**SUPPLEMENTARY DATA**

**Geographic and stratigraphic units’ names**

The regional geographic proper names in the Finnmark County and stratigraphic units’ names (group, formation, member) based on the type localities are adjusted to the current spelling in the indigenous Sámi people language of northern Norway, which is used and printed on the maps. These names may slightly differ from the names used in previous publications but are recognizable, e.g. Digermul=Digermulen Peninsula, Tanafjord=Tanafjorden, Mortensnes=Mortensneset Fm., Lillevatn=Lillevannet Mbr, Innerelv=Indreelva Mbr, Manndraperelv=Manndrapselva Mbr, Stappogiedde=Stáhpogieddi Fm. (Farmer et al., 1992; Högström et al., 2013; Jensen et al., 2018; Fig. 2).

**Materials and methods**

The fossils were studied with a reflected light microscope Leica M205C and photographed by attached digital camera, and the images were not digitally edited but only the background was masked in black colour. Selected specimens were also studied with an environmental scanning-transmission electron microscope STEM Zeiss Supra 35-VP field emission SEM equipped with a SEM detector for transmission microscopy, a VPE detector for low vacuum conditions, and a Robinson BSD for back scattered detection. The STEM microscope is also equipped with an EDAX Apex 4 (Ametek, Mahwah, USA) that is energy dispersive detector for X-ray microanalysis and spectroscopy. The energy dispersive spectroscopy (EDS) for elemental composition and elemental mapping of fossils was performed on specimens without coating and before being prepared for STEM observations. For STEM imaging, the fossils were plated with palladium 22 nanometres (nm) thick. These studies were performed at the Microscopy and Imaging Unit, Evolutionary Biology Centre (EBC), Uppsala University.

Computed Tomography (CT) with X-ray computed tomography scanner was used for

digital geometry processing to generate a three-dimensional volume of the specimens from a large series of two-dimensional X-ray images. The specimens were CT-scanned at the Natural History Museum, University of Oslo, using a Nikon Metrology XT H 225 ST set at 150 kV, 200 µA, with a 1 s exposure time. Two images were used per projection, with a total of 3017 projections. The resulting voxel resolution was 13,2 µm. The resulting image stacks were imported into Mimics v19 (Materialise software, Belgium). Manual thresholding segmentation of anatomical structures was performed in Mimics, and surface renders and animations of segmented objects were produced in Blender v2.79 (Blender Foundation). The computed tomography analyses have been performed by Daniel Snitting and Ben Kear, with the assistance by Øyvind Hammer. Animation of *Anulitubus* *formosus* n. gen. et sp. is shown in the side view of the wall and from the aperture in movies CT-*Anulitubus*-side.avi and CT-*Anulitubus*.aperture.avi.

The Laser-Raman spectroscopy was performed with a micro-Raman spectrometer in

back scattering geometry with charge-coupled detector. The scattered light was analyzed with a high-throughout single stage imaging spectrometer and collected by a CCD detector (1600 x 400 pixels). The intensity of the Rayleigh peak was largely reduced by two holographic notch filters. The excitation source was the diode-pumped solid-state laser with a wavelength of 532 nm and was focused on 2–4 µm on fossil surface by a 20x objective lens. The spectrometer was calibrated against the fluorescence peak positions of a neon lamp and the Raman peak of a single silicon crystal. The special resolution of the system is around 4 cm–1 and the accuracy estimated from the calibration procedure is around 2 cm–1. The laser power at the specimen surface was set to 2 mW and the typical collecting time was 20-30 minutes for each spectrum. Raman spectra were recorded at the 100–800 cm –1 and 1090–1700 cm –1 ranges to examine the spectral characteristics of mineral content and carbonaceous material, respectively. The Fityk software was used in baseline correction, spectral deconvolution and peak fitting (Wojdyr, 2010). The Raman spectra from several points on various parts of specimens were acquired to check the consistency of spectral characteristics. The Laser-Raman spectroscopic examination by Lei Liu and Peter Lazor was conducted in the Laser Laboratory, Mineralogy, Petrology and Tectonics Program at Uppsala University.

