

Authors' Replies to Reviewers

Dear editor,

We have very much appreciated the overall effort of both reviewers as well as their fair criticism and thorough reading of our manuscript. We have revised the text, accepted most reviewers' comments and added new figures as suggested. At the same time, two figures were moved to supplementary information. Below, we are responding stepwise to comments made the reviewers (our answers are given in italics). In the revised text we highlighted (by tracking changes in the reviewing mode) all the changes to our manuscript and kept major deletions to enable easy comparison with the original text.

Reviewer #1:

First, the microbial mats should be described more thoroughly. I don't see the microbial mats in Fig. 8. These micrographs (recorded under cross polars, which is not mentioned) only show the minerals, and it is impossible to see the claimed microbial mats – dark zones may simply represent pure epoxy resin. At least plane polarized photomicrographs of the same zones should be added to show, e.g. green-pigmented mats. It would be better to use fluorescence techniques (e.g. Gérard et al. ISMEJ 2013,: : :) to clearly shown the microorganisms.

Figure 8 shows thin sections of dry samples from the black zone visible on Figure 2a. That is why the biofilm is represented only by a very thin black layer.

We are sorry for this unclear situation and we modified the accordingly the figure legend as well as the text itself. The use of cross polars method was also added. Moreover the fluorescence technique was used to demonstrate the presence of living mats on the rock surface (added as new Fig. 6).

Also, I'm not convinced with the rock pictures that the dark surface of the rocks is dark because of the presence of cyanobacteria, since the basaltic rocks would also be darks: could the cyanobacteria be very thin and transparent? Or do they have very dark pigments? Microscopy pictures of the cyano and algae are lacking in the paper. *The black colour of the rock surface shown of Fig. 6 (as Fig. 5 in the new version) is definitely caused by the presence of cyanobacteria. The dominant species Calothrix elsteri contains high amount of the dark pigment scytonemin (data not shown here). The black colour of this species is demonstrated on the micrphoto added as new Fig. 4 (together with photo of the co-dominating filamentous alga as requested above).*

In Fig.7b, arrows should be used to better distinguish mucilage and filaments. *Arrows were added to the Fig. 7b to make the picture clearer.*

It is claimed that "The regular leather biofilm structure with distinct cyanobacterial-microalgal composition and incorporated mineral grains is a modern analogue of some of the oldest well-described 10 Archean stromatolites (sensu Allwood et al., 2006)." – this is wrong, there is no similarity at all. Paleoarchean stromatolites do not show trapping and binding, they only show alternance of carbonaceous laminae and silica/carbonate laminae, which is not observed in your modern samples as you apparently only have a single mat layer with scarce carbonate precipitation.

This statement was deleted from the text.

Second, the finding of the carbonates spicules is very interesting and well documented and should be discussed in more depth. Many references are cited on carbonates precipitated from evaporation: do any of those resemble the spicules (I guess not, which could be a biogenicity argument)?

As far as we know, structures similar to the spicules observed in our study have not been documented, yet. We tried to reflect this in the title of the paper as well as in the discussion, where a sentence was added to stress more this biogenicity argument.

Moreover, a tubular hollow is shown in Fig. 8d in a carbonate spicule and claimed as a cyanobacterial filaments: abiotic carbonates may form hollow mineral tubes without requiring the presence of a filament of cells (Fan & Wang, Advanced Materials, 2005).

The possibility of abiogenic formation of these hollows was added to the discussion.

More importantly, the surface textures of the spicules, interpreted as “worn” etching figures can also be interpreted as primary structures: in Fig. 9 I see a new type of mesostructured carbonate crystal formed through highly oriented growth of micro/nanocrystals: see the references below showing and discussing in vitro and biotic growth of mesocrystalline structures. In general, mesostructured crystals strongly suggest growth in presence of organic matter, such as mucilage.

The possibility of primary origin of the surface textures of spicule presented on Fig. 9a-b was added to the text together with some of the suggested references.

Minor comments:

“lake water was mostly formed by detached benthic species; no substantial phytoplankton developed in the lakes.” – is that published elsewhere (please cite) or not (maybe show pictures of floating microorganisms)

The characteristics of phytoplankton in the lakes was not published. The low biomass in the open water was formed by detached filaments or tiny filament clumps, and no floating mats were observed. This part of the text was amended to describe better the situation.

What do you mean by “soft mineral”? “

By “soft mineral” we mean the mixture of dry or semi-dry cells, sheets and mucilage of cyanobacteria and algae biofilm infilled with crystals of feldspathoids (tectosilicate minerals) and mineral grains (semi-rounded quartz grains). In the text, we changed it to “soft mineral matter”.

Studies based on field or laboratory experiments have shown that some cyanobacteria and algae are able to tolerate prolonged periods of desiccation.” – please cite these studies

The references Tashyreva and Elster (2015) and Pichrtová et al. (2014) were added to demonstrate the ability of both cyanobacteria and algae to tolerate dessication.

The segregation of Ca^{2+} and HCO_3^- between ice and the residual solution depend on the freezing rate and hydrogen – oxygen isotope fractionation” – I don’t understand this sentence. Do you mean that H/O isotope fractionations can distinguish biotic and freezing-related precipitations?

The sentence above was deleted in the revised text. Based on our measurements, we cannot clearly decide if the winter abiotic calcite precipitation accompanies microbial lithogenic processes.

Reviewer #2:

General comments:

The present paper describes characteristics of unique organosediment structured from shallow Antarctic endorheic lakes. The paper is comprehensive and well written and I have only few comments.

