Gondwana Research 40 (2016) 1–20

Contents lists available at ScienceDirect

Gondwana Research

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

Archean coastal-plain paleosols and life on land

Gregory J. Retallack [a,*], David H. Krinsley [a], Robert Fischer [b], Joshua J. Razink [b], Kurt A. Langworthy [b]

[a] Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA
[b] Center for Advanced Materials Characterization, University of Oregon, Eugene, OR 97403, USA

ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form 26 July 2016
Accepted 28 August 2016
Available online 15 September 2016

Handling Editor: M. Santosh

Keywords:
Archean
Paleosol
Microfossil
Western Australia

ABSTRACT

Coastal-plain paleosols in the 3.0 Ga Farrel Quartzite of Western Australia have organic surface (A horizon) and sulfate-rich subsurface (By) horizons, like soils of the Atacama Desert of Chile, Dry Valleys of Antarctica, and 3.7 Ga paleosols of Mars. Farrel Quartzite paleosols include previously described microfossils, permineralized by silica in a way comparable with the Devonian Rhynie Chert, a well known permineralized Histosol. Five microfossil morphotypes in the Farrel Quartzite include a variety of spheroidal cells (*Archaeosphaeroides*) as well as distinctive large spindles (new genus provisionally assigned to cf. *Eopoikilofusa*). Previously published cell-specific carbon isotopic analyses of the Farrel Quartzite microfossils, and unusually abundant sulfate considering a likely anoxic atmosphere, allow interpretation of these morphotypes as a terrestrial community of actinobacteria, purple sulfur bacteria, and methanogenic Archaea.

1. Introduction

The search for evidence of Archean life on Earth has been unusually successful over the past three decades because of a "basic strategy: look in black (carbon-rich) cherts that are in fine-grained (unmetamorphosed) rocks and associated with *Cryptozoon*-like stromatolites" (Schopf, 1999). Like stromatolites, the Archean fossil record has been interpreted as marine (Allwood et al., 2006; Flannery and Walter, 2012; House et al., 2013), and rarely lacustrine (Awramik and Buchheim, 2009), although lacustrine is apparently controversial (Sakurai et al., 2005). The variety of putative and likely Archean paleosols are reviewed by Rye and Holland (1998), who assumed that all were sterile to simplify estimates of past atmospheric conditions. Possible microfossils in paleosols have been discounted as remnants of ephemeral ponds (Rye and Holland, 2000). Microbial mats in floodplain and intertidal facies (Homann et al., 2015) also appear more like freshwater aquatic (Flannery and Walter, 2012) than terrestrial crusts (Retallack, 2012). Nevertheless, Archean coastal-plain paleosols may have been hiding in plain sight for several decades as coastal sabkha, playa and salina facies. For example, Buick and Dunlop (1990) concluded that 3.5 Ga evaporites were "almost everywhere laid down in a shallow submarine to intermittently exposed environment". Lowe and Worrell (1999) conclude that 3.4 Ga evaporites "represent sedimentation in marginal hypersaline salinas and low-energy coastal lagoons." These are not only sedimentological facies, but also what soil scientists regard as soils, variously classified as Gypsids (Soil Survey Staff, 2014) or Solonchaks (Food and Agriculture Organization, 1974). Playa and salina soils are inundated less commonly than many floodplains, and their development of desiccation cracks, salt crystals, and shear planes is soil-forming rather than a sedimentary process (Retallack, 2001). Evaporitic paleosols of the Farrel Quartzite (3.0 Ga) were also assigned to "shallow to sub-aerial sedimentary environment" by Sugitani et al. (2003). We confirm the discovery by those authors of diagnostic non-marine features and minerals, including sand crystals (Retallack, 2013, 2014; Nabhan et al., 2016), and nahcolite (Lowe and Worrell, 1999; Jagniecki et al., 2015). This study of evaporitic coastal-plain paleosols with preserved microfossils provides geochemical and microfossil evidence for Archean terrestrial microbial communities.

