

Evidence for early life in Earth's oldest hydrothermal vent precipitates

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Although it is not known when or where life on Earth began, some of the earliest habitable environments may have been submarine-hydrothermal vents. Here we describe putative fossilized microorganisms that are at least 3,770 million and possibly 4,280 million years old in ferruginous sedimentary rocks, interpreted as seafloor-hydrothermal vent-related precipitates, from the Nuvvuagittuq belt in Quebec, Canada. These structures occur as micrometre-scale haematite tubes and filaments with morphologies and mineral assemblages similar to those of filamentous microorganisms from modern hydrothermal vent precipitates and analogous microfossils in younger rocks. The Nuvvuagittuq rocks contain isotopically light carbon in carbonate and carbonaceous material, which occurs as graphitic inclusions in diagenetic carbonate rosettes, apatite blades intergrown among carbonate rosettes and magnetite-haematite granules, and is associated with carbonate in direct contact with the putative microfossils. Collectively, these observations are consistent with an oxidized biomass and provide evidence for biological activity in submarine-hydrothermal environments more than 3,770 million years ago.

There are no confirmed microfossils older than 3,500 million years (Myr) on Earth, probably because of the highly metamorphosed nature of the oldest sedimentary rocks¹. Therefore, studies have focused almost exclusively on chemical traces and primarily on the isotopic composition of carbonaceous material, which has led to controversies regarding the origin of isotopically light reduced carbon². Schists from the approximately 3,700-Myr-old Isua supracrustal belt in southwest Greenland contain up to 8.8 wt% graphitic carbon that is depleted in ¹³C, and this depletion has been attributed to biological activity^{3,4}. However, because non-biological decarbonation reactions and Fischer-Tropsch-type synthesis⁵ can produce reduced carbon with similar isotopic compositions, non-biological interpretations are possible². Apatite with graphite coatings, within iron formations from the approximately 3,830-Myr-old Akilia supracrustal belt in southwest Greenland, has been interpreted as the metamorphosed product of biogenic matter⁶, supported by the presence of biologically important heteroatoms within the graphite⁷. However, it has been suggested that some graphite in the Akilia iron formations was deposited by metamorphic fluids^{8,9}. This latter interpretation is echoed in the Nuvvuagittuq supracrustal belt (NSB) by the presence of poorly crystalline, fluid-deposited graphite that coats apatite¹⁰, demonstrating that some apatite-graphite occurrences are produced abiotically during fluid remobilization and high-grade metamorphism.

The NSB in northeastern Canada represents a fragment of the Earth's primitive mafic oceanic crust. The NSB is composed predominantly of basaltic metavolcanic rocks (Extended Data Fig. 1), which locally preserve pillow lava structures¹¹ consistent with a submarine setting, and of chemical sedimentary units including iron formations and minor jasper (quartz-rich rocks with haematite and magnetite) and carbonate-bearing iron formations. The iron formation units occur between sequences of tholeiitic and calc-alkaline metabasalts, suggesting deposition at the same stage of volcanic evolution and seafloor-hydrothermal activity. The minimum age for the belt is constrained

by cross-cutting trondhjemitic intrusive rocks that yield U-Pb zircon ages of 3,774–3,751 Myr (refs. 12, 13). Furthermore, ¹⁴⁶Sm–¹⁴²Nd systematics suggest an age of 4,280 Myr for the metabasaltic unit of the NSB^{14,15}. The exact age of the NSB is debated (see Supplementary Information); nonetheless, the NSB includes one of the oldest—if not the oldest—iron formations known on Earth. The iron formation has seawater-like chemical signatures^{16,17} and heavy Fe isotopic compositions^{17,18}, consistent with formation by the precipitation of iron derived from hydrothermal fluids associated with volcanism¹⁹. Bulk-rock rare earth element data for the NSB jasper and carbonate iron formations—especially the presence of positive Eu anomalies—suggest a link to seafloor-hydrothermal activity (Extended Data Fig. 2). The presence of well-preserved, 20–3,000- μ m chalcopyrite crystals within the NSB jasper and carbonate iron formations (Extended Data Fig. 3a) demonstrate the lack of post-depositional oxidation.

Most NSB rocks were subjected to upper amphibolite-facies metamorphism around 2,700 Myr ago^{14,20}. Here we describe parts of the NSB that were less affected by deformation (Supplementary Table 4) and focus on sites where the metamorphic grade appears not to have exceeded lower amphibolite facies¹⁷. This setting is evidenced by local outcrops in the southwestern margins of the belt that preserve primary chert, diagenetic calcite rhombohedra with poikilitic textures, and minerals of low metamorphic grade such as euhedral stilpnomelane and minnesotaite in chert that lack pseudomorphic retrograde textures.

