, and construct ash, density, and gas content correlation (Seidle, 2011). Johnston and Scholes combined gamma ray, density, neutron, and resistivity logs to determine coal cleating and maceral groups (Johnston and Scholes, 1991). Mullen (Mullen, 1991) worked on implementation of microlog, which measures mudcake and formation resistivities, for qualitative assessment of coal cleating. Due to the fact that no significant research studies were found for coal lithotype characterisation, this research problem was chosen as a main subject of the research study which is described by this thesis. The main characteristics of wireline measurements and their potential usage for coal characterisation are presented below based on Thomas, Rider and Ellis (Thomas, 2013; Rider and Kennedy, 2013; Ellis and Singer, 2007).

Wireline logs are widely used to identify different lithologies in clastic sedimentary rocks, and cluster analysis, often referred to as electrofacies analysis, is used for that purpose. Electrofacies, in contrast to geological facies, is an interval defined on wireline logs, with consistent or consistently changing wireline log responses and characteristics - sufficiently distinctive to separate it from other electrosequences (Rider and Kennedy, 2013). Electrofacies analysis involves partitioning a set of log data into electrofacies units and presenting them in a manner that is comparable to that used by geologists for interpretation purposes – each electrofacies is assigned a number, or index, which can be plotted against depth or used to control colour coding on displays (Ye and Rabiller, 2005). Coal characterisation problem is similar to lithology characterisation, thus, it was decided to implement electrofacies analysis for coal lithotype characterisation.

2.3. WIRELINE LOGS OVERVIEW

Wireline logs are tools that are attached to a “wireline”, or steel cable, lowered to the bottom of a well after each major stage of drilling and then hauled back (Gluyas and Swarbrick, 2004). As the tools pass by the various rock layers on the way back to the drilling rig, they record both intrinsic and induced properties of the rocks and their fluids. Whether run during or after drilling, logs are used to give information about the rock, its pore space, and the fluids therein. Depth of investigation and vertical resolution of wireline logs can vary in different formation conditions and receiver-transmitter spacing (especially for resistivity tools) but the general average values (according to Rider and Kennedy, 2013) are summaries in Table 1.

Table 1 Average depth of investigation and vertical resolution of logging tools

Type	Logging tool	Vertical resolution	Depth of investigation
Resistivity	Induction	80-100 cm	Up to 300 cm
	Laterolog	80-100 cm	Up to 150 cm
	Microresistivity	5 cm	5-10 cm
	Microimager	0.5 cm	Up to 5 cm
Radioactivity	Neutron	38 cm	Up to 70 cm
	Gamma ray	32 cm	Up to 50cm
	Density	20-30 cm	Up to 40 cm
	Photoelectric factor	5 cm	7 cm
Acoustic	Sonic	60 cm	Up to 20 cm

GAMMA RAY LOG

The gamma ray log measures the naturally occurring radiation in geological formations (Thomas, 2013). The radiation emanates from naturally occurring uranium, thorium and potassium. The geological significance of radioactivity lies in the distribution of those three elements. The simple gamma ray log cannot distinguish the contributions from these three individual elements and simply outputs a total count rate (Rider and Kennedy, 2013). Most rocks contain traces of gamma-emitting elements and are radioactive to some degree; igneous and metamorphic rocks more so than sedimentary rocks. Amongst the latter, shales normally have the highest gamma activity. It’s explained by the fact that the isotope potassium-40, which is a principal source of radioactivity in rocks, is usually associated with clay minerals.

Conversely, good quality coals and clean sandstones (with the exception of uranium-rich “hot” sandstones and detrital sandstones with significant amount of rare-earth minerals such as zircon) have a very low level of natural radiation. As the amount of included clay material increases, in the form of clay partings in coal and as clay clasts and clay matrix in sandstones, so the natural radiation increases. Also, low gamma ray values of coal are resulted from the fact that uranium, which is absorbed by organic matter in reduced conditions, and causes the high gamma ray values in organic rich shales, is not absorbed by organic matter in the terrestrial swamps where no clay is present.

To sum all, the gamma ray log is not wholly diagnostic, and in normal practice it is used in conjunction with other geophysical logs in order to fully distinguish formations. The use of natural radiation to determine the ash content is an unreliable technique, as coals with the same ash content may emit differing amounts of natural radiation, due to the make-up of the mineral content of the ash fraction in the coal. However, gamma ray logs might be exploited for the qualitative estimation of mineral content in coals (and as a result, to distinguish between mineral poor bright coal and mineral-rich dull coal) in conjunction with other wireline logs, mostly density log.

DENSITY LOG

The density log is a continuous record of a formation's bulk density. This is the overall density of a rock including solid matrix and the fluid enclosed in the pores. All density tools exploit so-called gamma-gamma scattering to measure density. A radioactive source emits a continuous beam of high energy gamma rays into the formation. Some of these are scattered back to a pair of gamma ray detectors located a maximum distance of 50 cm from the source. The term gamma-gamma refers to the fact that the tool both emits and detects gamma rays. The density of the formation is measured because the count rate at a detector depends on the density of the material between it and the emitter. The gamma ray can be considered to have diffused through the material between the source and detector, and the density logs will be affected equally by all this material.

In coal exploration, the density log is used as a principal means of identifying coal, principally because coal has a uniquely low density compared with the rest of the coal-bearing sequences. In certain circumstances there is the additional benefit of an approximate linear relationship between ash content and density for a given coal seam in a given area. It makes density measurement potentially useful in the distinguishing of bright and dull coals (Calvert et al, 2011).

PHOTOELECTRIC FACTOR LOG

It is a continuous record of the effective photoelectric absorption cross-section index of a formation. The photoelectric index is strongly dependent on the average atomic number of the constituents of the formation, which implies the composition and, by inference, the lithology; the effect of porosity is minimal. The photoelectric response to heavy, high atomic number elements, and even traces of very heavy elements, are disproportionate and can dominate a reading. The photoelectric factor is derived from the photoelectric capture cross-section which is a measure of how effectively a material can absorb gamma rays. Thus, it can help identify lithology and it might potentially be used for coal lithotype determination.

PEF can potentially be exploited for coal lithotype characterisation. First of all, pure coal is characterised by very low values of PEF and an increase of mineral matter significantly increase PEF characteristics of coal. It was also observed during the research that PEF might help track subtle changes in the amount of inertinite matter in dull coal due to the fact that PEF can react to oxidised material presented in coal.

NEUTRON LOG

The neutron log provides a continuous record of a formation's reaction to neutron bombardment. The neutron tool consists of a source that provides a continuous spectrum of high energy neutrons and a detector sensitive only to low energy neutrons. Hydrogen is the most effective element in the slowing down or moderating neutrons (then, hydrogen is called the principal neutron moderator). Once slowed down, the neutrons diffuse away from the source, and are gradually captured. The measurement is given in neutron porosity units, which are related to a formation's hydrogen index, an indication of its hydrogen richness.

Unlike most other measurements, the neutron porosity is not a well-defined physical property. It's a measurement of neutron count rate. There are several different types of neutron tool. All emit high energy neutrons into the formation but they differ in what precisely they detect. The first group of tools measures the number of neutrons that are scattered back towards the tool. Those tools are intended to respond primarily to the amount of hydrogen in the formation. Other existing neutron tools measure the secondary gamma rays produced when neutrons collide with nuclei in the formation.

These are the geochemical and neutron lifetime tools. The data which were used in the research were gathered by the neutron tools from the first group.

Hydrogen is found in the rock matrix itself, in water chemically bound to the rock molecules, and also in the fluid in the pore spaces of the rock. Coal gives a response of around 60% effective porosity due to its structure of hydrogen and carbon. Any change in count rate can reflect changes in calorific values, which are on ash-free basis, and can be considered as a coal rank parameter (Thomas, 2013). Where moisture is relatively constant, the neutron log can give an approximate guide to the amount of volatile matter present. Attempts have been made to develop a simple method of measuring in situ moisture content in coal, but moisture levels in coal deposits are usually too high and render conventional neutron tools insensitive (Thomas, 2013). During the course of study, some attempts have been made to utilise neutron data for coal rank analysis. They were not successful as the relationship between coal rank and neutron response was not clear based on the observation made.

RESISTIVITY LOG

Resistivity is an intrinsic property of matter that quantifies its ability to conduct electricity. The higher the resistivity the more difficult it is to pass a current of a particular magnitude. The resistivity log is a measurement of this in subsurface formations. Nearly all minerals and fluids that are encountered in the subsurface have very high resistivities. In fact logging tools are simply not designed to be able to measure them. The most exception is water. Most of the time formation resistivity is controlled by its amount and distribution. When a formation is porous and contains salty water (which is conductive) the overall resistivity will be relatively low. However, when this same formation contains hydrocarbons, its resistivity will be higher. It is this difference that is exploited by log analysts when they estimate hydrocarbon volumes by calculating the water saturation from resistivity logs.

As a downhole measurement, resistivity is distinguished from most other properties in that it can be measured in several ways. Two different arrangements for measuring the resistivity of subsurface rocks can be used:

- Direct electrical connection between the tool and formation in which current flows from the tool to the formation and back.

- Indirect methods in which electromagnetic fields are introduced in the formation by a transmitter in the tool. The resistivity is measured or calculated from the behaviour of these fields.

Tools using the first method are often described as resistivity tools and the second as conductivity tools. Resistivity tools which use the direct electrical connection are also known as laterolog tools. The current normally passes between two electrodes (but in practice far more are needed to produce an accurate measurement), at least one of which is located in the downhole tool, and the second may actually be the cable armour or even a separate electrode at the surface. Different electrodes are used to monitor the voltage drop which is input to the resistivity equation. The data from these tools were used for the research.

Tools using the indirect methods induce an electromagnetic field in the formation and then monitor how the field behaves by its effect on one or more receiver coils. Within the broad area of non-contact arrangements there are two distinctly different tool types. The first ones are the induction tools that work by using a transmitter, operating at a few kHz, to introduce a current to flow around the borehole. The strength of this induced current depends on the conductivity of the formation and hence tools using this method are sometimes also called conductivity tools. The second types of tools which use indirect methods are known as a propagation tools. They emit short pulses of radio waves. These are more strongly attenuated in low resistivity media than resistive rocks and so, by measuring their attenuation, resistivity can be inferred. Logging while drilling tools operate based on this principle. These data were not used for the study but can be exploited in the same manner as laterolog wireline data.

Resistivity logs cannot be used for a first recognition of the common lithologies; there are no characteristic resistivity limits for shale, or limestone, or sandstone. However, in any restricted zone, gross characteristics tend to be constant and the resistivity log may be used as a lithology discriminator. Resistivity logs can also distinguish coal that is burnt close to an intrusion, or is oxidised due to weathering. Burning has an effect of reducing resistivity close to an intrusion.

Some words must be said about vertical (or bed) resolution of resistivity logs. Bed resolution for a resistivity tool can be determined as the thinnest bed that the tool can resolve to give a true formation resistivity (Rider and Kennedy, 2013). Vertical resolution of laterolog resistivity tools (the data from which were used in the study) depends on transmitter-receiver spacing, thus, vertical resolution of DLL tool is about 60cm. This might restrict their implementation for coal studies as the thickness of individual coal layers is far below the resolution of such tools. However, the wireline, pad-mounted, borehole electrical imagers are capable of resolving the features which are 0.5cm thick.

BOREHOLE ELECTRICAL IMAGES

With introduction of borehole imaging technology, the formation is no longer sampled by a single sensor to create a single log, it is sampled many times horizontally, and at a high rate vertically, to form a matrix of measurements from which an image is created. This is not a picture like a core photo made in visible light: it is a computer created image based on geophysical measurements such as electrical conductivity, acoustic reflectivity or formation density and displayed in false colour.

Images can be produced from electrical, acoustic, density, photoelectric, gamma ray and caliper measurements. The highest resolution comes from the electrical borehole images and implementation of the data from such tools can help solve the problem of poor bed resolution of conventional laterolog tools.

The specialist, high resolution, wireline electrical imaging tools use the detailed electrical response of a formation to create the image. These tools are mostly multi-pad (4-8) type devices with array of small electrodes. The fine resistivity responses of all the electrodes are processed together, as a matrix, into an image.

Compact MicroImager™ (CMI) Weatherford tool data were used for this study. Other companies also have equivalents to CMI tool: FMI (Schlumberger), EMI (Halliburton), STAR (Baker Hughes). CMI contains 176 (64 in slimhole configuration) small button electrodes which are situated on 4 pads and 4 flap pads (slimhole configuration has only pads). Borehole electrical imagers work on the same principle as laterolog tools do: each button emits a pencil shaped beam of current into the formation, and it is the resistance that this current encounters that builds the image. Each button produces a single data channel. These microimager raw data are to be converted into microresistivity image by use of processing software. The resulting images are exploited in many different ways for both sedimentary (for example, sedimentary facies identification) and structural (for instance, structural dips and unconformities) analysis. In most cases, the image plays a role of pseudo-core.

As it was mentioned in Introduction chapter, one of the research questions was to study whether high-resolution wireline data would improve the results of coal characterisation. Due to the fact that microresistivity tool data were absent, it was decided to use microimager resistivity data. However, as microimager's resistivity data present an array of resistivity curves, the algorithm to convert image into microresistivity curve was required to make an electrical image more suitable for coal characterisation.

Establishing of this algorithm was recognised as an additional problem which needs to be solved in the course of study. Resolving of this problem provided the researcher with high-resolution resistivity curve which can be used to replace laterolog conventional resistivity data which vertical resolution is not sufficient for coal seam gas studies. Although electrical images were never converted into single microresistivity curve, some studies demonstrated that it was done for another array data such as NMR (Nuclear Magnetic Resonance) (Ye and Rabiller, 2000). The similar approach was planned to be applied on array resistivity data from microimagers. Nevertheless, microresistivity and conventional resistivity were both used in the research in order to estimate the impact of vertical resolution of the resistivity on final result of coal lithotype profiling.

SONIC LOG

Sonic tools measure the acoustic characteristics of a formation, the log giving a formation's slowness or interval transit time, designed delta-t, the reciprocal of the velocity. It's a measure of formation's capacity to transmit sound waves. This is basically accomplished by measuring the time for a pulse of sound to travel a known distance through the formation. At its simplest, a logging tool therefore consists of a transmitter and one or more receivers a known distance apart. However, modern sonic tools have more complex configuration in order to perform different measurement.

Sonic logs are now principally used as an aid to seismic investigations. The log can be simply used to tie well to the seismic which then allows an accurate depth conversion, interval velocity and velocity profile to be calculated. Although sonic log was previously used to calculate porosity, this is now secondary. Geologists generally still only use the compressional wave velocity despite the shear wave velocity frequently being available.

The compressional wave velocity is sensitive to subtle textural variations (of which porosity is only one). The compressional sonic log can help to identify lithology, indicate source rocks, normal compaction and overpressure, and is frequently used in correlation. The array, dipole sonic can be further used to identify permeability, quantify wellbore damage, calculate formation mechanical properties and elastic moduli, and identify gas and gas hydrates.

Delta-t sonic log has a similar response to the density log, as a result of the close relationship between compaction and density. In lithological interpretation it is not better than a density log, and is rarely run as a simple lithology log. It can be more useful to use sonic delta-t together with density log for interpretation of coal rank (Thomas, 2013). Due to the fact that only three wells with sonic logs were available for the research, this method was not tested during the research, although it might present some potential for future investigations.

2.4. SUMMARY

To sum all, it can be noticed that the problem of coal lithotype characterisation and inertinite- and vitrinite-rich coal distribution is quite important for the industry and number of attempts were made to solve this problem. Previous studies have used different methods to obtain the coal lithotype but most of them either rely on coal samples analysis or require predefined cut-off values or specific wireline measurements if they are based on wireline log data. Overall, wireline geophysical logs can successfully be exploited for coal characterisation as they might provide information about coal fundamental properties which can further be linked to coal lithotypes. The critical problem was to find a suitable approach and establish reliable and repeatable method which would be able to automatically operate with the whole wireline dataset and provide the results which could easily be validated and implemented for regional study. If that method is established and validated, it might help geologists to execute coal lithotype characterisation in the absence of coal core samples.

Implementation of high-resolution wireline logs for coal characterisation also required establishing new interpretation techniques.

After the analysis of wireline logs available for the study, the following measurements were chosen for the study: gamma ray, bulk density, laterolog resistivity, borehole electrical images. Borehole electrical images were converted into microresistivity curve which was included into the input dataset. The algorithm of the conversion is presented in Paper 1 (see Chapter 3).

Coal lithotype characterisation required an interpretation of all input wireline data together. Simultaneous interpretation of the amount of wireline curves bigger than 3 might be difficult to be performed manually. In order to be able to handle all input wireline data, electrofacies analysis was chosen as an approach for the study. Number of research demonstrated that electrofacies analysis was successfully applied for different reservoir characterisation tasks: permeability modelling (Knecht et al, 2004), permeability prediction (Rabiller, 2001), and gas content analysis (Rabiller et al, 2013). The detailed methodology of electrofacies analysis implementation for coal characterisation is explained in Paper 2 (see Chapter 4).

This thesis was mostly focused on the methodology which made possible the implementation of wireline borehole data for coal lithotype characterisation but the thesis also demonstrates the application of the results obtained during the research. Regional analysis of stratigraphic and geographic inertinite-rich coal distribution was performed based on the outcomes of the study. This analysis is summarized in Paper 3 (see Chapter 5).

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3. PAPER 1 Microresistivity Curve Extraction from Electrical Images

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Alexandra Roslin (MPhil candidate) performed the study, established the method which is described in the paper, prepared figures and tables, wrote manuscript.

One of the research questions which were raised at the beginning of the research was: which wireline log set is the most suitable one for coal lithotype characterisation. After wireline methods review, the following dataset was chosen for the research: gamma ray, density, PEF and deep laterolog resistivity. Taking into account the fact that the vertical resolution of deep laterolog resistivity curve exceeds the thickness of individual coal bands, it was suggested that microresistivity data could be exploited to improve coal characterisation. Initially, it was supposed that enhanced vertical resolution of microresistivity curve could provide better coal characterisation that deep laterolog resistivity did. Microresistivity curve was not logged in the studied wells but CMI™ (Compact MicroImager Weatherford tool) data were available for the study. In order to be implemented for the research, array of microimager data had to be converted into single microresistivity data.

This paper focused on the problem of borehole microimager array data conversion to a microresistivity curve. The automated method suggested in this paper was established based on the mathematical algorithm that was previously used for another array data (Nuclear Magnetic Resonance data) but has never been applied on the borehole electrical imager data. This algorithm is based on mathematical data analysis and fully automated. The main idea of the method is that the distribution of array data is analysed for each depth with predefined depth step (which was chosen to be equal to other wireline logs sample rate) and mean value is taken to represent the relative microresistivity at each depth point. This microresistivity curve is called relative as microimager's data don't present real formation resistivity. Then, the relationship between relative microresistivity and deep laterolog resistivity is estimated and the relative microresistivity is converted into microresistivity curve which reflect real formation resistivity. As a result high-resolution microresistivity curve has a vertical resolution comparable to that of other wireline methods (gamma ray, bulk density, photo-electrical factor) and computed depth of investigation which is comparable to that of deep laterolog resistivity.

Microresistivity Curve Extraction from Electrical Images

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Abstract

This paper describes a new automatic processing methodology for extracting microresistivity curves from electrical borehole images in unconventional reservoirs. Real wireline geophysical data were used to develop the technique.

Resistivity curves are mostly used for reservoir identification when the separation between shallow and deep readings is interpreted as a sign of permeable layer. Being true for the conventional reservoirs, this rule does not work for the unconventional ones and the coal seam gas reservoir is amongst them. The latter is described by more complex relationships between its formation properties and most of them are still to be established.

Coal seam reservoirs are commonly characterised by their density and fracture distribution which, in turn, affects wireline geophysical curves response. Both of the former mentioned properties are related to the lithotype layering or brightness and the thermal maturity rate and this study investigates the use of microresistivity data for their determination.

Borehole electrical images have been chosen as a source of microresistivity data and an algorithm of these data extraction from microresistivity images has been created. The Weatherford Compact MicroImager (CMI) resistivity tool data were used but any other microimager can be used to perform this algorithm.

Introduction

Although resistivity tools are commonly used in the petroleum exploration, they are not as common in the coal industry. Moreover, the vertical resolution of conventional resistivity tools might exceed several times the thickness of individual coal seams and cannot surely be used for coal properties characterisation due to this drawback. Microresistivity tools might be of interest in that case but the problem is that these devices are even more rarely exploited in coal studies than previously mentioned conventional resistivity tools.

As opposed to microresistivity sondes, high-resolution resistivity imagers are widely used in exploration. For example, resistivity microimagers are used in the petroleum industry for formation textural features interpretation and dip angles determination (Ye, Rabiller and Keskes, 1997, 1998). The only problem of these data results from the fact that they are presented as an image which looks like a graphical object.
Finding the way to transform microresistivity imager data into a single microresistivity curve might give resistivity data with perfect vertical resolution (5 mm). For unconventional reservoirs, in particular coal seams, this level of resolution enhances the capture of laminations or banding properties used for characterisation.

Methodology

Background

The images represent formation response at the borehole wall and give a continuous vertical record of the entire borehole circumference (for acoustic images) or as much as possible in the case of the electric images (Ekstrom et al, 1987).

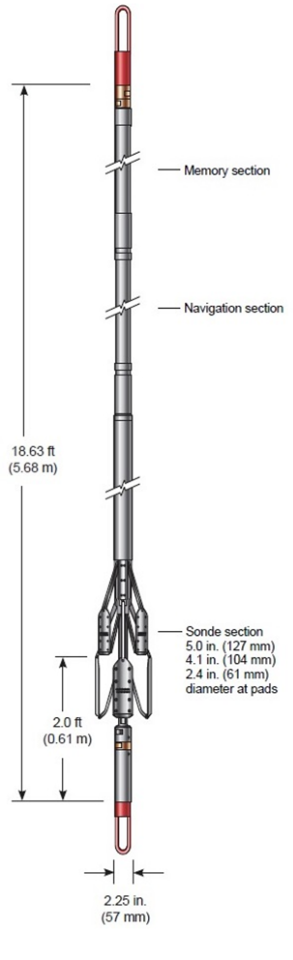

Figure 1 Weatherford CMI tool

The Compact MicroImager log or CMI consists of a memory section (MIM) and a measurement section (MIE). High-resolution, time-based data are recorded into memory while 3.937-in. (10-cm) depth-based data is transmitted to surface. The CMI features two offset, four-arm, calliper mechanisms. The upper callipers provide tool centralization while the lower callipers act independently. The CMI has a total of 176 button electrodes, equally distributed over eight pads, providing excellent borehole coverage. When configured as CMI 2.4, the tool has a total of 64 button electrodes. CMI tool provides borehole images with excellent vertical resolution (0.2in, or 5mm).
The raw data acquired by an electrical imaging tool is a series of microresistivity curves (Rider, 1996). For the CMI (Figure 1) there are 176 (64 in slimhole configuration). By use of processing software, these raw data are to be converted into microresistivity image (Figure 2). Then, this image is used for lithological interpretation, fracture identification and dip determination either manually or automatically (Ye and Rabiller, 1998).