The mineral composition of mudstone containing the fossils was examined by X-ray

diffraction (XRD), a powder diffraction method with a Rigaku SmartLab XRD diffractometer (copper anode, step of measurement 0.05, counting time 1 s). The main phases were identified by means of the measurement of interplanar distances and the subsequent comparison of the obtained set of data with the pattern set. Diffraction data processing was performed based on the data present in the directory ICDD (International Center for Diffraction Data 2014) and a computer program XRAYAN. The sample was analysed by Jarek Majka, Mineralogy, Petrology and Tectonics Program at Uppsala University.

**Wall composition revealed by Laser-Raman spectroscopy**

The Laser-Raman spectra were acquired from several points on the surface of different parts of the fossils. These spectra are typical of quartz and anatase minerals in all specimens and representing all studied species (Figs 8, 13, 17­–18). Additionally, carbonaceous material is detected in *Anulitubus formosus* n. gen et sp. (Fig. 8) and *Fistula crenulata* n. gen. et sp. (Fig. 18a).

In *Anulitubus formosus* n. gen et sp., two spectral windows of 100–800 cm –1 and

1090–1700 cm –1 revealed the Laser-Raman signatures (Fig. 8). The Raman spectra of measured points 1, 2, and 4 are consistent with quartz (SiO2, RRUFF ID: R040031, the strongest peak located at 466 cm–1), and that of point 3 with anatase (TiO2, RRUFF ID: R060277, strongest peak locate at 150 cm–1). Raman spectra in the narrow window of 1090–1700 cm –1 acquiredin four points show elevated signatures and the two distinct bands at ~ 1350 cm–1 and ~ 1550 cm–1 in point 2, whichrecord the carbonaceous material. These bands are characteristic of disordered D-, and graphitic G-bands, and are signatures of carbonaceous material derived from organic matter (Kudryavtsev et al., 2001; Schopf et al., 2005). The carbonaceous material reaveled by Laser-Raman spectra alone may be questioned whether it is directly derived from to organism or geochemically altered and showing similar signature (Kudryavtsev et al., 2001; Schopf et al., 2005), but in the present case study the possible contamination or diagenetic/metamorphic alteration is excluded. This is because the fossil wall is solid, not fractured or altered, and the sourrounding sediment does not contain carbonate minerals as a possible source of carbon. The thermal maturity of this carbonaceous material indicated by the Laser-Raman D- and G-bands is consistent with insignificant alteration and low metamorphic grade of diagenesis of the host sediment as compared to maturity observed in organic-walled microfossils (Schopf et al., 2005). The Laser-Raman spectroscopy allowed to correlate the chemical composition with optically observed morphology of specimen that is definitely biological object with mineralized wall. The wall chemical composition is shown to be siliceous by Laser-Raman spectra and independently by STEM EDS elemental content, which also indicates the presence of organic material. The original organic material is admixed with silica in constructing the exoskeleton of ancient animal.

*Coniculus elegantis* n. gen. et sp. (Fig. 13) shows strong Laser-Raman spectral peaks

characteristic of quartz and anatase and similarly supporting the conclusion that the fossil wall is composed of quartz while the anatase is a foreign mineral from the depositional environment.