The thermal regime section (3.2) is too descriptive and unnecessary, given that majority of the information can be gathered by looking at Figures 3, 4 and 5. Having three figures (Fig. 3-5) showing seasonal changes in air and water temperatures is also unnecessary as well. I would recommend using only one figure and moving the others into supplementary materials.

The section 3.2 was significantly shortened, and the former Figures 4 and 5 were moved to Supplementary materials as suggested.

The biological characteristics of the organosediment structures (section 3.3) could be better described and better presented and would benefit from including light microscopy photographs of the different cyanobacterial and algal species.

The microphotos of the dominant species were added as new Figure 4.

The discussion should be tightened up and some sections could be either entirely omitted or moved to the Results, particularly the descriptions of the environmental properties (section 4.1.).

The section 4.1 was shortened. However, we believe that the discussion of environmental properties (chemistry and thermal regime) is crucial for the understanding of benthic community characteristics and functioning and also for the explanation of possible origins of the calcite structures.

The discussion would benefit from adding a section discussing the possible origins of the structures as well as clearly describing the process of their formation.

The section discussing possible origin of calcite spicules was amended and new aspects based on available literature were added to the text

Unfortunately, process of formation of the spicules could not be assessed in detail based on available data.

There are too many figures in the manuscript and some of them are not very informative and thus could be moved to supplementary materials.

The original figures 4 and 5 were moved to supplementary materials.

Specific comments:

Page 13594, Line 26: Remove “on a range of spatial scales”
Removed.

Page 13595, Line 3: Preclude the development of larger organisms
Corrected.

Page 13595, Line 4: Organosedimentary structures instead of Organisedimentary
The sentence is not entirely clear
Corrected.

Page 13595, Line 14: related "to" rather than related "with" Sentence starting with
Calcite is too complex and should be divided into several sentences
Preposition corrected and the sentence was divided.

Page 13596, Line 6: Pleistocene and Holocene
Corrected.

Page 13596, Line 16: Missing ")" after Nedbalova
Corrected.

Page 13597, Line 12: Catchment areas would be more meaningful in km² than in m²
Catchment area units changed to km².

Page 13597, Line 15: How dramatically?
A sentence was added to clarify the extent of water level fluctuations.

Page 13604, Line 17: FSD instead of FDS
Corrected

Page 13608, Line 24: Please add reference for the trapping of the mineral grains
The reference Riding (2011) was added.

Unusual biogenic calcite structures in two shallow lakes, James Ross Island, Antarctica

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Abstract

The floors of two shallow endorheic lakes, located on volcanic surfaces on James Ross Island, are covered with calcareous organosedimentary structures. Their biological and chemical composition, lake water characteristics, and seasonal variability of the thermal regime are introduced. The lakes are frozen down to the bottom eight-nine months per year and their water chemistry is characterized by low conductivity and neutral to slightly alkaline pH. The photosynthetic microbial mat is composed of filamentous cyanobacteria and microalgae that are considered to be Antarctic endemic species. The mucilaginous black biofilm is covered by green spots formed by a green microalga and the macroscopic structures are packed together with fine material. Thin sections consist of rock substrate, soft biofilm, calcite spicules and mineral grains originating from different sources. The morphology of the spicules is typical of calcium carbonate monocrystals having a layered structure and [worn surfacespecific surface](#)

[texture](#), which reflect growth and degradation processes. The spicules chemical composition and structure correspond to pure calcite. Lakes age, altitude, morphometry, geomorphological and hydrological stability, including low sedimentation rates, together with thermal regime predispose the existence of this community. We hypothesize that the precipitation of calcite is connected with the photosynthetic activity of the green microalgae that were not recorded in any other lake in the region. This study has shown that the unique community producing biogenic calcite spicules is quite different to any yet described.

1 Introduction

The floors of most Antarctic lakes are covered with photosynthetic microbial mats (Vincent and Laybourn-Parry, 2008). However, the degree of disturbance plays a key role in the development of microbial mats. When growing in low-disturbance habitats, interactions between benthic microbial communities and their environments can produce complex emergent structures ~~on a range of spatial scales~~. Such structures are best developed in extreme environments, including benthic communities of deep, perennially ice-covered Antarctic lakes, where physical and chemical conditions, and/or geographical isolation preclude [the development of](#) larger organisms that could otherwise disrupt organised microbial structures (Wharton, 1994; Andersen et al., 2011). Many organo*is*sedimentary structures that emerge in these conditions are laminated and accrete through episodic trapping of sediments or grains and precipitation of minerals within a growing biogenic matrix (e.g. Arp et al., 2001; Reid et al., 2003). In perennially ice-covered lakes, the seasonality of growth imposed by the summer-winter light-dark conditions can induce annual growth laminations (Hawes et al., 2001), reinforced by calcite precipitation during growth and sediment diagenesis (Wharton et al., 1982; Wharton, 1994; Sutherland and Hawes, 2009). Calcite precipitation is not, however, a prerequisite for laminated, stromatolite-like communities (Walter, 1976; Schieber, 1999; Yamamoto et al., 2009). [A diversity of micro- to nanostructured CaCO₃ associated with extracellular polymeric substances and prokaryotes was described from the sediments of an East Antarctic lake \(Lepot et al., 2014\). There is also a growing experimental evidence that some carbonate precipitates are only produced in the presence of organic matter \(Cölfen and Antonietti, 1998; Pedley et al., 2000\).](#)

Precipitation of calcite by expulsion (segregation) is also a common process in the nature related ~~to~~[with](#) the freezing of common low ionic strength Ca²⁺ - HCO₃⁻ waters. Calcite precipitation related to water freezing was observed and described also from various polar-