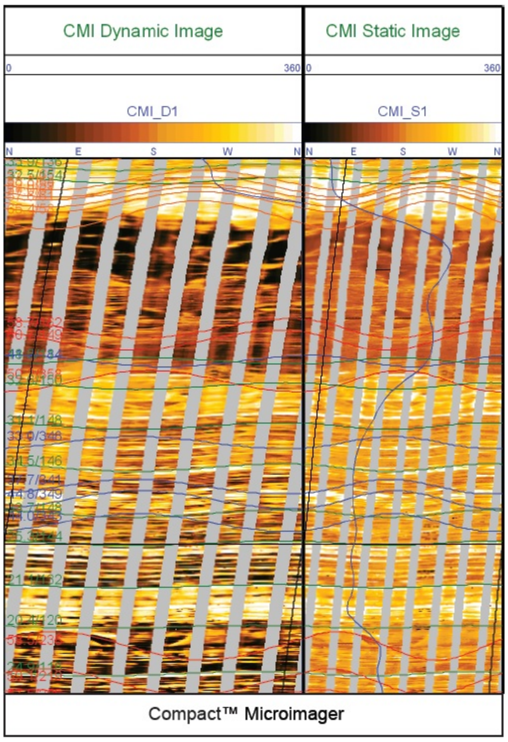

Figure 2 Example of CMI tool images

The raw data acquired by an electrical imaging tool is a series of microresistivity curves, but none of them can be used separately as a microresistivity curve due to the fact that they all together form an array of data. Each individual element of the array (each microresistivity curve) represents only a small part of array and only the whole array represents the required property (formation resistivity).

Proposed methodology

Histogram upscaling and further processing of the upscaled results was suggested to convert an array of resistivity data into a single resistivity curve.

The histogram is a graphical representation of the distribution of data; it’s a representation of tabulated frequencies (Figure 3). Upscaling is a procedure when the software steps a sliding window through the selected log, calculating a histogram at each step. The main purpose of histogram upscaling is to generate an array log which can be mathematically characterised and processed into an individual continuous curve.

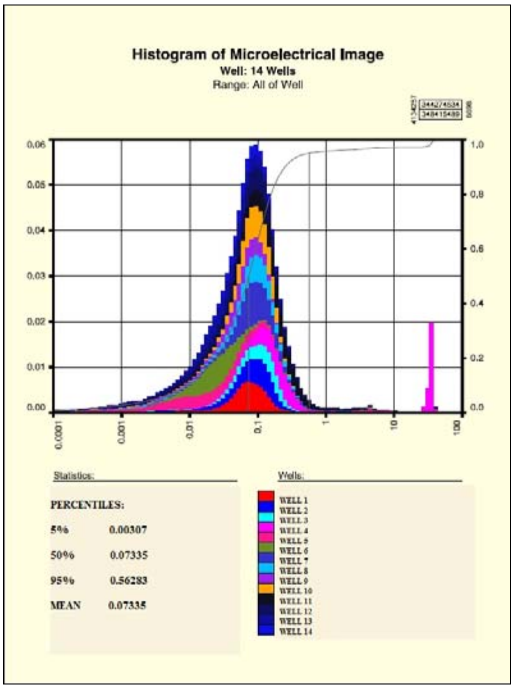

Figure 3 Raw resistivity data distribution

Resistivity is plotted on axis X on logarithmic scale, Frequency is plotted on the left axis Y, Percentage is plotted on the right axis Y, Number of decades = 6 (values from 0.0001 to 100). This histogram is to estimate resistivity data distribution and choose minimum and maximum values for further processing. Percentiles mean that 5% of data has resistivity values less than 0.00307, 50% are less than 0.07335 and 95% are less than 0.56283.

After examining the histogram of raw array resistivity data, the histogram upscaling procedure was performed in Geolog software. Table 1 shows the parameters used in Geolog and short explanation of the parameters is given in Appendices.

Upscaling operation allowed representation of the electrical image in a form which resembles a continuous curve (Figure 8, see Appendices) and gave the necessary input for microresistivity data derivation from the microimager data.

The next step was to convert the histogram upscale result into a single resistivity curve. An algorithm which had been established by Philippe Rabiller was chosen to achieve this goal. The algorithm was performed automatically in Geolog software and its inputs and outputs are listed in Table 2 with explanation below. Table 2 is presented in Appendices.

The algorithm results in curves which represent minimum, median and maximum values of data array. Let's further call them processed curves for our convenience.

Results

Having analysed the processed curves, it was noticed that the median curve is a curve of choice to describe an array of resistivity data. This fact can be explained based on the histogram (Figure 3). The mean of data array approximately lies in the area of maximum frequency. It means that mean value would represent the majority of data. The median curve obtained by running the algorithm is a continuous sequence of mean values at each depth step (which is determined from upscaling). Thus, choosing the median curve for further manipulations we literally take the whole of massive of data reduced to a single value per depth. That's why we performed histogram upscaling: we needed to split an image into a histogram with predetermined depth steps in order to extract a mean value at each depth step. The depth step is determined by sample rate of the wireline curves as it makes the wireline curves and the processed curves applicable for comparison.

As it can be observed from the Figure 8, the median curve shows a very good correlation with image and there is a similarity in behaviour of wireline resistivity curves and the median one.

One should remember that an electrical image represents relative but not absolute resistivity values of the formation. This fact results from borehole image obtaining methods (Rider, 1996). Thus, the median curve perfectly represents the resistivity contrast between individual layers of the formation, as does an electric image, but doesn't show "real" resistivity values.

In order to solve this problem, the median curve was plotted versus wireline resistivity curves and a relationship was established to convert the median into microresistivity (Figure 4, 5, 6).

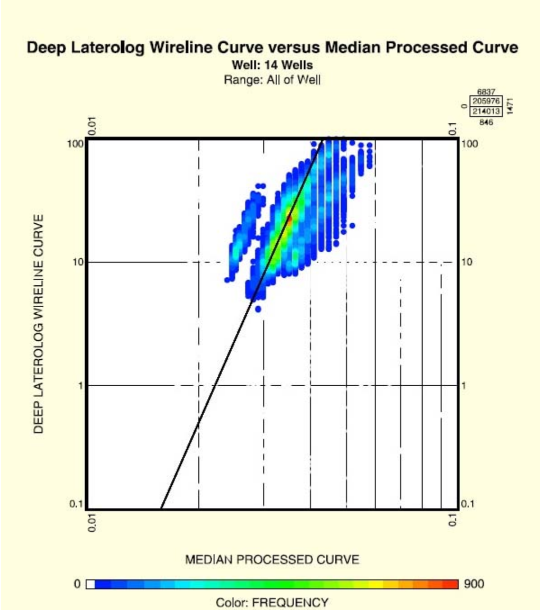

Figure 4 Median processed curve plotted versus deep laterolog wireline curve

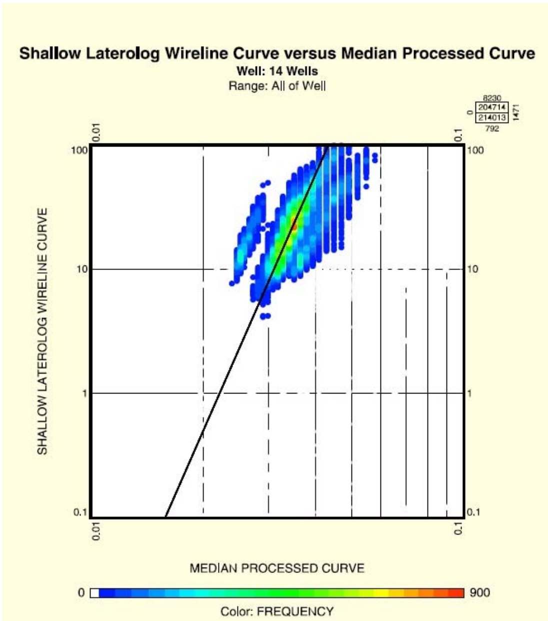

Figure 5 Median processed curve plotted versus shallow laterolog wireline curve

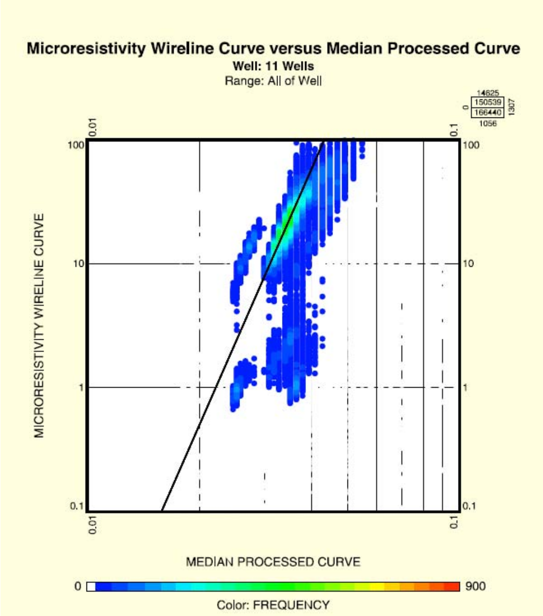

Figure 6 Median processed curve plotted versus microresistivity wireline curve

It was observed that there is a good correlation between all wireline resistivity curves and the median curve. Any of these curves might have been used for conversion but the deep resistivity is preferable due to its deep depth of investigation: the bigger the depth of investigation which the resistivity curve has, the closer the curve to true formation resistivity.

The relationship which links deep laterolog resistivity data and the processed median curve was established to deduce a formula that will result in microresistivity curve.

The required formula is of the form of:

*Rmicro = 10(A+B*Log10 (Rmedian))*

A and B are the coefficients which can be determined from a cross-plot. A determines an intercept and B determines a gradient of the curve which describes the relationship between deep resistivity wireline and processed median curves.

This formula has the following view for our particular dataset:

*Rmicro = 10(17+10*Log10 (Rmedian))*

The final result shows that the resulting microresistivity curve extracted from the image data overlays quite well with wireline resistivity ones (Figure 7).

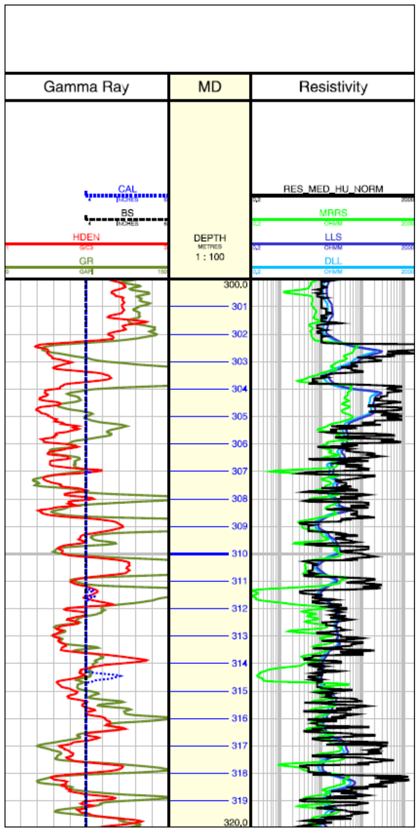

Figure 7 Microresistivity curve obtained from image in comparison to wireline curves Track 1 shows gamma ray (green), density (red), caliper (blue) curves and borehole size (black); Track 2 is the depth track and Track 3 shows deep laterolog (dark blue), shallow laterolog (light blue), microresistivity wireline (light green) and microresistivity processed (black) curves

If there aren't any resistivity wireline data available apart from an image, the median curve can still be used, but one should bear in mind that its values are relative.

Discussion

The method which is described in the paper allows obtaining of microresistivity curve from borehole electric images in five simple steps as listed below:

Histogram analysis: raw resistivity data are plotted as a histogram and data distribution is analysed;

Histogram upscaling: an automatic process which results in inputs which are necessary for the next step;

Processing of array data statistics: automatic process which uses a formerly written algorithm in order to obtain maximum, median and minimum curves;

Cross-plot analysis: processed curves are analysed versus wireline resistivity data in order to find a relationship to convert the median curve into microresistivity;

Microresistivity curve extracting: the median curve is converted into microresistivity. This method required no cut-offs or special parameters as all mandatory inputs are obtained from a simple raw data analysis procedure. Most steps are automatic and were performed in Geolog software but can be repeated in similar petrophysical package.

The result of this five-step method is a processed microresistivity curve which has a very high resolution (0.2 in.) because it was calculated based on borehole image. In the same time, as the deep resistivity curve was also used for this operation, the processed curve corresponds to formation resistivity better than the wireline microresistivity. Processed microresistivity curve can be used when the wireline microresistivity curve is not available or in comparison to it to indicate some borehole effects.

For example, Figure 5 shows quite significant separation between wireline and processed microresistivity curves at depths between 311 and 312m and between 314 and 315m. Caliper shows an increased borehole. Thus, curve separation is due to the fact that wireline curve reacts on borehole wash-out while the processed curve ignores it. Also, processed microresistivity recognises small layers of different resistivity while deep wireline curve demonstrates a smooth profile due to its poor vertical resolution. We might note that resistivity shows good correlation with gamma ray and density curves (Figure 7).

These are only some of the examples how processed microresistivity curve can be exploited. In a broad sense, this curve might be treated as a computed curve with deep pseudo depth of investigation and high vertical resolution. It opens up a wide area for processed microresistivity curve exploitation. In future research, the microresistivity curve will be used to interpret coal lithotypes and thermal maturity.

Conclusion

In this paper an automated microresistivity extraction process has been presented. It begins with raw data analysis, continues with histogram upscaling, then array data are analysed, compared versus wireline data and a microresistivity curve is finally calculated. The method results in a computed microresistivity curve which has high vertical resolution and deep pseudo depth of investigation. This method doesn’t require any special parameters, cut-offs or assumptions, it’s based on raw data analysis only and, thus, it’s immune to interpreter bias.

The output of the method might be used in different ways depending on interpreter needs. For example, coal characterisation is performed by use of the processed median curve. Median curve is exploited as an input for electrofacies analysis in Facimage. This job is performed in Coal Seam Gas Centre of the University of Queensland.

Acknowledgments

The author thanks School of Earth Sciences and the Vale Coal Geosciences Program for support; and Arrow Energy for access to data. The author is grateful to Professor Joan Esterle for an internal review and for comments which improved the paper a lot. In addition, the author thanks Philippe Rabiller and Peter Boles for their keen input on several technical issues and Daniel O'Dell for considerable support with Geolog software.

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Appendices

Table 2 Histogram upscaling algorithm

Mode	Comment	Name	Value
Input	Window size in frames	WINDOW_SIZE	50

Input	Number of cutoff missing frames within the window to output missings.	CUTOFF_MISSING	0
Input	Window step in frames	WINDOW_STEP	25
Input	Number of input bins	NUM_BINS	60
Input	Axis scaling, linear or logarithmic	SCALE	LOGARITHMIC
Input	Define min and max automatically or manually?	MIN_MAX_OPTION	MANUAL
Input	Min limit for histogram	MIN_LIMIT	0.01
Input	Max limit for histogram	MAX_LIMIT	100
Input	Input log	LOG_IN	IMAGE.IMAGE_RAW_1
Output	Histogram log	HISTOGRAM	HISTOGRAM

Necessary input variables:

WINDOW_SIZE = WINDOW_STEP*2

WINDOW_STEP = (wireline logs sample rate) / (borehole image sample rate)

NUM_BINS = number of decades from the histogram*10 bins (as 10 bins per each decade of histogram is enough for good data quality)

SCALE = LOGARIPHMIC (as it's the resistivity data)

MIN_MAX_OPTION = MANUAL

MIN_LIMIT = minimum from histogram

MAX_LIMIT = maximum from histogram

LOG_IN = raw resistivity array data channel

Table 3 Algorithm for minimum, median and maximum curves extraction from an array of data

Mode	Comment	Name	Value
Input	number of bins in log from G6 frequency report	N	49
Input	Lower limit of first bin of occurence Histogram	MIN_OCC_HISTO	0
Input	Upper limit of last bin of occurence Histogram	MAX_OCC_HISTO	50
Input	Lower threshold for cumulative frequency (%)	L_THRES	0.0125
Input	Upper threshold for cumulative frequency (%)	U_THRES	0.9875
Input	sampling rate	SR	0.025
In_Out	Log from G6 'frequency' report or any array data	OCCURENCES	HISTOGRAM
Output	histogram of frequency	FREQUENCY	LOG_HIST_FREQ
Output	cumulative frequency	CUM_FREQ	LOG_CUM_FREQ
Output	cumulative occurrence	CUM_OCC	LOG_CUM_OCC
Output	Thickness of dominant facies	THICK_MPP	LOG_THICK_MPP
Output	Lower threshold for cumulative frequency (%)	L_THRES_A	

Output	Upper threshold for cumulative frequency (%)	U_THRES_A	
Output	log value at lower threshold on cumulative frequency	LOC_FREQMIN	RES_MIN_HU
Output	log value at upper threshold on cumulative frequency	LOC_FREQMAX	RES_MAX_HU
Output	local median	LOC_MED	RES_MED_HU
Output	histogram main peak position	HIST_MPP	LOG_HIST_MPP
Output	Frequency of dominant facies (value at MPP)	HIST_MPPV	LOG_HIST_MPPV
Output	Array to be displayed as image and with colour bar	ARRAY_BKGD	LOG_ARRAY_BKGD
Output		BIN_SIZE	BIN_SIZE

Necessary input variables:

N (number of bins) = MAX_OCC_HISTO – 1 (as the lower limit is stated to 0 and the upper limit is stated to 60)

MIN_OCC_HISTO = 0

MAX_OCC_HISTO = number of decades from the histogram*10 bins (as 10 bins per each decade of histogram is enough for good data quality)

SR = sample rate (should be equal to that of wireline logs)

OCCURANCES = the log which results for histogram upscaling

Resulting outputs:

RES_MIN_HU = curve which represents the minimum of array

RES_MED_HU = curve which represents the median of array

RES_MAX_HU = curve which represents the maximum of array

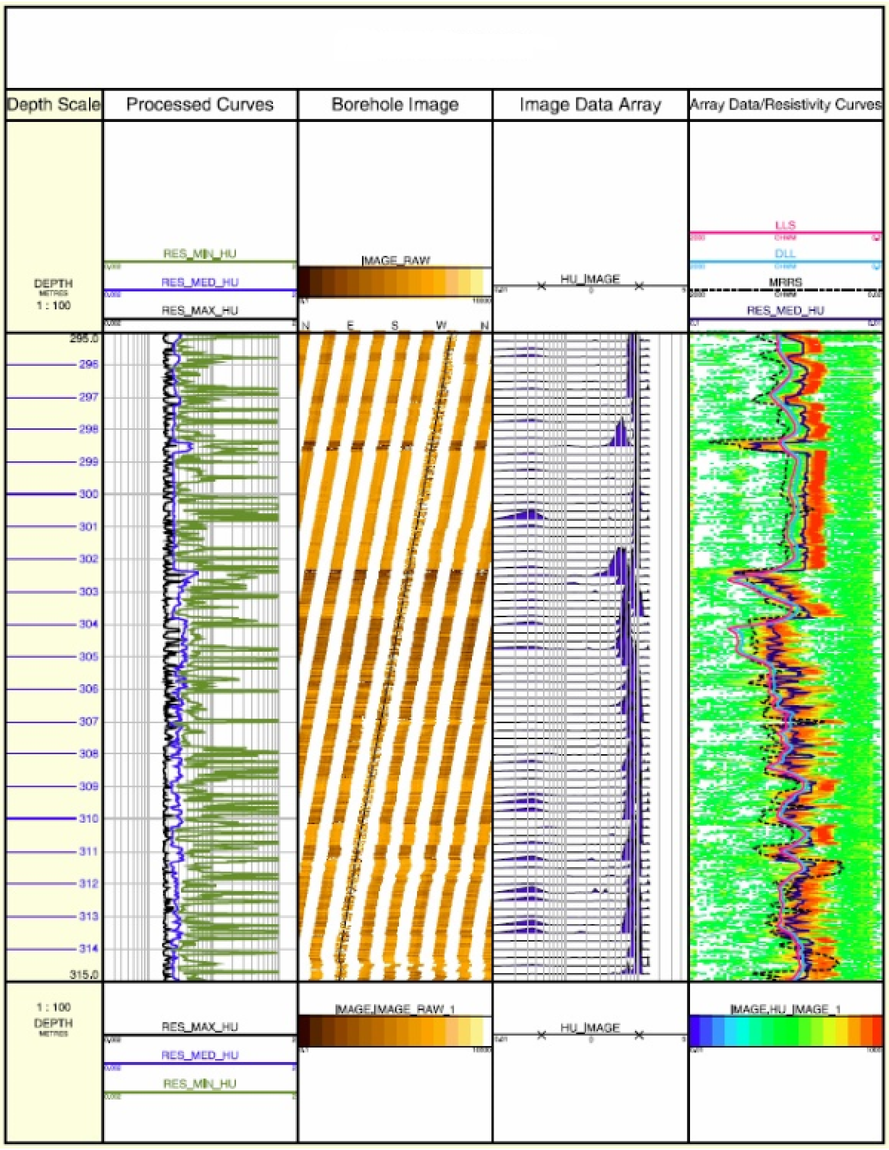

Figure 8 Histogram Upscaling results

The left track shows the depth scale. Track 2 shows the processed curves which represent array data statistics, the raw CMI image is on Track 3 and colours range from black to pale, representing the resistivity of the unfolded image. Track 4 shows the histogram upscaled image presented as an array of data; Track 5 shows the histogram upscaled image pictured as an image (rainbow colour scheme has been chosen for better visualisation) versus wireline and processed curves (the black dashed curve is the microresistivity wireline curve, the navy blue one is the median curve, the light blue is the deep resistivity wireline curve and the violet one is the shallow resistivity wireline curve)

4. PAPER 2 Electrofacies analysis for coal lithotype profiling based on high-resolution wireline log data

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Submitted to Computers &Geosciences Journal, under review.

Alexandra Roslin (MPhil candidate) performed the study, established the method which is described in the paper, prepared figures and tables, wrote manuscript;
Joan S. Esterle (Principal MPhil supervisor) reviewed, discussed and edited manuscript.

The next step of the research which is described in the second paper in more details was focused on establishing a methodology which allows automated or semi-automated coal characterisation based on wireline geophysical logs and its validation without using any pre-determined cut-off values. Electrofacies analysis was used as a suitable approach for the study. Electrofacies analysis consisted from three main steps:

- Data preparation;
- Clustering analysis; and
- Electrofacies classification.

Input data set which was used for the study included gamma ray, density, deep laterolog resistivity, microresistivity (that was obtained from CMI™ Weatherford tool) and PEF wireline data from 26 wells from the northern part of the Bowen Basin.

Multi-Resolution Graph-Based Clustering (MRGC) tool was used for the clustering as this method allows running clustering procedure without pre-defined knowledge of the number of clusters. MRGC provides the user with three sets of clusters which represent different level of details.

