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Geobiology of the late Paleoproterozoic Duck Creek Formation, Western Australia

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ABSTRACT

The ca. 1.8 Ga Duck Creek Formation, Western Australia, preserves 1000 m of carbonates and minor iron formation that accumulated along a late Paleoproterozoic ocean margin. Two upward-deepening stratigraphic packages are preserved, each characterized by peritidal precipitates at the base and iron formation and carbonate turbidites in its upper part. Consistent with recent studies of Neoarchean basins, carbon isotope ratios of Duck Creek carbonates show no evidence for a strong isotopic depth gradient, but carbonate minerals in iron formations can be markedly depleted in ^{13}C. In contrast, oxygen isotopes covary strongly with depth; $\delta^{18}O$ values as positive as 2‰ VPDB in peritidal facies systematically decline to values of −6 to −16‰ in basinal rocks, reflecting, we posit, the timing of diagenetic closure. The Duck Creek Formation contains microfossils similar to those of the Gunflint Formation, Canada; they are restricted to early diagenetic cherts developed in basinal facies, strengthening the hypothesis that such fossils capture communities driven by iron metabolism. Indeed, X-ray diffraction data indicate that the Duck Creek basin was ferruginous throughout its history. The persistence of ferruginous waters and iron formation deposition in Western Australia for at least several tens of millions of years after the transition to sulfidic conditions in Laurentia suggests that the late Paleoproterozoic expansion of sulfidic subsurface waters was globally asynchronous.

1. Introduction

When the Paleoproterozoic Era (2500–1600 million years ago; Ma) began, Earth's atmosphere and ocean contained little free oxygen (Holland, 2006). By the time it ended, however, sulfidic water masses commonly lay beneath an oxygenated atmosphere and surface ocean (Canfield, 1998; Shen et al., 2002, 2003; Brocks et al., 2005; Scott et al., 2008). Accumulating evidence suggests that Paleoproterozoic environmental transition was episodic, with an initial influx of O_2 near the beginning of the interval followed nearer to its end by a resurgence of iron formation and subsequent long term loss of ferruginous deep waters (Poulton et al., 2004; Johnston et al., 2006). Available paleobiological data are consistent with hypothesized environmental changes. For example, distinctive microfossil assemblages of the type first reported from cherts of the Gunflint Formation, Canada (Barghoorn and Tyler, 1965; Cloud, 1965), occur broadly in successions deposited after the initial rise of atmospheric oxygen and before the long term loss of ferruginous deep waters. To date, however, there have been only limited attempts to integrate paleobiological, biogeochemical, and environmental geochemical data within a tightly constrained framework of sequence stratigraphy and geochronology.

To better understand the relationship between evolving ocean chemistry and Paleoproterozoic life, we examined the Duck Creek Formation, a late Paleoproterozoic carbonate platform preserved in the Ashburton Basin of Western Australia. The Duck

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Creek succession contains more than 1000 m of well preserved carbonate-dominated stratigraphy. Early mapping (e.g., Daniels, 1970) facilitated reconnaissance level studies of microfossils (Knoll and Barghoorn, 1976; Schopf, 1983; Knoll et al., 1988) and carbon isotopes (Schopf, 1983; Veizer et al., 1992a; Lindsay and Brasier, 2002), as well as detailed investigations of stromatolites (Walter, 1972; Grey, 1985; Grey and Thorne, 1985) and sequence stratigraphy (Thorne, 1983; Grey and Thorne, 1985) through at least part of the succession. Moreover, SHRIMP U–Pb dates for zircons in intercalated volcanic rocks now constrain depositional ages for Duck Creek and succeeding Ashburton strata (see below). This study documents sequence development for the entire Duck Creek succession and uses this framework to interpret carbon and oxygen isotopes at high stratigraphic resolution, in addition to mineralogical and paleobiological data from the same samples.

2. Geologic setting

In the northwestern corner of Western Australia, Paleoproterozoic sediments are preserved in the Ashburton Basin, a 12 km package of siliciclastics, carbonates, volcanics, and iron formation distributed over 30,000 km^2 (Fig. 1). Accommodation space resulted from crustal loading associated with collision of the Pilbara and Yilgarn cratons during the Capricorn Orogeny, creating the Ashburton foreland (Thorne and Seymour, 1991). The Paleoproterozoic Wyloo Group lies disconformably above modestly to moderately metamorphosed iron formations, carbonates and other lithologies of the Neoarchean–Paleoproterozoic Mount Bruce Supergroup. The Wyloo Group contains two carbonate platforms capped by volcanics and a thick siliciclastic succession, and was itself deformed during subsequent Capricorn events, with the metamorphic grade increasing toward the south. Because deformation is basically limited to thin-skinned folding and thrusting, the degree of structural rotation is, in most places, low (30–40°), and overlying Ashburton Formation mudstones and iron formation have experienced only sub-greenschist metamorphism. This is in contrast with the rocks of the Earaheedy Group to the southeast, deposited on the southern margin of the orogen (Halilovic et al., 2004; Jones et al., 2000).

