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The palaeoenvironmental context of Neoproterozoic carbon-isotope excursions

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Supplementary appendices

Abstract

The Neoproterozoic record of sedimentary carbonates preserves > 20‰ of variability in carbon-isotope ($\delta^{13}C$) values that dwarfs the ~4‰ variability recorded in Phanerozoic marine carbonates known to record changes in the Earth's carbon cycle through time. When interpreted as primary seawater values, large magnitude $\delta^{13}C$ swings in Neoproterozoic strata are commonly interpreted to reflect significant changes to the biosphere that are causally related to the oxygenation of the Earth's atmosphere, global-scale glaciations and the evolution of complex metazoan life. This thesis considers each of the key isotopic features used to define the $\delta^{13}C$ record of Neoproterozoic seawater to identify the potential for local sedimentary controls on $\delta^{13}C$ variation versus global secular change by focussing on the origin of the host carbonate phases from which the $\delta^{13}C$ values are recorded.

The expected bias toward shallow-water intracratonic basins preserved in the Precambrian record predicts that intervals of the record are particularly susceptible to hydrologic restriction and physical isolation from marine connections. The Bitter Springs Formation of the Amadeus Basin in central Australia records a positive-negative-positive stratigraphic $\delta^{13}C$ trend in its upper Gillen Member. This $\delta^{13}C$ excursion has been termed the Bitter Springs Anomaly and is routinely used as a global stratigraphic tie point at ~800 Ma. A detailed sedimentological study of the Wallara-1 and BRO5 drill cores and two field sections in the Amadeus Basin reveal that two distinctly different facies associations occur, a lower unit of cyclic-bedded microbial and grainstone marine limestones and an upper unit of red beds and dolostones interbedded with evaporites and characterised by evidence of subaerial exposure and desiccation. The abrupt decline in recorded $\delta^{13}C$ values from +6‰ to -4‰ and the following recovery back to +6‰ occurs across the stratigraphic transitions between the evaporative lacustrine and shallow-marine carbonate intervals. Positive $\delta^{13}C$ values occur exclusively in the evaporative lacustrine facies and were likely modified locally by evaporative processes in a highly restricted sabkha-type basin, indicated by interbedded and nodular anhydrites, halite pseudomorphs and karstic dissolution. Where local facies changes to subaqueous cyclic stromatolitic facies are preserved, $\delta^{13}C$ values abruptly fall to -4‰ producing the binary isotopic shift that defines the Bitter Springs Anomaly here. The recurrence of this stratigraphic and isotopic association across the basin suggests that changes to local depositional conditions resulting from periodic hydrological restriction and evaporation explain the Bitter Springs Anomaly here rather than global isotopic change in a seawater value that should be decoupled from changes in local sediment composition.

The Trezona Formation in the South Australian Flinders Ranges records a -18‰ decline in $\delta^{13}C$ values stratigraphically below Marinoan-aged (~635 Ma) glacial deposits that is used to argue for a link between carbon cycle perturbations reflected in seawater DIC and global glaciation. A high resolution sedimentary study of 9 field sections across the Flinders Ranges shows that the lower Trezona Formation records evidence of deposition at or near base level, indicated by a sequence boundary at its base described by palaeosols and trough cross bedded channelised sandstones, and mud cracks and channelised siliciclastic (fluvial) deposits throughout. The upper Trezona Formation records an uninterrupted sequence of microbial and grainstone carbonates with little evidence of emergence. The vertical recovery from $\delta^{13}C$ values of -9‰ towards modest values of -2‰ begins across the facies change between lower Trezona Formation interbedded mudstones and limestones and upper Trezona Formation microbial limestones in each section examined, regardless of variations in the stratigraphic thickness of each unit. Indicators of shallow water and exposure coupled with the limited aerial distribution of the Trezona Formation describes a water body that was physically isolated during sea level fall and may have periodically supported phases of non-marine deposition. Here, the dominance of meteoric fluids bearing negative $\delta^{13}C$ values over seawater exchange allowed for a -9‰ carbonate phase to be precipitated that is likely primary,

but is unrepresentative of coeval seawater chemistry. This value then systematically recovered to -2‰ with changing sediment composition as local basinal conditions developed along a deepening trend, inconsistent with the shoaling upward trend toward glacial lowstand proposed by previous studies and obscuring the interpreted causal link between isotope values and the onset of glaciation.