Clustering analysis was performed three times with different input wireline logs:

1) Method#1: gamma ray, density, laterolog and microresistivity;

2) Method#2: gamma ray, density, laterolog and PEF;
3) Method#3: gamma ray, density, microresistivity and PEF.

The contingency tables for each method were analysed for validation of the clustering results and it was concluded that the method #2 represents the better results.

Electrofacies classification was performed by the analysis of wireline logs trends and comparison with fixed carbon content and ash yield trends for double control. The results of electrofacies classification were validated by comparison of weighted average proportion of different coal electrofacies to the weighted average proportion of corresponding coal lithotypes obtained by millimetre scale logging results. This comparison demonstrated that the discrepancy between methods doesn’t exceed 20% apart from the Vermont Upper coal seam where the mismatch between the results is significant (near 50%). Due to the fact that the discrepancy is consistent for all studied wells and observed only in the Vermont Upper coal seam, it was decided that the constituent of this seam determines the response of wireline logs which was not taken into account in the course of this research.

In addition to coal lithotype characterisation, the research study resulted in the inertinite-rich dull coal determination. It was observed that the methodology, which is presented in the paper in more details, allows distinguishing between bright low density coal and inertinite-rich dull low density coal. It was possible to determine inertinite-rich dull coal by adding PEF curve to the input data set. The results of the inertinite-rich coal study were validated by the comparison to maceral analysis data.

To sum all, the second step of the research resulted in the semi-automated method that allows performing coal characterisation based wireline geophysical logs by using electrofacies analysis. Compared to the conventional cut-off approach this method doesn’t require any pre-determined cut-off values. The established method exploits MRGC tool for clustering procedure which makes it easy to run and validate the results statistically. The results of the electrofacies analysis were converted into weighted average proportions and validated by comparison to millimetre scale logging results. The discrepancy generally doesn’t exceed 20% but reach up to 50% in the Vermont Upper coal seam. Such anomalous behaviour of this particular coal seam was explained by the constituent of the coal seam (more specifically, its mineral matter composition). Including PEF curve into the electrofacies analysis allowed distinguishing between inertinite-rich low density dull coal and bright low density coal what was not possible by the convenient cut-off approach. The results of inertinite-rich dull coal study were validated by maceral analysis data.

ELECTROFACIES ANALYSIS FOR COAL LITHOTYPE PROFILING BASED ON HIGH-RESOLUTION WIRELINE LOG DATA

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ABSTRACT

The traditional approach to coal lithotype analysis is based on a visual characterisation of coal in core, mine or outcrop exposures. As not all wells are fully cored, the petroleum and coal mining industries increasingly use geophysical wireline logs for lithology interpretation.

This study demonstrates a method for interpreting coal lithotypes from geophysical wireline logs, and in particular discriminating between bright or banded, and dull coal at similar densities to a decimetre level. The study explores the optimum combination of geophysical log suites for training the coal electrofacies interpretation, using neural network conception, and then propagating the results to wells with fewer wireline data. This approach is objective and has a recordable reproducibility and rule set.

In addition to conventional gamma ray and density logs, laterolog resistivity, microresistivity and PEF data were used in the study. Array resistivity data from a compact micro imager (CMI tool) were processed into a single microresistivity curve and integrated with the conventional resistivity data in the cluster analysis. Microresistivity data were tested in the analysis to test the hypothesis that the improved vertical resolution of microresistivity curve can enhance the accuracy of the clustering analysis. The addition of PEF log allowed discrimination between low density bright to banded coal electrofacies and low density inertinite-rich dull electrofacies. The results of clustering analysis were validated statistically and the results of the electrofacies results were compared to manually derived coal lithotype logs.

KEYWORDS

Reservoir Characterisation, Electrofacies analysis, Artificial Networks, Wireline logs, Coal lithotype

1. INTRODUCTION

Along with rank and grade, coal organic composition, defined megascopically by lithotype and microscopically by maceral analysis, will control the physical and chemical properties of coal that influence its utilisation and coal seam gas reservoir behaviour. Accordingly, geologists manually log core and use the distribution of lithotypes (Figure 1) to characterise the coal seams for correlation and sampling for further laboratory analysis. Visual analysis of coal lithotypes can be subjective, and once the coal is sampled, crushed and analysed, its megascopic properties are destroyed. Core is also considered expensive, and as a result, geophysical wireline logs have become an alternative source of information for coal characterisation (Reeves, 1976; Johnston, 1991; Sutton, 2014). The impetus for this study was that the coal seams in the study area were not contiguously cored, so full seam characterisation was not possible unless we developed a characterisation method based on the wireline logs.

A common approach to coal characterisation using wireline data applies cut-off values on each wireline log measurement (Zhou and Esterle, 2007). Density is used for identification of coal, and gamma ray or sonic values (among others) for interburden lithology. Provided good correlation between sampled core properties and the selected wireline, the approach demonstrates quite good results. This method might produce significant errors if the wrong cut-off values were chosen, or if they vary between different coal seams or formations (Fullagar et al., 2004).

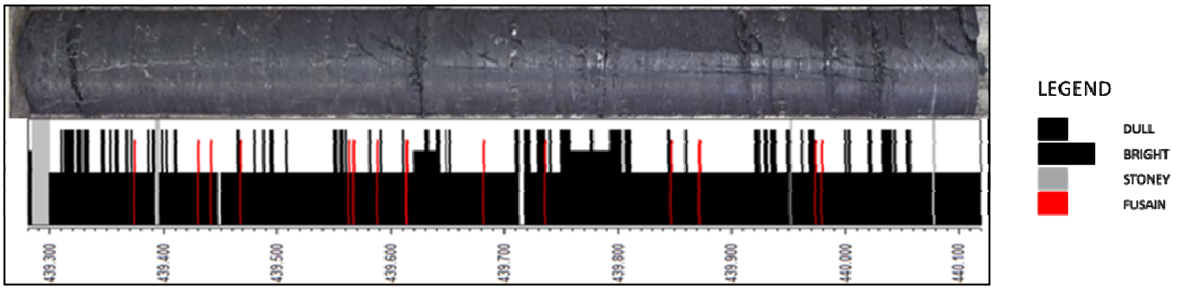

Figure 1 An example of a manual coal lithotype profile plotted next to coal core for end member coal lithotypes. Core is 80cm long (image provided by Natalya Taylor, University of Queensland).

This paper describes a methodology that exploits geostatistical cluster analysis of wireline geophysical data and uses laboratory and visual core logging analysis data for initial control and subsequent validation of the results. It doesn't require any predefined cut-offs and assumptions about coal quality which potentially makes the method less prone to an interpreter bias and more robust and reproducible. In addition to identification of high or low density coal, the method is interpreted to discriminate inertinite-rich low density dull from mineral-rich dull from higher density or mineral matter rich dull coal and from banded or bright (high vitrinite) low density coal.

2. METHODOLOGY

2.1. BACKGROUND

The application of cluster analysis, often referred to as electrofacies analysis, to identify different lithologies of facies in clastic sedimentary rocks is common (Ellis and Singer, 2008; Rider and Kennedy, 2013), so a similar approach could be applicable for coal lithologies. The term "electrofacies" refers to a cluster or group with common wireline log signatures or values that distinguishes it from other clusters. Ye and Rabiller (2005) define electrofacies as an element of the N-Dimensional (N being the number of wireline logs considered) data structure created by all petrophysical material available, whose ordering reveals the organised relationship imparted to petrophysical properties of interest by natural geologic systems ordering (Ye and Rabiller, 2005). Electrofacies, in contrast to geological facies, is an interval defined on wireline logs, with consistent or consistently changing wireline log responses and characteristics - sufficiently distinctive to separate it from other electrosequences (Rider and Kennedy, 2013). Electrofacies analysis involves partitioning a set of log data into electrofacies units and presenting them in a manner that is comparable to that used by geologists for interpretation purposes – each electrofacies is assigned a number, or index, which can be plotted against depth or used to control colour coding on displays (Ye and Rabiller, 2005).

Electrofacies ordering can be performed by different algorithms such as genetic algorithms (Goldberg, 1989) and neural networks. Artificial neural networks are computational models inspired by biological neural networks and are used to approximate functions that are generally unknown. There are many types of artificial neural networks and more details can be found in Potvin (1993). The neural-network scheme, first developed by Angeniol et al. (1988) is derived from the Kohonen's Self-Organising Map (SOM). An advantage of the SOM is that the resulting map is automatically ordered in the data space. A self-organising map (SOM) or self-organising feature map (SOFM) is a type of artificial neural network (ANN) that is trained using unsupervised learning to produce a low-dimensional (typically two-dimensional), discretised representation of the input space of the training samples, called a map. Self-organising maps are different from other artificial neural networks in the sense that they use a neighbourhood function to preserve the topological properties of the input space. An SOM performs an ordered mapping from a hyper-dimensional data space onto a lower (one- or two-) dimensional lattice of points (neurons). It can be considered as a non-linear regression of the reference vectors (neurons) through the input data (Ye and Rabiller, 2005).

The SOM network is made up of a specified number of neurons interconnected into a one- or two-dimensional array. This interconnection among neurons is called the lateral relationship. Neurons are initialised randomly. The input data are iteratively presented to the network for a given number of cycles. The convergence is controlled by two learning parameters: the width of the neighbourhood (Gaussian) function and the learning rate. In the neuron-splitting technique, all the input data are presented to the learning mechanism simultaneously instead of successively as in the SOM. Ye and Rabiller (2005) presented a simple and fully automated method based on the neuron-splitting technique using a 1D line-structured SOM. The input data are electrofacies kernels. These could be derived from any method. Multi-Resolution Graph-based Clustering (MRGC) method (Ye and Rabiller, 2000) available within Geolog^{TM} software was used for this coal electrofacies research.

MRGC is a multi-dimensional dot-pattern-recognition method based on non-parametric K-nearest-neighbour and graph data representation (Ye and Rabiller, 2000). The underlying structure of the data is analysed, and natural data groups are formed that may have very different densities, sizes, shapes, and relative separation. MRGC automatically determines the optimum number of clusters, yet allows the geologist to control the level of detail actually needed to define the electrofacies. Some vector analysis programs let the user to decide how many clusters based on a "goodness of fit". In turn, Geolog^{TM} software offers a number of probability tables to estimate and validate the clustering results. These probability tables were used in this research for validation of the clustering results.

The electrofacies ordering method which was presented by Ye and Rabiller (2005) performs a complete training of the SOM between each splitting process, whereby the newly split neurons are fully trained before being split again. This process was called a Coarse-to-Fine Self-Organising Map (CFSOM), because the electrofacies ordering is made from a low-resolution (coarse) map towards a high-resolution (fine) map. There are no concerns about how many cycles of input data presentation are necessary to split neurons and what the optimal parameters for SOM might be when the data configuration and the size of problem are changed. All that is needed is for the algorithm to add a reasonable number of neurons at each step and re-apply the ordinary SOM algorithm.

2.2. DATASET

The research was focused on the northern Bowen Basin (Figure 2) and included geophysical wireline logs from wells intersecting three main Late Permian coal measures – Moranbah, Fort Cooper and Rangal. In general, the character of the coals changes stratigraphically up section, with a general increase in inertinite group macerals in the Rangal Coal Measures (Mutton, 2003). That area is also characterised by good collection of high-quality wellbore data and has previous research results that were exploited for validation of the current study.

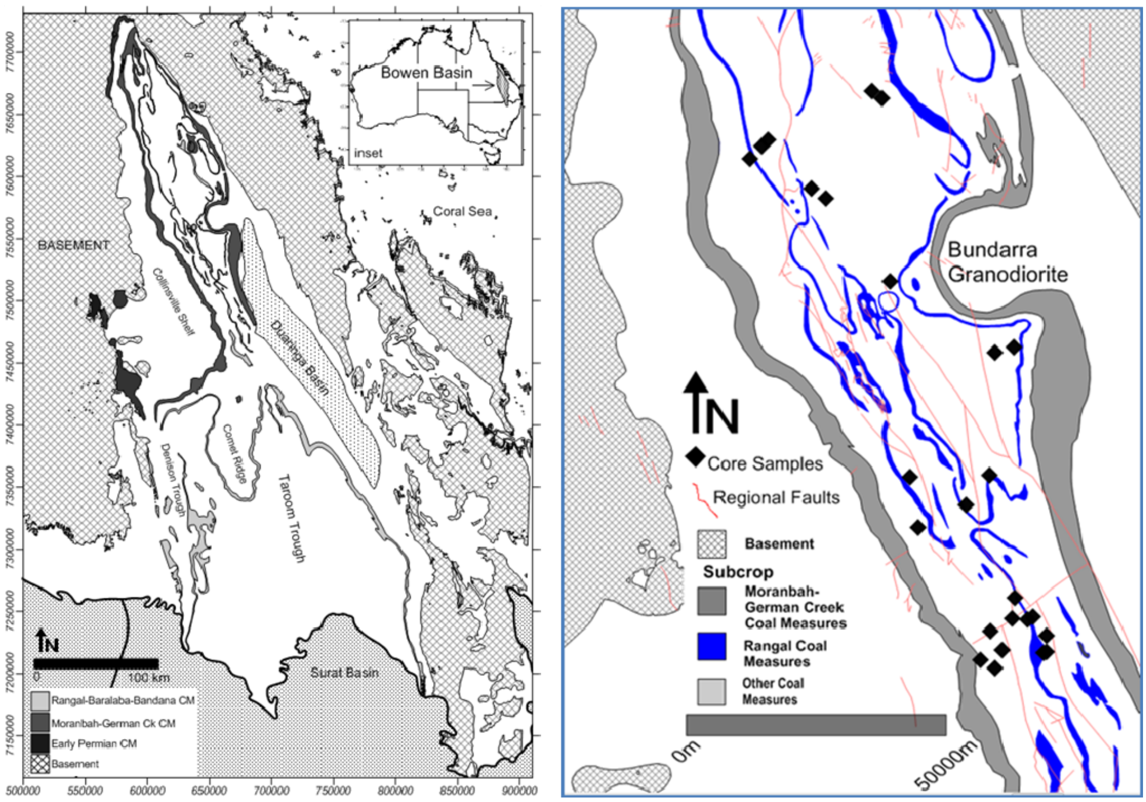

Figure 2 Location map of the study area within a) simplified map of economic coal measures in the Bowen Basin, with inset of location within Australia and b) close up showing location of core samples with wireline logs. Note that the Fort Cooper Coal Measures, which occur between the Moranbah and Rangal coal measures, are not shown. Compiled from IRTM shape files www.irtm.qld.gov.au

Table 1 Data available for the study.

Well	Wireline geophysical logs						Borehole electrical images	Coal proximate analysis	Maceral analysis data	millimetre scale coal logging data	Reference or application set?
	GR	Density	PEF	Neutron	Resistivity	Sonic					
W1	yes	yes	yes	yes	yes	no	no	no	yes	yes	Application
W2	yes	yes	yes	yes	yes	no	yes	no	yes	yes	Reference
W3	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W4	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	Reference
W5	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W6	yes	yes	yes	yes	yes	no	no	yes	yes	yes	Application
W7	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	Reference
W8	yes	yes	yes	yes	yes	no	no	yes	yes	yes	Application
W9	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W10	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	Reference
W11	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	Reference
W12	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W13	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Application
W14	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Application
W15	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	Reference
W16	yes	yes	yes	yes	yes	no	no	yes	no	yes	Application
W17	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W18	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W19	yes	yes	yes	yes	yes	no	no	yes	yes	yes	Application
W20	yes	yes	yes	yes	yes	no	no	yes	yes	yes	Application
W21	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	Reference
W22	yes	yes	yes	yes	yes	no	no	no	no	no	Application
W23	yes	yes	yes	yes	yes	yes	yes	yes	no	no	Reference
W24	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	Reference
W25	yes	yes	yes	yes	yes	no	yes	yes	no	yes	Reference
W26	yes	yes	yes	yes	yes	no	no	yes	yes	yes	Application

The dataset included 26 wells which had been geophysically logged and cored. Wireline logs included caliper, gamma ray (GR), laterolog resistivity, density, photo-electric factor (PEF) and thermal neutron porosity; three wells contained sonic data (dt and dipole data). Borehole electrical images were available for 18 of the 26 wells. Of these 26 wells, not all coal seams were fully cored and analysed, making the validation against megascopic description a bit sporadic. The lack of contiguous coring was actually an impetus for this study, so that complete seams might be characterised within the measures. Coal proximate analysis data were available for samples from 23 wells. Visual lithotype logging (using an end member millimetre scale approach (Esterle and Kolatchek, 2002), maceral and reflectance analysis data were available for 182 sampled metres of core from 12 wells. The summary of data available for the research is shown in Table 1. The location of these wells is presented in Figure 4 and discussed below.

2.3. METHODOLOGY WORKFLOW

The automatic algorithm which was implemented for coal lithotype profiling is performed in three steps: 1) data preparation; 2) electrofacies analysis; 3) model propagation. The algorithm was run in the Facimage^{TM} module of Geolog^{TM} software (Paradigm package). The workflow is presented on Figure 3. Facimage^{TM} is Geolog^{TM}'s application for use in the interpretation of log data based on statistical and neural network methods following Ye and Rabiller (2000). Parameters which were used in the study are shown in the Appendix.

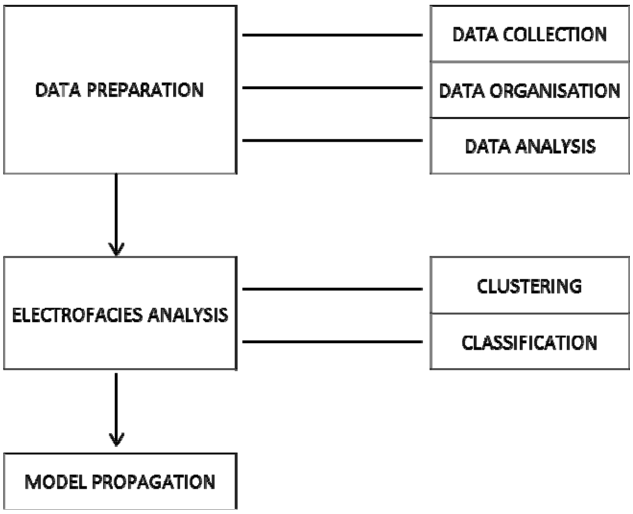

Figure 3 Methodology workflow.

2.3.1. DATA PREPARATION

The first step of the workflow is data preparation and includes three basic procedures: data collection, data organisation and data analysis (Figure 3). The following geophysical data were chosen for analysis: gamma ray, density, PEF and laterolog resistivity and microresistivity from borehole electrical images. This particular choice of wireline measurements is explained by the relationship between those measurements and coal properties which, in turn, reflect coal lithotype and grade.

All wells are organised into two datasets: reference and application. The former is used to generate the model which would be further applied on all wells which form the application dataset. The reference dataset ideally includes the deepest wells which have a full collection of data (wireline logs, core data, etc.) and characterise the whole geological profile. For this study, the reference set contained 16 wells and the application set included 10 wells (see Table 1) which were equally spread over the study area (Figure 4).

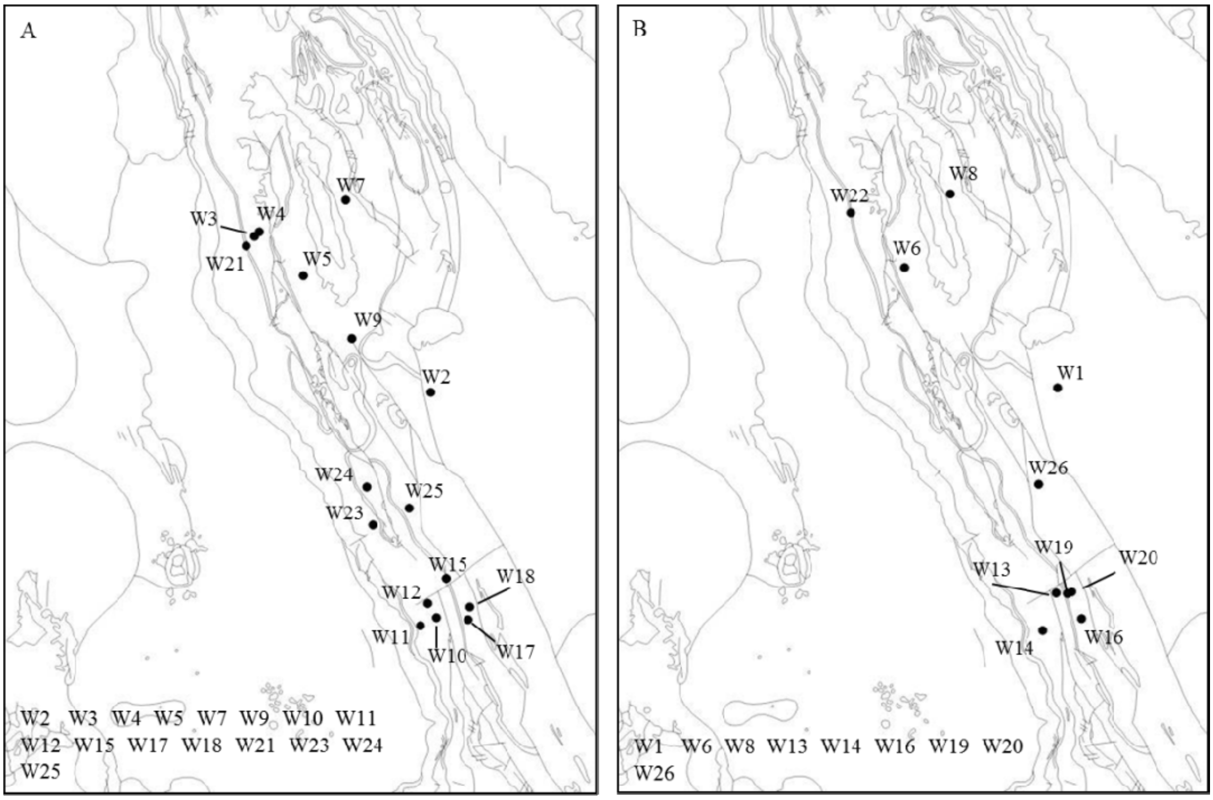

Figure 4 Distribution of wells in the study area: A) Reference dataset; B) Application dataset.

Finally, all data was analysed and prepared for modelling so that for all wells all measurements have the same sample rates and measurement units, each measurement is on an appropriate scale and erroneous values (such as resistivity values in casing) are excluded from the data range. Data were prepared in the following way: gamma ray was plotted on a linear scale between 0 and 200 GAPI; density on linear scale between 1 and 3 g/cc; laterolog resistivity and microresistivity were both on logarithmic scale between 0.5 and 50 OHHM (for microresistivity) and between 0.02 and 2000 OHHM (for laterolog resistivity); PEF was on a linear scale between 0 and 4 B/E (Figure 5). Data were reprocessed to start just below the casing shoe and have a sample rate 0.025 metres.