Haematite tubes and filaments

Modern hydrothermal Si-Fe vent deposits host communities of microorganisms, some of which are Fe-oxidizing bacteria that form distinctive tubes and filaments^{21–26}. Epifluorescence imaging of modern vent samples has shown that cylindrical casts composed of iron oxyhydroxide are formed by bacterial cells and are undeniably biogenic²⁵. Hence, morphologically similar tubes and filaments in ancient jaspers may be taken as biosignatures^{25,27–30} that can survive elevated temperatures

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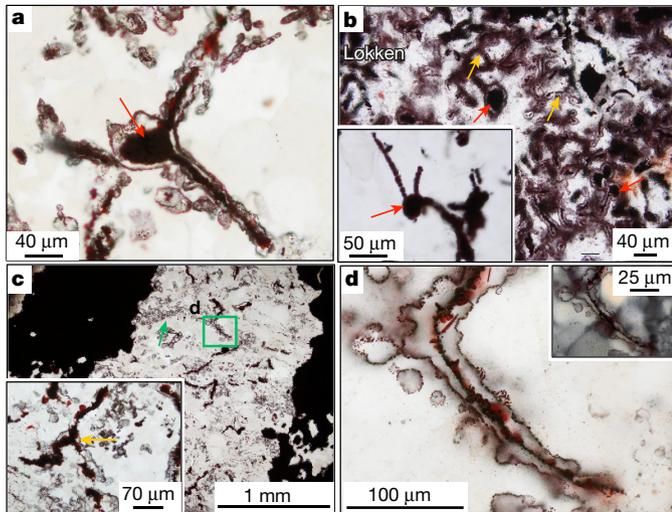


Figure 1 | Transmitted light images of haematite filaments from the NSB and Løkken jaspers. **a**, Filaments from the NSB attached to a terminal knob (arrow) coated with nanoscopic haematite. **b**, Filaments from the Løkken jaspers coated with nanoscopic haematite and attached to terminal knobs (red arrows) and branching (orange arrows). Inset, multiple filaments attached to a terminal knob. **c**, Filaments from the NSB in quartz band with haematite rosettes (green arrow). Inset, branching filament (orange arrow). Green box defines **d**. **d**, Filament from the NSB enveloped in haematite (inset, same image in cross polars).

and pressures³¹, even though such jaspers generally lack carbonaceous material^{22,28,32,33}. The presence of abundant microcrystalline quartz in jaspers may provide strong protection of primary features, such that deformation and metamorphism do not obliterate all depositional and diagenetic textures preserved by haematite²⁹.

Haematite filaments in the NSB jasper are between 2 and 14 μm in diameter and up to 500 μm in length (Fig. 1; Extended Data Fig. 4). Some of the filaments exhibit loose coils (Extended Data Fig. 4a), some are branched (Fig. 1c), and some form twisting plates of haematite around a core that radiate from terminal knobs (Extended Data Fig. 4e, f). They occur within quartz layers of the jaspers, in millimetre-sized domains together with haematite rosettes (Fig. 1c), and comprise micrometre-sized grains of haematite that are in turn enveloped by nanoscale haematite (Fig. 1d). Cross-polar images show that the filaments do not occur along grain boundaries (Fig. 1d). Some filaments are associated with micrometre-sized carbonate grains, which locally occur together with graphite (Extended Data Fig. 5). The NSB filaments (Fig. 1a–d) have morphologies and compositions similar to those of filaments that occur commonly in Phanerozoic jaspers of seafloor-hydrothermal origin, such as those from Løkken, Norway (see Supplementary Information; approximately 480 Myr; Fig. 1b) and the Franciscan Complex, California,

USA (approximately 185 Myr)³³. The NSB filaments are also similar to microbial filaments found in modern, low-temperature hydrothermal vents^{23,26}, some of which display twisted and branched morphologies known to be formed by iron-oxidizing bacteria^{21,26,30}.

Within the NSB jasper, cylindrical tubes with walls composed of dense nanoscale haematite grains are preserved within coarse (50–500 μm) quartz, which encapsulates the entire structure and fills the centres (Fig. 2). Depth reconstructions demonstrate the consistent shape of the tubes and filaments along their lengths and the cylindrical morphology of the tubes in three dimensions (Fig. 2b, Extended Data Fig. 4). The tubes are straight, have diameters of 16–30 μm (Extended Data Fig. 4), and vary in length from 80 to 400 μm. Most tubes are filled with quartz only, but some encapsulate a filament composed of micrometre-sized, platy grains of haematite that extend radially outward from the core of the filament (Fig. 2c), similar to those in younger jaspers (Fig. 2g). The NSB tubes form aligned clusters within patches of locally coarser quartz (Fig. 2a, e), similar to tubes in the Løkken jaspers (Fig. 2h), and occur in lamination-deflecting, concretionary structures (Extended Data Fig. 3b, c) and within quartz layers between millimetre-thick haematite–magnetite layers (Extended Data Fig. 3f). About one in ten tubes in the NSB terminate with a haematite knob (80–120 μm in diameter); about half of those have a second tube attached (Figs 1a, 2f).

The tubes exhibit features attributed in other seafloor-hydrothermal jaspers to fossil remains of iron-oxidizing bacteria²⁸: 1, tubes contain internal haematite filaments, similar to those of modern microbial remains^{23,26}; 2, some tubes are attached to terminal haematite knobs, like microbial tubes documented throughout the geological record^{28,32} and in modern hydrothermal precipitates^{21,24}; 3, uniform tube diameters are in the same 16–30-μm range as those of tube microfossils in the Mt. Windsor and Uralian jaspers^{29,34}; 4, tubes are aligned in a similar direction (as in some ancient jaspers³⁴), which is characteristic of some modern iron-oxidizing bacteria^{24,28,30,35}; and 5, tubes and filaments co-occur with apatite, carbonate, and carbonaceous material, as in microfossils within the Løkken (Extended Data Fig. 5) and other Phanerozoic jaspers³⁶.

