Characterizing nutrient cycles in late Precambrian lakes

Final report for the Lewis & Clark Fund for exploration and field research in astrobiology

Eva E. Stueeken

1. Introduction and motivation

The purpose of this field trip was to collect rock samples from the late Mesoproterozoic Torridonian Supergroup in Scotland for my postdoctoral research project. The project focuses on investigating the potential role of non-marine environments during the early evolution of life on Earth. Most of what is known about metabolic innovations or the appearance of complex life is based on data from marine sedimentary rocks. The record of life on land is sparse, partly because soils and fluvial or lacustrine sediments are rarely preserved. However, it is conceivable that terrestrial environments were important habitats, because they were oxidized much earlier than the deep ocean (reviewed by Lyons et al., 2014) and may therefore have had a higher supply of nutrients and metabolic energy sources.

The Torridonian Supergroup (1.2-1.0 Ga, Fig. 1) is one of the few Precambrian sequences that was likely deposited in a non-marine setting (Stewart, 2002). It contains the oldest known non-marine eukaryotic fossils (Strother et al., 2011), the largest sulfur isotope fractionation prior to the Neoproterozoic (Parnell et al., 2010), and a rich record of microbial mats (Callow and Brasier, 2011; Prave, 2002), making it a promising target for further investigations. My goal in this project is to characterize the carbon, nitrogen, and sulfur cycle as well as the micronutrient inventory (Mo, V, Cu, Zn, Cd, Zn) and to compare those to existing marine records. Furthermore, I am planning to analyze zinc isotopes in sediments and surrounding crustal source rocks to establish a source-sink mass balance and advance our understanding of the zinc isotope proxy for further applications in the Precambrian. Together these data may allow me to constrain nutrient availability and biological productivity in the Torridonian lakes relative to the ocean.

The samples for this project were collected during a field trip to the Scottish Highlands (Fig. 2) from September 9 to 17, 2014. Sampling sites were mostly based on previous studies (Parnell et al., 2010; Stewart, 2002; Strother et al., 2011). Prof. A. Prave (University of St. Andrews) provided additional advice and maps, Prof. T. Lyons (UC Riverside) joined for part of the trip and provided expertise during sample collection.

2. Field itinerary

The Torridonian Supergroup in northwest Scotland is divided into three groups (Fig. 1), the Stoer Group, the Sleat Group and the Torridon Group, all of which have been interpreted as non-marine, *i.e.* fluvial and lacustrine deposits (Stewart, 2002). The Torridon Group (~1.0 Ga) overlies the Stoer Group (~1.2 Ga) in the north and the Sleat Group further south on the Isle of Skye, but the exact age of the Sleat Group is unknown (Turnbull et al., 1996). All three units are predominantly composed of sandstones, greywackes and conglomerates, commonly interpreted as fluvial deposits (Stewart, 2002). Shales and carbonates, the major targets of this study, are relatively rare, but present as centimeter- to meter-scale horizons within some of the sandstone beds. The Torridonian Supergroup unconformably overlies the Lewisian Gneiss Complex (Johnson et al., 2002), consisting primarily of metamorphosed mafic and felsic igneous rocks of early Precambrian age, which have contributed significantly to the sediments of the Torridonian Supergroup (Stewart, 2002). A variety of Lewisian rocks were sampled during this trip to constrain the isotopic and elemental composition of source material to the lake basins.

2.1. The Sleat Group (September 9-10)

I collected samples of the Loch na Dal Formation and the Beeinn na Seamraig Formation in the Sleat Group on the eastern part of the Isle of Skye. This part of Torridonian Supergroup is of slightly higher metamorphic grade, making the rocks harder and more difficult to sample. Because metamorphism can affect the abundance and isotopic composition of organic matter, the Sleat Group samples are of lower priority for this study. Carbon/hydrogen and carbon/nitrogen ratios will later be used to assess metamorphic degradation.

