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Diverse microbially induced sedimentary structures from 1 Ga lakes of the Diabaig Formation, Torridon Group, northwest Scotland

Richard H.T. Callow *, Leila Battison, Martin D. Brasier

Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK

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ABSTRACT

The siliciclastic lacustrine rocks of the ~1000 Ma Diabaig Formation, northwest Scotland, contain a remarkable diversity of macroscopic structures on bedding planes that can be compared with various kinds of microbially induced sedimentary structures (MISS). Field sedimentological investigations, combined with laboratory analysis of bedding planes and petrographic study of thin sections have allowed us to characterise a range of depositional environments and document the spectrum of biological structures. MISS are reported from frequently subaerial environments, through commonly submerged facies, and down to permanently sub-wavebase settings. Palaeoenvironmental conditions (water depth, exposure, hydrodynamic energy) control the distribution of MISS within these facies. This demonstrates that mat-forming microbial communities were arguably well adapted to low light levels or periodic exposure. Some MISS from the Diabaig Formation are typical of Precambrian microbial mats, including reticulate fabrics and 'old elephant skin' textures. In addition to these, a number of new and unusual fabrics of putative microbial origin are described, including linear arrays of ridges and grooves (cf. 'Arumberia') and discoidal structures that are comparable with younger Ediacaran fossils such as *Beltanelliformis*. These observations indicate that benthic microbial ecosystems were thriving in freshwater lake systems ~1000 Ma, and indicate how microbially induced sedimentary structures may be applied as facies indicators for Proterozoic lacustrine environments. The discovery of structures closely resembling Ediacaran fossils (cf. *Beltanelliformis*) also serves to highlight the difficulty of interpreting simple discoidal bedding plane structures as metazoan fossils.

1. Introduction

How ancient is life on land and how good is its early geological record? The first widespread colonisation of the land is usually envisaged as late Cambrian to Ordovician (e.g. Wellman, 2010), reaching a higher stage of complexity by the Devonian (e.g. Trewin and Rice, 2004). Geochemical evidence has been used to argue for a greening of the land either during the late Proterozoic (Knauth and Kennedy, 2009), or even during late Archean (Watanabe et al., 2000). Molecular phylogeny likewise suggests that both actinobacterial and cyanobacterial lineages could plausibly have evolved on land nearly three billion years ago (Battistuzzi et al., 2004), and a number of basal cyanobacterial groups are known only from freshwater environments (Battistuzzi and Blair Hedges, 2009; Blank and Sánchez-Baracaldo, 2010). It has even been suggested that life originated in Precambrian freshwater environments (Horodyski and Knauth, 1994).

Both siliciclastic and carbonate (i.e. travertine and calcrete) depositional systems can provide promising windows in the search for early terrestrial ecosystems (Brasier, 2011; Strother et al., 2011). One of the most promising places for establishing a baseline for the early terrestrial (non-marine) biosphere is the ~1000 Ma Torridon Group of northwest Scotland, a c. 6 km thick succession of siliciclastic sedimentary rocks deposited in an intermontane or foreland system of rivers and intercontinental rift basin lakes on Laurentia, spanning the late Mesoproterozoic and early Neoproterozoic (Figs. 1 and 2; Moorbath, 1969; Stewart, 1982; Turnbull et al., 1996; Rainbird et al., 2001; Stewart, 2002; Kinnaird et al., 2007; Cawood et al., 2010; Parnell et al., 2011).

2. Stratigraphic context

The Proterozoic Torridon Group outcrops in northwest Scotland (Fig. 1) is unconformable with the underlying Lewisian Gneiss and Stoer Group and is unconformably overlain by Lower Cambrian rocks (Fig. 2). The Torridon Group has also been correlated with the Morar Group of the Moine Supergroup (Krabbendam et al., 2008). The term "Torridonian" is used as an informal non-stratigraphic term that encompasses all the Proterozoic siliciclastic sedimentary rocks of northwest Scotland (sensu Stewart, 1982, 2002).

* Corresponding author at: Department of Earth Sciences, Memorial University of Newfoundland, 300 Prince Philip Drive, St John's, Newfoundland, Canada A1B 3X5. Tel.: +1 709 864 6762; fax: +1 709 864 7437.
E-mail addresses: rcallow@mun.ca (R.H.T. Callow), leilab@earth.ox.ac.uk (L. Battison), martinb@earth.ox.ac.uk (M.D. Brasier).