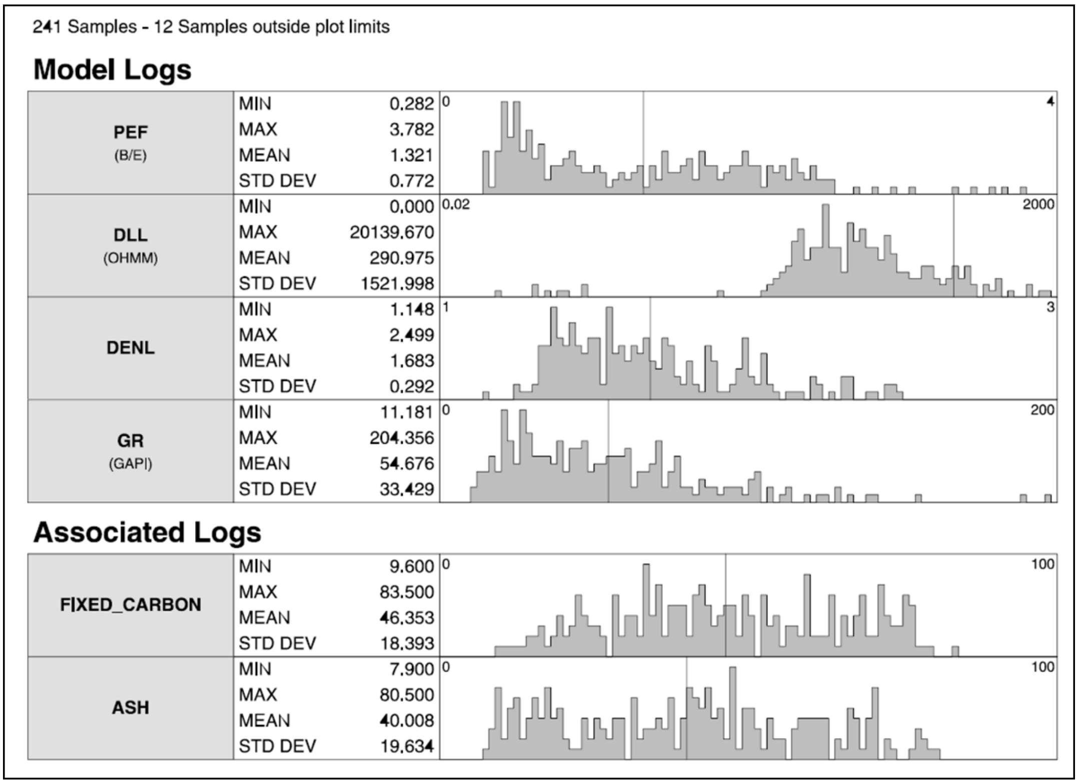

Figure 5 Input wireline logs statistics.

2.3.2. ELECTROFACIES ANALYSIS

The second step of the workflow is the electrofacies analysis. Electrofacies analysis is performed by two successive procedures: clustering which assumes partitioning the set of data into clusters (or electrofacies units) and classification which involves assigning geological meaning to each electrofacies unit.

2.3.2.1. CLUSTERING

Clustering can be explained as a grouping of all data into smaller groups based on their similarity or close proximity in N-dimensional space. A classic approach to facies analysis, automatic clustering, requires an a priori estimate of the number of clusters, which can force or skew the results (Ye and Rabiller, 2000). Performing this task manually in high-dimensional space (when the amount of logs is higher than 3) is still difficult, slow, somewhat subjective and requires a skill or expertise that is not always readily available.

The MRGC chosen in this study doesn't require the user to determine a number of clusters before starting the analysis. Instead, MRGC proposes to the user several optimum numbers of clusters corresponding to different resolutions. The user is able to compare several results and choose the most appropriate one. In addition, the results of MRGC are organised in hierarchical way so that the clusters of higher resolutions are always sub-clusters of the lower-resolution clusters (Ye and Rabiller, 2000).

Clustering was performed three times with different input wireline logs ("methods" 1, 2 and 3 in Table 3). Different types of resistivities were tried in order to investigate the influence of vertical resolution of resistivity tools on the result of electrofacies analysis, and PEF was added to the dataset to check the hypothesis that PEF might help determine a presence of inertinite matter in dull but low density coal. MRGC input parameters are shown on Table 2.

Table 2 MRGC input parameters.

Normalize Using	Plot Range
Minimum Number of Electrofacies	8
Maximum Number of Electrofacies	35
Number of Optimal Models	5
Initial Neurons for CFSOM	4

MRGC offered three different levels of detail. Thus, for method #1 Geolog™ produced: 1) fourteen clusters; 2) twelve clusters; 3) nine clusters (Table 3). Probability tables were used for validation of clustering analysis (see Appendix). How the validation was done for clustering results is explained in the next section.

Table 3 Input data for three different clustering methods.

METHOD	INPUT DATA	Number of clusters		
		Cluster Set #1	Cluster Set #2	Cluster Set #3
METHOD #1	GR, DENSITY, DEEP LATEROLOG RESISTIVITY, MICRORESISTIVITY	14	12	9
METHOD #2	GR, DENSITY, DEEP LATEROLOG RESISTIVITY, PEF	14	11	8
METHOD #3	GR, DENSITY, MICRORESISTIVITY, PEF	15	12	10
METHOD #4	VALIDATION SET (MILLIMETRE SCALE LOGGING RESULTS)			

2.3.2.2. ELECTROFACIES CLASSIFICATION

The next step of electrofacies analysis is electrofacies classification in order to assign proper geological meaning to each electrofacies unit (or cluster). This procedure is performed manually by labelling each cluster according to the interpretation of wireline log characteristics of each electrofacies and the detailed description is given in the next section.

Clustering resulted in a number of clusters (electrofacies), each with a statistical distribution (range, mean, standard deviation), for which an example from Method #2 is shown in Table 3.

In Table 4, these electrofacies were organised according to an increase of density and gamma ray values. This trend was then examined against fixed carbon and ash yield to perform the classification of these electrofacies.

Looking at the trends in distribution of wireline logs values and the statistics of the distribution, all clusters were classified according to the understanding of properties of dull mineral matter rich coal, dull inertinite-rich coal etc. Some clustered were classified similarly (Figure 6) as the authors didn't see significant difference (in terms of statistical distribution of wireline logs values) between them and these clusters were merged together. Those clusters which were classified similarly then, were merged together. The validation at this stage was performed in Geolog^{TM} by the analysis of the contingency tables (see below).

Initially, it was assumed that the increase of density and gamma ray values correlated to the corresponding decrease of fixed carbon and increase of ash yield which generally reflects an increase in coal dullness (provided that rank is held constant). If coal lithotypes were only based on density, then all bright and banded coal would be low and all dull coals would be high density. But density/gamma ray and fixed carbon/ash trends were also compared to the distribution of resistivity and PEF curve values and the following observations were made:

- heat affected (heated and coked coal) coal electrofacies was interpreted based on the distribution of resistivity values and comparison to core descriptions;

- mineral matter rich dull coal electrofacies was distinguished by an increase of gamma ray and density and corresponding increase of ash yield;

- bright and banded coal electrofacies was determined by a decrease of gamma ray and density which is correlated to a decrease of ash yield;

- inertinite-rich dull coal electrofacies was distinguished from low density bright coals by the distribution of PEF values, as its gamma ray and density distribution was similar to bright and banded coal electrofacies.

Table 4 Statistics for electrofacies clustering results (method #2).

CLUSTER	PHOTOELECTRIC EFFECT				DEEP LATEROLOG RESISTIVITY				BULK DENSITY				GAMMA RAY			
	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION
ELECTROFACIES_1	0.37	2.37	0.82	0.67	0	856.11	77.92	258.1	1.34	2.3	1.76	0.24	19.14	103.85	46.17	27.23
ELECTROFACIES_2	1.96	3.64	2.46	0.44	0.15	41.11	15.44	8.95	1.88	2.5	2.27	0.16	50.08	196.83	106.81	35.9
ELECTROFACIES_3	0.83	3.58	2.22	0.74	14.92	75.62	28.44	16.44	1.66	2.09	1.93	0.15	46.6	110.03	70.27	19.45
ELECTROFACIES_4	0.47	2.48	1.95	0.43	11.36	368.07	48.9	76.82	1.33	2.06	1.81	0.19	22.04	155.94	90.16	32.02
ELECTROFACIES_5	1.25	1.94	1.7	0.2	13.86	41.08	22.87	8.8	1.81	2.07	1.94	0.08	60.46	85.14	70.24	7.39
ELECTROFACIES_6	0.48	3.78	1.71	0.56	12.74	7871.58	351.52	1359.08	1.44	2.34	1.68	0.17	26.98	83.72	50.47	12.34
ELECTROFACIES_7	0.43	1.56	0.95	0.31	10.2	1158.39	282.95	273.75	1.25	1.57	1.43	0.08	11.18	40.73	23.86	7.94
ELECTROFACIES_8	0.51	1.98	0.81	0.49	8.79	68.87	30.95	21.47	1.46	1.81	1.62	0.11	24.82	95.04	48.5	20.95
ELECTROFACIES_9	0.59	1.47	1.25	0.26	28.74	216.48	78.73	55.21	1.15	1.72	1.51	0.15	30.95	55.27	43.01	7.48
ELECTROFACIES_10	0.36	1.77	1	0.46	0.12	275.53	56.94	65.47	1.35	1.99	1.7	0.2	22.42	96.51	65.14	19.86
ELECTROFACIES_11	0.28	2.81	0.78	0.67	20.87	198.95	81.23	43.69	1.31	1.99	1.47	0.18	14.58	71.11	31.18	13.85
ELECTROFACIES_12	0.45	1.49	0.92	0.24	25.77	183.63	76.92	44.3	1.38	1.73	1.58	0.09	29.17	76.88	56.43	11.81
ELECTROFACIES_13	0.4	0.8	0.5	0.13	67.82	315.59	182.12	64.95	1.33	1.51	1.39	0.05	12.39	30.47	18.44	4.76
ELECTROFACIES_14	0.31	0.87	0.52	0.19	0	20139.67	2414.15	5029.54	1.24	1.62	1.42	0.11	16.32	39.3	27.24	6.75

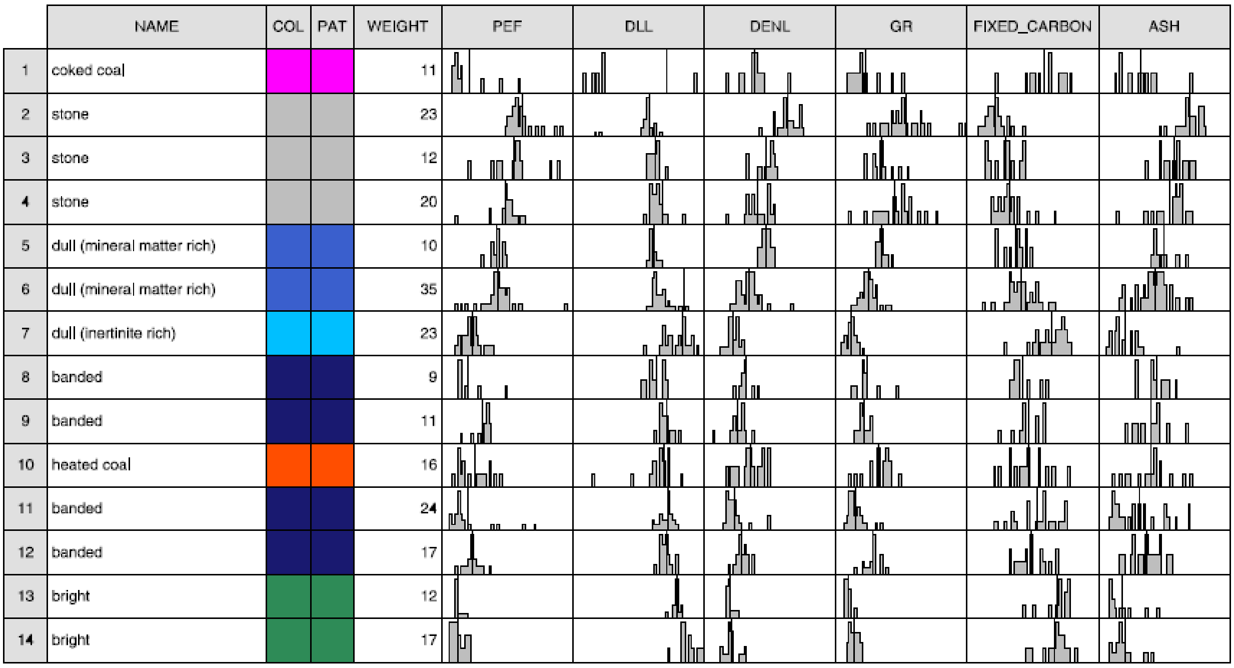

Figure 6 Interpreted electrofacies units and the distribution of wireline logs values presented as histograms.

PEF = photoelectric effect factor; DLL = deep laterolog resistivity; DENL = bulk density; GR = gamma ray; FIXED_CARBON = fixed carbon content; ASH = ash yield

2.3.3. MODEL PROPAGATION

The final step of electrofacies analysis is model propagation. Data clustering and electrofacies classification based on the reference set data are procedures which are required to "teach" neural network, or build a model, how to recognise electrofacies in a N-dimensional space; in turn, propagation is used to apply the obtained model on all application set data. Electrofacies propagation is achieved by KNN (K-nearest neighbour) method. It means that in order to assign value for any application set point, distance-weighted average of K nearest (in N-dimensional log space) values of reference data set are used. FNN propagation method assumes that the first nearest value is taken for propagation. This method has been chosen because FNN method applies no smoothing to the results and can capture heterogeneity. FNN propagation was performed for 10 wells from application set.

3. VALIDATION

In order to validate clustering results, Geolog™ produces a number of contingency tables to evaluate the amount of samples dropped to each particular cluster, or electrofacies, and their probabilities (See Appendix). A probability of 100% means that all samples belong only to that electrofacies; probability other than 100% means that those samples can also belong to another facies. The probability reflects the degree of uncertainty of clustering results. The higher the probability, the better is the result of clustering.

Comparing different contingency tables for the different methods (refer Table 2), it was observed that the probability is the highest for 14 (or 15 in case of method #3) clusters (see

Appendix). Contingency tables for all three different "methods" were compared and the highest probabilities were observed for method #2. This method was regarded as the most reliable one. The input set for method #2 included gamma ray, density, laterolog resistivity and PEF. As method #2 shows better results than method #3 (where laterolog resistivity was replaced by microresistivity), this suggests that microresistivity data (i.e. the image logs) does not improve clustering results. However, the PEF log does improve the electrofacies analysis more than method #1 or #3, as it can discriminate another low density facies that is interpreted as high inertinite dull rather than bright coal. This conclusion is demonstrated by contingency tables (see Appendix).

4. FIELD EXAMPLE

The results of the electrofacies coal lithotype characterisation were compared to the coal lithotype profiling results obtained by millimetre scale logging. It was done by comparison of the weighted average proportion of each electrofacies to the weighted average proportion of corresponding coal lithotypes obtained by millimetre scale logging results. The results of the analysis of 26 wells were summarised in tables and presented in a number of charts for comparison. Two wells (W2 and W21) were selected as examples. These wells were chosen as they represent almost the whole geological profile and most of plies of the major coal seams.

4.1. COAL LITHOTYPE STUDY

Charts on Figure 7 show the overall distribution of dull, banded and bright coal electrofacies plotted together with corresponding coal lithotypes obtained from millimetre scale logging results. The results of four different methods are presented in the chart:

- method #1 involves electrofacies analysis based on gamma ray, density, laterolog and microresistivity;
- method #2 includes gamma ray, density, laterolog and PEF;
- method #3 involves gamma ray, density, microresistivity and PEF;
- method #4 is the millimetre scale coal lithotype profiling which is based on visual characterisation of coal lithotypes in core samples.

Some observation can be made based on the charts. First of all, it can be seen that there is a good correlation between electrofacies analysis results and millimetre scale logging results, although some discrepancy exists (Figure 7). In most cases the quantitative difference between electrofacies results and manual coal lithotype profiling doesn't exceed 20 % (Figure 7). Method #2 which was regarded as the best method among all three electrofacies analysis methods shows the results that are close to those used for validation apart from only one exception which is consistent in all wells. The Vermont Upper seam (VU1) demonstrates higher percentage of bright coal electrofacies compared to millimetre scale logging results. The authors don't have a sufficient explanation of that phenomenon but it can possibly be explained by the constitution of Vermont Upper coal. The possible explanation is that the mineral constituent of the seam affect the wireline response which was not taken into account in the research and a subject for further study.

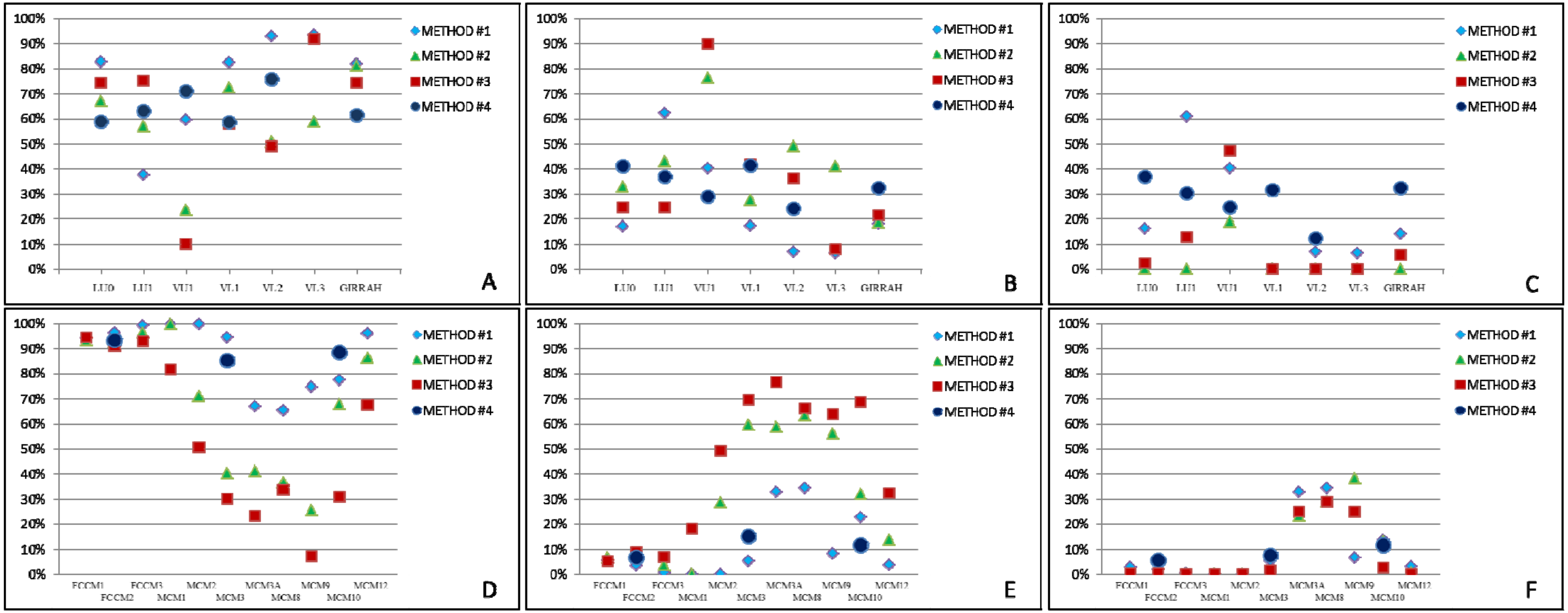

Figure 7 Proportion of different coal lithotypes obtained by different methods:

Horizontal axis shows coal seam; vertical axis represents the percentage of a given coal electrofacies for methods #1, #2 and #3, and coal lithotype for method #4;

Horizontal scale: LU = Leichhardt Upper; VU = Vermont Upper; VL = Vermont Lower; FCCM = Fort Cooper Coal Measures; MCM = Moranbah Coal Measures

A-C) Well W2: A) Dull coal; B) Bright + banded coal; C) Bright coal;

D-F) Well W21: D) Dull coal; E) Bright + banded coal; F) Bright coal

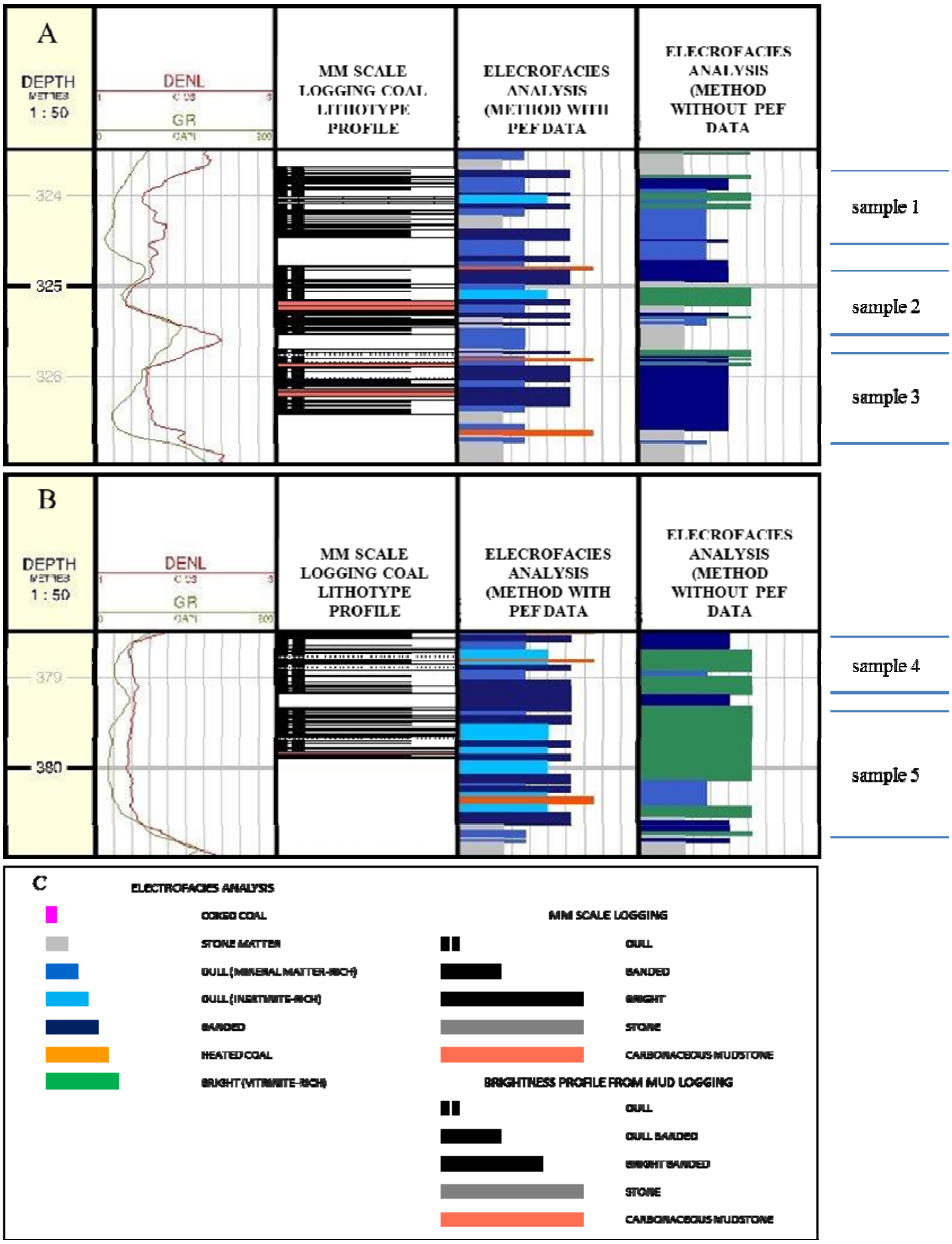

Figure 8 The comparison of coal lithotype profiling obtained by different methods: A-B) the measured depth presented on Track 1; Track 2 shows density and gamma ray; millimetre scale logging coal lithotype profile is plotted on Track 3 and Facimage results are on Track 4 (PEF, gamma ray, density, laterolog were used as the input data) and Track 5 (gamma ray, density, laterolog, microresistivity were used as the input data). Some depth shift exists for mud logging data.