The 3.0 Ga Farrel Quartzite is famous for microfossils of at least five distinct morphotypes (Sugitani et al., 2007, 2009, 2011), validated as genuine microfossils by a variety of isotopic (House et al., 2013), maceration (Grey and Sugitani, 2009), chemical and ultrastructural tests (Oehler et al., 2010). The Farrel Quartzite has been mapped though complex structures (Sugitani et al., 2006), and its hydrothermal and metamorphic history elucidated using whole rock and trace element chemistry (Sugahara et al., 2010). Its sedimentary facies and structures have also been interpreted over an outcrop strike of 7 km (Sugitani et al., 2003). Virtually every aspect of the Farrel Quartzite has been studied except its paleosols.

2. Materials and methods

Geological and paleosol sections of the Archean (3.0 Ga) Farrel Quartzite near Mt. Grant in the Pilbara region of Western Australia (Fig. 1) were measured and sampled at centimeter scale using a tape measure, and by noting Munsell color and field reaction with dilute hydrochloric acid (Fig. 2). Both color and calcareousness were altered by

---

[*] Corresponding author.
E-mail address: gregr@uoregon.edu (G.J. Retallack).

http://dx.doi.org/10.1016/j.gr.2016.08.003
1342-937X/© 2016 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

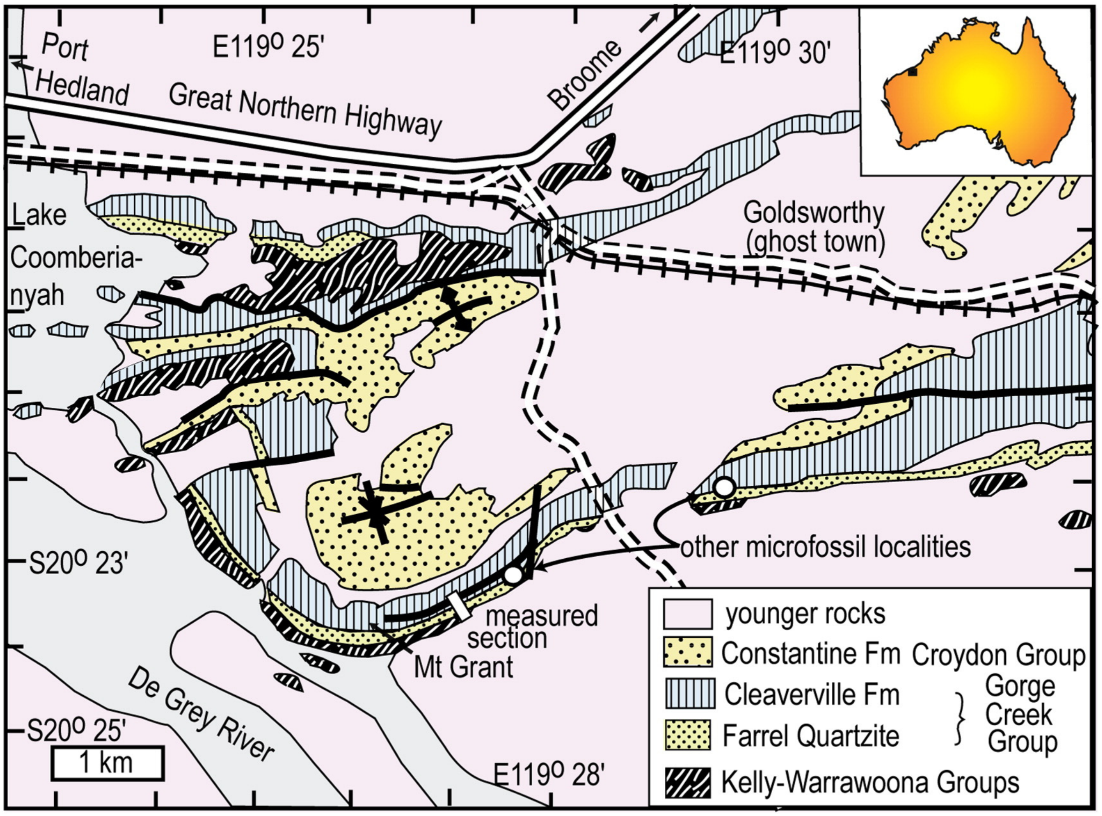

Fig. 1. Location of studied section of Archean paleosols in the Farrel Quartzite near Mt. Grant, Western Australia. Simplified after DeGrey 1:100,000 sheet geology (Smithies et al., 2004) with updated stratigraphic nomenclature (Van Kranendonk et al., 2006).