To assess the biogenicity of the NSB putative microfossils we consider as a null hypothesis plausible abiogenic mechanisms that could create haematite tubes and filaments through metamorphic stretching or diagenetic processes (see Supplementary Information), such as fluid flow, precipitation reactions, and self-assembly. However, no known mechanism can wholly facilitate the growth of multiple tubes from a single haematite knob at varying angles (Fig. 1a, Extended Data Fig. 4) during metamorphic or diagenetic reactions, together with the formation of internal coiled, branched, and twisted filaments (Extended Data Fig. 4) with haematite envelopes (Fig. 1d), in addition to their close spatial association with carbonate and graphitic carbon (Extended Data Fig. 5). Collectively, our observations cannot be explained by a single or combined abiogenic pathway, and therefore we reject the null hypothesis.

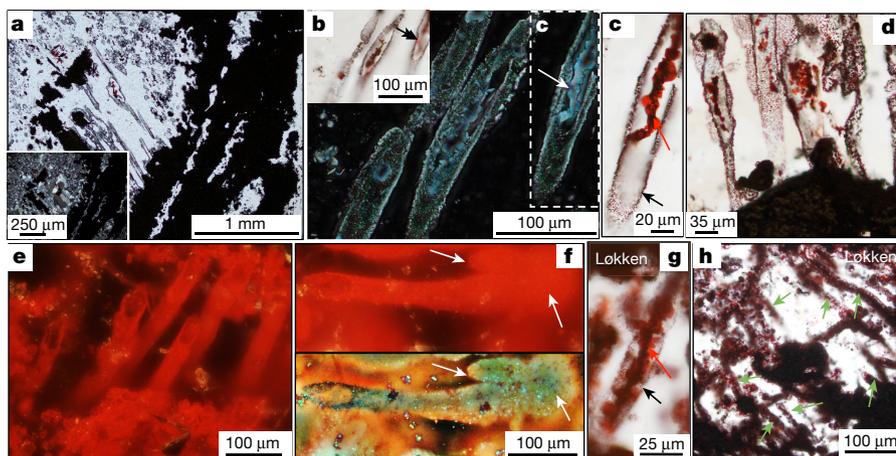


Figure 2 | Transmitted light images of haematite tubes in the NSB and Løkken jaspers. **a–f**, Tubes from the NSB. **a**, Tubes associated with iron oxide band. **b**, Depth reconstruction of tubes with haematite filament (arrow). Inset, image of tubes at the surface. **c**, Tube showing a twisted filament (red arrow) and walls (black arrow). **d**, Strongly deformed tubes. **e**, Depth reconstruction of tubes. **f**, Two tubes attached to terminal knob (arrows); lower image taken in false colour. **g, h**, Tubes from the Løkken jaspers. **g**, Tube showing filament (red arrow) and walls (black arrow). **h**, Aligned tubes (green arrows).

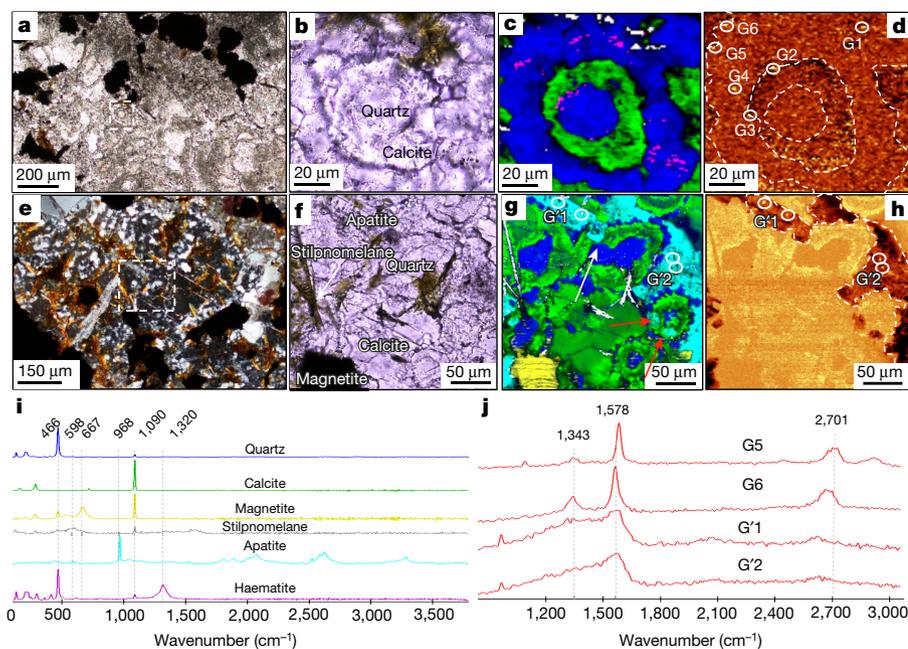
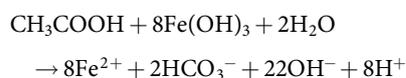


