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Testing models for post-glacial 'cap dolostone' deposition: Nuccaleena Formation, South Australia

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ABSTRACT

Sedimentologically and geochemically distinctive carbonate sequences consistently drape the glacial deposits associated with the younger Cryogenian ice age. The presence of ice-rafted debris in the basal dolostone implies that at least the lower portion of the cap sequence records deglaciation. An isochronous model proposes that cap dolostones were deposited synchronously around the world regardless of water depth, whilst a diachronous model proposes that deposition tracked glacioeustatic flooding during deglaciation. The Nuccaleena Formation of the Adelaide Rift Complex (ARC), South Australia, exhibits many of the unique sedimentary features observed in other younger Cryogenian cap dolostones around the world. Some bedforms are the product of wind-driven oscillatory flow, thus constraining post-glacial dolostone deposition to <400 m. These sedimentary features are absent in the deepest basinal facies in the northern ARC, suggesting that this region was below storm wave base even at the glacial sea level lowstand. In the north Flinders Ranges, there is a distinct relationship between lateral facies variability in the pre-, syn- and post-glacial sediments and the axes of 50 km scale structural folds. The northern fold limbs are characterised by basinal facies, whilst the southern limbs are associated with upper-slope facies. We interpret the abrupt facies transitions to reflect lower slope to upper slope/shelf breaks across a series of linked, south-facing half-grabens. The majority of cap dolostone carbon isotope records show monotonic declines in $\delta^{13}C$ of <2‰, with starting points between −0.5 and −3.5‰. An isochronous model implies a ~3.0‰ lateral gradient from platform to lower slope that varies dramatically on a short spatial scale and non-systematically with palaeobathymetry. If pre- and syn-glacial facies are used to infer palaeobathymetry, and cap dolostones are deposited diachronously as sea level rises during deglaciation, then $\delta^{13}C$ values becomes progressively lighter with time, implying that cap dolostone deposition tracked the glacioeustatic sea-level rise over a series of half-grabens that deepened to the north. The carbon isotope dataset cannot rule out uniquely isochronous or diachronous models. Given the high frequency spatial variability of $\delta^{13}C$ values, temperature cannot be the dominant control on the isotopic variability of the cap dolostone.

1. Introduction

Two Neoproterozoic (1000–542 Ma) glacigenic poorly-sorted conglomeratic units are present on all continents, often interrupting carbonate platform sequences, and sometimes found at the palaeomagnetic equator. Therefore, at least twice during this era, continental glaciers reached sea level in the low-latitudes (Embleton and Williams, 1986; Schmidt and Williams, 1995; Sohl et al., 1999; Evans, 2000; Macdonald et al., 2010). These two Cryogenian glaciations are generally referred to as the older 'Sturtian' and younger 'Marinoan' glaciations. Sedimentologically and geochemically distinctive carbonate sequences consistently drape both glacial deposits (Williams, 1979; Kennedy, 1996; Kennedy et al., 1998). These 'cap dolostones' are genetically linked with the glacigenic sediments based on their ubiquitous juxtaposition and the presence of ice-rafted debris within the basal dolostone (Hoffman et al., 1998). The younger Cryogenian cap dolostone (~635 Ma; Hoffmann et al., 2004; Condon et al., 2005) is laterally persistent in shelfal settings, blanketing the underlying syn-glacial sediments (Hoffman, 2005), and has been used as a lithological means to correlate the glacial units (Kennedy, 1996; Prave, 1999; Halverson et al., 2005). This cap dolostone is a laterally continuous buff to pink-coloured grainstone with a global average thickness of 18.5 m and is characterised by a unique set of sedimentary features, including isopachous sheet-crack cements, low-angle cross-stratified peloidal grainstones, pseudotepees, and vertical tube-like structures within 'plumb' stromatolites (Hoffman et al., 2007). In addition, the younger Cryogenian cap dolostone records a declining $\delta^{13}C$ isotopic trend, typically ranging between −1 and −3‰. This result implies that cap dolostones worldwide are the physical and chemical recorders of the greenhouse-driven disintegration of a snowball Earth (Hoffman et al., 1998, 2002, 2007; Higgins and Schrag, 2003).