I focused on exposures around Loch na Dal and Glenn Arroch, where outcrops were well accessible in road cuts. The abundant sandstones and siltstones in the Sleat Group commonly show cross bedding (Fig. 3a), which may support the argument of fluvial deposition (Stewart, 2002). The silts and shales (Fig. 3b) show no visible evidence of desiccation, unlike in the Torridon and Stoer Group, possibly indicating sedimentation in a deeper water column after turbidity flows (Stewart, 2002).

2.2. The Torridon Group (September 11-13 and 15)

The principle site for dark grey shales of the Torridon Group was the Diabaig Formation, in particular at its type locality near the town of Diabaig (Fig. 4a), where the grey shale sequence is ~110 m thick. The shales are interlaminated with silt and fine sand. Sandstone increases in abundance and iron oxide content up section; interbedded shales eventually change from grey to red. Mudcracks are common on bedding planes throughout the grey and red shale (Fig. 4b), suggesting deposition in a shallow environment exposed to the atmosphere. Many surfaces show crinkled ornamentation, possibly representing fossilized microbial mats (Callow and Brasier, 2011; Prave, 2002, Fig. 4c). The sandstone frequently displays symmetric wave ripples and cross bedding and likely represent brief energetic intervals, perhaps caused by turbidites (Stewart, 2002). From this 110m section, I collected 40 samples in stratigraphic order at 0.5-3m spacing. The samples thus cover environmental gradients from quiet (shale, microbial mat coating) to turbulent (silty, sand-rich, cross-bedded), and from anoxic (dark grey shale) to oxic (red shale), which will be valuable for reconstructing biogeochemical cycles under changing conditions. The Lewisian Gneiss Complex is also exposed along Diabaig beach, which allowed me to collect the potential source rock that may have shed sediments into the Diabaig basin.

To investigate lateral variation between basins, I also collected samples from smaller outcrops of the grey Diabaig shales near Badachro and Victoria Falls, around 10km further north. In both cases, the upper Diabaig Fm is only a few meters thick. The site near Badachro is within a few meters of the Lewisian basement, and blocks of gneiss and amphibolites can be seen in basal conglomerates of the lower Diabaig Formation (Fig. 5), supporting the idea that the Lewisian gneiss was an important source rock.

Mudrocks in the Cailleach Head Formation, the upper-most unit of the Torridonian Supergroup, are different in character from the Diabaig shales. The Cailleach Head Formation is thought to represent repetitive cycles of deepening and shallowing of the depositional environment (Stewart, 2002, Fig. 6). The mudrocks would thus represent the deepest interval, but unlike in the upper Diabaig Formation, they are only decimeters in thickness and only light grey or red. These samples are also of relatively higher metamorphic grade, making them lower priority for the project. With the help of Prof. Tim Lyons, I collected mudrocks from several different horizons separated by several meters.

2.3. The Stoer Group (September 14 and 16)

The upper Bay of Stoer Formation is best exposed at its type locality in the Bay of Stoer. The lower part of the formation consists primarily of red, cross-bedded sandstone with minor beds of red shale. The upper part is composed of a muddy red sandstone with cm-sized angular volcanic fragments and spherical accretionary lapilli (Fig. 7a, Stac Fada Member), followed by a unit of red and minor grey shale and carbonate (Fig. 7b, c, Poll a’ Mhuilt Member). I collected samples from the Stac Fada Member, because the process that caused the lapilli, i.e. either volcanism or a meteorite impact (Young, 2002) may have been an additional source of sediments and solutes to the Stoer Basin. In the overlying Poll a’ Mhuilt Member, Prof. Tim Lyons and I collected nearly 40 samples in stratigraphic order, with particular focus on the carbonate and grey shale unit. Sulfur isotope ratios reported from sulfide minerals in the grey shale unit show the largest fractionation in the mid-Proterozoic (Parnell et al., 2010), making these rocks an important target for further biogeochemical investigation. Mudcracks are abundant in the red shale (Fig. 7d) but were not observed in the grey shale. Hence the latter was perhaps deposited in a stagnant anoxic water body, which filled up, leading to shallower, frequently exposed conditions under an oxic atmosphere.