Figure 3 | Carbonate rosettes from the NSB. **a**, Transmitted light image of calcite rosettes. Box defines **b**. **b**, **c**, Transmitted light image in **b** of area targeted by Raman spectroscopy in **c**. **d**, Raman filter map at 1,580 cm⁻¹ (width 40 cm⁻¹) with spectra of graphite particles circled. **e**, Transmitted light and cross-polar image of calcite rosettes; box defines **f**. **f**, **g**, Transmitted light image in **f** of target area shown in **g**. White arrow shows apatite cutting a carbonate rosette; red arrows show apatite inclusions in a carbonate rosette. **h**, Carbonaceous material Raman filter map at 1,565 cm⁻¹ (width 50 cm⁻¹). **i**, **j**, Selected average Raman spectra from maps and carbonaceous material.

Uniformitarianism, epitomised by younger examples of microbially produced haematite tubes in hydrothermal vent precipitates throughout the geological record (Supplementary Table 5), leads us to conclude that haematite tubes and filaments within the NSB jaspers are the mineralized remains of bacterial sheaths and extracellular filaments. Filaments were probably coated by iron oxyhydroxide or silica after being discarded by the microbes, and subsequently coated with silica and recoated by iron oxyhydroxide in successive venting cycles^{23,35}, producing filament structures that are thicker than the initial structure. Residual carbonaceous material from the microbes is now preserved in association with carbonate in contact with the filaments. Whereas tubes and filaments in younger jaspers are typically attributed to iron oxidizers, other bacteria such as cyanobacteria can produce aligned³⁷, hollow cylindrical casts of iron oxide³⁸. However, the attachment of filaments to terminal knobs is characteristic of some iron oxidizers in hydrothermal systems²¹, but not of cyanobacteria. These knobs are morphologically similar to bacterial cells of the anoxygenic photoferrotroph *Hyphomicrobium*, which produces stalks during reproduction. Alternatively, the knobs may be better compared to bacterial holdfasts created by chemolithotroph *Leptothrix*-type bacteria. A twisted morphology in some filaments also closely resembles the iron-rich stalks formed by the extant ζ -proteobacterium *Mariprofundus*.

Carbonate rosettes, apatite and carbonaceous material

If biological processes were involved in the genesis of iron formations, the characteristic absence of carbonaceous material in iron formations could be due to organisms such as photoferrotrophs that separate ferric iron from the cells and allow most carbonaceous material to escape sedimentation³⁹. Any carbonaceous material that enters the sediments may be diagenetically oxidized in conjunction with the reduction of ferric iron⁴⁰. This reaction may be understood from the following equation:



A consequence of this reaction is the oxidation of carbonaceous material to carbonate and the reduction of insoluble ferric iron into soluble ferrous iron, followed by precipitation of iron-bearing carbonate, ferrous silicates, and magnetite. The formation of carbonate from oxidized carbonaceous material is well illustrated in the approximately 2,470-Myr-old Brockman Iron Formation of Western Australia (Extended Data Fig. 6h, i), in which carbonate rhombohedra

occur in layers of disseminated carbonaceous material mixed with carbonate rosettes.

Of particular note is the presence of carbonate rosettes, 50–200 μm in diameter, that typically contain microscopic inclusions of carbonaceous material. Such rosettes are found in the NSB iron formations (Fig. 3, Extended Data Fig. 6) as well as in younger jaspers and iron formations (Supplementary Table 6). In the Løkken jasper, for example, carbonate rosettes with inclusions of carbonaceous material overgrow haematite filaments (Extended Data Fig. 6k) attributed to mineralized bacteria²⁷. In this interpretation, carbonaceous material was sourced from the bacteria. Carbonate rosettes have also been grown in diagenetic experiments using ferrihydrite and carbonaceous material⁴⁰.

Both NSB and ancient jaspers, and modern hydrothermal vent precipitates, commonly preserve haematite rosettes^{27,32,41} (Supplementary Table 7, Extended Data Fig. 7), albeit of debated origin⁴². Ferrihydrite rosettes that form today in the Lau Basin are intimately associated with microbial filaments, but may be a result of abiogenic precipitation⁴¹. In the Løkken jaspers, haematite rosettes are attributed to Fe-Si gel maturation on the seafloor²⁷. Such textural relationships may require micro-chemical Eh-pH gradients that reduce ferric iron, followed by mobilization and oxidation of Fe²⁺ and its re-precipitation as haematite. Given the close proximity of haematite rosettes to microbial filaments in modern vent precipitates⁴¹, it is plausible that microbial carbonaceous material served as a reductant and ferrihydrite as an oxidant.