Picture A shows LU0 (Leichhardt Upper rider seam)

Picture B shows LU1 (Leichhardt Upper main seam)

The legend is shown on picture C

Figure 8 demonstrates the comparison of brightness profile obtained from millimetre scale logging which data were used for the validation and electrofacies analysis results – both with PEF and without PEF.

One can observe that there is a similarity between the outcomes of different electrofacies analysis methods. Both methods seem to recognise dull and bright+banded coal but when PEF data are not involved, the analysis mistakenly determines dull inertinite-rich coal as bright coal, because it also has low density. Especially, it is observed for LU1 (Leichhardt Upper main seam) coal seam (Figure 8B).

A very good correlation is observed between millimetre scale logging data and electrofacies results. Thus, brightness profile of sample 1 (Figure 8A) demonstrates (from the top to the bottom) that bright and bright banded coal is followed by dull coal and then changes to bright and banded coal again. Electrofacies analysis (method which involves PEF data) results shows exactly the same distribution of dull and bright+banded coal.

4.2. INERTINITE-RICH COAL STUDY RESULTS

The weighted average proportion of inertinite-rich electrofacies was compared to the results of petrographic analysis data.

The results of inertinite-rich coal electrofacies analysis results were summarised and presented in a number of charts for comparison to maceral analysis data and for stratigraphic trends analysis. Chart demonstrates an increase of the amount of inertinite-rich dull coal electrofacies from the FCCM towards the top of RCM (the Leichhardt Upper seam) which corresponds to an increase of total inertinite observed from maceral analysis data (Figure 9). On a global scale, Leichhardt Upper is known as the coal seam which is rich in inertinite matter (Hunt, 1989), that is also in conjunction to the observations of this study.

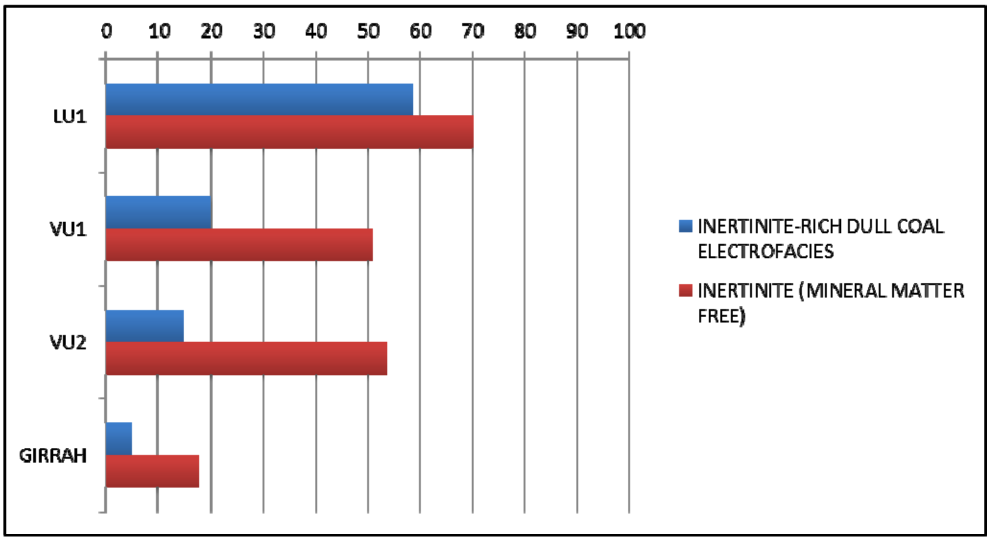

Figure 9 The comparison of inertinite-rich dull coal electrofacies (from electrofacies analysis) and inertinite mineral matter free (from maceral analysis) for well W15.
LU = Leichhardt Upper; VU = Vermont Upper

5. CONCLUSIONS

The methodology developed in this study was in response to a need to characterise coal seams in the absence of complete and contiguous coring, beyond the assumption that high density coal is dull and low density coal is bright and banded. The author's initial view was that image logs were required, but it was not the case. Three different sets of input data were used during the study:

4) Gamma ray, density, laterolog and microresistivity;
5) Gamma ray, density, laterolog and PEF;
6) Gamma ray, density, microresistivity and PEF.

When clustering is performed on these combinations of wireline logs, the objective is to group all data points into clusters based on proximity in N-dimensional data space, which in each of these cases N=4. The number of mathematical output clusters is based only on proximity or similarity of wireline log values, without any regard to geological meaning. The labelling or geological interpretation of the clusters usually results in the further grouping, which in this case was focussed on recognition end member coal lithotypes. The grouping and interpretation into these lithotypes were validated by the contingency tables and by comparison to millimetre scale logging data. The contingency tables were used as a measure of the goodness of fit, or the probability that all data points belongs to that particular lithotype or group.

It was observed that the second method provides the best clustering results and demonstrates the best match between electrofacies analysis data and millimetre scale logging results. This method might be suggested for further use to perform coal lithotype profiling of coal. Two hypotheses were tested in the course of research:

1) Microresistivity data can improve the electrofacies analysis results; and
2) PEF data can help to distinguish dull inertinite-rich coal.

The first hypothesis was rejected, while the second one was proved that is supported by contingency tables (see Appendix).

Based on the analysis and comparison of the results, a number of conclusions were made:

1) The most reliable method of coal lithotype profiling using electrofacies analysis amongst tested involves gamma ray, density, laterolog resistivity and PEF;
2) PEF can help recognise inertinite-rich coal and this fact is proved by analysis of contingency tables, millimetre scale logging results and maceral analysis data;
3) Being included into input dataset, microresistivity doesn't significantly improve the results of electrofacies analysis;
4) Coked coal is very well recognised by all electrofacies methods;
5) Vermont Upper coal seam demonstrates a discrepancy between electrofacies analysis and millimetre scale logging results. The discrepancy was explained by the mineral matter composition of the coal seam which was not taken into account in this research.

The coal rank study is an interesting problem and can potentially be solved by exploitation of sonic data. This problem left out of focus of this research due to a lack of sonic data.

To sum all, in this paper an automated coal lithotypes profiling algorithm has been presented. This method is based on wireline geophysical logs data and doesn't require any predefined cut-offs or assumptions, it's based on raw data analysis only and, thus, it's immune to interpreter bias. The results of automated coal lithotype profiling were validated by millimetre scale logging data and analysed. Some recommendations were made about which wireline log data are appropriate for coal lithotype profiling. The problem of inertinite-rich dull coal was also successfully solved during the course of the research and the solution is explained in the paper.

ACKNOWLEDGEMENT

This paper utilised opportunistic log and coal characterisation data as part of a study into the variability in coal quality for Rangal Coal Measures. The Australian Coal Association Research Program (ACARP) and the Vale Coal Geosciences Program are thanked for their support; Arrow Energy for access to their data. The authors are grateful to Philippe Rabiller, Shin-Ju Ye and Peter Boles for their keen input on several technical issues. The authors also thank Sarah Collins and Matthias Klawitter who conducted brightness profiling of the core, and these data were utilized in this study. The authors are grateful to Sandra Rodrigues for being the reviewers of the paper.

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APPENDIX
CONTINGENCY TABLES

APPENDIX 1
METHOD #1 (GAMMA RAY, DENSITY, DEEP LATEROLOG RESISTIVITY, MICRORESISTIVITY)
APPENDIX 1 (METHOD#1).xlsx

APPENDIX 2
METHOD #2 (GAMMA RAY, DENSITY, DEEP LATEROLOG RESISTIVITY, PEF)
APPENDIX 2 (METHOD#2).xlsx

APPENDIX 3
METHOD #3 (GAMMA RAY, DENSITY, MICRORESISTIVITY, PEF)
APPENDIX 3 (METHOD#3).xlsx

5. PAPER 3 Electrofacies analysis using high-resolution wireline geophysical data as a proxy for inertinite-rich coal distribution in Late Permian coal seams, Bowen Basin.

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Submitted to International Journal of Coal Geology, accepted for publication.

Alexandra Roslin (MPhil candidate) performed the study, performed the analysis of data distribution, prepared maps, figures and tables, wrote manuscript;
Joan S. Esterle (Principal MPhil supervisor) reviewed, discussed and edited manuscript.

The third part of the research was focused on analysis of different coal lithotypes (in particular, inertinite-rich dull coal) distribution over the Northern Bowen Basin. Coal electrofacies obtained from the electrofacies analysis was used as a proxy for corresponding coal lithotypes. The distribution of coal lithotypes was analysed stratigraphically and geographically. The following observations were made in the course of the research:

1) Rangal Coal Measures (RCM) is characterised by an increase of dull facies towards the top of coal measures and dull coal is mostly presented by inertinite-rich dull coal;
2) Fort Cooper Coal Measures (FCCM) contains a large amount of mineral matter rich dull coal and stone matter, and the FCCM Upper is mostly characterised by mineral matter rich dull coal while the FCCM Lower generally consists of stone matter;
3) The amount of dull and bright+banded matter is nearly equal in FCCM and RCM;
4) The amount of inertinite-rich dull coal is increased in the northern direction and towards the top of the Late Permian coal.

The third paper examines in details stratigraphical and geographical distribution of coal lithotypes and discusses possible explanations of the observed distribution.

To sum all, it was observed that:

1) The decrease of inertinite rich dull coal towards the south is suggested to be related to the increase of subsidence rate in that direction. It's not possible to explain such geographical distribution of inertinite-rich dull coal by palaeoclimatic changes that took place in the study area as no evidence that variation in the Permian flora might have caused such distribution of coal types was found in the course of research. Thus, it was suggested that regional tectonic subsidence can be considered to be the major factor controlling peat accumulation and preservation and, in turn, coal type.
2) The increase of inertinite-rich coal towards the top of the Late Permian coal measures correlated to strong climatic signatures of temperature, carbon dioxide and atmospheric oxygen content. It was suggested that the observed stratigraphical distribution is explained by global climate changes which took place near the boundary between Late Palaeozoic Era and Early Triassic Period.

ELECTROFACIES ANALYSIS USING HIGH-RESOLUTION WIRELINE GEOPHYSICAL DATA AS A PROXY FOR INERTINITE-RICH COAL DISTRIBUTION IN LATE PERMIAN COAL SEAMS, BOWEN BASIN

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ABSTRACT

This paper examines the stratigraphical and geographical distribution of coal composition in main Bowen Basin Late Permian coal measures, using coal electrofacies as a proxy for inertinite maceral group content. At a basin scale, inertinite group macerals are known to increase upwards at the end of the Permian as aridity increases in tandem with increasing influx of sediment into the subsiding foreland basin. Data for this research comes from some 26 wells in the northern part of Bowen Basin. The companion paper Roslin and Esterle (2015, in review) introduced the methodology which is based on electrofacies analysis and uses high-resolution wireline data (including microresistivity from Compact Micro-Image (CMI) tool and Photoelectric Factor (PEF) data in addition to conventional gamma ray, density and laterolog resistivity to obtain coal electrofacies. The validation of the methodology was performed by comparison of the weighted average proportion of coal electrofacies to the weighted average proportion of the corresponding coal lithotypes obtained from millimetre scale logging and to the percentage gathered from maceral content analysis. This methodology and its validation are explained in more details in the companion paper. The former also substantiates the choice of input wireline logs. For the study explained in the current paper, the weighted average proportion of dull inertinite-rich coal electrofacies (independent of rank and heat effect) for different seams was analyse for stratigraphic and geographic distribution in the Late Permian seams in the northern part of the Bowen Basin.

From the base upward, the main Late Permian coal measures are the Moranbah (MCM), Fort Cooper (FCCM) and Rangal (RCM) and their stratigraphic equivalents across the basin. Within these measures laterally traceable seams and tuffs provide stratigraphic marker horizons. The proportion of inertinite-rich dull coal electrofacies increases in the RCM, with specific thick and merged seams showing distinctive electrofacies signature. Within the study area, the coal measures and individual seams split from north to south, reflecting increased subsidence and sediment influx into basin depocentres. As the seams split, the proportion of inertinite-rich dull coal electrofacies decreases in the tested sample set.

KEYWORDS

Bowen Basin, Electrofacies analysis, Wireline logs, Coal lithotype, Inertinite-rich coal, Coal distribution

1. INTRODUCTION

Many studies (summarised in Diessel, 2010) have noted compositional changes in coal maceral constitution in response to vegetational succession and peat degradation as water tables respond to changing depositional setting and climate. In the Late Permian coals in the Bowen Basin, Australia, the proportion of inertinite group macerals increases up section towards the Triassic boundary, and this is interpreted to respond to increasing aridity resulting in dropping water table, increased peat degradation and frequency of peat fires (Diessel, 2010). Whether this stratigraphic change occurs everywhere, independent of basin subsidence control on water table, or shows regional changes has not been fully explored for the Bowen Basin. Hunt and Smyth (1989) suggested that basins and/or areas of low accommodation would accumulate relatively thick and non-split coals, with abundant inertinite group macerals composition. Areas of higher subsidence would develop split coals intercalated with thick clastic influx, and this increased subsidence would contribute to more anoxic conditions and enhanced preservation resulting in vitrinite-rich coals.

The authors of this paper examined the spatial variability in coal electrofacies as a proxy for maceral composition, which is reflected megascopically in the brightness profile. The weighted average proportion of inertinite-rich dull coal electrofacies was taken from electrofacies analysis to examine the stratigraphical and geographical distribution of inertinite-rich dull coal. Electrofacies analysis of wireline logs can eliminate bias that results from sampling and testing the main seams only. This approach does not rely on the availability of coal samples, and provides an opportunity to exploit currently underutilised borehole data. The geophysical methodology underpinning the research is explained only briefly, and is set out in great detail in the companion paper (Roslin and Esterle, 2015, in review).

2. BACKGROUND

2.1. GEOLOGICAL SETTING

The Bowen Basin (Figure 1) is a large, intracontinental coal-bearing basin that developed in eastern Queensland during the Early Permian – Middle Triassic as the northern part of the much larger basin system that includes the Gunnedah and Sydney Basins in the New South Wales (Totterdell et al. 2009). From the Middle to Late Devonian until the Cretaceous, eastern Australia was part of eastern Gondwana. A west-dipping subduction zone influenced the active, convergent plate margin, which was located eastwards to the basin system. This resulted in the development of the Early Permian to Middle Triassic Bowen-Gunnedah-Sydney Basins complex and the Early Jurassic to Early Cretaceous Surat Basin in response to a series of interplate events in this backarc tectonic system (Korsch & Totterdell, 2009a; Korsch et al., 2009). The event, which initially formed the Bowen and Gunnedah Basin in the Early Permian, is called the Denison Event. During the Late Permian the extension phase changed to a contraction phase followed by west oriented thrusting from the early Late Permian to Middle Triassic at the New England Orogen at the eastside of the basin system. This caused the foreland loading and subsidence in the Bowen and Gunnedah Basins along with the basin fill (Korsch et al., 1998, 2009; Holcombe et al., 1997).

The northern Bowen Basin comprises three coal measures of the Blackwater Group, which are termed the Moranbah Coal Measures (MCM), Fort Cooper Coal Measures (FCCM) and Rangal Coal Measures (RCM) (from bottom to top) (Figure 1 and 2). These coal measures are interpreted to have formed in the Late Permian on generally prograding alluvial to coastal environments in response to foreland crustal loading and propagation of thrust sheets during the Hunter-Bowen orogenic event (Holcombe et al., 1997; Fielding et al, 1993). Base level fluctuations occurred periodically, resulting in marine incursions and/or lacustrine conditions that punctuated fluvial progradation. Within this, coal seams developed during periods of relative stability where peat accumulation kept pace with subsidence. The Late Permian peat mires accumulating in the high latitudes also experienced the global climatic shift to a drier Triassic climate (Hunt, 1989). These factors influenced the architecture, composition and rank of the coals.

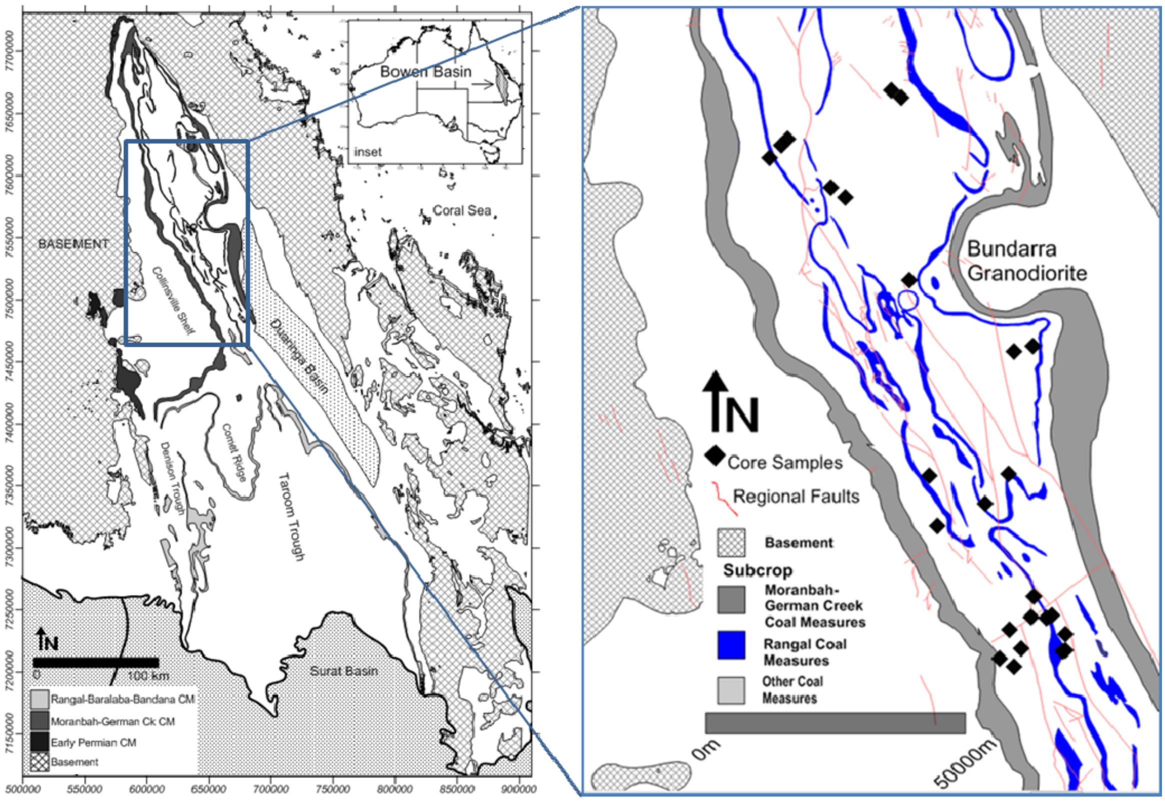

Figure 1 Location map of the study area within a) simplified map of economic coal measures in the Bowen Basin, with inset of location within Australia and b) close up showing location of core samples with wireline logs. Note that the Fort Cooper Coal Measures are not shown. Compiled from IRTM shape files www.irtm.qld.gov.au

COAL MEASURE	SEAM	MARKER
RANGAL COAL MEASURES	PHILLIPS	PH1
		PH2
	LEICHHARDT RIDER	LU0
	LEICHHARDT UPPER	LU1
		LU2
	LEICHHARDT LOWER	LL1
		LL2
	VERMONT UPPER	VU1
		VU2
		VU3
		VU4
FORT COOPER COAL MEASURES	VERMONT LOWER	VL1
		VL2
		VL3
	GIRRAH	GIRRAH
unnamed FORT COOPER - FAIRHILL SEAMS		FCCM1
		FCCM2
		FCCM3
		FCCM4
		FCCM5
MORANBAH COAL MEASURES		MCM1
		MCM2
		MCM3
		MCM3A
		MCM6
		MCM8
		MCM9
		MCM9A
		MCM10
		MCM11
		MCM12
		MCM13
		MCM14
		MCM15

Figure 2 Stratigraphic framework for the study area. Seam names and markers used for this study only.

3. METHODOLOGY

The study which is described in this paper has used a novel method for coal characterisation (Roslin and Esterle, 2015, in review), based on electrofacies analysis of wireline geophysical logs. An electrofacies is an interval defined from wireline logs, through which there are consistent or consistently changing log responses and characteristics, sufficiently distinctive to separate it from other electrofacies (Rider and Kennedy, 2013). Electrofacies analysis implies dividing the whole geological profile into a finite number of electrofacies and geologically classifying them.

Electrofacies partitioning is performed by a clustering procedure and classification is done by the interpreter based on knowledge of the relationship between wireline log responses and coal properties (Roslin and Esterle, 2015, in review). The clustering method which was used for the research is MRGC (Multi-Resolution Graph-based Clustering). This automatic clustering method is based on the analysis of log data distribution and does not require any predefined cut-offs or assumptions about number of electrofacies. Classification is performed by the analysis of wireline logs values distribution trends against physical coal properties trends such as yield, maceral composition or lithotype composition where available.

For the purpose of this study, 26 wells were selected for electrofacies analysis and the following wireline measurements were used: gamma ray, density, laterolog resistivity, photoelectric factor (PEF) and microresistivity, which were processed from borehole electrical imager data (Roslin, 2015). Data were divided into two datasets – reference and application ones – and the reference dataset was exploited as an input dataset for electrofacies analysis. The reference dataset contained 16 wells which had the full collection of wireline geophysical data (including borehole electrical images), maceral analysis data and coal proximate data; the application dataset included the rest of the wells. The reference dataset logs were implemented for electrofacies analysis which was performed in two steps. Firstly, clustering procedure was performed in Facimage^{TM} module of Geolog^{TM} software (Paradigm package).

Clustering was automatically run three times with different inputs:

1) Gamma ray, density, deep laterolog resistivity, microresistivity;
2) Gamma ray, density, deep laterolog resistivity, PEF;
3) Gamma ray, density, microresistivity, PEF.

Validation of the clustering was performed by the analysis of the contingency tables and demonstrated that the best results were provided by the second method (Roslin and Esterle, 2015, in review). The results of this method were used in this paper.

