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Decoupling $\delta^{13}C$ response to palaeoflora cycles and climatic variation in coal: A case study from the Late Permian Bowen Basin, Queensland, Australia

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ABSTRACT

The Late Permian coal measures of the Bowen Basin, Australia express both environmental and climatic changes that occurred prior to the Permian Triassic (P–T) boundary. In order to decouple the influence of environmental factors (salinity, pH, base level and temperature) from depositional and climatic factors (atmospheric CO_2) in organic $\delta^{13}C$, a high resolution study was performed on 24 coal seams (total 24.6 m) in the Late Permian stratigraphy in the northern Bowen Basin. The Late Permian stratigraphy of the Bowen Basin records a transition from deltaic and lacustrine conditions within the Tinowan Formation and Black Alley Shale Formation, to fluvial deposition in the Kaloola and Bandanna Formations. Intermittent volcanism is recorded by tuff layers during periods of peat accumulation. Variations of coal lithotypes were recorded and formed the basis of sampling for petrography and isotope analysis. Coal samples were etched to expose cellular anatomy, and systematically identified to recognise palaeoflora assemblages. When observed within seam, $\delta^{13}C$ of the coal varied cyclically (^{13}C enriched-depleted-enriched) as a response to environmental changes expressed in palaeoflora communities. The total range of $\delta^{13}C$ was −26.6‰ to −21.9‰. The overall trend of $\delta^{13}C$ progresses to increasing ^{13}C enrichment, corresponding with dull lithotypes (rich in inertinite) which indicate fluctuations in base level. The ^{13}C enrichment peaks at −22.5‰ within the Kaloola Member and shifting rapidly toward a depletion (maximum −26.6‰) of ^{13}C in the upper Bandanna Formation, prior to the P–T boundary. These changes are expressed in palaeoflora communities where ecosystems shifted from dominant *Glossopteris* flora, to climax community flora including *Palaeosmunda*, Cycadales and *Ginkgo*, suited to temperate, early Mesozoic climates. The results of this study represent an insight into the effects of environmental variables on ^{13}C uptake of plants. The identification of flora within coal gives an insight into palaeowetland evolution, and can be partnered with classic petrographical techniques for integrated analysis in coals. Both the geochemistry and the anatomical aspects of coal represent an important tool for future palaeowetland research.

1. Introduction

Enrichment and depletion of ^{13}C in coal is an indicator of palaeoenvironmental and palaeoclimatic settings (Schoell et al., 1994; Lücke et al., 1999; Widodo et al., 2009). Factors of deposition, salinity, altitude, acidity, atmospheric CO_2, water availability and plant type can be determined from carbon isotope information (Smith et al., 1976; Arens et al., 2000). Different macerals, the biochemical components of coal (Teichmüller, 1989), and phyterals, the anatomical components of plants preserved in coal (Lapo and Drozdova, 1989), also vary in $\delta^{13}C$ (Rimmer et al., 2006). Liptinites have the most depleted ^{13}C of the maceral groups, followed by vitrinite, semifusinite and fusinite as a function of decreasing hydrocarbon content of the original plant (Benner et al., 1987; van Bergen and Poole, 2002; Faure and Mensing, 2005; Rimmer et al., 2006). Organic $\delta^{13}C$ is a dominant proxy for atmospheric CO_2 through geological time, though prior research has indicated that changes in metabolic fractionation of plants influence ^{13}C distribution (Bowen, 1959; Krishnamurthy and Epstein, 1990; Lücke et al., 1999). ^{13}C fractionation in plants is often regarded as a problem when addressing the data from a purely geochemical standpoint, as environmental variables influencing plant growth mask the influence of atmospheric CO_2 composition (Francey and Farquhar, 1982; Lloyd and Farquhar, 1994; Schleser, 1995; Poole et al., 2006).

The origins of coal as an organically derived rock, allow it to act as an important tool in understanding seasonal and stratigraphic changes in palaeoenvironments and palaeoclimates, by analysing its biological components (Diessel, 1992; Poole et al., 2006). Whilst petrographic techniques on coal are well established (Teichmüller, 1989), there has been limited research into extracting botanical information from coals given the problematic nature of compression and diagenesis experienced during the coalification process (Lapo and Drozdova, 1989;

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Winston, 1989). Studies into the enhancement of cellular structure of plant components in coals, through a method of oxidation dubbed "etching", were critical in establishing palaeobotanical identification, although did not have adequate resolution of samples to effectively interpret vegetational cycles (Pierce et al., 1991; Moore and Swanson, 1993). The taxonomic recognition of key species preserved within coal has significant implications on the interpretation of geochemical data, as most botanical species are well constrained by environmental variables which control their growth and distribution (Cameron et al., 1989; Grocke, 1998; Mitsch and Gosselink, 2007). For modern peats, wetland development stages are controlled by successions in floral communities (Mitsch and Gosselink, 2007; Newton and Bottrell, 2007). These successions have been identified in coal balls (e.g. Raymond, 1988), however, they are not yet correlated to non-mineralised coal. Botanical occurrences can work to further constrain the number of depositional factors that influence δ^{13}C, and observe feedback between the atmosphere and biogeosphere (Poole et al., 2006). Constraining depositional environment, based on palaeoflora, is commonly used in organic facies analysis and organic geochemistry (Mendonça Filho et al., 2012), though not as widespread when applied to coal, which does not have limitations on preservation and abundance of organic matter.

