Sedimentary Geology 216 (2009) 1–14

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Sedimentology and C-isotope geochemistry of the 'Sturtian' cap carbonate, South Australia

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ARTICLE INFO

Article history:
Received 13 August 2008
Received in revised form 21 January 2009
Accepted 23 January 2009

Keywords:
Cap carbonate
Neoproterozoic
Carbon isotopes
Stratification
Upwelling
Depth gradient

ABSTRACT

A combined sedimentary and isotopic analysis of the Sturtian-aged Tindelpina cap carbonate in South Australia has revealed a strong relationship between sedimentary facies and $\delta^{13}C_{carb}$. Depositional water depths for the cap carbonate are difficult to constrain, however, a lack of diagnostic shallow water structures and the inferred magnitude of post-glacial transgression (several 100 m) indicates a relatively deep-water environment for each key facies. The shallowest facies (peloidal dolomite) has $\delta^{13}C$ values ranging between −3.6‰ and −0.3‰, in comparison to deeper water laminated limestones, which have lighter values ranging between −5.5‰ and −3.5‰. Equivalent calcareous shales deposited at basinal depths show even more ^{13}C depletion, with values ranging between −6.7‰ and −3.7‰. The average difference in $\delta^{13}C$ between the shallowest and deepest cap facies is up to 3.6‰ and may be an approximation of the seawater $\delta^{13}C$-depth gradient at the time of deposition. We interpret this high $\delta^{13}C$-depth gradient as the result of prolonged physical ocean stratification, both during and after deglaciation. Variations in the rates of upwelling/mixing under this stratified regime may have significantly influenced the climate, as well as controlling the precipitation and isotopic composition of the cap carbonate.

1. Introduction

'Cap carbonates' are thin (typically <10 m) carbonate units that lie conformably above Neoproterozoic glacial successions on all continents. They are globally ubiquitous features of both Cryogenian post-glacial successions (of Sturtian and Marinoan age) (Kennedy, 1996; Kennedy et al., 1998, Hoffman et al., 1998a,b), and may also have counterparts of Ediacaran and Palaeoproterozoic age (Gaskiers and Huronian glaciations respectively, Myrow and Kaufman, 1999; Bekker et al., 2005).

There are a number of reasons cap carbonates are considered particularly unusual. Firstly, they lack any evidence of glacial influence, highlighting the extremely rapid nature of Neoproterozoic climatic transitions. Secondly, they are present in successions that, in part, record the coldest conditions in Earth history (i.e. global glaciations, Hoffman et al., 1998a,b), implying unusually high levels of seawater carbonate saturation (high $[CO_3^{2-}]$) in the post-glacial ocean. This is particularly true of Marinoan cap carbonates, which follow the most severe of all Neoproterozoic glaciations and are characterized by sedimentary features indicative of carbonate supersaturation (Kennedy, 1996; James et al., 2001; Hoffman and Schrag, 2002; Nogueira et al., 2003). During Phanerozoic time, such supersaturation has typically been restricted to warmer climates (Williams, 1979; Tucker, 1986; Fairchild, 1993). Thirdly, cap carbonates are geochemically distinct, and punctuate many of the negative carbon isotope excursions known from this time, with $\delta^{13}C$ values commonly as low as −6‰ to −7‰ (James et al., 2001; Lorentz et al., 2004; this study), but ranging between −41‰ (Jiang et al., 2003, 2006) and +5‰ (Rieu et al., 2007).

The mysterious nature of cap carbonates and their association with glacial events of unparalleled extent has led to the emergence of numerous hypotheses to explain their origin. Due to the abundance of unusual sedimentary features and the accessibility of outcrop on all continents, research has been focused predominantly on Marinoan successions (e.g. the 'gas hydrate destabilisation hypothesis', Kennedy et al., 2001; the 'plumeworld' hypothesis, Shields, 2005), and consequently Sturtian examples remain poorly described.

Due to the general lack of these unusual sedimentary features in Sturtian examples, there is a lack of complexity in them that may help elucidate a common, dominant process in the formation of cap carbonates. In this paper new sedimentological and carbon isotope data are presented from the Sturtian post-glacial sequence of the Adelaide Geosyncline, South Australia (Fig. 1). The data show evidence for facies-dependent $\delta^{13}C$ variation within the cap carbonate, consistent with that reported for the Marinoan-aged Doushantuo cap carbonate in China (Zhou et al., 2004; Shen et al., 2005). This

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doi:10.1016/j.sedgeo.2009.01.007