Sub-spheroidal rosettes of iron calcite (Supplementary Table 8) in carbonate-rich iron formations from the NSB (Fig. 3, Extended Data Fig. 6a, b) have quartz cores and dimensions of approximately 50–200 μm¹⁹. Some carbonate rosettes locally contain apatite inclusions and are cut by apatite laths hundreds of micrometres in length (Fig. 3g), and by acicular stilpnomelane that cuts both rosettes and apatite (Fig. 3, Extended Data Fig. 6g), demonstrating that the apatite and rosettes are pre-metamorphic. The apatite contains myriad inclusions of aqueous fluid, haematite, magnetite, and carbonaceous material (Fig. 3f–h). Moreover, the rosettes occur with micrometre-sized particles of graphitic carbon, randomly disseminated throughout the rings and surrounding chert (Fig. 3c). Raman spectra of the graphitic carbon show sharp and prominent G-bands ranging from 1,565 to 1,584 cm⁻¹ and minor D-bands from 1,331 to 1,349 cm⁻¹ (Fig. 3j, Extended Data Fig. 6e). Whereas apatite-hosted carbonaceous material displays Raman G-peak positions consistent with those of graphitic carbon, the broad D-band suggests the presence of disordered sp³-bonded carbon (Fig. 3j) or a contribution from nanoscale haematite, which has

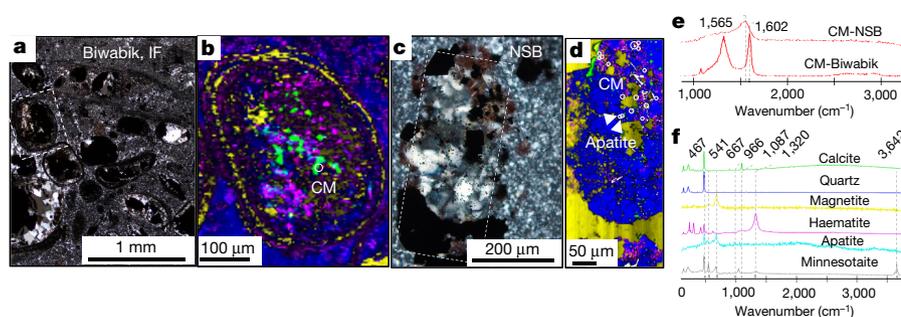


Figure 4 | Granules from the Biwabik and NSB jaspers. **a**, Cross-polar image of granules in Biwabik jasper. IF, iron formation. **b**, Raman map of area shown with dotted outline in **a**. CM, carbonaceous material. **c**, Cross-polar image of granule in the NSB. **d**, Raman map of area shown with dotted outline in **c**. **e**, **f**, Selected average Raman spectra of carbonaceous material and minerals from maps.

a broad peak at $1,320\text{ cm}^{-1}$, partly explaining the broad and intense Raman D-peak. Iron oxides can be seen associated with carbonaceous material in transmitted light and by micro-Raman spectroscopy (Extended Data Fig. 8a). Raman spectra of graphitic carbon within the carbonate rosettes (Fig. 3j) yield a range of calculated crystallization temperatures⁴³ between 396 °C and 564 °C (Supplementary Tables 9, 10), which is partly consistent with mineral geothermometers obtained from the Ujaraaluk amphibolite¹⁷, distinct from those of poorly crystalline, fluid-deposited graphite in silicate iron formations from other parts of the NSB¹⁰ (Extended Data Fig. 8, Supplementary Table 11). Additionally, Raman spectra of graphitic carbon found in layered jaspers of the NSB (Extended Data Fig. 8b–e) show that graphite from two different samples shares common crystallization temperatures of approximately 500 °C . The formation of syngenetic carbon preserved as graphite can be explained by the production of carbonaceous material via abiogenic synthesis⁵, carbonate decarbonation², or from an original microbial biomass.

Isotopically light carbonate (-15 to -5 ‰) in iron formations has been attributed to the oxidation of isotopically light carbonaceous material derived from microbial activity⁴⁴, but precludes neither the oxidation of isotopically light abiogenic carbonaceous material nor a contribution from marine carbonate. The $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{org}}$ values for jaspers from the NSB are -8.3 to -6.7 ‰ and -25.7 to -19.7 ‰ , respectively¹⁰, consistent with a biogenic origin, although not unambiguously. However, in the case of the NSB, the phosphorus (an element vital in biology) in laths of apatite intergrown with the graphite-bearing carbonate rosettes suggests a biological source for the carbon in graphite. In modern ocean sediments, accumulations of carbonaceous material on the seafloor may concentrate phosphorus through biological metabolisms⁴⁵. Furthermore, the presence of apatite in some NSB carbonate rosettes is analogous to occurrences of apatite rosettes between stromatolitic phosphorite columns in a flourishing late Palaeoproterozoic microbial ecosystem⁴⁶. Whereas structures similar to carbonate rosettes may form in open spaces and cavities⁴⁷, the well-banded, siliceous carbonate gels that formed precursors to these carbonate iron formations could not have had a porous texture, and so the formation of carbonate rosettes by open-space filling can be ruled out. This conclusion is reinforced by the presence of morphologically similar, diagenetic graphite-bearing carbonate rosettes in the Løkken jasper²⁷ (Extended Data Fig. 6j–m). Combined with evidence of filamentous microfossils and their direct association with carbonate and graphitic carbon, and with numerous other observations supporting biological activity in the NSB, the carbonate rosettes are best explained as having formed by the oxidation of biomass. Such reactions may have proceeded as chemically oscillating reactions akin to the Belousov–Zhabotinsky reaction⁴⁸, in line with inferences from similar structures in younger iron formations (Extended Data Fig. 6h–m) and diagenetic experiments⁴⁰.

