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Remarkably preserved prokaryote and eukaryote microfossils within 1 Ga-old lake phosphates of the Torridon Group, NW Scotland

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ABSTRACT

The ∼1000 Ma Torridon Group of northwest Scotland are here shown to contain a rich diversity of organic walled microfossils preserved in exceptional detail within sedimentary phosphate. The phosphatic nodules and bands in which they occur are autochthonous, as are the organic fossils they contain. The associated sedimentology of this phosphate is shown to be consistent with a lacustrine setting. Informal taxonomic treatment of the microfossils allows statistical assessment of the relative abundances of different morphotypes across a range of lacustrine environments. Exceptional preservation of pristine organic-walled eukaryotes and prokaryotes, together with a taphonomic spectrum in both physicochemical and biological degradational conditions allows a picture to be built of the earliest lacustrine ecological communities.

1. Introduction

The Mesoproterozoic–Neoproterozoic transition, around 1000 Ma, was a critical interval for the evolution of complex eukaryote cells (Knoll et al., 2006). Cellular microfossil lagerstatten dating from this time are found worldwide in marine sedimentary rocks, and they can be used to record the appearance and diversification of eukaryotic microfossils. Such remains consist largely of compacted carbonaceous materials in shales, and three dimensional organic structures within cherts. For example, the first widely accepted eukaryotic microfossils appeared in shallow marine to deltaic argillites of the 1400 Ma Roper Group (Javaux et al., 2001), while later examples of possible red algal affinity have been reported from marine cherts of the ∼1200 Ma Hunting Formation of Arctic Canada (Butterfield, 2000).

While such exceptionally preserved remains have been used to chart the diversity of putative eukaryotic cells at this time, various preservational or study biases have limited the documentation of the full microbial assemblages. The non-marine Torridonian rocks of northwest Scotland have recently been shown to contain robust evidence for the earliest non-marine eukaryotes (Strother et al., 2011). Phosphatic bands and nodules within the lacustrine rocks have been known to contain a sparsely documented cellular lagerstatten for over a century (Geikie, 1900; Teall, 1907). We here explore the potential of these lagerstatten deposits to preserve a varied assemblage of microfossils, including not only the enigmatic eukaryotic forms, but also autotrophic and heterotrophic bacteria, allowing greater insights into ecosystem components at this time.

Previous reports of microfossils from the Torridon rocks have been obtained almost exclusively from acid maceration of grey shales (Downie, 1962, 1984; Cloud and Germs, 1971; Zhang, 1982; Peat and Diver, 1982). Such a technique reveals only the more recalcitrant and complete organic structures for study because smaller and more delicate forms may be damaged or lost, resulting in the loss of information. As such, the phosphatic nodules, which preserve the organic structures in virtually uncompressed three dimensional suspension, offer a unique opportunity to study a relatively diverse and well preserved microfossil assemblage.

A large number of morphotypes are preserved in phosphate, and these can range in preservation from almost pristine organic microfossils to extensive carbon dissemination, allowing some assessment of biological degradation processes, as well as an estimation of the relative proportions of eukaryotic and prokaryotic forms in these ambient non-marine assemblages.

Some ecological assessment is also made possible within these Torridonian phosphates, owing to the exceptional levels of cellular preservation that the cryptocrystalline mineral structure of the apatite affords. Phosphatic bands and nodules are found throughout the relatively limited extent of the palaeo-lakes, meaning that microfossils have been recovered across much of the basin, potentially allowing a wide range of materials and microorganisms to be analysed.

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2. Geological setting

Rocks of the Torridon Group outcrop along the northwest coast of Scotland, from the Isle of Skye in the south, to Cape Wrath in the north (Fig. 1a and b). They overlie Archaean to Palaeoproterozoic gneisses of the Lewisian basement, with a minimum age 1409 Ma, from K–Ar dating of micas (Fettes et al., 1992). These basement rocks also display a phase of deformation not present in the Torridon, dated between 980 and 999 Ma, indicated by $^{40}Ar/^{39}Ar$ isotopes (Sherlock et al., 2008).

The Torridon Group is divided into four conformable units, from the base upwards, as follows (Fig. 1): the lowermost Diabaig Formation, dated at 994 ± 48 Ma, using Rb–Sr estimates from the phosphatic nodules (Turnbull et al., 1996); the Applecross Formation; the Aultbea Formation, with a whole rock Rb–Sr age of 977 ± 39 Ma (Turnbull et al., 1996); and the Cailleach Head Formation (Stewart, 2002). The whole group reaches a maximum thickness of 6km onshore, and is unconformably overlain by late Lower Cambrian quartzites of the Eriboll Formation (Peach et al., 1907; Cowie and McNamara, 1978).

Around Ullapool and Lochinver (Fig. 1), the group is underlain by sedimentary rocks of the Stoer Group (1177 ± 5 Ma from $^{40}Ar/^{39}Ar$ dating on feldspars (Parnell et al., 2011)), which may have equivalents on Skye (Fig. 1), placed within the Sleat Group (Stewart, 2002; Strother et al., 2011). The relationship between these two latter groups remains enigmatic because the Sleat Group lies within the Kishorn Nappe on the Isle of Skye which, together with its greater degree of metamorphic alteration, make resolving its stratigraphic relationship problematic (Stewart, 2002).