diagenesis and metamorphism, but these observations are useful for locating the sections. Size, stratigraphic limits, and percentage area occupied by nodules and crystals were also measured in the field. Oriented thin sections prepared vertical to bedding were point-counted using a Swift automated stage and Hacker counting box. Point counting was adjusted for pervasive silicification and recrystallization to crystallites minimally 5 μm across, so that this grain size and smaller was counted as clay. Evaporite minerals were all quartz pseudomorphs, and counted from a distinctive chalcedonic texture unlike simple to undulose extinction of quartz and recrystallized chert. Original evaporite mineralogy could not be determined in thin section, but followed previous identifications based on polished slabs and microprobe analyses of Sugitani et al. (2003). Opaque grains include both kerogen and opaque oxides. Two counts were made from each thin section: one for grain size and one for mineral composition (See Supplementary Information Tables S1 and S2).

Chemical analyses of selected samples (Supplementary Information Table S3) were performed by ALS Chemex of Vancouver, British Columbia, using XRF on glass disk and FeO by Pratt titration. The standard for the analyses was Canadian Certified Reference Materials Project standard SY-4, a diorite gneiss from near Bancroft, Ontario. Errors (2σ) are from 89 replicate analyses of the standard in the same laboratory. This technique failed for analysis of titania, which was below detection (<0.01 wt.%) for two samples (R4336 and R4337), but this sample level was analyzed previously in Japan (Sugahara et al., 2010, sample GFSV6) by XRF at 0.0053 wt.%. Many chemical compositions were identical to those previously determined for these rocks by Sugitani et al. (2003, 2006), and Sugahara et al. (2010). Cores from the abandoned Mt. Goldsworthy Mines were neither used by their studies nor ours, which are based on the freshest possible samples collected from outcrops.

Bulk densities were determined from 20 to 40 g samples using paraffin (Retallack, 1997a) at the University of Oregon, with errors from 10 replicate density determinations of Western Australian Archean chert (specimen R4309) in order to calculate gains and losses (mass transfer of Brimhall et al., 1992) of elements in a soil at a given horizon ($\tau_{w,j}$ in moles) from the bulk density of the soil (ρ_w in $g \cdot cm^{-3}$) and parent material (ρ_p in $g \cdot cm^{-3}$) and from the chemical concentration of the element in soils ($C_{j,w}$ in wt.%) and parent material ($C_{p,w}$ in wt.%). These data are needed to calculate diagenetic and metamorphic alteration as well as soil formation. Also needed are changes in volume within a single bed during weathering, silicification and metamorphism (strain of Brimhall et al., 1992), estimated from an immobile element in soil (such as Ti used here) compared with parent material ($\varepsilon_{i,w}$ as a fraction). Parent material is the rock with sedimentary structures immediately below the profile in which such structures are obscured. The relevant Eqs. (1) and (2) (below) are the basis for calculating divergence from parent material composition.

$$\tau_{j,w} = \left[\frac{\rho_w \cdot C_{j,w}}{\rho_p \cdot C_{j,p}}\right]\left[\varepsilon_{i,w} + 1\right] - 1 \tag{1}$$

$$\varepsilon_{i,w} = \left[\frac{\rho_p \cdot C_{j,p}}{\rho_w \cdot C_{j,w}}\right] - 1 \tag{2}$$

Quantitative counts of abundance of five recognized morphotypes of microfossils recognized by Sugitani et al. (2011) were made from ten photomicrographs 1300 by 890 μm in size at subdivisions of oriented thin sections. These ten counts were then averaged to obtain numbers of each morphotype per square millimeter. Separate counts were made for microfossils within matrix and enclosed within sand-sized clasts (Supplementary Information Tables S4 and S5). Also counted were spherical pyrite grains and clusters of spherules like framboids of microbial origin (Wignall and Newton, 1998). The fossiliferous thin