Granules

Magnetite-rimmed granules are common in late Palaeoproterozoic iron formations and typically occur between stromatolite columns (Extended Data Fig. 3i) and host microfossils. The oldest known granular iron formation from the Mozaan Group in South Africa is about

2,900 Myr old and contains magnetite-rimmed granules, isotopically light carbonate, and zero-to-positive $\delta^{56}\text{Fe}$ values, suggesting involvement of iron-oxidizing microbes⁴⁹.

Comparable $100\text{--}500\text{-}\mu\text{m}$ spheroidal to sub-spheroidal granules occur in the NSB jaspers that crop out together with the carbonate iron formations and banded jaspers hosting the microfossils (Extended Data Fig. 3b, f). These granules occur in a matrix of chert (Fig. 4c) and have rims composed of coarse magnetite with interiors of coarser-grained quartz compared to the matrix. Micro-Raman images reveal that the granules contain micrometre-sized minnesotaite, magnetite, calcite, haematite, apatite, and carbonaceous material (Fig. 4d). The inclusions of carbonaceous material within the granules are $1\text{--}4\text{ }\mu\text{m}$ in size and display a predominant Raman peak at about $1,560\text{--}1,580\text{ cm}^{-1}$ and a broad, poorly resolved D-peak (Fig. 4e). Granules of a similar size ($200\text{--}400\text{ }\mu\text{m}$) in jaspers from the late Palaeoproterozoic Biwabik Iron Formation (Fig. 4a) and the Løkken jasper (Extended Data Fig. 9i) also contain quartz coarser than in the surrounding matrix, and a comparable mineralogy dominated by magnetite-rimmed granules accompanied by haematite, carbonate, carbonaceous material, and ferrous silicates. Carbonaceous material within granules from all of these jaspers is typically associated with, and coats, micrometre-sized diagenetic carbonate (Extended Data Fig. 9). This close spatial association and the occurrence of carbonaceous material concentrated in diagenetic granules suggest that such carbonaceous material is a primary phase. Less commonly, Løkken granules contain haematite filaments with terminal knobs (Extended Data Fig. 9l).

We propose that the mineralogical constituents of iron-oxide granules of these jaspers reflect oxidation–reduction reactions. This model implicates carbonaceous material and ferric iron as original reactants, whereas ferric–ferrous silicates, apatite, magnetite, and carbonate are considered reaction products. Given the similar morphology, mineralogy, and composition, and the common occurrence of rosettes, granules, and filamentous microfossils in the Biwabik, Løkken, and NSB jaspers, these diagenetic reactions would have proceeded in a similar manner. This conclusion and the well-documented occurrence of microfossils within some granules⁵⁰ (Extended Data Fig. 9l) point to an origin involving microorganisms on the Nuvvuagittuq seafloor.