The stratigraphic reproducibility of Neoproterozoic $\delta^{13}C$ profiles of similar age within and between basins provides a principal line of evidence supporting their utility as global chronological tie points and monitors of whole-ocean change. The upper Andrée Land Group of NE Greenland records a shift in $\delta^{13}C$ values from +6‰ to variable negative values of -4‰ to -10‰, before recovering to +6‰ stratigraphically below Sturtian-aged (~720 Ma) deposits interpreted as glaciogenic in origin, and is termed the Islay Anomaly. The upper platform to slope transition that precedes the onset of diamictite deposition was studied on Ella Ø in NE Greenland and compared to a lateral section on Kap Weber that was calibrated along two regionally traceable sequence boundaries, providing time-significant surfaces along which spatially disparate $\delta^{13}C$ profiles can be compared. In both sections, platform carbonates comprising dolomitised stromatolites, pisolitic limestones, and laminated microsparites exclusively record positive $\delta^{13}C$ values of ~+6‰ while dolomite-bearing siltstones, mudstones and carbonate debrites associated with slope deposition record negative values of -4‰ to -10‰. On Kap Weber, a return to positive $\delta^{13}C$ values follows slope-mudstone deposition coincident with a return to platform carbonate deposition that is absent on Ella Ø, which instead records negative $\delta^{13}C$ values into the base of Sturtian-aged glacial diamictites with no unconformity, confirmed by interbedding and soft sediment deformation across the facies transition. This disparity in terminal $\delta^{13}C$ values at the base of the glaciogenic Ulvesø Formation suggests that the most negative $\delta^{13}C$ values recorded in the basin (-10‰) occur broadly synchronous with values of +6‰, but are related to local sediment composition and the dominant process by which carbonate was precipitated on the platform versus the slope. Further, the onset of diamictite deposition occurs asynchronously across the basin, with a correlative conformity at the base of the Ulvesø Formation on Ella Ø corresponding to erosion and subaerial exposure on Kap Weber. Elemental mapping of slope mudstones shows that the carbonate phase that records the negative $\delta^{13}C$ values that define the Islay Anomaly here is a rhombic dolomite phase that is unsorted with surrounding sediment and associated with clays, organic matter and euhedral pyrite, supporting an authigenic origin associated with bacterial sulphate reduction that is not expected to constrain marine water-column $\delta^{13}C$ variation.

The Neoproterozoic $\delta^{13}C$ record in general preserves a positive 'background' value of approximately +6‰ that is punctuated by negative excursions. When interpreted in the same way as Phanerozoic deep-ocean records, sustained $\delta^{13}C$ values of +6‰ implies significantly elevated rates of global carbon burial as photosynthetic biomass, inconsistent with the low oxygen conditions during the Neoproterozoic. While Cenozoic deep-marine pelagic sediments record $\delta^{13}C$ values as positive as +2.5‰, a compilation of coeval platform carbonates shows values as positive as +6‰ attributed to photosynthetic effects under hydrologically restricted conditions. Positive $\delta^{13}C$ values from eight different Neoproterozoic sections from Australia, NW Canada, East Svalbard and NE Greenland, including six intervals that preserve analogous carbonate platform sedimentation as thick packages of microbial and grainstone carbonates, karstic features, desiccation cracks and dolomitisation, are compared with these modern data and are shown to largely plot within the $< +6‰$ range of $\delta^{13}C$ variation. As the majority of Neoproterozoic carbonate successions are known to have accumulated above carbonate platforms and ramps, in inland seas, and in other cratonic and transitional-marginal environments, it is proposed that some portion of the positive background $\delta^{13}C$ value reflects the inherent bias in Neoproterozoic stratigraphy towards these types of depositional conditions.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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