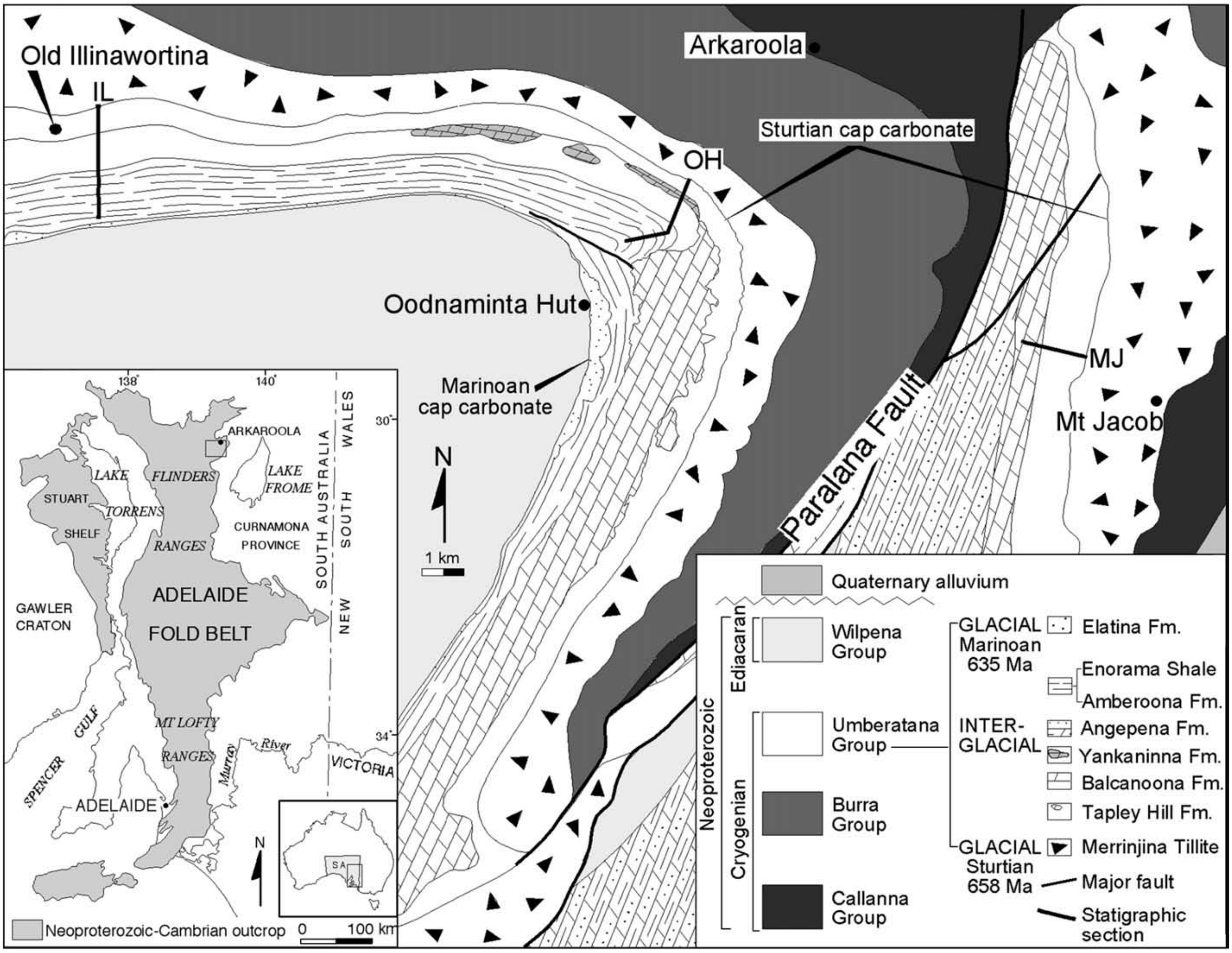

Fig. 1. Locality map of the Adelaide Geosyncline and simplified geological map of the northern Flinders Ranges, south of the Arkaroola Village. The locations of the cap carbonate sections are also shown (MJ, OH and IL). Modified from Coats (1973).

evidence may provide important insight into the origin of these enigmatic carbonates, and could greatly improve our understanding of the biogeochemical carbon cycle during this critical time in Earth history.

2. Geological setting

Neoproterozoic strata in the Adelaide Geosyncline are subdivided into four separate groups that record a complete history of sedimentation from the initiation of rifting at ~830 Ma (Preiss, 1993, 2000) through to the early Cambrian. The Umberatana Group forms the focus of this study, encompassing both lower and upper Cryogenian glacial successions (of Sturtian and Marinoan age respectively) and including a thick interglacial succession of mixed carbonate and siliciclastic sediments. Deposition following the Sturtian glaciation is recorded by the Tapley Hill Formation and its basal member, the Tindelpina Shale Member, represents the post-glacial transgression and period of maximum flooding (McKirdy et al., 2001). The base of the Tindelpina Shale commonly consists of a thin layer of dolomite and/or limestone (up to 15 m; Preiss, 1987) which we interpret as equivalent to cap carbonates overlying Sturtian glacial sequences in other Neoproterozoic basins of Australia and the world (e.g. lower Aralka Formation, Amadeus Basin; lower Wirara Formation, Kimberley Region; lower Twitya Formation, MacKenzie Mountains, Canada; Rasthof Formation, Congo Craton, Namibia).

The age of the sequence is constrained by a U–Pb zircon date of 658 Ma obtained from a tuffaceous horizon within Sturtian diamictite below the base of the Tindelpina Shale Member (Fanning and Link, 2006), supported by a Re–Os age of 643 ± 2.4 Ma from the Tindelpina Shale Member itself (Kendall et al., 2006). These ages are in approximate agreement with that determined for an interpreted Sturtian cap carbonate in China (663 ± 4 Ma, Zhou et al., 2004, but are considerably younger than radiometrically dated Sturtian diamictites in North America (685 ± 7 Ma, Lund et al., 2003) and the Sturtian Sete Lagoas cap carbonate in Brazil (740 ± 22 Ma, Babinski et al., 2007). Such a discrepancy in age remains unresolved (Meert, 2007) but must be due either to two periods of long-lived Sturtian glaciation (>20 Ma), multiple Sturtian glaciations with separate cap carbonates, or strongly diachronous glaciation.

Fieldwork was carried out in the northern Flinders Ranges (northern Adelaide Geosyncline) where stratigraphic sections were measured at three different localities—Mt. Jacob, Oodnaminta Hut and Illinawortina (Fig. 1). The Oodnaminta Hut/Illinawortina and Mt. Jacob sections are located either side of a large thrust fault system (Paralana Fault) that has resulted in repeated exposure of the same sedimentary succession either side of the main lineament. Although the two successions are equivalent there are differences in their depositional histories that reflect differences in proximity to the palaeo-shoreline. The eastern side of the fault (Mt. Jacob section) represents a more proximal setting, and the succession west of the fault (Oodnaminta