Classification of the clustering results was performed by the authors based on the analysis of the distribution trends from the wireline log values (Roslin and Esterle, 2015, in review): for gamma ray, density PEF and resistivity values and comparison to trends in fixed carbon content and ash yield. Generally, for the studied coal, an increase of gamma ray and density, supported by an increase of ash yield, was correlated to an increase of “dullness” of coal. Examination of resistivity logs trends helped determine the coked coal electrofacies and PEF logs distribution distinguished an inertinite-rich dull coal electrofacies: this electrofacies demonstrated low gamma ray, low density, low ash values and resembled the bright coal electrofacies, but was different to the latter by slightly high PEF values.

The results of the electrofacies analysis were propagated on 10 wells from the application dataset. Electrofacies propagation is commonly achieved by the KNN (K-nearest neighbour) method. It means that in order to assign a value for any application set point, distance-weighted averages of K nearest (in N-dimensional log space) values of reference data set are used. The authors used the FNN propagation method that assumes that the first nearest value is taken for propagation (Ye and Rabiller, 2001). In addition, the FNN method applied no smoothing to the results and provided a higher resolution suitable for highly banded coal in this study.

In order to validate the results of the electrofacies analysis classification, the weighted average proportion of coal electrofacies were compared to those obtained from the millimetre scale logging (method described in Esterle et al., 2002) and the discrepancy between the results generally did not exceed 20 per cent apart from the Vermont Upper coal seam for which the discrepancy was up to 50 per cent. It was suggested that such a high discrepancy was caused by the composition of the Vermont Upper coal seam mineral matter which was not taken into account in the course of the study.

Each electrofacies (or e-facies) was correlated to a particular coal lithotype as a proxy for coal composition as follows: stone, mineral matter rich dull, inertinite-rich dull, banded, bright, coked and heat affected coal e-facies. Stone e-facies represents non-coal rock and heated e-facies represents dull coal which had undergone some thermal influence but not sufficient enough to become coked coal. The distribution of the inertinite-rich dull coal e-facies was investigated in this paper.

26 wells were used for the study and the results of two wells were chosen to illustrate stratigraphical distribution of coal e-facies. Wells W2 and W21 were chosen for two reasons: first of all, they together represented almost the whole stratigraphic profile of the studied area and secondly, these wells were used in the previous paper which focused on a detailed explanation of the methodology. Maps were built from the weighted average proportions of coal electrofacies for each of the coal seams using proportional-to-the-distance interpolation algorithm in Surfer^{TM}. This method was utilised as it shown the best results for small number of wells (26 wells) dispersed over a large area (Northern Bowen Basin, Figure 3).

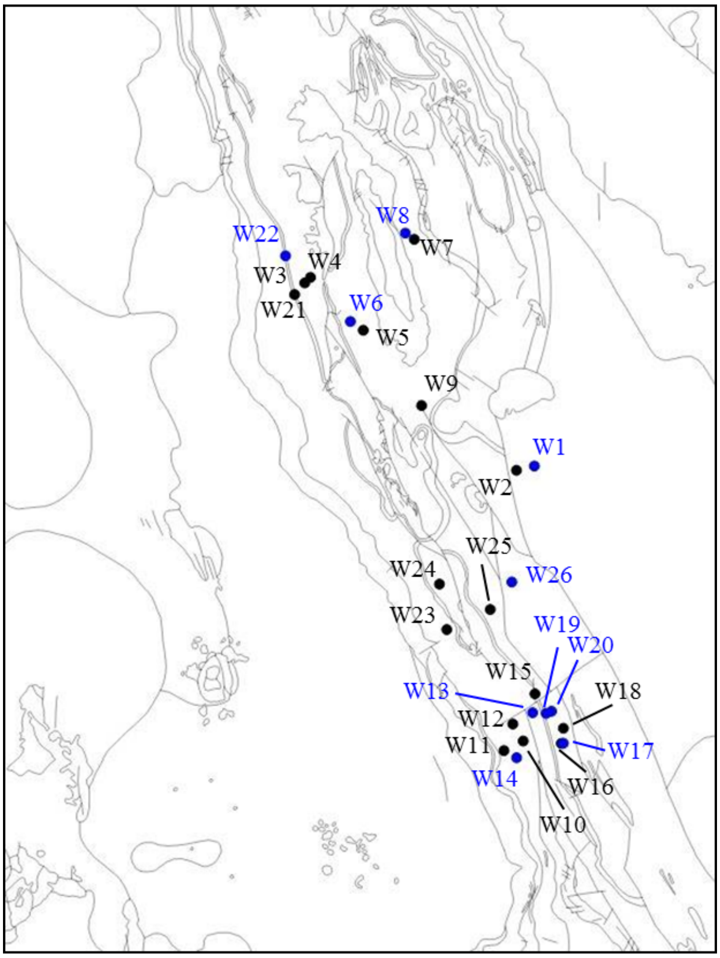

Figure 3 Map showing the distribution of wells with wireline logs used in the study, relative to the outline of the Central and Northern areas of the Northern Bowen Basin. The reference dataset is highlighted in black, the application – in blue

4. RESULTS

The results of the electrofacies analysis are presented in a form of coal lithotype profile where each electrofacies corresponds to each individual coal lithotype according to the classification. The weighted average proportions of each coal electrofacies were calculated and summarised in tables 1 and 2.

In this research, coal electrofacies are used as proxies for the corresponding coal lithotypes but one should understand that electrofacies analysis is based on the wireline geophysical logs characterisation of the formation and represents the indirect method of rock characterisation. Thus, the weighted average proportion of inertinite-rich dull coal electrofacies does not provide the researcher with the percentage of inertinite matter in coal but allows estimation of an increase or decrease in the amount of this coal type.

Table 1 The weighted average proportion of coal electrofacies for each coal seam for well W2.

FORMATION	SEAM	DEPTH FROM	DEPTH TO	STONE	DULL (MINERAL)	DULL (INERTINITE)	BANDED	BRIGHT	HEATED	COKED	DULL (TOTAL)	BANDED + BRIGHT	BRIGHT
1	2	3	4	5	6	7	8	9	10	11	12	13	14
RCM	LU0	323.68	326.72	15.6%	41.7%	6.6%	32.9%	0.0%	3.3%	0.0%	67.2%	32.9%	0.0%
	LU1	378.47	380.80	4.3%	17.2%	30.1%	43.1%	0.0%	5.4%	0.0%	56.9%	43.1%	0.0%
	VU1	416.81	418.93	2.4%	7.1%	10.6%	57.5%	18.9%	3.5%	0.0%	23.6%	76.4%	18.9%
FCCM	VL1	419.75	422.37	52.5%	9.5%	0.0%	27.5%	0.0%	10.5%	0.0%	72.5%	27.5%	0.0%
	VL2	436.44	436.79	14.5%	36.3%	0.0%	49.1%	0.0%	0.0%	0.0%	50.9%	49.1%	0.0%
	VL3	437.11	437.71	12.3%	46.6%	0.0%	41.1%	0.0%	0.0%	0.0%	58.9%	41.1%	0.0%
	GIRRAH	492.09	504.79	54.1%	15.9%	6.5%	18.9%	0.0%	4.5%	0.0%	81.1%	18.9%	0.0%

Table 2 The weighted average proportion of coal electrofacies for each coal seam for well W21.

FORMATION	SEAM	DEPTH FROM	DEPTH TO	STONE	DULL (MINERAL)	DULL (INERTINITE)	BANDED	BRIGHT	HEATED	COKED	DULL (TOTAL)	BANDED + BRIGHT	BRIGHT
1	2	3	4	5	6	7	8	9	10	11	12	13	14
FCCM	FCCM1	359.28	404.74	55.55%	34.59%	0.33%	6.82%	0.00%	2.69%	0.00%	93.17%	6.82%	0.00%
	FCCM2	422.86	454.87	61.30%	25.69%	0.70%	7.50%	0.00%	4.76%	0.00%	92.46%	7.50%	0.00%
	FCCM3	486.78	495.09	87.87%	5.82%	0.00%	3.61%	0.00%	2.71%	0.00%	96.39%	3.61%	0.00%
MCM	MCM1	520.17	521.68	87.86%	2.22%	0.00%	0.00%	0.00%	9.95%	0.00%	100.00%	0.00%	0.00%
	MCM2	543.64	544.86	30.81%	19.84%	0.00%	28.76%	0.00%	20.54%	0.00%	71.19%	28.76%	0.00%
	MCM3	601.93	603.44	3.32%	33.65%	0.00%	59.68%	0.00%	3.32%	0.00%	40.28%	59.68%	0.00%
	MCM3A	603.62	605.03	0.00%	16.25%	12.48%	35.66%	23.18%	12.48%	0.00%	41.20%	58.83%	23.18%
	MCM8	606.56	607.43	8.64%	25.12%	0.00%	34.57%	28.80%	2.88%	0.00%	36.65%	63.37%	28.80%
	MCM9	662.31	666.81	2.78%	4.45%	17.23%	17.79%	38.35%	1.11%	18.34%	25.57%	56.14%	38.35%
	MCM10	700.54	703.19	16.06%	20.59%	0.00%	18.90%	13.23%	31.18%	0.00%	67.83%	32.13%	13.23%
	MCM12	707.05	710.15	55.72%	13.62%	1.62%	12.92%	0.81%	15.34%	0.00%	86.30%	13.73%	0.81%

Tables 1 and 2 illustrate changes within and between coal measures. The FCCM (Table 2) contains a large amount of stone e-facies and coal electrofacies are mostly represented by mineral matter-rich coal e-facies with a minor proportion of banded coal e-facies and only small amount of inertinite-rich dull coal e-facies. The Girrah seam (Table 1) is characterised by high amount of stone and mineral matter rich dull coal e-facies. Bright coal e-facies is not observed but banded coal e-facies becomes more abundant compared to the FCCM coal seams. The Vermont Lower seam contains a large amount of stone, mineral matter rich dull coal e-facies and minor proportion of banded coal e-facies. Mineral matter rich dull coal e-facies is presented mostly in the middle of seam but it is dominated by stone e-facies in the upper part of the seam.

Above the Vermont Lower is a regional marker horizon, the Yarabee Tuff that demarcates the change into the RCM. The Vermont Upper seam demonstrates the presence of bright coal e-facies. The amount of inertinite-rich dull coal electrofacies dramatically increases in the Leichhardt Upper seam. Stone and mineral matter-rich dull coal electrofacies are presented in small quantities if any in the Leichhardt Upper and Vermont Upper. In turn, the Leichhardt Upper rider (LU1) seam is dominated by mineral matter-rich dull coal e-facies with a small amount of banded coal and stone electrofacies. Inertinite-rich dull coal electrofacies composes only a small portion of the rider seam.

In order to compare stratigraphic and regional changes in the electrofacies of the different seams and coal measures, a number of charts and maps were built based on the weighted average proportions of coal electrofacies.

4.1. STRATIGRAPHICAL DISTRIBUTION

The charts which are shown on Figures 4 and 5 represent the stratigraphical distribution of coal electrofacies. Figure 4 illustrates the distribution of coal electrofacies for well W2 and such distribution is typical of the RCM and Upper FCCM (the Vermont Lower and Girrah seams) in the studied wells. The following observations were made based on these charts.

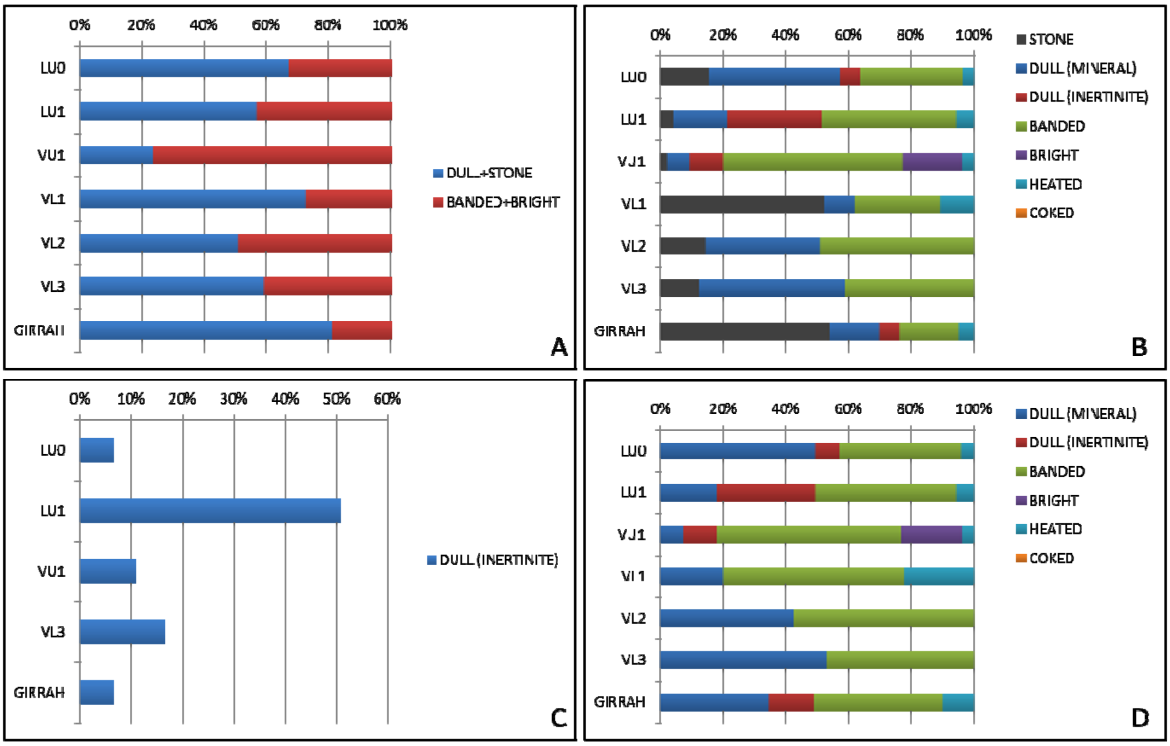

Figure 4 Proportion of different coal electrofacies (Well W2):
Horizontal axis shows the percentage of coal electrofacies; vertical axis represents the coal seam
Vertical scale: LU = Leichhardt Upper; VU = Vermont Upper; VL = Vermont Lower

A) Proportion of dull + stone and bright + banded;
B) Proportion of stone, mineral matter-rich dull, inertinite-rich dull, banded, bright, heated and coked coal;
C) Proportion of inertinite-rich dull coal out of all electrofacies;
D) Proportion of stone-free mineral matter-rich dull, inertinite-rich dull, banded, bright, heated and coked coal

Except for the single thin and stony VL1 seam, there is an obvious trend from the FCCM seams to the RCM seams. Dull coal electrofacies are abundant in the Girrah seam, decline upwards throughout the Vermont Lower seams and then increase again in the Leichhardt seams. Among the dull coal electrofacies, those within the Girrah and Vermont seams are characterised by mineral matter rich dull coal and stone e-facies, whereas the amount of inertinite-rich dull coal e-facies increases in the RCM within the Vermont Upper (VU) and especially the Leichhardt Upper main seam (LU1) which is characterised by the highest amount of inertinite-rich dull coal electrofacies among all seams. The Leichhardt Upper rider seam (LU0) reverts to the mineral matter rich dull coal e-facies at the top of the RCM. More specifically:

1) The RCM is characterised by an increase of dull coal e-facies towards the top of the unit while the amount of dull coal e-facies is relatively constant throughout the whole Upper FCCM (the Vermont Lower and Girrah coal seams). The overall amount of dull and bright + banded (a sum of bright and banded) coal electrofacies is quite similar between the RCM and Upper FCCM.
2) Although the charts show that the overall amount of dull coal electrofacies is similar for the RCM and FCCM, the character of this dull coal e-facies can be different for those two coal measures: the RCM contains a significant amount of inertinite-rich dull coal e-facies, while the FCCM is mostly characterised by mineral matter rich dull coal e-facies which stays quite constant throughout the whole Upper FCCM
3) The charts demonstrate that in addition to mineral matter rich dull coal e-facies, the FCCM contains considerable amount of mineral matter (stone electrofacies), as opposed to the RCM which comprise only a little amount of mineral matter which is associated mostly with the uppermost RCM coal seam (LU0).
4) Bright coal e-facies was recognised in the Upper Vermont coal seam only (the lowermost RCM seam); other coal seams are mostly characterised by banded coal e-facies. The authors do not have sufficient explanation for that fact but assume that the composition of the Vermont Upper coal seam mineral matter can affect wireline response in a manner that was not taken into account in this research.

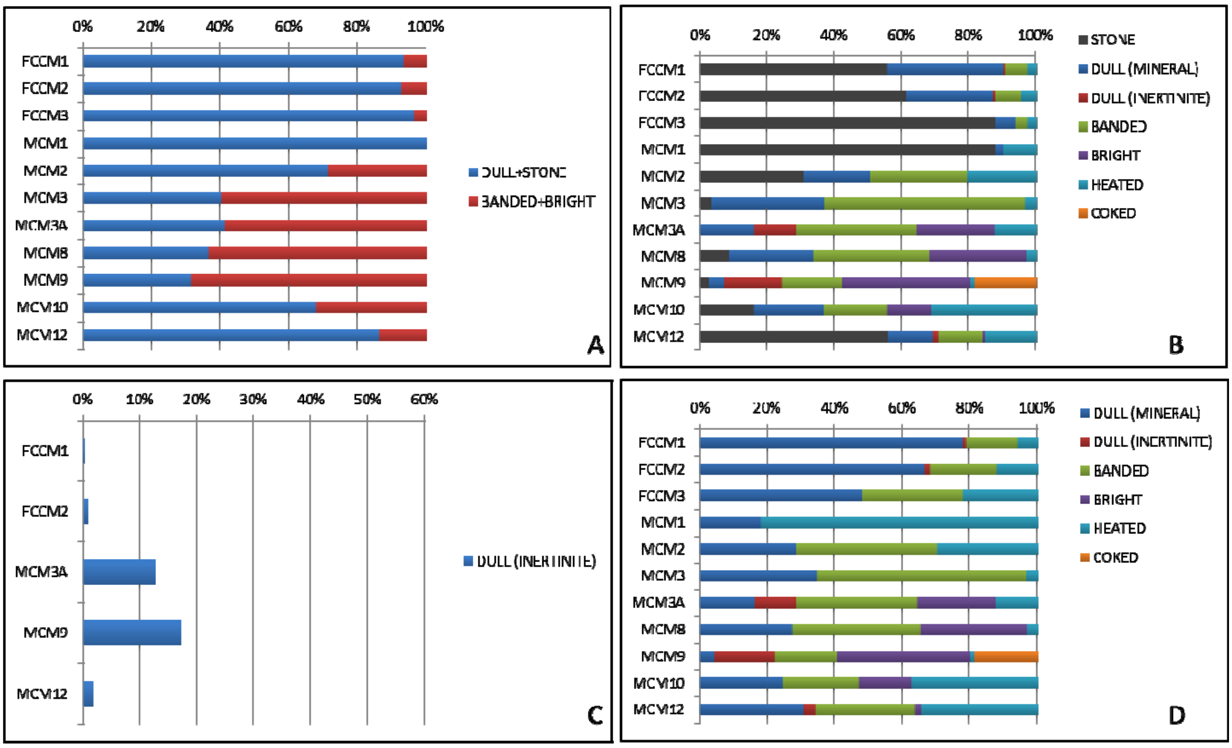

Figure 5 Proportion of different coal electrofacies (Well W21):

Horizontal axis shows the percentage of coal electrofacies; vertical axis represents the coal seam

Vertical scale: FCCM = Fort Cooper Coal Measures; MCM = Moranbah Coal Measures

A) Proportion of dull + stone and bright + banded;

B) Proportion of stone, mineral matter-rich dull, inertinite-rich dull, banded, bright, heated and coked coal;

C) Proportion of inertinite-rich dull coal out of all electrofacies;

D) Proportion of stone-free mineral matter-rich dull, inertinite-rich dull, banded, bright, heated and coked coal

Figure 5 shows the distribution of coal electrofacies for well W21 which is commonly observed in the FCCM Lower and the MCM over the studied area. The proportion of stone e-facies in the MCM seams is variable but declines in the middle part of the MCM before increasing into the upper part of the MCM and the FCCM Lower seams which remain dull throughout. The amount of mineral matter rich dull coal electrofacies is relatively constant throughout the MCM seams decreasing towards the top of the MCM / bottom of the FCCM Lower where it is replaced by abundant stone e-facies, and then, increasing again towards the top of the FCCM Lower. Conversely, the MCM seams contain abundant banded and bright coal e-facies which decreases in the FCCM Lower. Inertinite-rich dull coal electrofacies is presented in moderate quantities in the middle MCM seams but decreases towards the FCCM Lower. Inertinite-rich dull coal e-facies in the FCCM Lower is present in small quantities if any. In more details:

1) The MCM comprises small amounts of stone e-facies and mineral matter rich dull coal e-facies which are mostly in the uppermost and the lowermost parts of the MCM. Dull coal e-facies are presented by inertinite-rich dull coal e-facies.

2) Stone-free chart shows that the sum of bright and banded coal e-facies of the FCCM Lower is comparable to that of the RCM, but much smaller than the sum of bright and banded coal e-facies of the MCM.
3) Bright coal e-facies is not distinguished in the FCCM Lower but it is presented in high quantities in the MCM. Comparing the MCM and RCM, it can be noticed that the former contains more bright coal e-facies.
4) Coked coal electrofacies was observed in small quantities in the MCM.

4.2. GEOGRAPHICAL DISTRIBUTION

Amongst all coal electrofacies, the weighted average proportion of the inertinite-rich dull coal e-facies was taken to build some maps that might reflect the geographical distribution of inertinite-rich dull coal (Figures 6, 7, 8). Those maps were analysed and some conclusions were made:

1) In the MCM coals in general, the inertinite-rich dull coal e-facies does not exceed 20 per cent in the sample set, but does show a general decrease from the north to south in the study area.
2) In the FCCM Lower coals the amount of inertinite-rich dull coal e-facies is low overall, less than 5 per cent, but with a minimum in the central part of the studied area and increase to the north-east and south-east.
3) The Girrah seam of the FCCM Upper is still poor in inertinite-rich dull e-facies, less than 10 per cent, but also shows a central minimum with an increase to the north-east and south-east.
4) The Vermont Lower seam (the FCCM Upper) demonstrates an obvious increase of inertinite-rich coal e-facies towards the north and the percentage of inertinite-rich e-facies is as high as 25 per cent.
5) The Vermont Upper seam, which by definition is a part of the lower RCM, shows the same trend but the amount of inertinite-rich dull coal electrofacies increases up to 40 per cent.
6) The Leichhardt Upper generally demonstrates the same tendency of increased inertinite-rich coal e-facies towards the north but the percentage of inertinite-rich coal electrofacies raises up to a high of 60 per cent.

