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Sedimentary and tectonic history of the Holowilena Ironstone, a Neoproterozoic iron formation in South Australia

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ABSTRACT

The Holowilena Ironstone is a Neoproterozoic iron formation in South Australia associated with glacial deposits of the Sturtian glaciation. Through a comprehensive field study coupled with optical and scanning electron microscopy, X-ray fluorescence, and X-ray diffraction, a detailed description of the stratigraphy, sedimentology, mineralogy, and structure of the Holowilena Ironstone was obtained. The Holowilena Ironstone comprises ferruginous shales, siltstones, diamictites, and is largely made up of hematite and jasper, early diagenetic replacement minerals of precursor iron oxyhydroxides, and silica. These chemical precipitates are variably influenced by turbidites and debris flows contributing clastic detritus to the depositional system. Structural and stratigraphic evidence suggests deposition within a synsedimentary half-graben. A model for the Holowilena Ironstone is proposed, in which dense oxic fluids expelled during sea ice formation in the Cryogenian pool in the depression of the half-graben, allowing for long-lived mixing with the ferruginous seawater and the deposition of iron oxides. This combination of glacial dynamics, tectonism, and ocean chemistry may explain the return of iron formations in the Neoproterozoic.

1. Introduction

Iron formations are enigmatic chemical sediments, predominantly composed of iron oxides and silica, and represent a geological phenomenon for which there is no clear modern analogue. Almost all iron formations are of Archaean–Palaeoproterozoic age (Gole and Klein, 1981), and after the Palaeoproterozoic, iron formations are almost entirely absent from the geological record, with a few possible exceptions such as volcanogenic massive sulphide associated iron formations in the Phanerozoic (e.g. Goodfellow et al., 2003; Grenne and Slack, 2003). The Neoproterozoic, however, witnessed a brief and puzzling reappearance of iron formations. Neoproterozoic iron formations are found globally (e.g. Cox et al., 2013) and almost all are intimately associated with sediments of the Sturtian glaciation (~720–660 Ma; Rooney et al., 2015), the older of two Cryogenian low-latitude glaciations (Hoffman et al., 1998; Hoffman and Schrag, 2002). Despite their close association with one of the most extreme climatic shifts in geological history (Kirschvink, 1992), and the profound effect that this may have had on the evolution of some of the first multicellular life forms (Narbonne, 2005; Boyle et al., 2007), Neoproterozoic iron formations continue to be poorly understood.

The Holowilena Ironstone (Dalgarno and Johnson, 1965) is a Neoproterozoic iron formation that occurs in the Sturtian glacial succession (Yudnamutana Subgroup; Coats and Preiss, 1987; Preiss et al., 2011) of the Adelaide Geosyncline, South Australia (Coats and Preiss, 1987). This report documents the stratigraphic, structural, and petrologic character of the Holowilena Ironstone with the aim of constraining the depositional environment and mechanism by which this iron formation was deposited.

The close association of Neoproterozoic iron formations with glacial deposits led to their incorporation into the Snowball Earth hypothesis (Kirschvink, 1992). According to this hypothesis, the oceans are suggested to have experienced temporary anoxia due to restriction from the atmosphere during extreme glaciation allowing dissolved iron to build up in the newly anoxic oceans under ice cover. During glacial retreat, the oceans become oxidised, leading to the deposition of iron formations as a "last gasp" of the Sturtian glaciation (e.g. Kirschvink, 1992; Hoffman et al., 1998).

Other authors have suggested that glacial influence is not important and have suggested that iron minerals of Neoproterozoic iron formations were precipitated as a result of hydrothermal activity in small Red Sea-type basins during the break-up of the supercontinent Rodinia (e.g. Yeo, 1983; Breitkopf, 1988; Eyles and Januszczak, 2004; Freitas et al., 2011), potentially in association with mafic volcanism (e.g. Tang et al., 1987; Basta et al., 2011).