The Laser-Raman spectra of *Fistula crenulata* n. gen. et sp. (Fig. 17) show the

strongest peak characteristic of quartz in point 6 (SiO2, RRUFF ID: R040031, strong peaks locate at 129, 209, 267, 357, 405, 466, 505, and 697 cm-1), while the spectra from the points 1 and 8 are consistent with that of anatase (TiO2, RRUFF ID: R060277, strong peaks locate at 144, 198, 397, 516, and 637 cm–1). The spectra acquired from the point 2 are mainly from quartz with minor anatase, and those from the points 3 and 5 are predominantly from the anatase with minor quartz. Altogether, the spectral signatures are indicative of quartz (SiO2) with addition of anatase (TiO2) in the wall composition of the species. The wall was silicieous and formed the exoskeleton, and anatase is a contaminant mineral from the burial environment. The multiple Laser-Raman spectra of another specimen of *Fistula crenulata* n. gen. et sp. (PMU 34750) showed the strong quartz and weak anatase signatures and additionally element C in a disordered D-band (Fig. 18:1). Several spectra acquired in the entombing sediment and the host sediment some 10 m above the fossiliferous beds showed much weaker signatures of quartz, strong of hematite, and anatase, as well as carbonaceous material signature in D-band (Fig. 18:2–3). As described above in detail under this taxon, the strong Laser-Raman spectra of quartz in contrast to those weaker in the sediment samples are supportive in recognizing the primary silicieous composition of the specimen wall. The carbonaceous material signatures in D-band are derived from the organic matrix within the mineralized wall of the specimen and from disseminate organic matter preserved in the sediment.

The accessory mineral anatase (TiO2) detected in the specimens’ walls and the host

sediment is also reported in several siliciclastic successions in a regional scale of Scandinavia, and was authigenically crystallized in cements due to diagenetic kaolinization of detrital biotite and muscovite. The anatase crystals are well-recognized in quartz and phyllosilicate cements in Proterozoic sandstones and siltstones in the Brøttum Fm in the Sparagmite Basin of southern Norway, and the Dala Sandstone Formation in central Sweden (Morad, 1988). Anatase is recorded in the sandstone of the Nyborg Formation from the Varanger Peninsula alongside the high content of SiO2 (Siedlecka, 1995), and is preserved on the surfaces of new organic-walled microfossils from the topmost Nyborg Fm (Agić et al., 2019). It is observed herein in new fossils and interpreted accordingly as the contaminant from the host sediment.

Titanium dioxide is commonly present in the ambient environments of aquatic basins

and in the atmosphere, and is both hydrophilic and hydrophobic (Park, 2018). It reacts with metal oxide surfaces (Balajka et al., 2018), and Fe, Al, and Ma and their oxides co-existed in the host sediment and in small patches encrusted the specimens, and possible rendered the anatase precipitation. Both abiotic and biotic processes may lead to anatase precipitation in depositional environments and anatase is deposited due to the adsorptive and catalytic properties of clay minerals in sediments(Mann and Fyfe, 1989; Domingos et al., 2009; Pe-Piper et al., 2011; Cabral et al., 2012). The biological deposition of anatase is known to be mediated by bacteria, which are capable of binding metals, including titanium to form TiO2 nanoparticles, which are transformed into microcrystalline oxides(Cabral et al., 2012; and references therein). In natural environments, anatase nanoparticles are formed in association with pre-existing organic matter and due to bacterial growth, and carbonaceous material present in the studied fossils’ wall could be a substrate for post-mortem bacterial decay and deposition of anatase. The additional source of anatase on the studied fossils’ surfaces could be from the biogenic crystallization during the burial.

**References cited in Supplementary Data**

Agić, H., Högström, A.E.S., Moczydłowska, M., Jensen, S., Palacios, T., Meinhold, G.,

Ebbestad, J.O.R., Taylor, W., and Høyberget, M., 2019, Organically-preserved multicellular eukaryote from the early Ediacaran Nyborg Formation, Arctic Norway: Scientific Reports, v. 9: 14659. https://doi.org/10.1038/s41598-019-50650-x.

Balajka, J., Hines, M.A., DeBenedetti, W.J.I., Komora, M., Pavelec, J., Schmid, M., and

Diebold, U., 2018, High-affinity adsorption leads to molecularly ordered interfaces on TiO2 in air and solution: Science, v. 361, p. 786–789.

Cabral, A.R., Reith, F., Lehmann, B., Brugger, J., Meinhold, G., Tupinambá, M., and Kwitko-

Ribeiro, R., 2012, Anatase nanoparticles on supergene platinum–palladium aggregates from Brazil: Titanium mobility in natural waters: Chemical Geology, v. 334, p. 182–188.