63 alpine settings, e.g. from lake bottoms of Dry Valleys in Antarctica (Nakai et al., 1975) ~~or~~ as
64 a results of aufeis (icing, naled) formation in Northern Canada (Clark and Lauriol, 1997). ~~as~~
65 ~~e~~Crystalline precipitates that form subglacially on bedrock, ~~were~~ reported from numerous
66 locations (Ng and Hallet, 2002). ~~for example f~~ ~~as~~ fine-grained calcite powders ~~were observed~~
67 in subglacial deposits and in aufeis formations, Svalbard (Wadham et al., 2000) ~~or~~ ~~in~~ basal
68 ice and subglacial clastic deposits of continental glaciers of Switzerland (Fairchild et al.,
69 1993). ~~as~~ Calcite pendants occurred ~~ing~~ beneath coarse clasts in well-drained sediments ~~on~~,
70 Svalbard (Courty et al., 1994) ~~and~~ ~~as~~ calcite coatings ~~were found~~ in cavities in cold-climate
71 Pleistocene deposits of Western Transbaikalia, Russia, and in modern surface deposits at
72 ~~Se~~ymour Island, Antarctica (Vogt and Corte, 1996). ~~cryogenic calcite powder from modern~~
73 ~~cave environment (Clark and Lauriol, 1992).~~

74 James Ross Island belongs to a transitory zone between the maritime and continental
75 Antarctic regions (Øvstedal and Lewis Smith, 2001). Air temperature records indicate
76 progressive warming trends from 1.5 °C to 3.0 °C over the Antarctic Peninsula during the past
77 50 years (Turner et al., 2014). More than 80% of the island surface is covered with ice
78 (Rabassa et al., 1982). Only the northernmost part of the island, the Ulu Peninsula, is
79 significantly deglaciated and represents one of the largest ice-free areas in the northern part of
80 the Antarctic Peninsula. The origin of the lakes on James Ross Island is related to the last
81 glaciations of the Antarctic Peninsula ice sheet and retreat of the James Ross Island ice cap
82 during the late Pleistocene ~~and the~~ Holocene (Nývlt et al., 2011; Nedbalová et al., 2013).
83 Interactions between volcanic landforms and glacial geomorphology during previous glacial-
84 interglacial cycles, the Holocene paraglacial and periglacial processes and relative sea level
85 change have resulted in the complex present-day landscape of James Ross Island (Davies et
86 al., 2013). All of these processes have influenced the development of the lakes which are
87 found on the Ulu Peninsula at altitudes from <20 m above sea level (a.s.l.) near the coast to ~~e~~-
88 400 m a.s.l. in the mountain areas (Nedbalová et al., 2013).

89 During two Czech research expeditions (2008 and 2009) to James Ross Island, lake
90 ecosystems of the Ulu Peninsula were studied in respect to their origin, morphometry,
91 physical, chemical and biological characteristics (Nedbalová et al., 2013), together with
92 detailed cyanobacterial and microalgal diversity descriptions (Komárek and Elster, 2008;
93 Komárek et al., 2011; Kopalová et al., 2013; Škaloud et al., 2013; Komárek et al., 2015). As
94 part of this study, we encountered 1 to 5 millimetres scale calcareous organosedimentary
95 structures on the floor of two endorheic lakes, 1 and 2, which are quite different to any

microbially mediated structures yet described from modern environments. These shallow lakes on higher-lying levelled surfaces originated after the deglaciation of volcanic mesas which became ice-free some 6.5–8 ka ago (Johnson et al., 2011) and are considered among one of the oldest in the region. However, a later appearance of these lakes is also possible, as we have no exact dates from their sediments (Nedbalová et al., 2013).

The aim of this paper is to describe in detail the chemical and biological composition of the organosedimentary structures (~~stromatolites sensu Allwood et al., 2006~~) together with the limnological characteristics of the two lakes. A hypothesis concerning the formation of calcite spicules is also presented. The results of this study can serve as a baseline for understanding microbial behaviors in forming these organosedimentary structures, which will provide insight into the interpretation of fossil forms from early Earth.

2 Materials and methods

2.1 Study site

Endorheic lake 1 (63°54'11.7" S, 57°46'49.9" W, altitude 65 m a.s.l.) and endorheic lake 2 (63°53'54.6" S, 57°46'33.8" W, altitude 40 m a.s.l.) are shallow lakes located near Andreassen Point on the E coast of the deglaciated Ulu Peninsula, in the northern part of James Ross Island, NE Antarctic Peninsula (Figure 1). They are shallow with maximum depth of 1.1 and 0.9 m, and mean depth of 0.5 and 0.3 m. Their catchment areas are ~~0,340,515~~ and ~~0,3698,586~~ km², lake area 4220 and 2970 m² and water volume 2183 and 1037 m³, respectively (Nedbalová et al., 2013). Melt water from the surrounding snowfields feed the lakes for a few weeks during the austral summer. The water level in both lakes fluctuated dramatically. Water is mainly lost through evaporation from the ice free water surface. During this period, intense evaporation in both lakes is coupled with macroscopic changes in the littoral belt. The extent of water level fluctuation was documented for lake 1- (Figure 2).

Climate conditions of the Ulu Peninsula are characterized by mean annual air temperatures around –7 °C and mean summer temperatures above 0 °C for up to four months (Láska et al., 2011a). The mean global solar radiation is around 250 W m⁻² in summer (December-February), with large day-to-day variation affected by extended cyclonic activity in the circumpolar trough and orographic effects over the Antarctic Peninsula (Láska et al., 2011b). The bedrock is composed of two main geological units, namely Cretaceous back-arc basin

sediments and mostly subglacial Neogene to Quaternary volcanic rocks (Olivero et al., 1986). The terrestrial vegetation is limited to non-vascular plants and composed predominantly of lichen and bryophyte tundra. A large number of lakes can be found in this area, formed by glacial erosion and deposition, followed by glacier retreat during the Holocene (Nedbalová et al., 2013).