The Torridon Group as thus defined comprises a wholly clastic sequence of red and grey sandstones and shales that accumulated within a fluvio-lacustrine depositional environment (Park et al., 2003; Parnell et al., 2010; Strother et al., 2011), which is thought to have lain well within the continent of Rodinia (Stewart, 2002), at a latitude of around 42° S, as indicated by palaeomagnetism of hematized magnetite (Buchan et al., 2000). Mineral suites are consistent with a wet temperate environment at this latitude (Stewart, 2002).

The Diabaig Formation at the base of the Torridon Group is a well defined lithostratigraphic unit, comprising breccia and coarse sandstone derived directly from, and infilling large palaeovalleys in the underlying Lewisian gneiss. Upwards within this formation, the rocks become finer grained, culminating in a succession of laterally variable fine red sandstones and grey shales, rich in phosphatic nodules and bands. The latter unit corresponds to subunit II of the Diabaig Formation sensu Stewart (2002). Overall, the Diabaig Formation reaches a maximum thickness of around 115 m, including irregularities above the basal unconformity. The overlying Applecross and Aultbea formations make up the vast bulk of the Torridon Group. The Applecross Formation consists mainly of coarse grained pebbly red sandstone. The overlying Aultbea Formation is finer grained and is mostly lacking in pebbles. Rare argillaceous bands are known to occur in both of these red sandstones. Together, these formations reach a maximum thickness of 5000 m. At the top of the group is the Cailleach Head Formation, which reaches a maximum thickness of around 1800 m and its top is truncated by an angular unconformity beneath Cambrian quartzites of the Eriboll Formation. The Cailleach Head Formation is distinctive for preserving a thick sequence of coarsening upward cyclothems, from grey shales to fine to medium red sandstones. Phosphatic nodules and bands can be found widely within this formation.

The entire Torridon succession is currently regarded as of fluvio-lacustrine origin, with much sedimentological and geochemical evidence in support of this view (Stewart, 1982, 2002). Lateral variation of sedimentary structures within the Diabaig Formation is locally significant, including rapid changes from sandy deltaic settings of proximal aspect towards frequently desiccating muddy shorelines, as seen along the southern and northern shores of modern day Loch Torridon respectively. These features suggest the infilling of a small and ephemeral lacustrine basin. Large scale cross bedding and channel structures within the Applecross and Aultbea formations arguably preserve river system sediments of relative maturity. Small scale sedimentological structures are likewise suggestive of a lacustrine (rather than marine) origin for the silts and argillites. Cyclothems within the Cailleach Head Formation indicate periodic infilling of the basin by river-borne sediment, followed by subsequent deepening. There are at least 15 cycles of regularly fluctuating water depth. Small wavelength wave ripples, reaching a maximum of only 6 cm, are observed in all these units, consistent with a short wave fetch of the kind to be expected in a small and restricted water body. Carbonate minerals within the underlying Stoer Group (Upfold, 1984) are interpreted as pore-water calcretes formed within alluvial sediments (Brasier, 2011), but neither calcretes nor evaporitic minerals have been observed as yet within the overlying Torridon Group, even though desiccation cracks are abundant within certain parts of the succession. Nor have we found structures consistent with a marine setting, such as synaeresis cracks (formed during dewatering of sediments exposed to differing ambient salinities). Studies carried out on the boron content of illite clays are consistent with a terrestrial environment without marine influence (Stewart and Parker, 1979).

Black and waxy sedimentary phosphate occurs within the Diabiag Formation at the base of the Torridon Group, and in the Cailleach Head Formation at the top of the group (Stewart, 2002). Variously, it occurs as: laterally extensive bands up to 2 cm thick; millimetric and sub-millimetric veneers on argillaceous bedding surfaces; discontinuous nodules up to 2 cm thick, oriented parallel and subparallel to the bedding surface; and occasional elongated rip-up clasts less than 1 cm thick and 3 cm long, reaching a maximum of 45° inclination from the bedding surface, frequently concentrated near the bases of massive sandy horizons. The habit of the phosphate varies between formations, and also between locations within the Diabaig Formation. Overall, its appearance is not regular or cyclic, but neither is it confined to restricted spatial or temporal horizons. Within the Diabiag Formation, laterally discontinuous bands can be found within fine sandy portions of the section at the type locality of lower Diabiag (Fig. 1, locality 3), and thick lenses with restricted width are seen in Fladday, off the island of Raasay (Fig. 1, locality 4). At Cailleach Head (Fig. 1, locality 1), no continuous bands were observed, but many sandy beds contain rip-up clasts of variable size and orientation. Some laminated shales, for example those of the Diabaig Formation at Badachro (Fig. 1, locality 2), also contain a considerable amount of disseminated phosphate and carbonaceous material, giving them an overall dark waxy lustre. In general, the in situ bands and nodules of phosphate form upon laminar surfaces of the grey shales, but are uncommonly found draping the troughs of wave ripples in more sandy horizons and can be seen at the edges of desiccation cracks.

In thin section, the sedimentary phosphate appears amorphous and cryptocrystalline. Crystal sizes range from around 500 nm to 10 μm, and broad transitions are seen between zones of particular crystal sizes. Organic material or fossil structures are not limited to a particular crystal size domain, being equally distributed throughout entire bands or nodules. There appear to be two interfingering phases of phosphate in equal abundance in the lenses and bands. Preliminary elemental mapping suggests the phase difference to be due to enrichment of Fe in one phase, presumably substituting for Ca in the apatite framework. Further work remains to be carried out to understand the formation and significance of this mineralogy in relation to lake dynamics and fossil preservation. Locally, layering can also be picked out within the phosphatic matrix, derived variously from differing quantities of organic or clastic material, or