3. Conclusion and future steps

So far, the project has been successful. The outcrops in the Scottish Highlands were well accessible, allowing for a productive field trip. I was able to collect representative sets of samples from major localities of the Torridonian Supergroup and look forward carrying out the geochemical analyses during my postdoc. In particular the possibility of tracing gradients in redox, productivity and nutrient availability with samples from the Diabaig Formation and Bay of Stoer Formation may be important steps towards understanding the importance of these non-marine habitats for early life.

References:

Callow, R.H.T. and Brasier, M.D., 2011. Diverse microbially induced sedimentary structures from 1 Ga lakes of the Diabaig Formation, Torridon Group, northwest Scotland. Sedimentary Geology, 239: 117-128.

Johnson, M., Parsons, I., Smith, P., Raine, R. and Goodenough, K., 2002. Geological framework of the north-west Highlands. In: K.M. Goodenough and M. Krabbendam (Editors), A geological excursion guide to the north-west Highlands of Scotland. British Geological Survey, Edinburgh, Scotland.

Lyons, T.W., Reinhard, C.T. and Planavsky, N.J., 2014. The rise of oxygen in Earth's early ocean and atmosphere. Nature, 506: 307-315.

Parnell, J., Boyce, A.J., Mark, D., Bowden, S. and Spinks, S., 2010. Early oxygenation of the terrestrial environment during the Mesoproterozoic. Nature, 468: 290-293.

Prave, A.R., 2002. Life on land in the Proterozoic: Evidence from the Torridonian rocks of northwest Scotland. Geology, 30(9): 811-814.

Stewart, A.D., 2002. The later Proterozoic Torridonian rocks of Scotland: Their sedimentology, geochemistry and origin. Memoirs of theGeological Society, 24. Geological Society, Bath, UK.

Strother, P.K., Battison, L., Brasier, M.D. and Wellman, C.H., 2011. Earth's earliest non-marine eukaryotes. Nature, 473: 505-509.

Turnbull, M.J.M., Whitehouse, M.J. and Moorbath, S., 1996. New isotopic age determinations for the Torridonian, NW Scotland. Journal of the Geological Society, 153: 955-964.

Young, G.M., 2002. Stratigraphy and geochemistry of volcanic mass flows in the Stac Fada Member of the Stoer Group, Torridonian, NW Scotland. Transactions of the Royal Society of Edinburgh: Earth Sciences, 93: 1-16.