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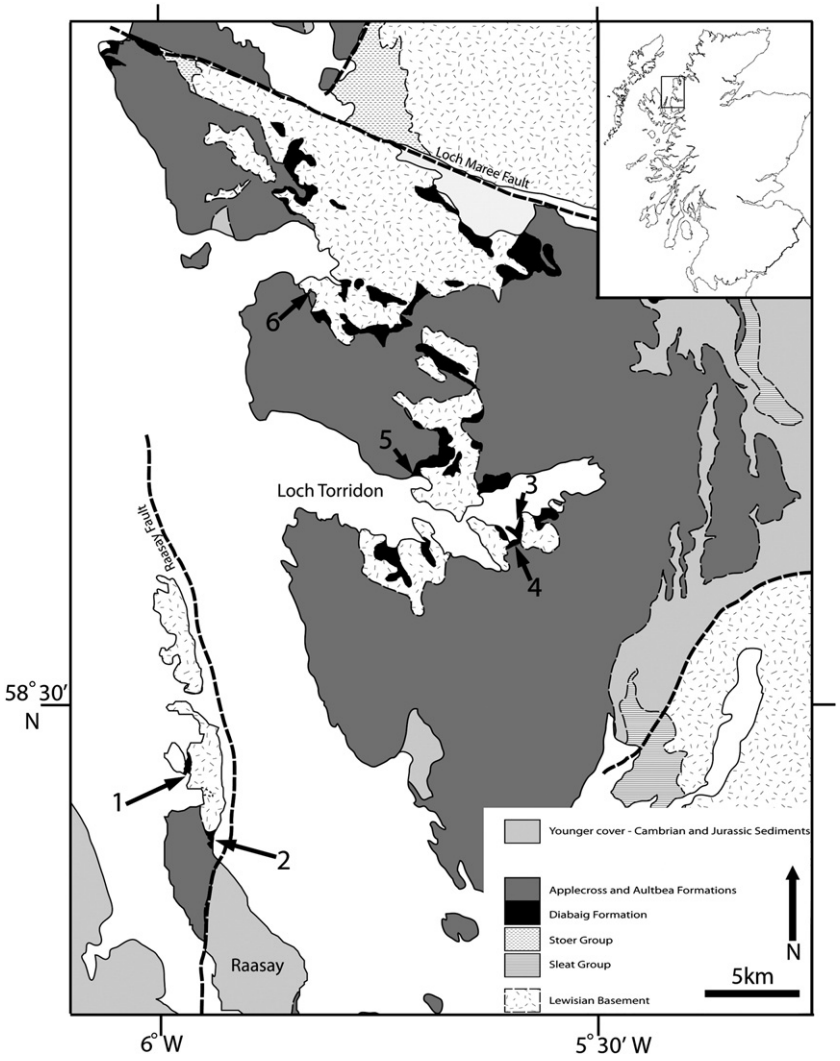

Fig. 1. Simplified geological map of field area showing key studied localities referred to in the text. 1: Fladda, 2: Brochel Castle, 3: Shieldaig North, 4: Shieldaig at Ob Mheallaidh bay, 5: Upper Diabaig village, and 6: Badachro village.

The rocks of the Torridon Group range from sub-wave base laminated mudstones, upper shoreface and intertidal sandstones and mudstones, to intertidal and supratidal deposits, fluvial and alluvial sandstones and siltstones and even conglomerates and alluvial fans (Figs. 2–7; Stewart, 2002). This study focuses upon the fine-grained sandstones, siltstones and mudstones of the Diabaig Formation (Fig. 2; Stewart, 2002). Although originally interpreted as a distal expression of the coarser grained Applecross Formation, field observations and detrital zircon analysis have shown that the fine-grained lacustrine Diabaig Formation is genetically distinct from both the underlying Stoer Group and the overlying coarser grained Applecross and Aultbea formations, which have been reported to be separated from the Diabaig Formation by a sequence boundary (Kinnaird et al., 2007). The rocks of the Diabaig Formation contain sedimentary structures indicating deposition in very shallow water, with periodic subaerial exposure (e.g. short wavelength, symmetrical wave ripples; Figs. 3–6).

Numerous lines of evidence have been used to infer a lacustrine palaeoenvironment for the Diabaig Formation, including; palaeogeographic reconstructions, sedimentological observations, the absence of marine evaporites, zircon provenance and the boron content of illite in shales (Stewart and Parker, 1979; Stewart, 2002; Kinnaird et al., 2007; Spinks et al., 2010; Strother et al., 2011). The Torridon Group has also been tentatively correlated with the non-marine orogenic rift sediments of the Keweenawan Supergroup of the US Midwest and may represent the eastern extension of this depositional system (Stewart, 2002).

Research on the Torridon Group was begun by the pioneering British Geological Survey geologists including Ben Peach, John Horne and Jethro Teall (e.g. Peach et al., 1907) and was continued by geologists including Selley (1965) and Stewart (1966, 2002 and references therein). Organic cellular remains were first discovered in thin sections of phosphatic nodules by Peach et al. (1907), and have subsequently been described from acid macerates of shales and from phosphatic nodules (e.g. Naumova and Pavlovsky, 1961; Downie, 1962; Cloud and Germs, 1971; Zhang et al., 1981; Peat and Diver, 1982; Zhang, 1982; Brasier and Callow, 2007; Brasier, 2009). Recent research suggests that Torridonian microfossil assemblages arguably include eukaryotes as well as other microbial lineages (Strother et al., 2011). Further evidence for flourishing terrestrial ecosystems in the Torridonian has been shown by the report of microbial sedimentary structures within non-marine rocks of the ~1200 Ma Stoer Group (Upfold, 1984; Prave, 2002). Below we provide evidence for a suite of microbially induced sedimentary structures (MISS sensu Noffke et al., 2001) on bedding planes from the c. 1000 Ma Diabaig Formation, Torridon Group (Fig. 2; Turnbull et al., 1996; Parnell et al., 2011).