2.2 Sampling procedures

Lake 1 was sampled on 22 February 2008. In 2009, lake 1 was sampled on 5 January, lake 2 on 12 January. Air temperature at 2 m above ground was measured by an automatic weather station (AWS) located nearby (Figure 1). Incident global solar radiation was monitored with a LI-200 pyranometer (LI-COR, USA) at Mendel Station, located 11 km northwest of the study site (Figure 1). The LI-200 spectral response curve covers wavelengths from 400 to 1100 nm with absolute error typically of $\pm 3\%$ under natural daylight conditions. Global radiation was measured at 10s time interval and stored as 30-min average values, while air temperature was recorded at 1 hour intervals from 1 February 2009 to 30 November 2010. In lake 1, water temperature was monitored from 10 February 2009 to 30 November 2010 at 1 hour intervals using a platinum resistance thermometer with Minikin T data logger (EMS Brno, Czech Republic) installed on the lake bottom.

Conductivity, pH, temperature and dissolved oxygen were measured in situ with a portable meter (YSI 600) at the time the lakes were ice free. Water samples were collected from the surface layer, immediately filtered through a 200- μm polyamide sieve to remove zooplankton and coarse particles. Chlorophyll-a was extracted from particles retained on Whatman GF/F glass microfiber filters according to Pechar (1987). After centrifugation, chlorophyll-a was measured by a Turner TD-700 fluorometer equipped with a non-acidification optical kit. The remaining water was kept frozen until analyzed at the Institute of Hydrobiology (Czech Republic). The chemical analytical methods are given in Nedbalová et al. (2013). The stones covered by photoautotrophic mats – biofilm collected in the field were transported to the Czech Republic in a frozen and/or dry state, documented with stereomicroscope (Bresser, HG 424018) and [imaging fluorometer \(FluorCam, PSI\)](#) and used for a) phytobenthos community description and isolation of dominant species, b) fix for thin section analyses, c) scanning electron and optical microscopy, and d) determination of the structure and chemical composition of calcium carbonate spicules.

2.3 Thin section analyses

Thin section analyses were made to observe both rock substrate and inorganic particles within biofilms. Dry microbial mat were saturated with epoxy resins in vacuum, subsequently cut perpendicularly and saturated again with epoxy resin. The sample was cemented to a glass slide after grinding and polishing, and a thin section was prepared by final sectioning, grinding and polishing to a desired thickness of 50–55 µm. Thin sections of rocks were studied in transmitted (PPL) and polarized (XPL) light (Olympus BX-51M) and documented in transmitted light of a Nikon SMZ-645 optical microscope using NIS-Elements software.

2.4 Biofilm scanning electron and optical microscopy

The morphology of photoautotrophic mats and calcareous spicules was studied using standard methods of scanning electron microscopy (SEM) using back-scattered electrons (BSE) (Jeol JSM-6380, Faculty of Science, Charles University) and optical microscopy (Nikon SMZ-645 using NIS-Elements software). Calcareous spicules were collected directly from the surface of biofilms. Samples studied in SEM were completely dried for 5 months at room temperature, then mounted on stubs with carbon paste and coated with gold prior to photomicrographing.

2.5 Structure and chemical composition of calcium carbonate spicules – EDS and EBSD analyses

The chemical composition of the analyzed spicules was measured by using the Link ISIS 300 system with 10 mm² Si-Li EDS detector on a CamScan 3200 scanning electron microscope (Czech Geological Survey, Prague). Analyses were performed using an accelerating voltage of 15 kV, 2 nA beam current, 1 µm beam size and ZAF correction procedures. Natural carbonate standards (calcite, magnesite, rhodochrosite, siderite and smithsonite) were used for standardization. Subsequent structural identification was confirmed by electron backscattered diffraction (EBSD). Identification data and crystallographic orientation measurements were performed on the same scanning electron microscope using an Oxford Instruments Nordlys S EBSD detector. The thick sections used for EBSD applications were prepared by the process of chemo-mechanical polishing using colloidal silica suspension. The acquired EBSD patterns were indexed within Channel 5 EBSD software (Schmidt and Olensen, 1989) applying calcite and aragonite crystallographic models (Effenberger et al., 1981; Caspi et al., 2005). Orientation contrast images were collected from a 4-diodes forescatter electron detector

(FSD) integrated into the Nordlys S camera. EBSD pattern acquisition was carried out at 20 kV acceleration voltage, 3 nA beam current, 33 mm working distance and 70° sample tilt.

3 Results

3.1 General description of the lakes and water chemistry

Pictures and detailed bathymetric parameters of both lakes together with marked lines of water level and the maximum extent of the photosynthetic microbial mat littoral belt in lake 1 are presented in Figure 2.

The physico-chemical characteristics of the lake water for both lakes are given in Table 1. The sampling of lake 1 (pH 7.4–7.9, saturation of oxygen 98.9 %) was performed during cloudy days. Oxygen supersaturation (128%) together with a relatively high pH (8.6) was observed in lake 2 during a sunny day. Conductivity was below 100 $\mu\text{S cm}^{-1}$ in both lakes. The concentrations of dissolved inorganic nitrogen forms were low, whereas the concentration of dissolved reactive phosphorus (SRP) was 19.3 $\mu\text{g L}^{-1}$ in lake 2. Relatively high concentrations of dissolved organic carbon, particulate nutrients and chlorophyll-a were also characteristic for lake 2 (Table 1). ~~The Low~~ autotrophic biomass in ~~lake-open~~ water was mostly formed by detached benthic species; no substantial phytoplankton ~~neither floating mats developed-occurred~~ in the lakes. The comparison of the two sampling dates available for lake 1 suggested high fluctuations of dissolved nutrient concentrations.