Preservation in the NSB of carbonaceous material and minerals in diagenetic rosettes and granules that formed from the oxidation of biomass, together with the presence of tubes similar in mineralogy and morphology to those in younger jaspers interpreted as microfossils, reveal that life established a habitat near submarine-hydrothermal vents before $3,770$ Myr ago and possibly as early as $4,280$ Myr ago. On the basis of chemical and morphological lines of evidence, the tubes and filaments are best explained as remains of iron-metabolizing filamentous bacteria, and therefore represent the oldest life forms recognized on Earth. Given this new evidence from the NSB, ancient submarine-hydrothermal vent systems should be viewed as potential sites for the origins of life on Earth, and thus primary targets in the search for extra-terrestrial life.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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- Bernard, S. & Papineau, D. Graphitic carbons and biosignatures. *Elements* **10**, 435–440 (2014).
- van Zuilen, M. A., Lepland, A. & Arrhenius, G. Reassessing the evidence for the earliest traces of life. *Nature* **418**, 627–630 (2002).
- Ohtomo, Y., Kakegawa, T., Ishida, A., Nagase, T. & Rosing, M. T. Evidence for biogenic graphite in early Archaean Isua metasedimentary rocks. *Nat. Geosci.* **7**, 25–28 (2013).
- Rosing, M. T. ^{13}C -depleted carbon microparticles in >3700-Ma sea-floor sedimentary rocks from West Greenland. *Science* **283**, 674–676 (1999).
- McCollom, T. M. & Seewald, J. S. Abiotic synthesis of organic compounds in deep-sea hydrothermal environments. *Chem. Rev.* **107**, 382–401 (2007).
- Mojzsis, S. J. *et al.* Evidence for life on Earth before 3,800 million years ago. *Nature* **384**, 55–59 (1996).
- Papineau, D. *et al.* Ancient graphite in the Eoarchean quartz-pyroxene rocks from Akilia in southern West Greenland II: isotopic and chemical compositions and comparison with Paleoproterozoic banded iron formations. *Geochim. Cosmochim. Acta* **74**, 5884–5905 (2010).
- Papineau, D. *et al.* Ancient graphite in the Eoarchean quartz-pyroxene rocks from Akilia in southern West Greenland I: petrographic and spectroscopic characterization. *Geochim. Cosmochim. Acta* **74**, 5862–5883 (2010).
- Lepland, A., van Zuilen, M. A. & Philippot, P. Fluid-deposited graphite and its geobiological implications in Early Archaean gneiss from Akilia, Greenland. *Geobiology* **9**, 2–9 (2011).
- Papineau, D. *et al.* Young poorly crystalline graphite in the >3.8-Gyr-old Nuvvuagittuq banded iron formation. *Nat. Geosci.* **4**, 376–379 (2011).
- O'Neil, J., Francis, D. & Carlson, R. W. Implications of the Nuvvuagittuq greenstone belt for the formation of Earth's early crust. *J. Petrol.* **52**, 985–1009 (2011).
- Cates, N. L., Ziegler, K., Schmitt, A. K. & Mojzsis, S. J. Reduced, reused and recycled: detrital zircons define a maximum age for the Eoarchean (ca. 3750–3780 Ma) Nuvvuagittuq supracrustal belt, Québec (Canada). *Earth Planet. Sci. Lett.* **362**, 283–293 (2013).
- Darling, J. R. *et al.* Eoarchean to Neoproterozoic evolution of the Nuvvuagittuq supracrustal belt: new insights from U-Pb zircon geochronology. *Am. J. Sci.* **313**, 844–876 (2013).
- O'Neil, J., Carlson, R. W., Paquette, J.-L. & Francis, D. Formation age and metamorphic history of the Nuvvuagittuq greenstone belt. *Precamb. Res.* **220–221**, 23–44 (2012).
- O'Neil, J., Carlson, R. W., Francis, D. & Stevenson, R. K. Neodymium-142 evidence for Hadean mafic crust. *Science* **321**, 1828–1831 (2008).
- Mloszewska, A. M. *et al.* The composition of Earth's oldest iron formations: the Nuvvuagittuq supracrustal belt (Québec, Canada). *Earth Planet. Sci. Lett.* **317–318**, 331–342 (2012).
- O'Neil, J. *et al.* in *Earth's Oldest Rocks* Vol. 15 (eds van Kranendonk, M. J., Smithies, R. H. & Bennett, V. C.) 219–250 (Elsevier, 2007).
- Dauphas, N., Cates, N. L., Mojzsis, S. J. & Busigny, V. Identification of chemical sedimentary protoliths using iron isotopes in the >3750 Ma Nuvvuagittuq supracrustal belt, Canada. *Earth Planet. Sci. Lett.* **254**, 358–376 (2007).
- Mloszewska, A. M. *et al.* Chemical sedimentary protoliths in the >3.75Ga Nuvvuagittuq supracrustal belt (Québec, Canada). *Gondwana Res.* **23**, 574–594 (2013).
- Cates, N. L. & Mojzsis, S. J. Metamorphic zircon, trace elements and Neoproterozoic metamorphism in the ca. 3.75 Ga Nuvvuagittuq supracrustal belt, Québec (Canada). *Chem. Geol.* **261**, 99–114 (2009).
- Edwards, K. J. *et al.* Ultra-diffuse hydrothermal venting supports Fe-oxidizing bacteria and massive uranium deposition at 5000 m off Hawaii. *ISME J.* **5**, 1748–1758 (2011).
- Juniper, S. K. & Fouquet, Y. Filamentous iron-silica deposits from modern and ancient hydrothermal sites. *Can. Mineral.* **26**, 859–869 (1988).
- Li, J. *et al.* Microbial diversity and biomineralization in low-temperature hydrothermal iron-silica-rich precipitates of the Lau Basin hydrothermal field. *FEMS Microbiol. Ecol.* **81**, 205–216 (2012).
- Boyd, T. D. & Scott, S. D. Microbial and hydrothermal aspects of ferric oxyhydroxides and ferrous hydroxides: the example of Franklin Seamount, western Woodlark Basin, Papua New Guinea. *Geochem. Trans.* **2**, 45 (2001).