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1.1. Models for the carbon isotopic evolution of cap dolostones

Three models propose to explain the chemical evolution of cap dolostones: gas-hydrate destabilisation and methane oxidation (Kennedy et al., 2001; Jiang et al., 2003; Font et al., 2006), plumeworld (Shields, 2005), and the snowball Earth models (Hoffman et al., 1998, 2002; Higgins and Schrag, 2003). The origin of isotope variability within the cap dolostone has critical implications for the temporal constraints on its deposition. For each model, the temporal evolution of cap dolostone deposition has been variably interpreted as isochronous (Kennedy et al., 2001; Jiang et al., 2003, 2006; Font et al., 2006), semi-diachronous (Shields, 2005), and diachronous (Hoffman et al., 2007), respectively.

1.1.1. Isochronous

The gas-hydrate destabilisation and methane oxidation model proposes that organic-rich marine sediments were subaerially exposed by sea-level fall during the glaciation, and methane produced within the sediments was sequestered as clathrate in the resulting permafrost (Kennedy et al., 2001). The sea-level rise accompanying deglaciation warmed and destabilised the clathrates, causing cold methane seeps on the sea-floor to fuel microbial sulphate reduction that created alkalinity and stimulated the precipitation of carbonate (Kennedy et al., 2001; Jiang et al., 2003). This depositional mechanism is isochronous, meaning that the base and top of the carbonate sequence are the same age everywhere. Therefore, basin-wide dolostone records environmental changes synchronously during deglaciation, but after the post-glacial sea level rise, and would have been deposited at different water depths as a blanket on existing bathymetry. The δ^{13}C variability would reflect lateral and vertical gradients in ocean chemistry (Fig. 1A).

1.1.2. Semi-diachronous

The plumeworld model proposes that low latitude deglaciation was so extensive and abrupt that the resultant low density meltwater plume extended worldwide, physically separating the surface and deep ocean reservoirs for $>10^3$ years (Shields, 2005).In this hypothesis, cap dolostones are formed primarily by microbially mediated precipitation of carbonate whitings within a low salinity ocean rather than by abiotic precipitation from normal salinity seawater. For both the isochronous and semi-diachronous models, the deposition of the cap dolostone is not restricted to the time taken for deglaciation. Therefore, the semi-diachronous model requires that the base of the carbonate is diachronous and tracked the glacioeustatic transgression whilst the top of the sequence remains isochronous (Shields, 2005) (Fig. 1B).

1.1.3. Diachronous

The snowball Earth model proposes that a global glaciation caused extremely high levels of CO_2 to build up in the atmosphere (Hoffman et al., 1998, 2002). A super-greenhouse climate developed during deglaciation that resulted in acidic meteoric waters, combined with an intensified hydrological cycle, leading to rapid carbonate and silicate weathering. This weathering delivered vast quantities of alkalinity to the oceans, resulting in the rapid precipitation of carbonate (Hoffman et al., 1998, 2002). Higgins and Schrag (2003) suggested that the observed >2‰ drop in δ^{13}C of the younger Cryogenian cap dolostone can be explained by an increase in sea surface temperature that reduces the isotopic fractionation between CO_2 and carbonate.

This model proposes diachronous cap dolostone deposition where the base and top of the carbonate sequence varies in age depending on the palaeoelevation when it was deposited. Cap dolostone deposition would track rising sea-level and onlap on to the underlying sediments (Fig. 1C). As a result, the cap dolostone would be deposited within the same range of water depths everywhere, and δ^{13}C variability at different locations would reflect time evolution of post-glacial oceans. The timescale of deposition would be restricted to the time taken to melt continental ice sheets.