3.2 Thermal regime

Figure 3a shows the annual variation of daily mean water temperature in lake 1 and of daily mean air temperature ~~measured 2 m above ground~~ in the Solorina Valley (locations of ~~air temperature, global radiation and water~~ temperature sensors are marked in Figures 1 and 2). Lake 1 ~~is-was~~ frozen to the bottom from the end of March to the end of October or beginning of November. ~~Air temperatures were frequently lower than water temperatures.~~ Minimum daily mean ~~winter~~ temperatures on the bottom of the lake were about $-12\text{ }^{\circ}\text{C}$ and $-10\text{ }^{\circ}\text{C}$ for 2009 and 2010, respectively. Minimum daily mean air temperatures in the same period were between $-32\text{ }^{\circ}\text{C}$ and $-25\text{ }^{\circ}\text{C}$. ~~Positive summer daily mean water temperatures on the bottom of the lake were between $5\text{ }^{\circ}\text{C}$ to $9\text{ }^{\circ}\text{C}$ from the beginning of November to the end of March. Air temperatures were frequently lower than water temperatures.~~ Mean monthly water

temperatures in the lake ranged from -10.4°C (August 2009) to 5.8°C (February 2010), while monthly mean air temperatures were between -18.7°C to 0.7°C . The differences were greater at the beginning of the winter season (June–July), due to a rapid drop of air temperature.

~~Diurnal water and air temperature amplitudes in lake 1 and the Solorina Valley are shown in Figure 3b.~~ The highest night-day air temperature fluctuations (up to 28°C) were recorded during the winter months, while the lowest, ~~in contrast~~, occurred in summer. ~~Conversely~~ In contrast, the highest night-day amplitudes of lake water temperature ~~on the bottom of the lake~~ were recorded from November to February, with typical values between 2°C and 4°C (Figure 3b).

The course of global solar radiation (Figure 3c) ~~is was~~ smooth, with the maximum daily mean of 385 W m^{-2} during clear sky conditions around the summer solstice. Global radiation ~~reached~~ the bottom of both lakes during the ice free period.

The relative frequency of hourly values of lake 1 water and air temperature ~~at the bottom of lake 1 and air temperature measured 2 m above ground in the Solorina Valley in the period from 10 February 2009 to 30 November 2010~~ is shown in Figure 4S1. Water temperature fluctuation ~~is was~~ narrow, ranging from ~~-15 – 16~~ to 8°C . ~~This plot also documents that t~~ The bottom of the lake ~~is was~~ dry frozen, with temperatures from ~~-15°C to most frequently -2 to -6° for most of the year, C and t~~ (Figure 4a). The growing season, with liquid water at temperatures from 2 to 4 – 8°C , covered only two-three months (Figure S1a). ~~In contrast to lake water thermal regime, a~~ With respect to air temperature fluctuations (Figure 4b), the seasonal thermal regime in the Solorina Valley ~~is were~~ much wider (typically from -38°C to 8°C) (Figure S1b). ~~in comparison with the thermal regime at the bottom of lake 1, where was from -16°C up to 8°C .~~

The ~~temperature at the lake bottom was permanently below occurrence of days with water temperature higher than -4°C in lake 1 and monthly mean global solar radiation in the period from February 2009 to November 2010~~ is shown in Figure 5. Owing to the variability of the weather conditions, lake water at the bottom is completely frozen only during the coldest ~~one~~ two-three months per year (Fig. S2) (July–August); water temperature is higher than -4°C in the rest of the year. The water temperature ~~is~~ above 0°C (liquid phase) was recorded from November to April (139 days in average). ~~The~~ number of days with temperature between 0

and -4 °C remains the same as for liquid water occurrence with small changes in the start and end dates towards to the transition period (February-June and September-November, respectively). In such thermal conditions, the benthic littoral community can be metabolically active.

3.3 Littoral phytobenthos – biofilm community description

The littoral benthic community in lakes 1 and 2 are dominated by the heterocytous cyanobacterium *Calothrix elsteri* Komárek 2011 (Figure 4a), which forms a flat black biofilm on the upper surface of bottom stones (Figure 56), followed by *Hassallia andreassenni* Komárek 2011 and *Hassallia antarctica* Komárek 2011. *Hassallia andreassenni* is associated with calcium precipitation, as described later. *Hassallia antarctica* was found in stone crevices, being only loosely attached to the substrate. Littoral benthic mats – biofilms on stones (Figure 6) are co-dominated on the surface of the blackish cyanobacterial biofilm by the green filamentous and richly-branched alga *Hazenia broadyi* Škaloud et Komárek 2013 (Ulotrichales, Chlorophyceae) (Figure 4b). *Hazenia broadyi* grew in macroscopic colonies producing green spots (Figure 56b,d). Later in the summer season, the green spots connected micro fortified mucilaginous lines (Figure 56c,d). Figure 56a shows the community in early spring whereas Figure 56b,d originated from later summer when the littoral benthic community was already well developed with a dense coverage of *Hazenia broadyi* green spots. More detailed pictures (Figure 56e,f) documented the structure of the black leather like biofilm with mucilaginous marble on its surface covered by green spots. When the biofilm gets dry, the net of precipitated micro fortified mucilage mixed with soft mineral matter particles and crystals of calcium carbonate is visible (Figure 65g,h).

