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Periglacial paleosols and Cryogenian paleoclimate near Adelaide, South Australia

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ABSTRACT

Late Cryogenian deformation of the Reynella Siltstone near Hallett Cove, South Australia has been interpreted as shallow marine methane seeps, which were furthermore proposed to have played a role in deglaciation from "Snowball Earth". Re-examination and new analyses of these same outcrops confirms an earlier interpretation of this intrastratal deformation as periglacial paleosols, which are evidence that even at maximum extent, late Cryogenian glaciers did not cover all continental lowlands, let alone the world ocean. Known Miocene and Pliocene methane seeps of California examined for this study are very different in their gray color, rounded nodules and clayey host rock, compared with red, highly deformed, and silty to pebbly Reynella Siltstone of Hallett Cove. Stable isotopic composition of nodular carbonate in the Reynella Siltstone fails to show extreme carbon isotopic depletion or the meteoric oxygen lines characteristic of known methane seeps and sphaerosideritic waterlogged paleosols, but instead shows covariance of carbon and oxygen isotopic composition comparable with that in pedogenic and subaerial carbonate of well drained soils. Mass balance geochemical analyses show modest weathering compatible with sand wedge structures and evaporitic pseudomorphs indicative of arid and frigid paleoclimate. Outcrops of Reynella Siltstone near Hallett Cove represent frigid low latitude floodplains, not submarine methane seeps nor global glaciation.

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1. Introduction

Coastal cliff exposures of the Reynella Siltstone Member of the Elatina Formation from Marino Rocks south to Hallett Cove, near Adelaide, South Australia (Fig. 1), played an important role in Neoproterozoic stratigraphy (Segnit, 1940), and remain important to understanding the last widespread Snowball Earth episode of the Neoproterozoic (Kennedy et al., 2008; Shields, 2008). There are beautifully preserved Permian tillites and striated pavements near Hallett Cove (Segnit, 1940), but other sea cliffs nearby have been disappointing as evidence of Cryogenian glaciation because they lack convincing Precambrian tillites like those known from the Flinders Ranges to the north (Mawson, 1940). The term Marinoan, from nearby Marino Rocks is used in a chronostratigraphic sense to include late Cryogenian and Ediacaran (Fig. 2; Mawson and Sprigg, 1950), but the terminal Cryogenian glacial advance during the Marinoan time-rock interval is best called the Elatina Glaciation (Mawson, 1939; Williams et al., 2008), and not "Marinoan glaciation" (Kennedy et al., 1998; Hoffmann et al., 2004). For many years the Elatina Formation near Hallett Cove has been interpreted as evaporitic, oxidizing, supratidal and intertidal paleoenvironments (Dyson and von der Borch, 1983; Alexander, 1984), including calcareous nodular and ice-deformed paleosols (Dyson and von der Borch, 1986; Williams, 1991), but more recently Kennedy et al. (2008) have interpreted nodules and deformation as submarine methane seeps. The paleosol hypothesis did not consider methane, and the methane hypothesis did not consider paleosols, so our study provides comprehensive stratigraphic, petrographic and geochemical data from multiple localities to test the alternatives of methane seeps or paleosols in the Reynella Siltstone Member of the Elatina Formation.

Testing of these hypotheses has wider implications, because methane seeps have been proposed as a source of greenhouse warming responsible for termination of the Elatina Glaciation and the Cryogenian Period (Kennedy et al., 2008; Shields, 2008). A soil rather than seep interpretation of these strata negates the idea of methane-driven dramatic climatic warming after Snowball Earth, and confirms lack of evidence for glacial moraines at Hallett Cove (Mawson, 1940), thus limiting the seaward extent of Elatina Glaciation from its mountain hinterland in the current Peake and Denison Range of South Australia (Lemon and Gostin, 1990; Retallack, 2011). Extensive Cryogenian equatorial oceans have been predicted by

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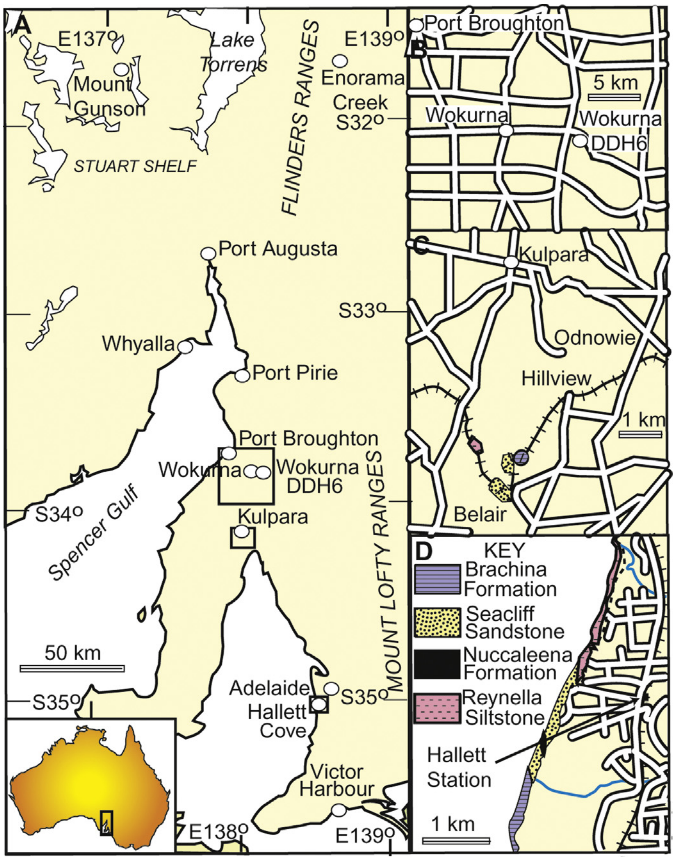