Domingos, R.F., Tufenkji, N., and Wilkinson, K.J., 2009, Aggregation of titanium dioxide

nanoparticles: role of a fluvic acid: Environmental Science and Technology, v. 43, p. 1282–1286.

Kudryavtsev, A. B., Schopf, J. W., Agresti, D. G., and Wdowiak, T. J., 2001, *In situ* laser-

Raman imagery of Precambrian microscopic fossils: Proceedings of the National Academy of Sciences of the United States of America, v. 98, p. 823–826.

Mann, H, and Fyfe, W.S., 1989, Metal uptake and Fe-­, Ti-oxide biomineralization by

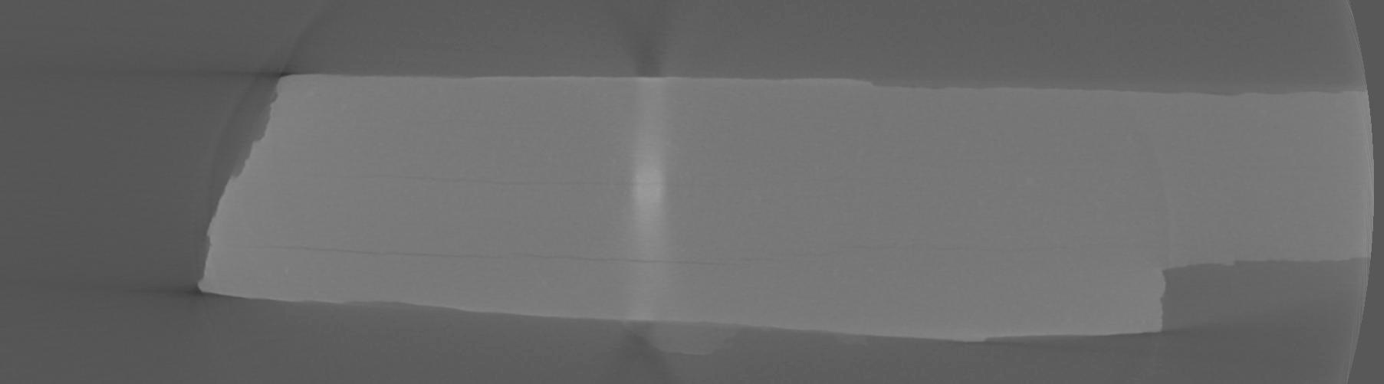
acidophilic microorganisms in mine-waste environments, Elliot Lake, Canada: Canadian Journal of Earth Sciences, v. 26, p. 2731–2735.

Morad, S., 1988, Diagenesis of titaniferous minerals in Jurassic sandstone from the

Norwegian Sea: Sedimentary Geology, v. 57, p. 17–40.

Park, J.Y., 2018, How titanium dioxide cleans itself: Science, v. 361, p. 753.

Pe-Piper, G., Karim, A., and Piper, D.J.W., 2011, Authigenesis of titania minerals and the

mobility of Ti: new evidence from pro-deltaic sandstones, Cretaceous Scotian Basin, Canada: Journal of Sedimentary Reseach, v. 81, p. 762–773.

Schopf, J. W., Kudryavtsev, A. B., Agresti, D. G., Czaja, A. D., and Wdowiak, T. J., 2005,

Raman Imagery: A New Approach to Assess the Geochemical Maturity and Biogenicity of permineralized Precambrian Fossils: Astrobiology, v. 5, p. 333–371.

Siedlecka, A., 1995, Major element geochemistry of Upper Proterozoic greywackes from

Norway and a coastal area of the Kola Peninsula in northern Russia: Norges geologiske undersøkelse Special Publication, v. 7, p. 285–296.

Wojdyr, M., 2010. Fityk: a general-purpose peak fitting program: Journal of Appied

Crystallography, v. 43, p. 1126–1128.

Animation of *Anulitubus* *formosus* n. gen. et sp. is shown in the side view of the wall and from the aperture in movies CT-*Anulitubus*-side.avi and CT-*Anulitubus*.aperture.avi.