Scanning electron micrographs document the structure of the biofilm (Figure 7). Figure 7a shows a lateral view (cross section) of a biofilm with cyanobacterial filaments (*Calothrix elsteri* and *Hassallia andreassenni*). A biofilm upper view (Figure 7b,d) shows the structure of the cyanobacterial-microalgae community producing the mucilaginous micro fortified net of filaments with spots on its surface.

3.4 Inorganic compounds of biofilms

Thin sections, showing both dry biofilms and rock substrate (Figure 8), provided information on various inorganic compounds associated with the soft tissue of the cyanobacterial – microalgal community. These inorganic compounds are represented by (1) allochthonous

281 mineral grains that are overgrown and incorporated by biofilms and (2) calcareous spicules of
282 different sizes ranging from 0.5 mm to 1 cm that are precipitated within the cyanobacterial-
283 microalgal community.

284 The rock substrate of biofilms is formed by subangular to subrounded pebbles to boulders of
285 basaltic rock, which is dark-grey in colour, compact and usually with a microcrystalline
286 porphyric texture. The rock is not homogenous, but contains numerous ball-like empty voids,
287 which are often partly filled with feldspathoids (Figure 8a). Crystals of plagioclase (feldspar
288 group) and augite (pyroxene group) are easily recognizable in thin sections (Figures 8a–c).

289 Biofilms are often partly covered with various mineral grains and rock fragments, but all
290 specimens studied also contain these particles incorporated directly within soft cyanobacterial
291 - microalgal filaments (Figure 8a–c).

292 Mineral grains embedded within biofilms close to the basaltic rock surface are mainly angular
293 to subangular crystal fragments of plagioclase and augite (Figures 8b,c), i.e. the main mineral
294 components of the basaltic rock substrate described above. In the upper part of biofilms,
295 however, partly or fully incorporated grains of quartz occur, being typically rounded or partly
296 rounded (Figures 8a,b). One of the thin sections shows a calcareous spicule in situ and
297 mineral grains within the biofilm (Figures 8c,d).

298 The structure and morphology of calcareous spicules was studied on SEM (Figure 9). The
299 spicules (see also Methods) show an intensively worn surface (Figure 9a), partial or intense
300 recrystallization (Figures 9a,b) and dissolution (Figure 9b). Crystal facets on the surface and
301 cleavage (crystallographic structural planes) in the interior of the spicules (Figures 9a,b) are
302 typical characteristics of calcium carbonate monocrystals.

303 A non-recrystallized superficial layer of microcrystalline calcite (e.g., Figure 9b) shows the
304 structure of parallel needle-like calcite microcrystals (Figures 9d–f). Partial corrosion and
305 dissolution of spicules show distinct layering of these needle-like microcrystals (Figure 9d).
306 The layered structure of even partly recrystallized spicules is confirmed in the ring-like
307 structures with a cyanobacterial filament in the centre (Figure 10).

308 The chemical composition of the studied calcareous spicules determined by [FSDS](#)
309 corresponds to pure CaCO_3 . Following chemical composition, calcite and aragonite structural
310 models were applied for the EBSD study focused on structural identification of the crystals
311 forming the spicule. Structural identification of the studied specimen especially prepared for
312 the EBSD study confirmed the absolute agreement between the recorded EBSD patterns and

modelled patterns for calcite. The presence of aragonite was not confirmed. FSD images acquired for chemical and orientation contrasts (Figure 10) show a layered structure especially visible in orientation contrast. This feature reflects continual growing processes on layers with very similar crystallographic orientation. Absolute angular differences between individual layers are below 0.8°.

4 Discussion

4.1 Environmental properties

~~The Ulu Peninsula is a region of high limnological diversity that is related to differences in lake age, bedrock and altitude.~~ The ~~endorheic~~ lakes under study are characterized by a low content of major ions due to their volcanic bedrock and lower marine influence. In comparison with other lakes of this area, the two lakes show no specific lake water chemistry characteristics with moderate SRP and nitrate concentrations frequently below the detection limit (Nedbalová et al., 2013). High pH together with oxygen supersaturation recorded in lake 2 could be associated with high photosynthetic activity of the mats at the time of sampling.

Because water in either liquid or solid form has a large heat storage capacity, it acts as an important buffer to temperature change. Local climatic conditions of shallow freshwater lakes is the principal external factor controlling their ecological functionality. Lake 1 is frozen to the bottom ~~with minimum daily mean temperatures between -12 °C and -10 °C~~ approximately eight-nine months per year. For most of the year, however, the temperature of the littoral and lake bottom is only from -2 to -4 °C. In such conditions, a thin layer of water probably covers the surface of the littoral benthic community ~~that (the community can be metabolically active at temperatures of about -4 °C)~~ (Davey et al., 1992). The growing season, with liquid water at temperatures between 2 to 4 °C, covers only two-three months.

In regards to heat balance, the studied shallow lakes are pond (wetlands) environments which freeze solid during the winter. This inevitability is a strong habitat-defining characteristic, which places considerable stress on resident organisms (Hawes et al., 1992; Elster, 2002). In summer, they must withstand drying in large parts of the littoral zone due to a considerable drop in water level. In freezing and desiccation resistance studies of freshwater phytobenthos in shallow Antarctic lakes, several ecological measurements have recorded seasonal, diurnal, and year round temperature fluctuations and changes in water state transitions (e.g., Davey,

1989; Hawes et al., 1992, Hawes et al., 1999). In localities with steady moisture and nutrient supplies, the abundance and species diversity of algae is relatively high. However, as the severity and instability of living conditions increases (mainly due to changes in mechanical disturbances, desiccation–rehydration and subsequent changes in salinity), algal abundance and species diversity decreases (Elster and Benson, 2004). The speed at which water state can change between liquid, ice, and complete dryness, is one of the most important ecological and physiological factors of these lakes. Studies based on field or laboratory experiments have shown that some cyanobacteria and algae are able to tolerate prolonged periods of desiccation (Pichrtová et al., 2014; Tashyreva and Elster, 2015). It is also obvious that there are strain/species specific differences in the overwintering strategies, and also between strains/species inhabiting different habitats (Davey, 1989; Hawes et al., 1992; Jacob et al., 1992; Šabacká and Elster, 2006; Elster et al., 2008). The ice and snow which cover the endorheic-lakes for about eight-nine months per year serve as a natural incubator which moderate potential mechanical disturbances and stabilise the thermal regimes of the lakes.