Though clearly present throughout the fold-and-thrust belt (and visible from air and satellite photos), outcrops of the middle Wyloo Group, including siliciclastic and carbonate sediments of the Mount McGrath Formation and Duck Creek Dolomite, are discontinuously exposed. However, just north of Wyloo Dome in the heart of the Duck Creek Syncline, Duck Creek Gorge offers near continuous exposure of the Duck Creek Formation on both sides of the drainage; this is the location of data presented here. Near Paraburdoo, farther to the southeast along the outcrop belt, another nearly complete Duck Creek Formation section is exposed. The formation is thinner there and appears to contain a slightly different facies succession (Thorne, 1983).

At Duck Creek Gorge (22°29′00″S, 116°19′10″E), carbonates cover a 4.5 km transect as exposed in map view; over approximately half of that distance, vegetation and alluvium prevent identification of bedrock (Fig. 1). Within the gorge, basal Duck Creek Dolomites lie conformably above siltstones of the Mount McGrath Formation. To the north of Duck Creek Gorge, the Duck Creek succession is overlain conformably by basalt and tuffs of the June Hill Volcanics, whereas the southwestern portion of the dolomite in the core of the Duck Creek Syncline is capped by the highly cleaved and foliated fine-grained siliciclastics and iron formation of the Ashburton Formation. The onset of Duck Creek sedimentation is constrained by a 2209 ± 15 Ma SHRIMP U–Pb date on the Cheela Springs Basalt, found lower in the Wyloo succession (Martin et al., 1998). Its end is constrained by a series of ca. 1800 Ma SHRIMP U–Pb ages on June Hill Volcanic rocks, including a new U–Pb SHRIMP date on a tuff approximately 5 km northwest of the study site, reported here (Nelson, 2002; Sircombe, 2003; Evans et al., 2003; see below). From the points of view of sedimentary patterns and basin analysis, the age of the Duck Creek Formation lies relatively close to the minimum age constraint provided by overlying June Hill tuffs (discussed below).

3. Methods

Rock samples were sectioned using a diamond saw and micro-drilled following methods of Kaufman et al. (1990) to obtain fresh powders. Carbonate $\delta^{13}C$ and $\delta^{18}O$ values for 418 samples were measured concurrently on a VG Optima dual inlet mass spectrometer fed by an Isocarb preparation device in the Harvard University Laboratory for Geochemical Oceanography. Carbonate samples (~1 mg) were dissolved in a common anhydrous phosphoric acid (H_3PO_4) bath kept at 90 °C for 8 min. Carbon dioxide gas was purified cryogenically and subsequently measured against an in-house reference gas (CO_2). Analytical uncertainty was ±0.1‰ (sample:standard ratio of 8:1); results are reported on a Vienna Pee Dee Belemnite scale.

Mineralogical composition was measured for 18 samples distributed throughout the formation. Constituent minerals were characterized by X-ray diffraction (XRD) with a Scintag, Inc. XDS 2000 diffractometer, using Cu Kα_1 radiation at 40 kV and 30 mA according to methods described by Tosca et al. (2004). For all samples, data were collected at 0.02°2θ steps, between 5° and 65°2θ. Peak matching of XRD patterns was done using Crystallographica Search-Match®, an iterative phase identification program used for multiphase powder diffraction patterns. Multiphase patterns were matched against the Powder Diffraction File with restrictions on phase chemistry that limited searches to minerals containing common rock-forming elements (H, C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Mn, or Fe). Phases with best fits were removed from the spectrum and the search was iterated for less-abundant phases. Mineral abundances were quantified using XRD data and the publicly available RockJock spreadsheet (maintained by the USGS and available at ftp://brrcrftp.cr.usgs.gov/pub/ddeberl). RockJock matches measured XRD peaks to a database of mineral XRD peaks in order to quantify percent abundances. Measured peaks were matched against a database of 22 carbonates and rock-forming minerals and 17 clay minerals. In order to identify any expandable clays that may have been present, a sample of the clay fraction from mid-Duck Creek iron formation was saturated in ethylene glycol.

Zircons were separated from a tuffaceous ash bed within the overlying June Hill Volcanics (Fig. 1C) using conventional heavy liquid and magnetic techniques followed by hand-picking by MinSep Laboratories, and mounted in epoxy with the BR266 zircon reference standard ($^{206}Pb/^{238}U$ age of 559 Ma and 903 ppm U). The epoxy mount was polished to expose grain cores in section, imaged using a scanning electron microscope and gold coated prior to SHRIMP (sensitive high resolution ion microprobe) analysis. The SHRIMP analytical procedures follow Compston et al. (1984) and Smith et al. (1998).

4. Duck Creek sequence stratigraphy

Thorne (1983; see also Grey and Thorne, 1985) provided detailed sedimentological and sequence stratigraphic interpretation of a 220 m section of the lower Duck Creek Formation prominently exposed in a canyon wall at Duck Creek Gorge. This work builds on that framework and extends it to cover the entire Duck Creek stratigraphy. In addition to the peritidal to shallow subtidal facies recognized by Thorne (1983), major developments of subtidal stromatolitic bioherms, mound-and-channel systems, deeper-water