Figures

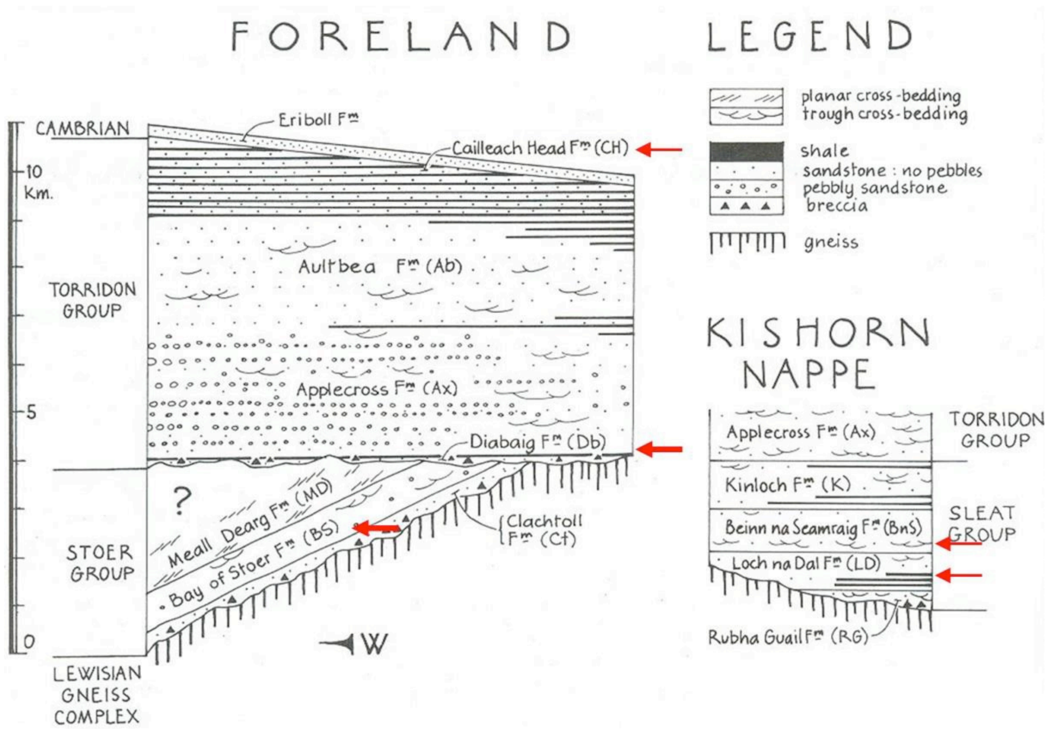

Figure 1: Stratigraphy of the Torridonian Supergroup, adapted from Steward (2002). Red arrows mark units that were sampled during this study, where heavy lines indicate areas of focus.

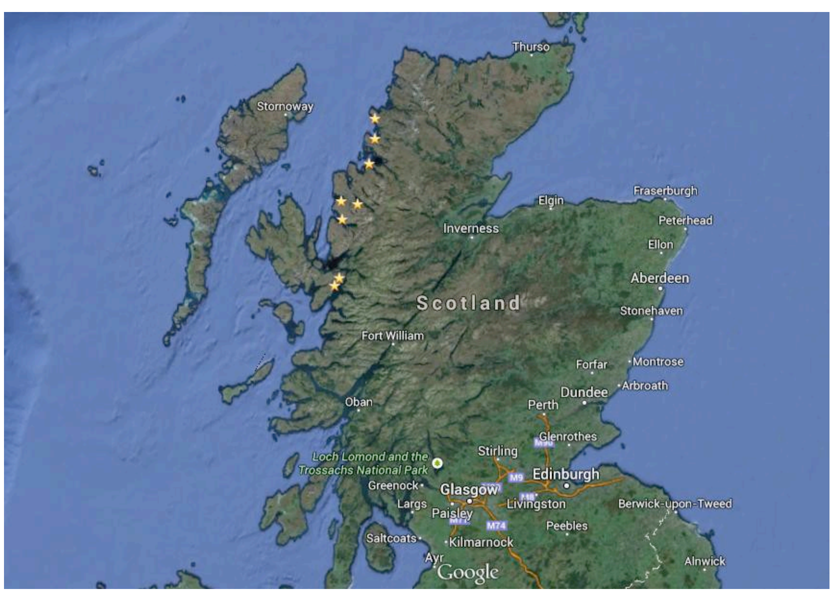

Figure 2: Field sites for the Torridonian Supergroup (yellow starts) in the Scottish Highlands. Adapted from www.maps. google.com.