4.2 Biodiversity

Patterns of endemism and alien establishment in Antarctica are very different across taxa and habitat types (terrestrial, freshwater or marine) (Barnes et al. 2006). Environmental conditions, as well as dispersal abilities, are important in limiting alien establishment (Barnes et al., 2006). Antarctic microbial (cyanobacteria, algae) diversity is still poorly known, although recent molecular and ecophysiological evidence support a high level of endemism and speciation/taxon distinctness (Taton et al., 2003; Rybalka et al., 2009; de Wever et al., 2009; Komárek et al., 2011; Strunecký et al., 2012; Škaloud et al., 2013).

The floors of the studied lakes are covered with photosynthetic microbial mats composed of previously described species of heterocytous cyanobacteria, mostly *Calothrix elsteri* Komárek 2011 followed by *Hassallia andreassenni* Komárek 2011 and *Hassallia antarctica* Komárek 2011 (Komárek et al., 2011). They are co-dominated by a newly described species of green filamentous and richly branched algae *Hazenia broadyi* Škaloud et Komárek 2013 (Ulotrichales, Chlorophyceae) (Škaloud et al., 2013). All the previously mentioned recently described species have special taxonomic positions together with special ecology and are considered at present as Antarctic endemic species.

The black leather like biofilm with mucilaginous marble on its surface is covered by green spots. These macroscopic structures form mats a few mm thick consisting of the above

mentioned species packed in mucilage glued together with fine material. The regular leather biofilm structure with distinct cyanobacterial-microalgal composition and incorporated mineral grains is ~~a modern analogue of some of the oldest well described Archean stromatolites (sensu Allwood et al., 2006)~~to our knowledge unique. During the limnological survey of the whole Ulu Peninsula (Nedbalová et al., 2013), this specific biofilm structure was observed only in these two endorheic lakes, although lakes with very similar morphometric and chemical characteristics are found in the area. The mat structure is thus apparently tightly linked to the species composition (Andersen et al., 2011).

The low abundance of benthic diatoms in the lakes is unusual, but not unprecedented as there are other areas in Antarctica where diatoms are scarce or absent (Broady, 1996, Wagner et al., 2004). The reason underlying the absence of diatoms is not immediately obvious, because diatoms are quite a common and frequently dominant component of microbial communities in most freshwater habitats of the Ulu Peninsula, James Ross Island (Kopalová et al., 2013). Local geographical separation of lakes 1 and 2 together with founder effect may have precluded successful colonization by the subset of diatoms that are common in the surrounding freshwater habitats. Although it has long been held that diatoms are dispersed widely, some recent reports document very small scale microbial distributions and endemism (Kopalová et al., 2012; Kopalová et al., 2013).

4.3 Inorganic compounds of biofilms

Based on the character of the rock substrate and lake sediments it is suggested, that one of the main prerequisites for existence of this cyanobacterial-microalgal community producing unusual biogenic calcite structures_ is; (1) flat and stable substrate in both lakes and (2) low sedimentation rate.

The substrate for biofilms is composed of boulders and pebbles of the stony littoral zone, petrographically corresponding to compact and massive basaltoids (Smellie et al., 2008; Svojtka et al., 2009). Rounded or sub-rounded quartz grains that are incorporated ("trapped") within biofilms cannot originate from basaltic volcanic rocks forming the bottom of both lakes and substrate of the studied biofilms. This is evidenced by the petrographic character of the basaltoids, which do not contain any quartz. The presence of abraded quartz grains in lake 1 and 2 can be easily explained by wind transport (e.g., Shao, 2008).

The specific cyanobacterial-microalgal community described above can prosper in the two shallow endorheic lakes, because of low sedimentation rates resulting from minor water input.

408 Low sedimentary input is the main necessary ecological parameter which facilitates the
409 existence of this special microbial community. The community is, however, well adapted to
410 seasonally elevated sedimentation rates coming from frequent and intense winds. During wind
411 storms, the wind is carrying a relatively large amount of small mineral grains and rock
412 microfragments (intense eolic erosion; e.g., Shao (2008) and references therein). These grains
413 and particles are usually derived from erosion of the rocks either in the very close vicinity of
414 the locality (weathering of basaltic rocks), but mainly come from remote locations where
415 especially Upper Cretaceous marine sedimentary sequences are outcropping (Smellie et al.,
416 2008; Svojtka et al., 2009). Even elevated amounts of mineral grains transported into the lake
417 by wind do not stop the growth of cyanobacterial-microalgae biofilms, due to their ability of
418 incorporating and "trapping" mineral grains within the living tissue (Riding, 2011).

