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A molecular and isotopic study of palaeoenvironmental conditions through the middle Cambrian in the Georgina Basin, central Australia

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A B S T R A C T

The Cambrian period marks an important point in Earth's history with profound changes in the ocean's biogeochemistry and the occurrence of the most significant evolutionary event in the history of life, the Cambrian explosion. The Cambrian explosion is described as a succession of complex cycles of extinctions and radiations. This study integrates biomarkers and their compound-specific stable carbon isotopes to investigate the palaeoenvironmental depositional conditions in middle Cambrian (Series 3) sedimentary rocks (Thorntonia Limestone, Inca Formation and Currant Bush Limestone) from two drillholes in the Undilla Sub-basin in the eastern Georgina Basin, central Australia. The occurrence of photic zone euxinia (PZE) was detected throughout these three formations by the identification of green sulfur bacteria *Chlorobiaceae*-derived biomarkers, including a series of 2,3,6-aryl isoprenoids and the intact biomarker isorenieratane. Pulses of enhanced PZE conditions were detected in two core intervals (90–110 mKB, Currant Bush Limestone and 170–200 mKB, Inca Formation) by an increase in the 2,3,6-aryl isoprenoids and C_{19} biphenyl concentrations. These enhanced PZE conditions were followed by blooms of phytoplankton, as demonstrated by the increase in algal-derived biomarker (i.e. pristane, phytane and the C_{19} *n*-alkane) concentrations and compound-specific isotopes. These observations confirm that palaeoenvironmental conditions were similar to those reported for the Permian/Triassic and Triassic/Jurassic mass extinction events. The sterane distributions varied across the three formations reflecting possible changes in the phytoplanktonic communities through time. Although a rise in atmospheric oxygen during the Cambrian has been previously associated with the rapid evolution of metazoans, the ecological challenges related to widespread anoxia must have had a major influence on the evolution of life in Cambrian oceans.

1. Introduction

The Cambrian period marks an important point in Earth's history. The Cambrian explosion is the most significant evolutionary event in the history of life on the planet, with a rapid transition from primitive microbial forms to a predominance of protists and taxonomically diverse multicellular organisms (Gould, 1989). The Cambrian explosion is commonly described as a complex succession of cycles of extinction and radiations (Knoll and Walter, 1992). While the first stages of the Cambrian radiation of metazoan life and spreading of skeletal reef fauna occurred in the early Cambrian (Terreneuvian and Series 2), metazoan reef systems had collapsed worldwide by the middle Cambrian (Boucot, 1990). Hence, the early–middle Cambrian represents a key point in the history of life. The causes of this crucial evolutionary event remain enigmatic and have been challenging evolutionary biologists for decades (Zhang et al., 2014). Although tectonic factors, variations in atmosphere and ocean chemistry, and significant changes in biogeochemical cycles have been suggested as potential triggers for the explosion, the actual environmental and/or biological causes of the Cambrian radiation remain unclear (Zhang et al., 2014).

Biomarkers are particularly useful for investigating palaeoenvironmental conditions and the presence and extent of photic zone euxinia (PZE), which corresponds to the presence of hydrogen sulfide within the sunlight zone of the water column

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(Grice et al., 2005; Schwark and Frimmel, 2004). The green sulfur bacteria *Chlorobiacea* thrive under such conditions and produce highly specific pigments, such as isorenieratene and chlorobactene (Grice et al., 1996). Preservation of these pigments lead to the distinctive saturated biomarkers isorenieratane and chlorobactane. However, the precursor lipids and pigments of other sedimentary hydrocarbons can be found in diverse types of organisms and their potential use as source specific biomarkers is therefore restricted (e.g. Volkman et al., 1998). Such issues can be further resolved by complementing the biomarker studies with stable isotope analysis which can provide information regarding biogeochemical cycles and phytoplanktonic community composition (Brocks and Grice, 2011). Biomarker and stable isotopic studies have been successfully applied to major biotic crisis events spanning the Permian/Triassic (Grice et al., 2005; Nabbefeld et al., 2010) and Triassic/Jurassic (Jaraula et al., 2013; Kasprak et al., 2015) boundaries. Therefore, the goal of the present study is to use a comprehensive biomarker and $\delta^{13}C$ compound-specific isotopic approach to obtain palaeoenvironmental information for middle Cambrian sedimentary rocks from the eastern Georgina Basin, central Australia. Environmental conditions (including PZE) and fluctuations in phytoplankton productivity and composition were investigated in cores from two drillholes in the Undilla Sub-basin (Fig. 1) in which the sedimentary section was known to be thermally immature for hydrocarbon generation.