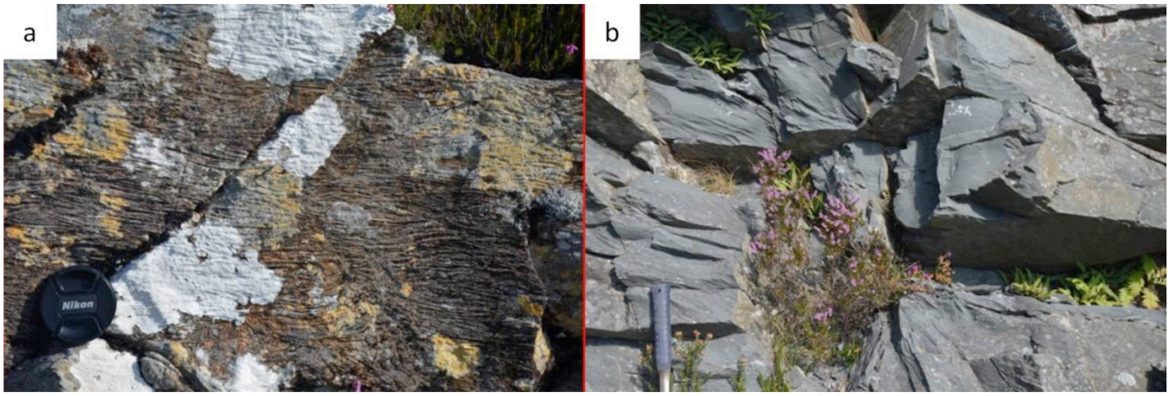

Figure 3: Sedimentary features in the Sleat Group. a:cross-bedding in sandstones. b: massive siltstone bed within sandstone unit of the Beeinn na Seamraig Formation.