The depositional models make specific predictions about how the cap dolostones record the evolution of sea water temperature and chemistry during the deglaciation. Whichever model is more accurate, the rare but compelling presence of ice-rafted debris in the basal part of the cap dolostone implies that the cap records conditions during deglaciation. There have been two independent

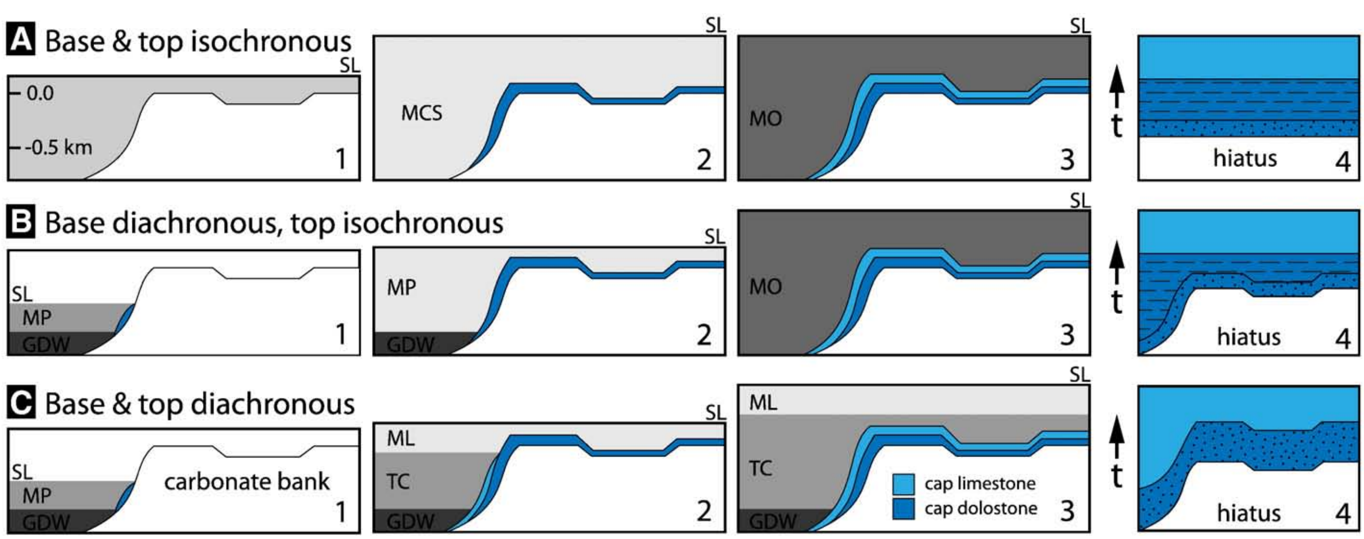

Fig. 1. Time-dependent models for post-glacial cap dolostone and limestone deposition (Hoffman et al., 2007). (A) Isochronous model: 1, depth–distance section during glacioeustatic rise, no carbonate deposited; 2, cap dolostone deposited in response to methane cold seepage (MCS) (Kennedy et al., 2001; Jiang et al., 2003, 2006); 3, cap limestone deposited in response to change in ocean chemistry (MO, mixed ocean; SL, sea level); 4, time–distance section of cap dolostone (dotted dark blue indicates shallow water, dashed dark blue indicates deeper water) and cap limestone (light blue). (B) Semi-diachronous model; 1, cap dolostone deposited from incipient meltwater plume (MP) above glacial deep water (GDW); 2, meltwater plume grows and floods the bank, cap dolostone deposited diachronously; 3, limestone deposited in response to mixing of MP and GDW (Shields, 2005); 4, time–distance section. (C) Diachronous model; 1, same as b1; 2, meltwater plume differentiates a mixed layer (ML), which deposits cap dolostone, and a thermocline (TC), which simultaneously deposits limestone; 3, TC floods the bank, causing diachronous change from dolostone to limestone at the ML–TC interface, an oxic–anoxic boundary in the meltwater column (Hurtgen et al., 2006); 4, time–distance section.