2. Geological background

Deposition within the intracratonic Centralian Superbasin occurred throughout the Neoproterozoic and Early Paleozoic, with remnant sedimentary sections being preserved in what are now known as the Amadeus, Georgina, Ngalia and Officer basins (Walter et al., 1995). This superbasin developed around 850 Ma (Haines et al., 2001) and was disrupted during the Petermann Orogeny (known as the Huckitta Movement in the Georgina Basin) from about 570 to 530 Ma (Walter et al., 1995) and then the Alice Springs Orogeny (Rodingan Movement) between 450 and 300 Ma (Maidment et al., 2007). Hydrocarbons generated by Neoproterozoic, Cambrian and Ordovician source rocks have been recovered from the Amadeus, Southern Georgina and Officer basins (McKirdy and Kanstler, 1980). In the Georgina Basin, exploration has targeted hydrocarbons derived from middle Cambrian organic-rich shales in the Thorntonia Limestone and Arthur Creek Formation (Boreham and Ambrose, 2007). The southern part of the basin is also prospective for base metals, manganese, phosphate, uranium, turquoise and diamonds (Dunster et al., 2007; Kruse et al., 2013). However, less attention has been given to the northern and eastern regions of the basin. The Georgina Basin contains sedimentary rocks of Neoproterozoic (Cryogenian) to Devonian age, with Cambrian rocks forming the majority of the Palaeozoic succession (up to 2.2 km) and mainly being composed of carbonates interbedded with shales and sandstones (Dunster et al., 2007).

The stratigraphic drillholes BMR Mount Isa 1 and BMR Camooweal 2 from the Undilla Sub-basin, north-eastern Georgina Basin (Fig. 1) penetrated three formations from the Narpa Group (Cambrian Series 3; 508–504 Ma; Fig. 2), the Thorntonia Limestone, the Inca Formation and the Currant Bush Limestone, which are all thermally immature.

The Series 3 Thorntonia Limestone is defined at the Thorntonia Station Queensland in the Undilla Sub-basin, where this outcrop is younger than the Series 2 Thorntonia Limestone (and informally known as the Hay River Formation) found elsewhere in the basin (Fig. 2). The Thorntonia Limestone comprises partially dolomitized limestone, pyritic-carbonaceous dolostone, marl and mudstone which were deposited in peritidal to marine depositional environments under dysoxic to anoxic conditions (Dunster et al., 2007). The sections of the Thortonia Limestone intersected in BMR Mount Isa 1 and BMR Camooweal 2 are early Templetonian in age (Laurie, 2013; Fig. 2).

The Inca Formation is composed of laminated pyritic shale and siltstone deposited in a marine environment under anoxic conditions (Southgate and Shergold, 1991). The sections of the Inca Formation intersected in BMR Mount Isa 1 and BMR Camooweal 2 are mostly Floran in age (Laurie, 2013; Fig. 2). The Currant Bush Limestone has a fairly localized distribution along the northern margin of the Undilla Sub-basin covering the eastern Mount Drummond (Northern Territory), western Lawn Hill and Camooweal (Queensland) regions. This formation consists of partially dolomitized argillaceous, quartzic and bioclastic limestone, with fine layers of shale, deposited under anoxic conditions, siltstone, marl and chert, deposited on a carbonate ramp (Southgate and Shergold, 1991; Rawlings et al., 2008). It contains a highly diverse fossil assemblage including trilobites, brachiopods, molluscs, hyoliths, echinoderms, and sponge spicules (Rawlings et al., 2008). The sections of the Currant Bush Limestone intersected in BMR Mount Isa 1 and BMR Camooweal 2 are mostly Undillan to possibly Boomerangian in age (Laurie, 2013; Fig. 2).

3. Material and methods

Methods for the extraction and analysis of biomarkers are routine, reported in numerous previous publications (e.g. Grice et al., 1996; Nabbefeld et al., 2010; Jaraula et al., 2013) and are described in detail in the supplementary online material.

4. Results and discussion

4.1. Sedimentology

The sedimentary succession intersected and studied in BMR Mount Isa 1 and BMR Camooweal 2 consists of shallow marine dolostones, limestone with chert interbeds and calcareous and dolomitic siltstones. The Thorntonia Limestone consists of vuggy limestone with abundant phosphatic shell fragments and algal mats. Phosphorites are typically deposited in low energy settings, such as either in lagoons or along the shelf where ocean circulation is limited, which allows the precipitation of phosphorus either directly from the water column or by the replacement of calcareous shells (Fig. 3a). Due to a relative rise in sea level, the platform started to drown and phosphorites were deposited on its edge. The Inca Formation was deposited in deeper water than the Thorntonia Limestone and comprises laminated calcareous siltstone/shale interbedded with limestone that contains abundant organic matter (Fig. 3b). In BMR Mount Isa 1, the deepening of the water column and simultaneous deposition of highly organic rich shale reached their maximum at ∼190–180 mKB depth. Sedimentary features, such as cross bedding, cross lamination, and soft sediment deformation of silty sediments indicate an increase in energy during a relative sea level fall, as recorded between 177 and 167 mKB. The contact between the Inca Formation and Currant Bush Limestone represents a continued relative falling of sea level. The evidence for brief subaerial exposure of the emergent platform occurs at ∼167 mKB depth, as shown by karst features within the lower Current Bush Limestone (Fig. 3c). The sediments between 30 and 167 mKB correspond to numerous rhythmic cycles of carbonate deposition and interbedded silty limestones and minor calcareous siltstone. The cycles are not as pronounced as those recorded by the Inca Formation when the platform drowned. The smaller oscillations in sea level in the Currant Bush Limestone (5–10 m cycles) may have been caused by Milankovitch cycles, while the cycle at