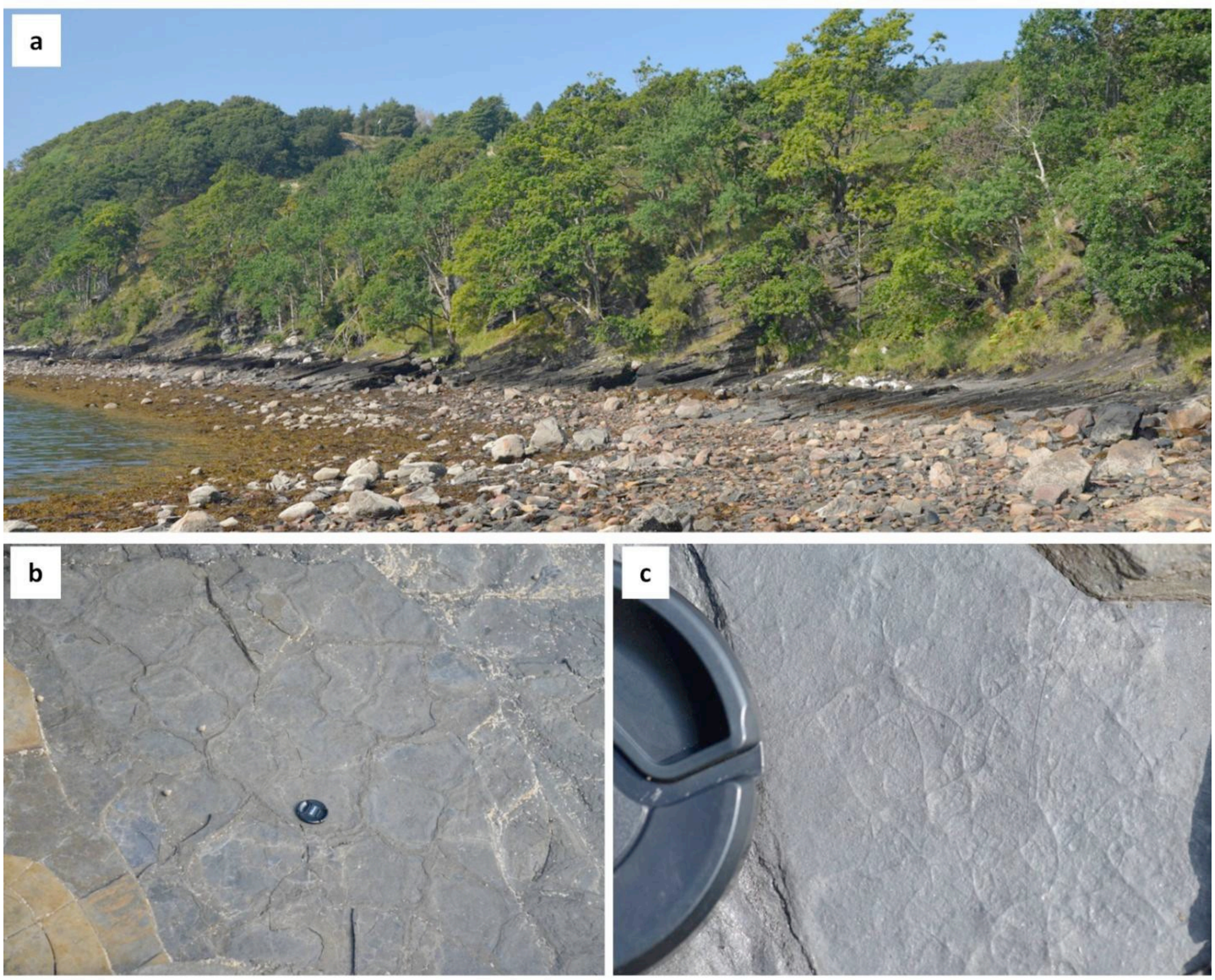

Figure 4: The upper Diabaig Formation at Diabaig beach. a: outcrop of dark grey shale. b: polygonal mudcracks (lense cap for scale ~7cm Ø), c: possibly biogenic structures on bedding surface.

Figure 5: Conglomerate in the lower Torridon Group containing blocks of Lewisian gneiss and amphibolites basement.

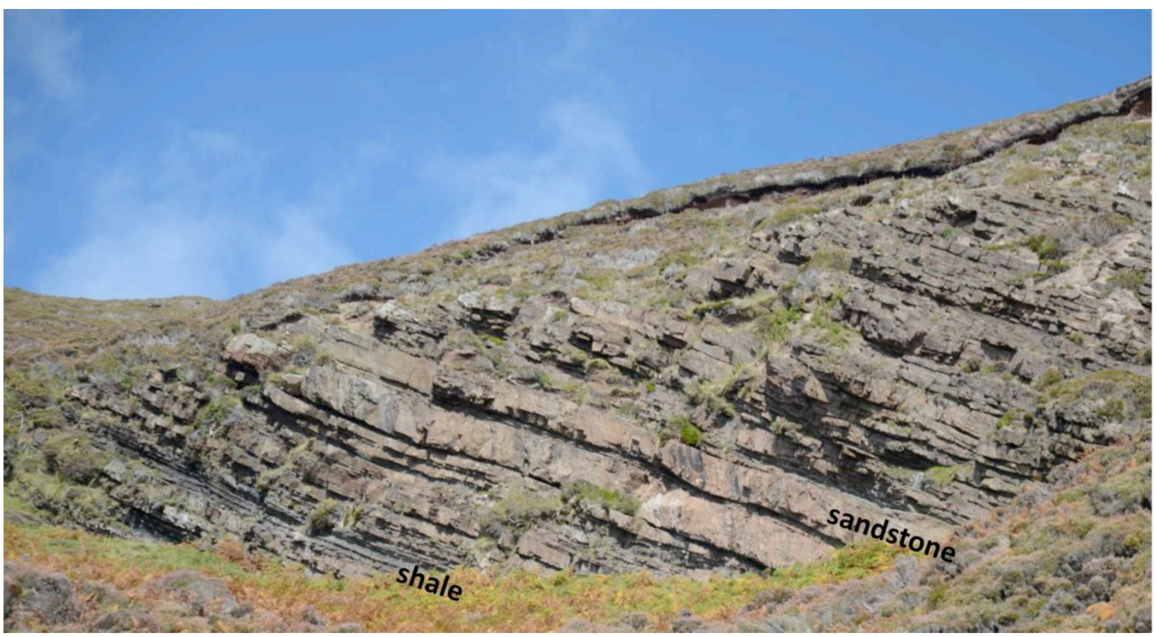

Figure 6: Cyclothem in the Cailleach Head Formation, repeatedly grading from shale to sandstone. Shales were sampled for this study.