In the absence of microscopic studies of botanical components, variation in coal lithotype and/or maceral composition is used as a proxy for gross vegetation and environmental changes (Beeston, 1986; Cameron et al., 1989; Diessel, 1992; Hower et al., 2008), particularly in response to base level (Moore and Shearer, 2003). Peat is highly susceptible to *in situ* weathering and maceration, with dull lithotypes representative of peat doming, fluctuating base level and stressed vegetative communities (Marchioni and Kalkreuth, 1991; Diessel, 2010). Repetition of increasing dull coal sequences within seam is attributed to relative base level rise and fall. Whilst coal lithotype alone is not adequate in assessing vegetational change due to base level sensitivity (Crosdale, 1993; Moore and Shearer, 2003), used carefully, it provides a basis for overall base level variation in sedimentary systems.

This paper presents a method of utilizing the effect of fractionation of ^{13}C in plants by comparing it with the botanical components (phyterals), and preservation levels (macerals), which together are expressed megascopically as coal lithotypes, to recognise changes in wetland communities. Floral successions during wetland development indicate changes in environmental variables (i.e. salinity, pH, temperature, base level change) within each seam. The approach aims to decouple atmospheric and depositional change from environmental changes expressed by palaeoflora successions within a coal seam. This method is partnered with 'traditional' interpretation of δ^{13}C as a proxy for atmospheric CO_2 to interpret both depositional and climatic feedback reflected in coal deposits. To properly interpret environmental changes within the lifecycle of a peat forming community, a high resolution data set is required. A core through the Late Permian sequence of the Bowen Basin of Australia was selected for sampling, to provide an adequate resolution of data for interpretation. This sequence contains abundant coal seams that were deposited through a period of major climatic and tectonic shift in Eastern Australia (Fielding et al., 2001; Retallack and Krull, 2006; Korsch and Totterdell, 2009). A single well, rather than multiple wells, was selected for the study to investigate finer scale, wetland flora variations. Geographic distribution of flora has already been investigated in macrofossil studies (Anderson et al., 1999), thus a smaller scale approach was taken for this research.

2. Geological setting

2.1. Location and local stratigraphy

Drillcore sampled in this study intersects the Permian to Triassic age strata in the Bowen Basin, shown in Fig. 1. An interval of 325 m of Permian stratigraphy with the Basin's major coal members was selected for sampling (Fig. 2). The stratigraphic sequence in the well location, is undeformed with no major erosional boundaries between the Late Permian units (Korsch and Totterdell, 2009).

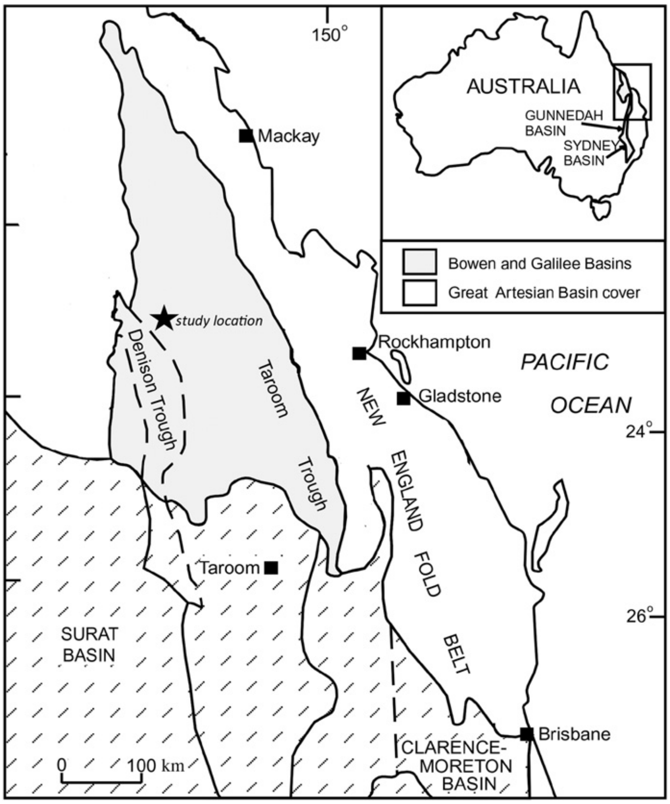

Fig. 1. Basin map of the Bowen-Gunnedah-Sydney Basin, showing major troughs and overlying basins (shown by dashed zones). Black star indicates the location of the core used for this study. Black squares indicate major regional towns or cities.
after Uysal et al., 2000; Fielding et al., 2001.

2.2. Basin development

The Bowen Basin consists of primarily 10 km thick sequences of Permian to Triassic rocks deposited in terrestrial settings (Goscombe and Coxhead, 1995; Fielding et al., 2001). The terrestrial strata include numerous layers of coal accumulations initially forming at the basin margins before further covering the interior of the basin in the Late Permian (Mallett et al., 1995). The basin is structurally complex, incorporating several major NNW–SSE troughs and ridges which have regionally impacted the well's surrounding stratigraphy (Fielding, 1992; Mallett et al., 1995). The Bowen Basin was formed by three significant tectonic events (Betts et al., 2002; Veevers, 2006). The first event occurred during the Late Devonian to Early Carboniferous, as roll-back of the Eastern Australian subduction margin, formed a back-arc basin, followed by thermal subsidence in the mid-Permian (Veevers, 2006). A final event in the mid-Late Permian compressed the basin into a foreland setting (Betts et al., 2002). Late Permian thermal events associated with these tectonic changes stimulated interaction of hydrothermal fluids with Late Permian coal measures producing CO_2 and CH_4 (Uysal et al., 2000). The quantitative effects this alteration, and other diagenetic changes, have on the δ^{13}C of coal remain unclear (Spiker and Hatcher, 1987; van Bergen and Poole, 2002; Poole et al., 2006).

2.3. Stratigraphy and depositional history

The Late Permian stratigraphy of the study location (from oldest to youngest) is the Tinowan Formation, Black Alley Shale Formation,