Fig. 1. Location of Hallett Cove (A), Wokurna 6 bore (B) and Kulpara (B) in South Australia.

some global circulation computer models (Hyde et al., 2000) and biomarker evidence for continued photosynthesis (Olcott et al., 2005). Equatorial seaways would have been important for the survival of life (Runnegar, 2000) compared with total freezing of lowlands and sea in snowball Earth scenarios of Hoffman et al. (1998) and Hoffman and Schrag (2002). Our study reconsiders these classical outcrops for evidence of methane seeps, glacial facies and paleosols, and implications for the extent and termination of the last Cryogenian glaciation.

2. Materials and methods

The Reynella Siltstone Member of the Elatina Formation was observed in two outcrops (Fig. 1): sea cliffs near Hallett Cove (S35.06317° E138.50136°), and the railway cuttings south of Kulpara (S34.12157° E138.033844°). Also examined was drill core of the Reynella Siltstone Member from Wokurna DDH 6 (S33.7134463° E138.1411738°), stored at Primary Industries Research of South Australia (PIRSA), in the Adelaide suburb of Glenside. At all locations paleosols were characterized, and measurements taken of the depth to salts, thickness of salt accumulation horizons and size of nodules (Supplementary information Table S1). Other correlative sections examined for this work include the Elatina Formation below basal Ediacaran stratotype monument on Enorama Creek (S31.33150° E138.63339°), and the Whyalla Sandstone and Cattle Grid Breccia (Williams and Tonkin, 1985; Williams et al., 2008) in Mt Gunson Mine (S31.44278° E137.135350°) workings on July 5, 2007 (Figs. 1 and 2).

For comparison with putative methane seeps of Hallett Cove (Kennedy et al., 2008), some undisputed Neogene methane seeps were examined from California (Aiello et al., 2001; Aiello, 2005): near Santa Cruz (N36.949961° W122.04539°), Jalama Beach (N34.51831° W120.50828°), and Santa Barbara, California (N34.408948° W119.856324°).

Samples were collected for a variety of petrographic and geochemical studies, which aimed to characterize mineral composition, grain size, major element and stable isotopic composition

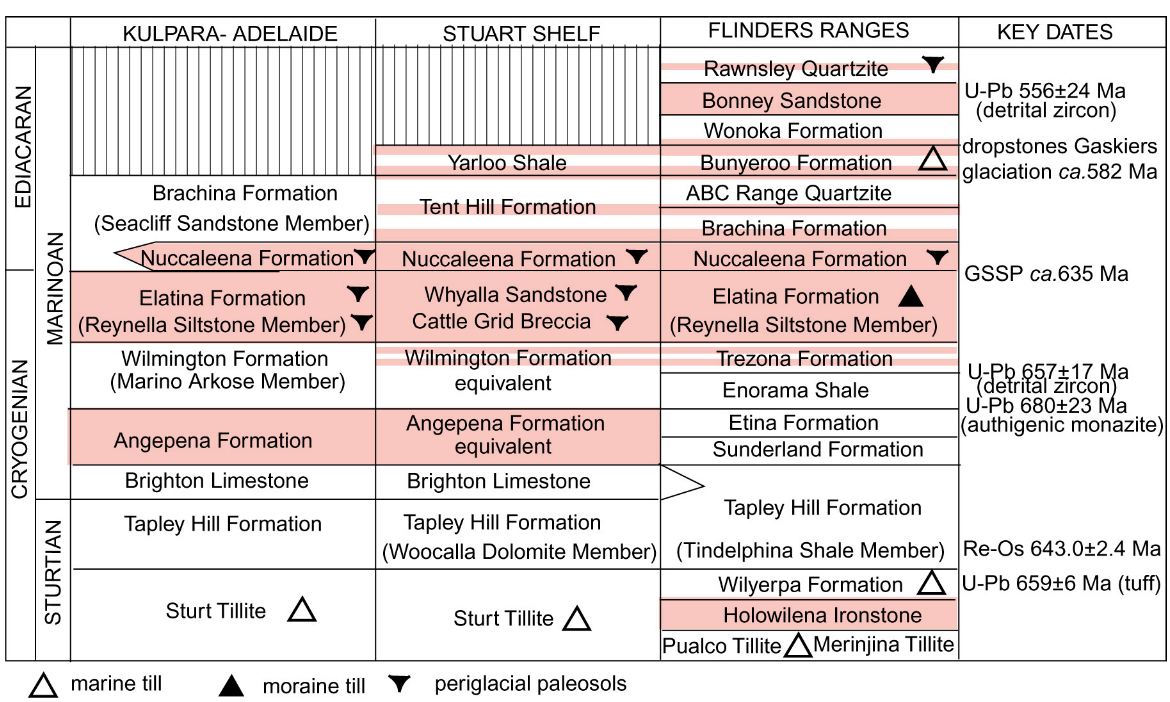

Fig. 2. Cryogenian–Ediacaran stratigraphy and radiometric dating of Adelaide–Kulpara and neighboring regions of South Australia (after Ireland et al., 1998; Calver et al., 2004, 2013; Kendall et al., 2009; Van Kranendonk et al., 2008; Williams et al., 2008; Fanning and Link, 2008; Mahan et al., 2010). Shaded units are red beds, and unshaded unites are bluish and greenish gray.