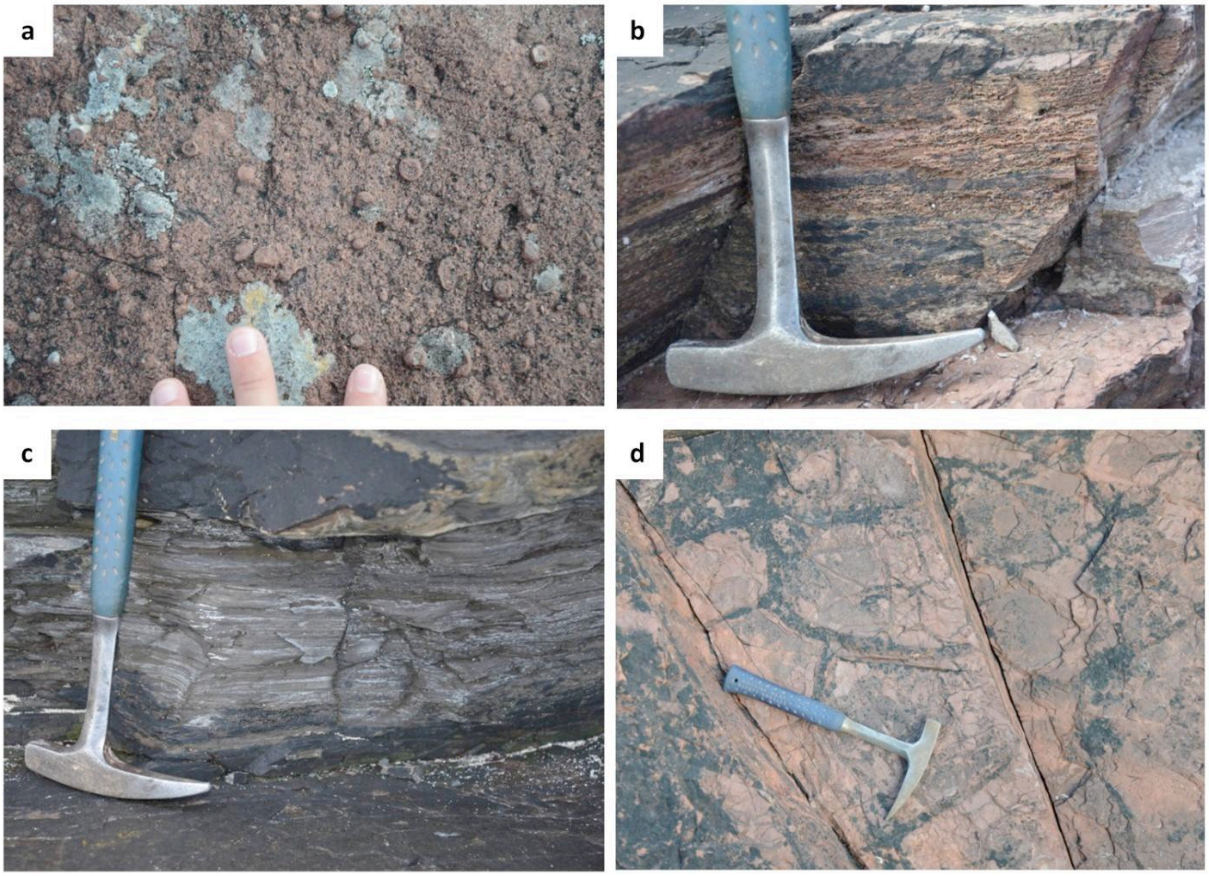

Figure 7: Sedimentary features in the upper Bay of Stoer Formation. a: accretionary lapilli in the Stac Fada Member, photographed at Enard Bay. b: carbonate unit in the Poll a' Mhuilt Member at Bay of Stoer. c: calcareous grey shale above carbonate unit. d: mudcracks at multiple scales in the red shales above the calcareous grey shale.