4.3. COAL MEASURES THICKNESS

In order to estimate the thickness of the main coal seams which is related to the subsidence rate, open file data from Queensland Petroleum Exploration Dataset (QPED) were interpreted and the RCM thickness was built (Figure 9). FCCM and MCM were intersected by few wells, thus thickness maps for those intervals were not built. The total thickness of the RCM was defined by the top seam (Phillips or Leichhardt) and the Yarabee Tuff. Map was built using proportional-to-the-distance interpolation algorithm in Surfer™ and the data for 83 wells were used. Map clearly demonstrates an increase of RCM thickness towards the south of study area.

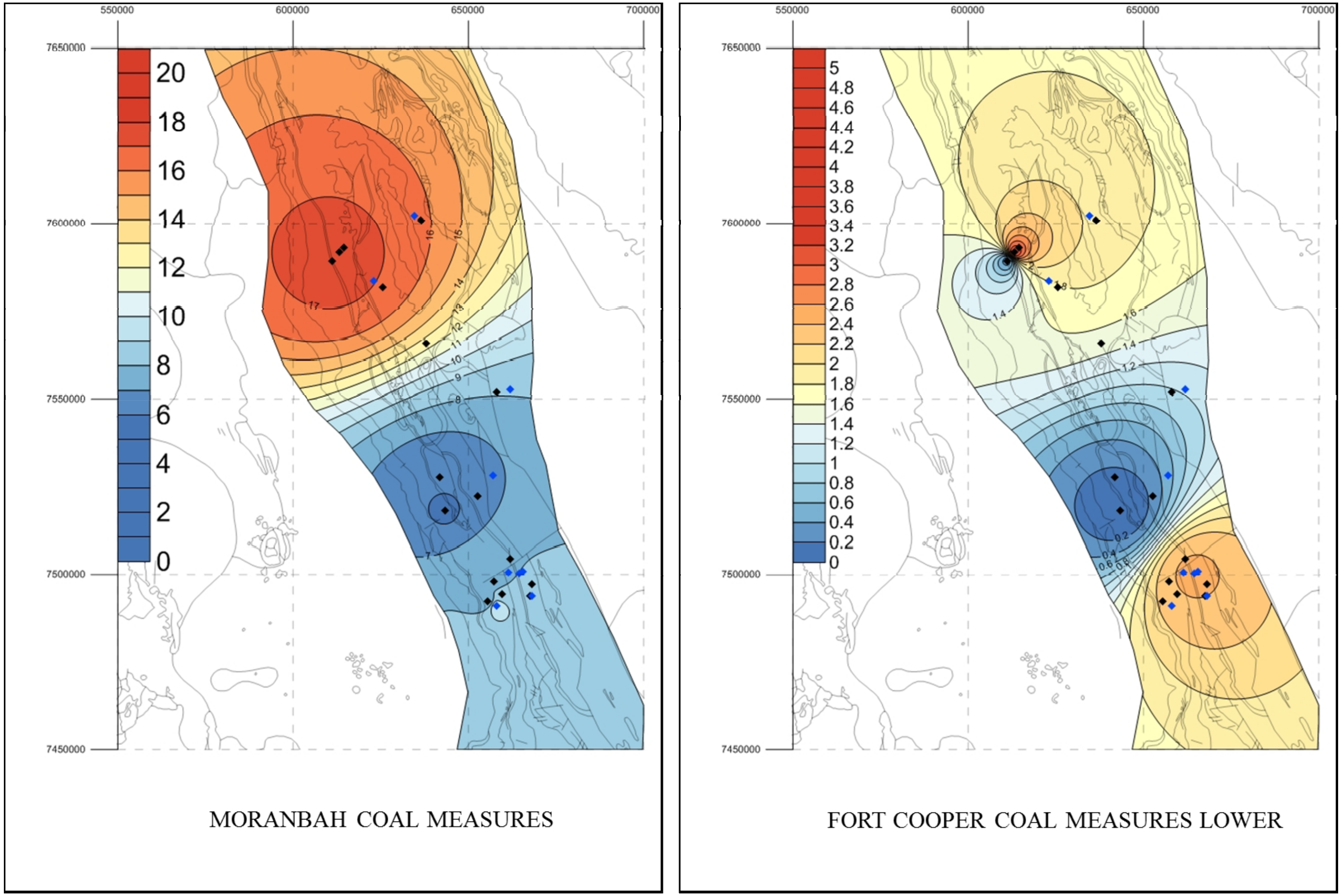

Figure 6 Geographical distribution of inertinite-rich dull coal electrofacies in different coal seams: the Moranbah Coal Measures and Fort Cooper Coal Measures. Scale represents the weighted average proportion of inertinite-rich dull coal electrofacies expressed in per cent. Red colour represents the high amount of inertinite-rich dull coal electrofacies, blue colour – low amount of inertinite-rich dull coal electrofacies

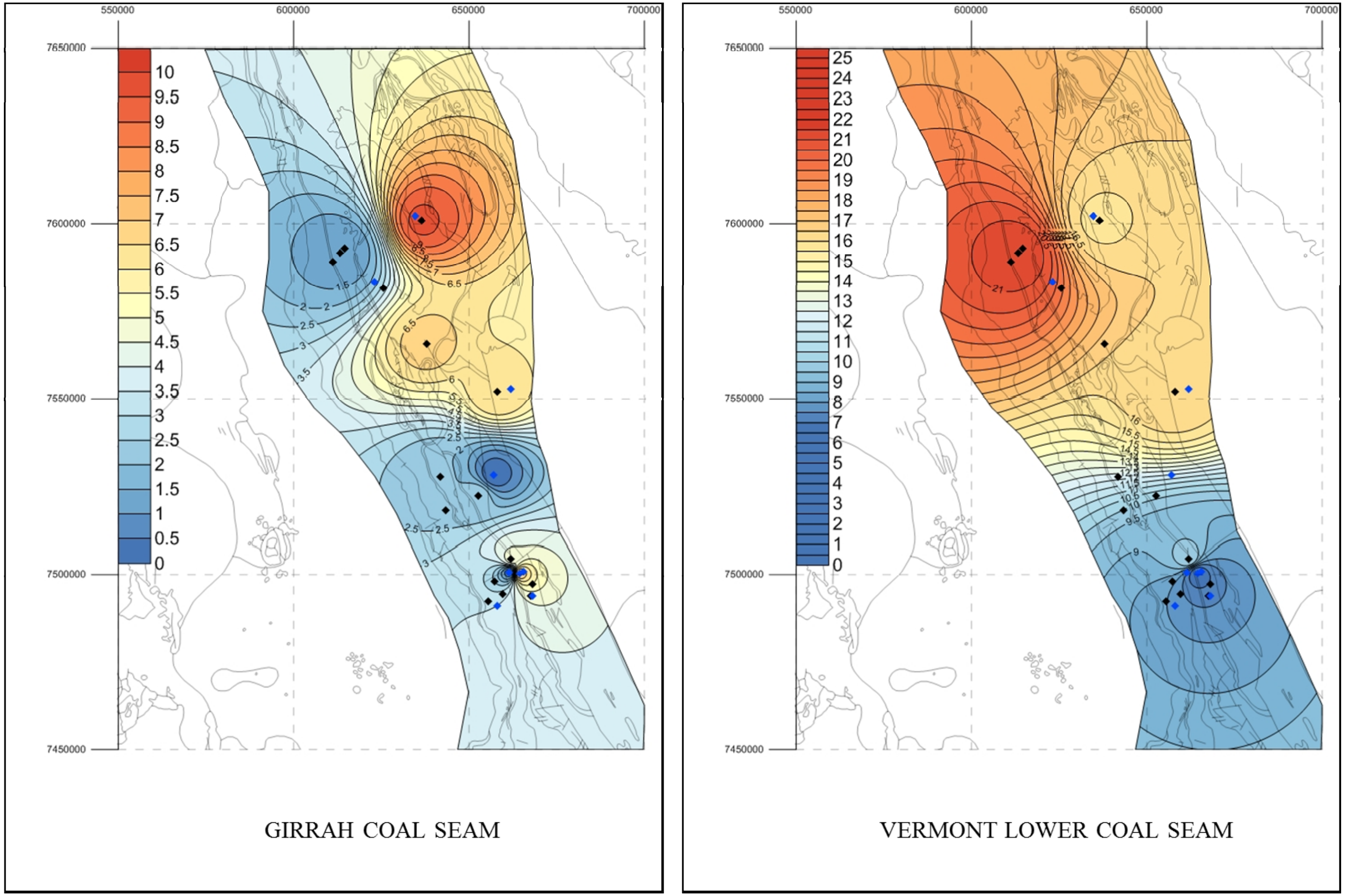

Figure 7 Geographical distribution of inertinite-rich dull coal electrofacies in different coal seams: the Girrah Coal Seam and Vermont Lower Coal Seam. Scale represents the weighted average proportion of inertinite-rich dull coal electrofacies expressed in per cent. Red colour represents the high amount of inertinite-rich dull coal electrofacies, blue colour – low amount of inertinite-rich dull coal electrofacies

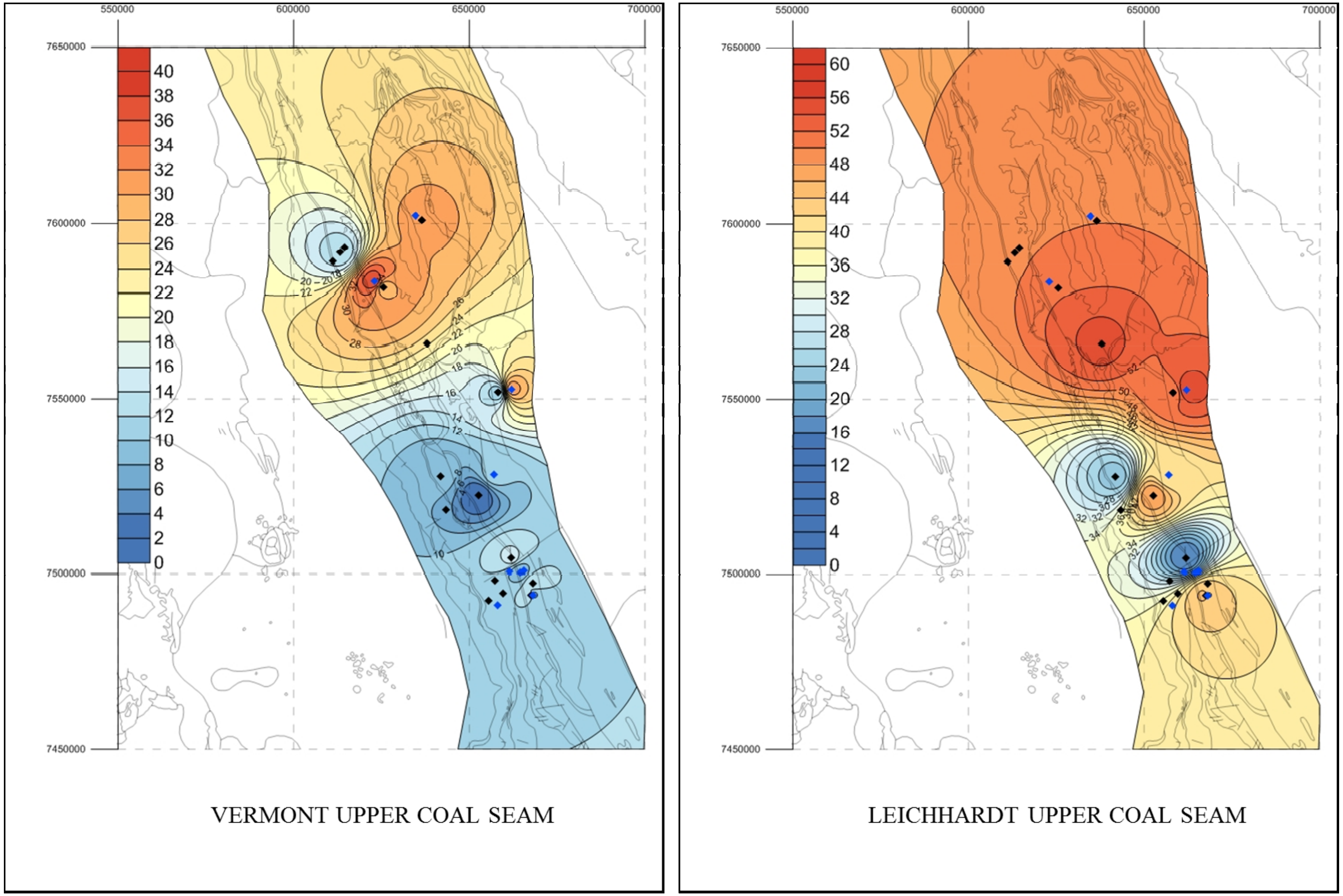

Figure 8 Geographical distribution of inertinite-rich dull coal electrofacies in different coal seams: the Vermont Lower Coal Seam and Leichhardt Upper Coal Seam. Scale represents the weighted average proportion of inertinite-rich dull coal electrofacies expressed in per cent. Red colour represents the high amount of inertinite-rich dull coal electrofacies, blue colour – low amount of inertinite-rich dull coal electrofacies

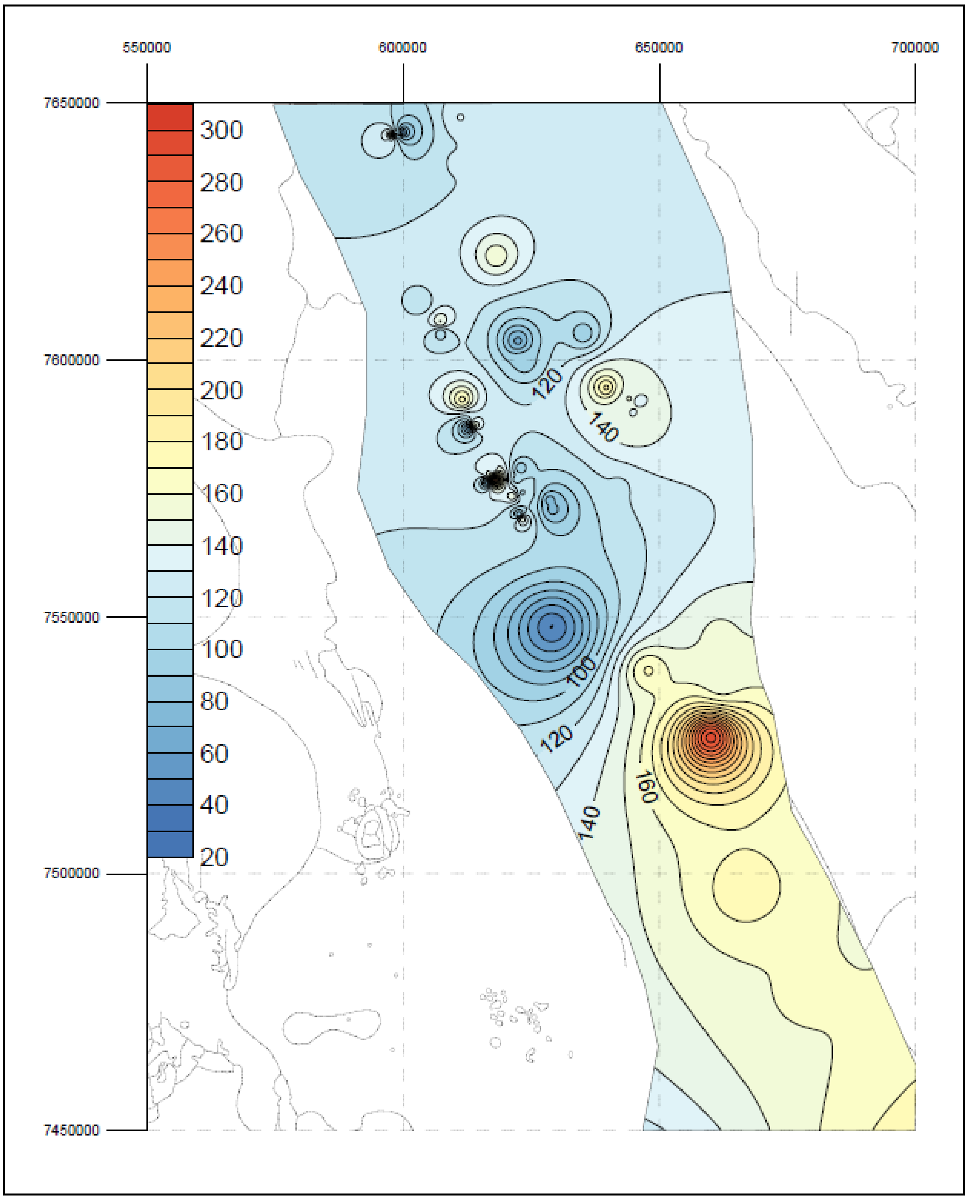

Figure 9 Rangal Coal Measures total thickness

5. DISCUSSION

Two main trends which were observed during the analysis of coal distribution are: a geographic increase of inertinite-rich coal electrofacies towards the north and a stratigraphic increase from MCM towards the top of RCM. The stratigraphic increase in inertinite towards the end of the Late Permian has been recognised previously in the Sydney Basin (Diessel, 2010) and locally in the RCM in Queensland. The trend was explained by a globally changing climate with an increase in temperature and aridity, resulting in increased oxidation and potential for peat fires. Interestingly, there is also a geographic shift in inertinite-rich dull coal e-facies for given seam intervals.

Hunt (Hunt, 1989; Hunt and Smyth, 1989) suggested that lateral variation in maceral composition is a function of subsidence, which affects water table, plant type, level of decomposition and preservation. Higher levels of inertinite were interpreted to occur in areas of lower subsidence. The prevailing effect of tectonic subsidence was also stated by Strakov (Strakov, 1962) who postulated that given a sufficiently humid climate, regional tectonic subsidence is considered to be the major factor controlling peat accumulation and preservation and, in turn, coal type. The thickness distribution of the RCM increases towards the south of the study area as a result of increased seam splitting and development of clastic interburdens. The areas of thinner RCM coincide with the areas of relatively higher inertinite-rich dull coal e-facies in most of the intervals, and in particular within the Leichhardt seam (Figure 9).

Therefore two processes are at play: a global stratigraphic shift of climate and a local geographic shift in subsidence.

6. CONCLUSIONS

This paper focused on the analysis of the coal lithotype distribution using electrofacies analysis, to examine stratigraphic and geographic trends in the Late Permian coals of the northern part of the Bowen Basin. The method employed is explained in a companion paper (Roslin and Esterle, 2015, in review). Briefly, this method is based on electrofacies analysis of wireline geophysical logs and results in a number of electrofacies which match corresponding coal lithotypes. For the study presented in this paper, the weighted average proportions of coal electrofacies were calculated and used as proxies for coal lithotypes to analyse stratigraphical distribution of different coal lithotypes. In turn, the inertinite-rich dull coal electrofacies was taken as a proxy for inertinite content to examine geographical distribution of inertinite-rich coal.

Stratigraphical and geographical distribution of coal lithotypes was analysed and it was observed that "dullness" of coal increases towards the top of the Late Permian Coal Measures (stratigraphically) and from the south to the north (geographically). Dull coal is presented by mineral matter rich dull coal in the lower coal seams and inertinite-rich dull coal in the upper coal seams, and inertinite-rich dull coal increases towards the top of Rangal Coal Measures.

The analysis of coal lithotype distribution allowed making some interpretation about the development of the studied area. The stratigraphical uptrend increase of dull coal (especially inertinite-rich dull coal) is correlated to strong climatic signatures of temperature, carbon dioxide and atmospheric oxygen content on a global scale (Diessel, 2010). It was suggested that the observed stratigraphical distribution is caused by global climate changes which took place near the boundary between Late Palaeozoic Era and Early Triassic Period.

The observed decrease of inertinite-rich dull coal towards the south is correlated to the increase of tectonic subsidence rate in the same direction and the conclusion is that regional tectonic subsidence is the major factor controlling peat accumulation and preservation and coal type can be made.

ACKNOWLEDGEMENT

The method exploited some research results which had previously been done at the University of Queensland by the authors and present the potential to be used for further research in coal characterization study in Coal Seam Gas Centre of the University of Queensland.

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6. DISCUSSION

This thesis was focused on the application of Petrophysics to characterise and map changes in coal quality, in particular type or composition, for the Late Permian coal measures of the northern part of Australian Bowen Basin.

A number of research questions were answered in the research:

1) What is the most suitable approach for coal analysis based on wellbore geophysical logs and borehole electrical images?

Electrofacies analysis was chosen as a suitable approach for coal characterisation. Electrofacies analysis was based on automatic clustering procedure and further electrofacies classification and demonstrated good results in the course of the research. Electrofacies analysis allows analysing all available wireline geophysical logs together with core and laboratory data. The results can be easily validated by other coal characterisation methods and demonstrated as a brightness profile or summarised as weighted average proportions of different coal lithotypes.

2) Is it possible to create a robust method for automatic coal lithotype identification using this approach?

This research resulted in a semi-automated coal lithotype characterisation method which is based on electrofacies analysis of wireline geophysical logs and doesn't require any pre-defined cut-off or knowing a number of electrofacies. This method utilises Multi-Resolution Graph-Based Clustering and automatically determines the amount of clusters, or electrofacies, but allow the user to choose the level of detail (offering three cluster sets, i.e. 15, 12 and 9 clusters in this research). Clustering results are validated by the analysis of contingency tables. Electrofacies classification is performed by the user by the analysis of observed trends in wireline logs data distribution and can be validated by core data or laboratory data. Millimetre scale logging results were used for validation of the result of this research. The method which was established in the research is robust and characterised by high-reproducibility.

3) How are the results of the study correlated to those obtained by other methods (coal proximate analysis, manual lithotype profiling, maceral content analysis)?

The weighted average proportions of electrofacies were compared to weighted average proportions of lithotypes obtained by millimetre scale logging (for coal lithotype analysis) and maceral analysis data (for inertinite-rich dull coal analysis). The former demonstrated that the discrepancy between the results generally didn’t exceed 20 per cent but reach up to high 50 per cent for the Vermont Upper coal seam. This fact was explained by the mineral composition of this coal seam which significantly affected wireline logs response and didn’t take into account in the research. Inetrinite-rich dull coal analysis demonstrated that the trends which were observed are correlated to the trends obtained from maceral analysis.

4) Which log set is the best input dataset and why? What is the difference in the results obtained from using high-resolution and conventional data? How this difference can be explained if there is any?

Three different dataset were exploited for the electrofacies analysis and the dataset which included gamma ray, density, deep laterolog and PEF curves demonstrated the best results. The most important observation was that PEF curve could help to distinguish between bright low density and inertinite-rich low density coal. No evidence that high-resolution resistivity data has any advantage over conventional deep laterolog resistivity was obtained. The validation of the results was done by the analysis of contingency tables and comparison of weighted average proportions of electrofacies to those of the corresponding coal lithotypes.

5) Can this method be applied to other areas and which restrictions or limitations does this method have?

Taking into account the uniform character of the established method, no restriction or limitations are observed for application of the method. However, some considerations are important: 1) the reference set that is used to perform electrofacies analysis should contain the deepest wells in the study area that represent the full geological profile and are characterised by the full set of data (wireline logs, core data etc.); 2) proper wireline geophysical data should be used for coal characterisation; 3) logs should be normalised

6) How are different coal lithotypes distributed over the studied area? What processes might have caused such distribution?