- Emerson, D. & Moyer, C. L. Neutrophilic Fe-oxidizing bacteria are abundant at the Loihi Seamount hydrothermal vents and play a major role in Fe oxide deposition. *Appl. Environ. Microbiol.* **68**, 3085–3093 (2002).
- Hein, J. R., Clague, D. A., Koski, R. A., Embley, R. W. & Dunham, R. E. Metalliferous sediment and a silica-hematite deposit within the Blanco Fracture Zone, northeast Pacific. *Mar. Georesour. Geotechnol.* **26**, 317–339 (2008).
- Grenne, T. & Slack, J. F. Bedded jaspers of the Ordovician Løkken ophiolite, Norway: seafloor deposition and diagenetic maturation of hydrothermal plume-derived silica-iron gels. *Miner. Depos.* **38**, 625–639 (2003).
- Little, C. T. S., Glynn, S. E. J. & Mills, R. A. Four-hundred-and-ninety-million-year record of bacteriogenic iron oxide precipitation at sea-floor hydrothermal vents. *Geomicrobiol. J.* **21**, 415–429 (2004).
- Duhig, N. C., Stolz, J., Davidson, G. J. & Large, R. R. Cambrian microbial and silica gel textures in silica iron exhalites from the Mount Windsor volcanic belt, Australia: their petrography, chemistry, and origin. *Econ. Geol.* **87**, 764–784 (1992).
- Krepeski, S. T., Emerson, D., Hredzak-Showalter, P. L., Luther, G. W., III & Chan, C. S. Morphology of biogenic iron oxides records microbial physiology and environmental conditions: toward interpreting iron microfossils. *Geobiology* **11**, 457–471 (2013).
- Picard, A., Obst, M., Schmid, G., Zeitvogel, F. & Kappler, A. Limited influence of Si on the preservation of Fe mineral-encrusted microbial cells during experimental diagenesis. *Geobiology* **14**, 276–292 (2016).
- Chi Fru, E. *et al.* Biogenicity of an early Quaternary iron formation, Milos Island, Greece. *Geobiology* **13**, 225–244 (2015).
- Little, C. T. S., Herrington, R., Haymon, R. & Danelian, T. Early Jurassic hydrothermal vent community from the Franciscan Complex, San Rafael Mountains. *Calif. Geol.* **27**, 167–170 (1999).
- Ayupova, N. R. & Maslennikov, V. V. Biomorphic textures in the ferruginous-siliceous rocks of massive sulfide-bearing paleohydrothermal fields in the Urals. *Lithol. Miner. Resour.* **48**, 438–455 (2013).
- Sun, Z. *et al.* Generation of hydrothermal Fe-Si oxyhydroxide deposit on the southwest Indian Ridge and its implication for the origin of ancient banded iron formations. *J. Geophys. Res. Biogeosci.* **120**, 187–203 (2015).
- Ayupova, N. R., Maslennikov, V. V., Sadykov, S. A., Maslennikova, S. P. & Danyushevsky, L. V. in *Biogenic–Abiogenic Interactions in Natural and Anthropogenic Systems* (eds Frank-Kamenetskaya, V. O., Panova, G. E. & Vlasov, Y. D.) 109–122 (Springer, 2016).
- Campbell, K. A. *et al.* Tracing biosignature preservation of geothermally silicified microbial textures into the geological record. *Astrobiology* **15**, 858–882 (2015).
- Parenteau, M. N. & Cady, S. L. Microbial biosignatures in iron-mineralized phototrophic mats at Chocolate Pots Hot Springs, Yellowstone National Park, United States. *Palaio* **25**, 97–111 (2010).
- Thompson, K. J., Liros, M., Michiels, C., Kenward, P. & Crowe, S. in *2014 GSA Annual Meeting* Vol. 46, 401 (Geol. Soc. Am. Abstracts with Programs, 2014).
- Köhler, I., Konhauser, K. O., Papineau, D., Bekker, A. & Kappler, A. Biological carbon precursor to diagenetic siderite with spherical structures in iron formations. *Nat. Commun.* **4**, 1741 (2013).
- Sun, Z. *et al.* Mineralogical characterization and formation of Fe-Si oxyhydroxide deposits from modern seafloor hydrothermal vents. *Am. Mineral.* **98**, 85–97 (2012).
- Heaney, P. J. & Veblen, D. R. An examination of spherulitic dubiomicrofossils in Precambrian banded iron formations using the transmission electron microscope. *Precamb. Res.* **49**, 355–372 (1991).
- Beyssac, O., Goffe, B., Chopin, C. & Rouzaud, J. N. Raman spectra of carbonaceous material in metasediments: a new geothermometer. *J. Metamorph. Geol.* **20**, 859–871 (2002).
- Heimann, A. *et al.* Fe, C, and O isotope compositions of banded iron formation carbonates demonstrate a major role for dissimilatory iron reduction in ~2.5 Ga marine environments. *Earth Planet. Sci. Lett.* **294**, 8–18 (2010).
- Cappellen, P. V. & Berner, R. A. A mathematical model for the early diagenesis of phosphorus and fluorine in marine sediments: apatite precipitation. *Am. J. Sci.* **288**, 289–333 (1988).
- Papineau, D. *et al.* Nanoscale petrographic and geochemical insights on the origin of the Palaeoproterozoic stromatolitic phosphorites from Aravalli Supergroup, India. *Geobiology* **14**, 3–32 (2016).
- Brasier, A. T., Rogerson, M. R., Mercedes-Martin, R., Vonhof, H. B. & Reijmer, J. J. G. A test of the biogenicity criteria established for microfossils and stromatolites on Quaternary tufa and speleothem materials formed in the “Twilight Zone” at Caerwys, UK. *Astrobiology* **15**, 883–900 (2015).
- Zaikin, A. N. & Zhabotinsky, A. M. Concentration wave propagation in two-dimensional liquid-phase self-oscillating system. *Nature* **225**, 535–537 (1970).
- Smith, A. J. B., Beukes, N. J., Gutzmer, J., Johnson, C. M. & Czaja, A. D. in *Goldschmidt*. 2384 (Mineralogical Society, 2012).
- Walter, M. R., Goode, A. D. T. & Hall, W. D. M. Microfossils from a newly discovered Precambrian stromatolitic iron formation in Western Australia. *Nature* **261**, 221–223 (1976).

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