Other models involve a rift basin setting, without rift-related hydrothermal activity, based upon the effect of palaeoceanography on ocean chemistry. Baldwin et al. (2012) proposed a model for the deposition of Neoproterozoic iron formation in the Rapitan Group, Northwest Territories, Canada, which involves a fully oxidised Neoproterozoic ocean,

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with iron formation deposition in a partially restricted bathymetric basin with inhibited deep circulation and mixing with the ocean proper. This palaeoceongraphic model is not dissimilar to snowball oases proposed by Hoffmann et al. (2004): both of these models invoke bathymetric sills resulting from active rifting that become restricted due to complete ice cover as a means of facilitating ferruginous conditions in an otherwise fully oxygenated Neoproterozoic ocean.

Most hypotheses for the origin of Neoproterozoic iron formations are aimed at explaining the ferruginous state of the ocean required for sedimentary iron formation. The disappearance of iron formations from the geological record during the Palaeoproterozoic led researchers to infer that a dramatic increase in atmospheric oxygen content around 2.4 Ga, dubbed the Great Oxidation Event, resulted in persistent deep ocean oxygenation (e.g. Holland, 1984). However, many recent investigations from a variety of different datasets indicate ferruginous oceanic conditions probably prevailed both before and after the Sturtian glaciation (e.g. Canfield et al., 2008; Johnston et al., 2010; Poulton and Canfield, 2011; Hood and Wallace, 2014; Hood and Wallace, 2015; Tahata et al., 2015). Hood and Wallace (2014, 2015) provide evidence of an extremely anoxic and ferruginous ocean for a long period following the Sturtian glacials. In fact, there is much evidence to suggest that deep waters remained ferruginous in the late Neoproterozoic and possibly into the Palaeozoic (Dahl et al., 2010; Johnston et al., 2010; Li et al., 2010; Wen et al., 2015).

If Neoproterozoic oceans were dominantly ferruginous before, during, and after the Sturtian glaciation, then hypotheses for glacial-induced oceanic iron sources are probably not necessary and perhaps not even relevant to the origin of Neoproterozoic iron formations. A more important problem might be what causes the oxidation of these ferruginous water bodies, and why iron formations are mostly restricted to the Sturtian glacial period and are not common in the Neoproterozoic in general.

2. Geological setting of the Holowilena Ironstone

The Holowilena Ironstone occurs within the Adelaide Geosyncline in the Central Flinders Ranges, South Australia: a sequence of Neoproterozoic to Cambrian sediments interpreted to have been deposited in rift basins during the break-up of Rodinia (Preiss, 2000). This study focuses on the Holowilena South area, near the Holowilena South station. The Holowilena Ironstone is a member of the Yudnamutana Subgroup which is interpreted to represent the "syn-glacial" sequence of the Sturtian glaciation (~750–700 Ma; Preiss, 1987). The Yudnamutana Subgroup is interpreted to have been deposited in the NW-SE-oriented marine rift complex of the Baratta Trough (Fig. 1) within the Adelaide Geosyncline during the rifting of Rodinia (Preiss, 2000).