7) Does the coal lithotype vary vertically and laterally within specific seams across the basin? Which processes may have caused those variations if there were any observed?

Stratigraphical and geographical distribution of coal lithotypes was analysed and it was observed that “dullness” of coal increases towards the top of the Late Permian Coal Measures (stratigraphically) and from the south to the north (geographically). Dull coal is presented by mineral matter rich dull coal in the lower coal seams and inertinite-rich dull coal in the upper coal seams, and inertinite-rich dull coal increases towards the top of Rangal Coal Measures.

The analysis of coal lithotype distribution allowed making some assumptions about the development of the studied area. The stratigraphical uptrend increase of dull coal (especially inertinite-rich dull coal) is correlated to strong climatic signatures of temperature, carbon dioxide and atmospheric oxygen content. It was suggested that the observed stratigraphical distribution is caused by global climate changes which took place near the boundary between Late Palaeozoic Era and Early Triassic Period.

The observed decrease of inertinite-rich dull coal towards the south is correlated to the increase of tectonic subsidence rate in the same direction and the conclusion that regional tectonic subsidence is the major factor controlling peat accumulation and preservation and coal type can be made.

7. CONCLUSION

The thesis was focused on the establishing the methodology of coal characterisation based on wireline geophysical borehole data but also included the analysis of the inertinite-rich coal distribution in the Northern Bowen Basin.

The study was performed in three stages:

1) At the first stages, all available wireline geophysical data were analysed in order to understand the relationship between wireline borehole measurements and coal properties which might help to distinguish different coal lithotypes. Borehole electrical image data required advanced processing techniques to be exploited for coal lithotype characterisation. The methodology for borehole electrical microimager array data conversion into single microresistivity curve with enhanced vertical resolution (0.1 in.) and deep depth of investigation was proposed. Successful implementation of this methodology for data used in the research allowed analysing whether high-resolution wireline geophysical data has an advantage over conventional wireline logs for coal lithotype characterisation. The research demonstrated that conventional deep laterolog data produces the results which as good as the results obtained from high-resolution resistivity data. It was explained by the fact that resistivity measurement is not the primary coal lithotype discriminator and thus, it's not necessary to use high-resolution microresistivity for coal lithotype characterisation. In the same time, the research demonstrated that photoelectric factor (PEF) curve is very important for lithotype characterisation as PEF can distinguish between bright low density and inertinite-rich dull low density coal.

2) The second stage of the study resulted in the methodology of automated or semi-automated coal lithotype characterisation. The significance of this achievement is due to the fact that previous studies focused on coal maceral characterisation required specific wireline measurements and cut-offs calibrated to geochemical data (Johnston et al, 1991; Ahmed et al, 1991). For the proposed methodology, electrofacies analysis was chosen as the most suitable approach. Electrofacies

analysis was performed in Facimage™ module of Geolog software (Paradigm package). Multi-Resolution Graph-based Clustering (Ye and Rabiller, 2000, 2001) was used to perform clustering and electrofacies classification was done by wireline geophysical logs trend analysis. Validation of clustering results was done by contingency tables analysis and electrofacies classification was validated by comparison of weighted average proportions of coal lithotype electrofacies to the weighted average proportions of the corresponding coal lithotypes obtained by millimetre scale logging (Esterle and Kolatchek, 2002). The discrepancy between those two methods generally doesn't exceed 20 per cent increasing to 50 per cent only in the Vermont Upper. The observed behaviour of this coal seam was explained by the mineral constituent of the Vermont Upper coal seam. The detailed study of the influence that mineral matter of the Vermont Upper coal seam has on wireline logs response and, in turn, causes the distortion or coal lithotype electrofacies results is a subject for future research..

3) The third part of the study was focused on the analysis of coal lithotypes distribution using corresponding coal lithotype electrofacies as proxies. Thus, Inertinite-rich dull coal electrofacies as a proxy for inertinite maceral content to analyse stratigraphic and geographic distribution of inertinite content in the Northern Bowen Basin. Two main trends were observed: 1) the amount of inertinite-rich dull coal increases towards the top of the Late Permian coal measures; and 2) the amount of inertinite-rich dull coal decreases from the north to the south. The first trend was explained by global climate change and the second trend is supposed to reflect regional tectonic subsidence pattern. These results are in conjunction to the observations made by other researchers (Hunt, 1989; Hunt and Smyth, 1989; Diessel, 2010).

To sum all, it can be concluded that the research was successfully solved all research questions that were risen at the beginning of the study. The methodology which was resulted from the research is robust and reproducible. Validation of the methodology was fully performed and then, the methodology was applied to the northern Bowen Basin data. The observations that were made are in conjunction to the previous research studies. The research might present a potential interest for future application. Author can see that some future can be done to investigate the mineral composition of the Vermont Upper coal seam. This research can also be used as a potential approach for coal rank study.

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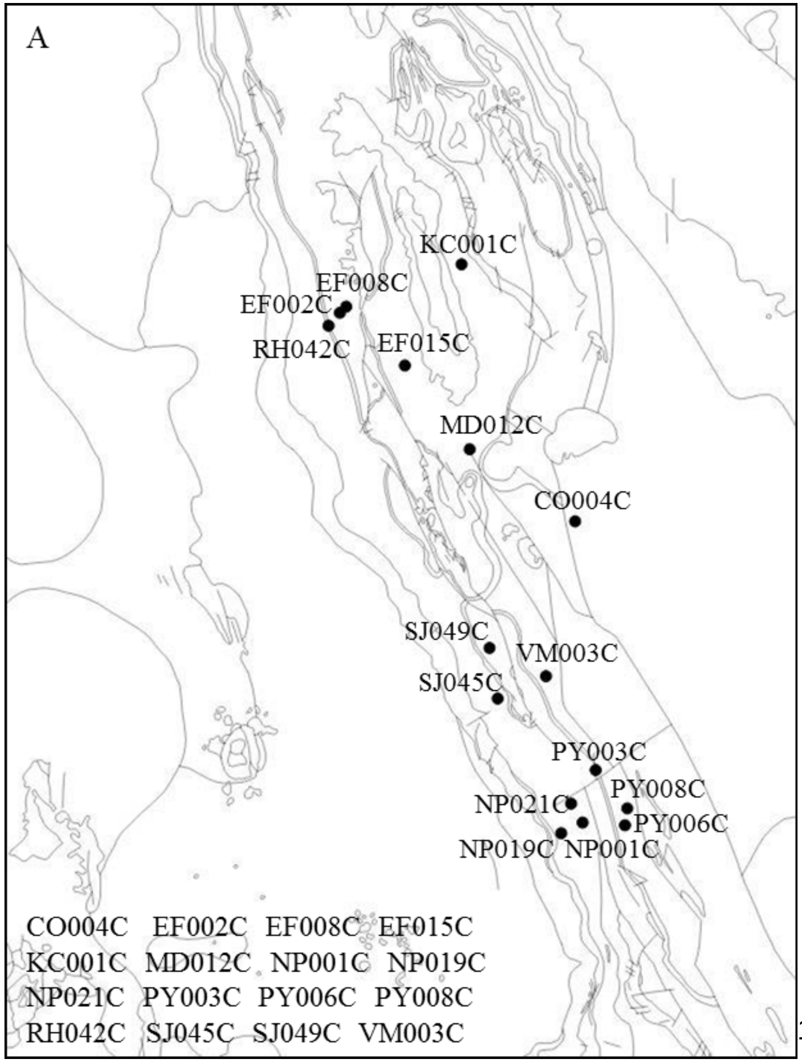
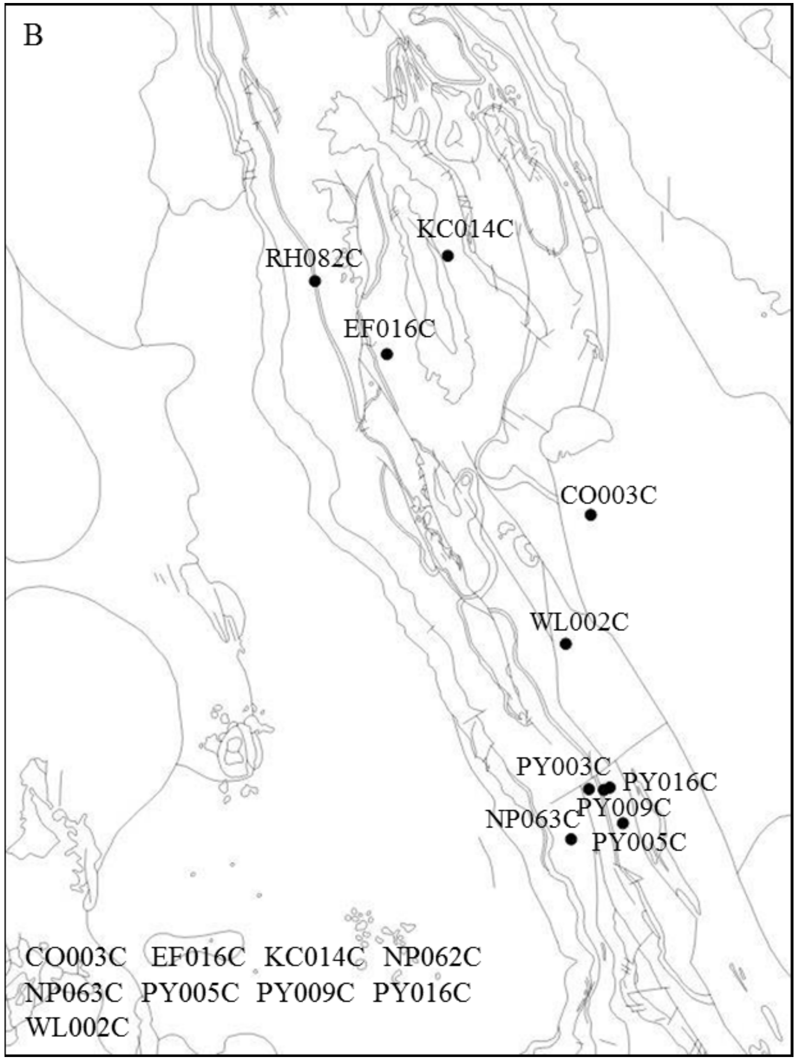
APPENDIX 1 Reference and application datasets

This Appendix shows the position of wells which form the reference set (A) and the application set (B) (see Papers 2 and 3).





APPENDIX 2 Electrofacies analysis results

This Appendix presents the tables that summarise the quantitative results of coal lithotype profiling based on electrofacies analysis compared to mm scale logging results. In addition to Paper 2 (see Chapter 4).

Each well contains the results for four different methods (please see Paper 2):

- method #1 involves electrofacies analysis based on gamma ray, density, laterolog and microresistivity;
- method #2 includes gamma ray, density, laterolog and PEF;
- method #3 involves gamma ray, density, microresistivity and PEF;
- method #4 is the mm scale coal lithotype profiling which is based on visual characterisation of coal lithotypes in core samples.

APPENDIX 3 Poster abstract presented at the 31st Annual Meeting of the Society for Organic Petrology, Sydney, NSW, Australia, 27-30 September and at the PESA Symposium, Brisbane, QLD, Australia, 25 September

ELECTROFACIES ANALYSIS USING HIGH-RESOLUTION WIRELINE GEOPHYSICAL DATA AS A PROXY FOR INERTINITE AND VITRINITE DISTRIBUTION IN LATE PERMIAN COAL SEAMS, BOWEN BASIN

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ABSTRACT

The Bowen Basin is a large, intracontinental coal-bearing basin that developed in eastern Queensland during the early Permian – Middle Triassic as the northern part of the much larger basin system that includes the Gunnedah and Sydney basins in New South Wales (Totterdell et al. 2009). The Rangal (RCM), Fort Cooper (FCCM) and Moranbah (MCM) Coal Measures are primary targets for coal and coal seam gas exploration and production in the central Bowen Basin (Draper, 1985). In spite of their stratigraphic proximity, they have quite different maceral group contents and rank (Beeston, 1986). This study examines both the stratigraphical and geographical distribution of inertinite and vitrinite content in these three main coal measures, using electrofacies analysis as a proxy. Data comes from some 26 wells in the northern part of Bowen Basin.

The study was performed by electrofacies analysis using high-resolution wireline data (including microresistivity from Compact Micro-Image (CMI) tool and Photoelectric Factor (PEF) data in addition to conventional gamma ray, density and laterolog resistivity). This method doesn't require any special parameters, cut-offs or assumptions, it's based on raw data analysis only and, results in a relative percentage of inetrinite-rich and vitrinite-rich electrofacies interpreted to represent the vitrinite and inertinite group content of coal (Roslin and Esterle, 2014, this volume).

The three main coal measures can be further divided into a number of coal seams in the study area. Leichhardt Upper (LU1 main and LU0 rider) seam is the uppermost main coal seam of RCM; the Vermont Upper (VU1) is the lowest seam of RCM, and underlain by the Yarabee Tuff marker horizon. Vermont Lower (VL3) seam is the first coal seam of FCCM which is followed by Girrah seam and number of other FCCM seams. MCM seams were not differentiated or correlated between wells, as they were poorly intersected in our dataset. Seam abbreviations used in this paper are our own.

Stratigraphically, the inertinite electrofacies are observed to increase from Vermont Upper towards Leichhardt Upper seam. Slightly similar trend was revealed in FCCM where inertinite electrofacies increases towards the top of the FCCM, although this trend is not always as obvious as in RCM. MCM is characterised by higher amount of vitrinite electrofacies than RCM and FCCM (Figure1). This observed shift in the electrofacies is generally confirmed by petrographic analysis of these seams. On a bigger scale, we might also recognise the dulling-up trend between MCM, FCCM and RCM.

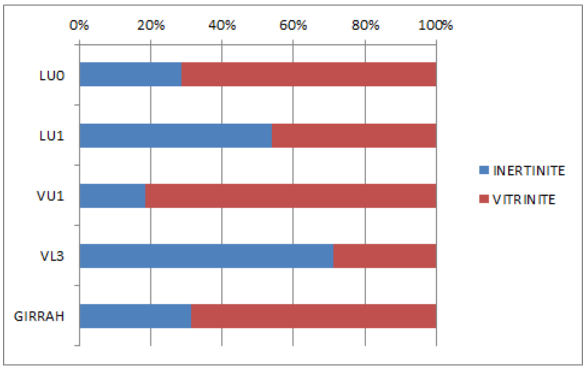

Figure 1 represents relative proportion of inertinite and vitrinite electrofacies for coal seams in well CO004C. Presented "stone free"

Trends in coal maceral composition are interpreted to reflect changes in vegetation, subsidence or climate at the time of peat accumulation, else shortly after. The increase in inertinite is supposed to reflect the change to increased aridity in the Late Permian RCM leading to the Early Triassic "coal gap" (Diessel, 2010). For a given coal seam, the amount of inertinite electrofacies decreases geographically from north to south in the study area. This trend can be explained by higher subsidence rates in a downwarping foreland tectonic regime and is supported by increased splitting and interburden thickness. This study also reveals some trends in thermal maturity rate changes between different coal seams and between northern and southern parts of studied area and helps to distinguish coked coal (Roslin and Esterle, 2014).

All these observations are in conjunction with previous studies (Hunt, 1989), however the innovation of the method is due to the fact that the study was performed based on wireline geophysical logs data only. Maceral analysis data and coal proximate results were used only for validation of the results.

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APPENDIX 4 Poster abstract presented at the 31st Annual Meeting of the Society for Organic Petrology, Sydney, NSW, Australia, 27-30 September

ELECTROFACIES ANALYSIS FOR COAL LITHOTYPE PROFILING BASED ON HIGH-RESOLUTION WIRELINE LOG DATA

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ABSTRACT

Coal lithotype or brightness profiling is used to investigate and display the differences in composition and texture within and between coal seams and measures.

Brightness profiles give a view of the overall character of the coal, and along with rank constrain the physical and chemical properties of the material. Hardness and strength respond to the properties which in turn relate to the fracture or cleat distribution in the coal, and affect reservoir response to gas retention and production.

The traditional approach to lithotype analysis is based on a visual characterisation of coal in core, mine or outcrop exposures. This method results in a very detailed brightness profile but the process is time-consuming and is subject to operator bias. Such characterisation relies on each particular interpreter's visual perception of coal brightness characteristics.

The lithotype analysis developed in this study involves geophysical log interpretation in coal characterisation. Typically one or two wireline curves might be exploited to visualise the stratigraphic sequence or for correlation of coal and other lithologies between wells. However, the whole log suite is recommended to be used in order to characterise the physical and lithological properties of a formation. Coal seam reservoirs are distinguished in well logs by the use of gamma-ray and density curves. These geophysical properties are enough to identify coal seam occurrence but are not detailed enough to determine lithotype. With a full log suite, lithotype may be extracted using electrofacies analysis which can simultaneously operate with the entire data suite (which might include both wireline and core data, else core data is used for validation). In addition to conventional gamma ray and density logs, microresistivity and PEF data were used in the study. For the first time array resistivity data from CMI imager were processed into microresistivity curve and this curve was exploited for electrofacies analysis together with conventional resistivity data. Electrofacies analysis involves partitioning a set of wireline log data into electrofacies units, and presenting them in a manner that is comparable to that used by geologists for interpretation of lithologies (Ye and Rabiller, 2005).

This study describes the method of coal lithotype profiling which was performed by electrofacies analysis. This method assumes that there is a correlation between coal lithotype and different coal properties which affect wireline logs response. It provides the interpreter with overall percentage of bright and dull coal seam content and distinguishes the coal seams of different rank. Although the method doesn't provide the exact values for thermal maturity rate, it's possible to observe the trends how the rank of the coal changes between different coal seams (figure 1). Multi-Resolution Graph-based Clustering (MRGC) which is used as an electrofacies cluster builder constitutes a fast, user-friendly, and versatile tool for electrofacies analysis bringing substantial added value to many log and core measurements. This method doesn't require any special parameters, cut-offs or assumptions, it's based on raw data analysis only and, thus, it's immune to interpreter bias. This approach is more objective than the visual estimation of coal in samples, and has a recordable reproducibility and rule set. Logs are more often available for coal characterisation than core samples, especially in deep wells. The method was applied on Bowen Basin data to analyse the stratigraphical and geographical distribution of dull/bright coal.

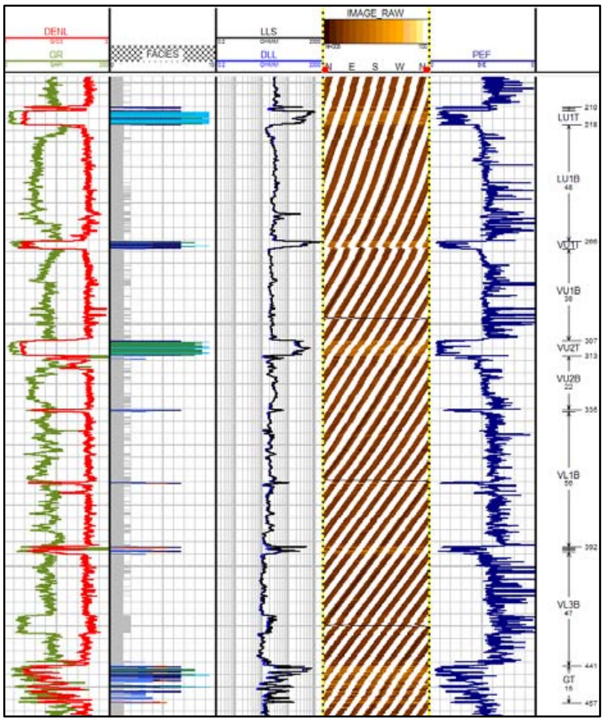

Figure 1 shows wireline data which were used for the study and the coal facies (second track). An increase of inertinite matter (cyan) can be observed towards the top of the RCM. Vitrinite matter (green) and vitrinite mixed with secondary amount of inertinite content (dark blue) increases towards the bottom of coal measures. Girrah seam of FCCM is characterised by small amount of dull coal, relatively high vitrinite content and big amount of mineral matter (violet blue). Thermal maturity rate sharply increases from RCM to FCCM (high thermal mature coal is shown by orange)

Quantitative results obtained from running the new method were compared to those of manual coal mm-scale logging and discussed and a very good similarity of two methods was observed. The method can provide the researcher with the percentage of dull and bright coal and give some clues about the distribution and character of bright and dull bands (thickness of bright and dull coal bands was estimated after comparison of electrofacies analysis data versus mm scale logging taking into account the resolution of both methods). In addition to the amount of dull and bright coal, the study demonstrated the insight into the character of coal organic matter and resulted in relative percentage of vitrinite and inertinite content of coal. The results that were obtained during the study were used further in more detailed analysis of Bowen Basin coal distribution.

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APPENDIX 5 Co-authored poster abstract presented at the 31st Annual Meeting of the Society for Organic Petrology, Sydney, NSW, Australia, 27-30 September

VERTICAL TRENDS IN MACERAL COMPOSITION IN INERTINITE-RICH COALS: A CASE STUDY FROM THE GALILEE BASIN

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ABSTRACT

The Permian Galilee Basin, located in central Queensland, is an intracratonic basin with studies performed by Hunt (1989) and Hunt and Smyth (1989) that discuss the origin of the high inertinite content of the coals. They attributed the abundant inertinite group macerals to the slow subsidence rates of the basin and the fluctuating water table causing a higher rate of sub-aerial and subaqueous oxidation (Hunt and Smyth, 1989). This study examines vertical and lateral trends in the maceral composition of the coal sequence from available open file data, and uses complementary analysis of wireline logs to develop a proxy for maceral composition. Three open file wells were used in this study to examine vertical trends in maceral composition and develop electrofacies, and preliminary results are presented here.

There are 5 main coal seams found in the Galilee Basin, located in the Bandana formation and Colinlea Sandstone and their stratigraphic equivalent, the Betts Creek Beds. Seams are generally referred as A through E, from top to bottom. Tuff banding of thicknesses 1cm-10cm is not uncommon, however one seam in particular, known as the C seam, sees a rise in tuff band frequency, with tuffaceous material occurring every 10cm-20cm. Despite being rich in inertinite (25.5 to 81.4% m.m.f., average of 59.6%), the C seam represents a vertical variation in vitrinite with, 31.4% m.m.f. at the base and increasing up to 48.6% m.m.f. at the top of the seam (average figures of the three wells). The numerous tuff bands found within the C seam could be beneficial to the preservation of vitrinite, providing either nutrients and stable ground for woody shrub growth, else pooling and/or sealing off the peat to prevent oxidation.

As well as the overall vertical increase in vitrinite through the C Seam it is seen that when splitting of the C seam occurs, the vitrinite content increases relative to the C seams that are coalesced elsewhere in the basin. The increase in accommodation leading to an influx in clastic sediments causing the seams to split (Wadsworth et al., 2002), reflects a relative increase in the subsidence rate, which is preferable to the preservation of vitrinite as little oxidation can occur. This trend was corroborated by the electrofacies analysis.

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