In the Holowilena South area, the Yudnamutana Subgroup trends broadly SW-NE and dips sub-vertically and has undergone negligible to lower greenschist facies metamorphism: lower grade than that of the correlative Braemar iron formation further south in the Central Flinders Ranges (Lottermoser and Ashley, 2000). The basal unit of the Yudnamutana Subgroup is the Pualco Tillite, which consists of massive diamictites, siltstones, sandstones, and carbonates (Forbes and Cooper, 1976). Boulders in the diamictites consist of a wide range of lithologies including quartzite, dolomite, and granite. Massive pebbly sandstone and abundant soft sediment deformation are also evident within this unit. The Pualco Tillite has been interpreted to represent glaciomarine deposition under an extensive floating ice-sheet during the extreme glaciation of the initial Sturtian glacial event (Preiss, 1987). Lonestones are of a wide provenance and are interpreted as ice-rafted dropstones, with diamictites commonly reworked due to currents and gravity flows to form massive, structureless tillite successions interbedded with carbonates and siltstones. The Pualco Tillite passes gradationally into the Holowilena Ironstone locally in the Holowilena South area, which is not laterally extensive within the Yudnamutana Subgroup. The Holowilena Ironstone was originally described as a "Sturtian glacigene unit" by Dalgarno and Johnson (1965). Overlying the Holowilena Ironstone is the Wilyerpa Formation, a thick (<2.5 km) sedimentary succession that is lithologically heterogeneous both laterally and up section. It is composed of massive and stratified diamictites and shales/siltstones with common lonestones interbedded with sandstones, dolomite, dolomitic siltstones, and shales. The Wilyerpa Formation, which overlies the Holowilena Ironstone, contains a wide range of lonestone lithologies, the lonestones being interpreted as ice-rafted dropstones and is interpreted as a glaciomarine succession (Busfield and Le Heron, 2014). The Wilyerpa Formation is overlain by the Tapley Hill Formation which consists of non-lonestone-bearing siltstones and shales and is interpreted to represent the beginning of an interglacial period following the Sturtian glaciation (Preiss, 1987).

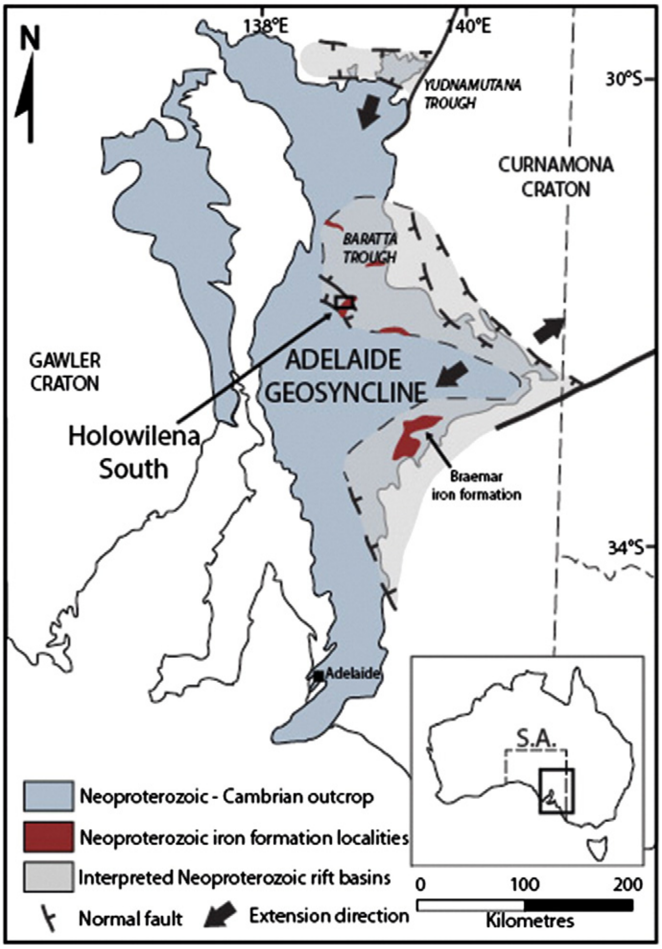

Fig. 1. Location of the study area, Holowilena South, within the Adelaide Geonsyncline, South Australia. Image modified after Giddings and Wallace (2009) and Preiss (2000).

3. Methods

Field work was undertaken near the Holowilena South station (AMG reference 300,000 mE, 460,000 mN) in the central Flinders Ranges, South Australia. Stratigraphic sections were measured through the Holowilena Ironstone and the Wilyerpa Formation, which overlies the Holowilena Ironstone. Fifty-five samples were collected from surface outcrop for petrographic analysis. Where possible, the sampling was intended to represent the range of facies types present in the Holowilena South area. Polished thin sections were prepared from the iron formation samples and petrographically analysed using transmitted and reflected light microscopy. Further petrographic analysis was conducted carried via scanning electron