419 This study has shown that inorganic substances precipitated by microbial lithogenetic
420 processes are exclusively represented by calcite spicules. Precipitation of carbonate outside of
421 microorganisms during photosynthesis as a mechanism of carbonate construction was
422 described for many filamentous cyanobacterial species (Schneider and Le Campion-
423 Alsumard, 1999). However, the biogenic calcite structures in both lakes are quite different to
424 any microbially mediated structures yet described from modern environments (Kremer et al.,
425 2008; Couradeau et al., 2011) and also to structures formed by abiotic precipitation (e.g., Vogt
426 and Corte, 1996). Although there are many lakes with thick mats and similar chemical
427 characteristics on the Ulu Peninsula, the calcite spicules were found exclusively in the two
428 endorheic lakes. We believe that their formation is linked to the specific photoautotrophic
429 mats present in the lakes. From Figures 6g,h it is clearly visible that the calcareous
430 organosedimentary structures keep contours of viable photosynthetic microbial mat after
431 desiccation or calcite spicules precipitation. More specifically, the co-dominance of a green
432 microalga is unique since mats in Antarctic lakes are most frequently formed by filamentous
433 cyanobacteria (Vincent and Laybourn-Parry 2008). Therefore, we hypothesise that the more
434 rapid photosynthesis rate of *Hazenia* in comparison with cyanobacteria may induce conditions
435 necessary for carbonate precipitation in the lakes (Schneider and Le Campion-Alsumard,
436 1999; Vincent, 2000). However, some role of abiotic precipitation of calcite is also possible.
437 The segregation of Ca^{2+} and HCO_3^- between ice and the residual solution depend on the
438 freezing rate and hydrogen-oxygen isotope fractionation (O'Neil, 1968; Žák et al. 2004).
439 From our measurements-observations we cannot clearly decide if the winter abiotic calcite
440 precipitation accompany microbial lithogenetic processes.

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Although we interpret the tubular hollow observed in the centre of some spicules as the result of the presence of cyanobacterial filament during the process of crystallization, such structures may form also as the result of abiotic precipitation of calcite –(Vogt and Corte, 1996; Fan and Wang, 2005).

It is striking that some calcite spicules probably exhibit recrystallization, forming spicules with the structure of calcite monocrystals. However, these spicules could be also interpreted as primary structures: mesostructured carbonate crystals formed through highly oriented growth of micro/nanocrystals and characterized by a specific surface texture (Fig. 9a–b). There is already evidence that some biominerals including calcite are mesocrystals (Cölfen and Antonietti, 2005) and the importance of extracellular polymeric substances for the formation of some types of carbonate precipitates was documented (Pedley et al., 2009).

Determining the structure and material of precipitated inorganic substances brought another relevant question: "Do calcite spicules have fossilisation potential"? Microcrystalline calcite forming the recrystallized spicule is a typical material of calcite shells of fossil invertebrates (e.g., Vodrážka, 2009). Although calcite fossils may be partly or completely dissolved during diagenetical processes in the fossil record (e.g., Schneider et al., 2011; Švábenická et al., 2012), their preservation potential is relatively high. Therefore, we expect to find fossil and/or sub-fossil calcite spicules from the Quaternary lake sediments of the studied area.

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References

473 ~~Allwood, A., Walter, M., Kamber, B., Marshall, C., Burch, I.: Stromatolite reef from the early~~
 474 ~~archaean era of Australia. Nature 441: 714–718, doi: 10.1038/nature04764, 2006.~~

475 Andersen, D. T., Sumner, D. Y., Hawes, I., Webster-Brown, J., ~~and~~ McKay, C. P.: Discovery
 476 of large conical stromatolites in Lake Untersee, Antarctica. Geobiology, 9, 280–293, doi:
 477 10.1111/j.1472-4669.2011.00279.x, 2011.

478 Arp, G., Reimer, A., ~~and~~ Reitner, J.: Photosynthesis-induced biofilm calcification and calcium
 479 concentrations in Phanerozoic oceans. Science, 392, 1701, doi: 10.1126/science.1057204,
 480 2001.

481 Barnes, D. K. A., Hodgson, D. A., Convey, P., Allen, C. S., ~~and~~ Clarke, A.: Incursion and
 482 excursion of Antarctic biota: past, present and future. Global Ecol. Biogeogr., 15, 121–142,
 483 doi: 10.1111/j.1466-822x.2006.00216.x, 2006.

484 Broady, P. A.: Diversity, distribution and dispersal of Antarctic terrestrial algae. Biodiv.
 485 Conserv., 5, 1307–1335, doi: 10.1007/BF00051981, 1996.

486 Caspi, E. N., Pokroy, B., Lee, P. L., Quintana, J. P., ~~and~~ Zolotoyabko, E.: On the structure of
 487 aragonite. Acta Crystallogr. B 61, 129–132, doi: 10.1107/S0108768105005240, 2005.

488 ~~Clark, I. D., Lauriol, B.: Kinetic enrichment of stable isotopes in cryogenic calcites. Chem.~~
 489 ~~Geol. 102: 217–228, doi: 10.1016/0009-2541(92)90157-Z, 1992.~~

490 Clark, I. D. ~~and~~ Lauriol, B.: Aufeis of the Firth River basin, Northern Yukon Canada:
 491 insights to permafrost hydrology and karst. Arct. Alp. Res., 29, 240–252, doi:
 492 10.2307/1552053, 1997.

493 Courty, M. A., Marlin, C., Dever, L., Tremblay, P., ~~and~~ Vachier, P.: The properties, genesis
 494 and environmental significance of calcite pendants from the high Arctic (Spitsbergen).
 495 Geoderma, 61, 71–102, doi: 10.1016/0016-7061(94)90012-4, 1994.

496 Couradeau, E., Benzerara, K., Moreira, D., Gérard, E., Kaźmierczak, J., Tavera, R. ~~and~~
 497 López-García, P.: Prokaryotic and eukaryotic community structure in field and cultured
 498 microbialites from the alkaline lake Alchichica (Mexico). PloS ONE, 6(12), 1–15, doi:
 499 10.1371/journal.pone.0028767, 2011.

500 [Cölfen, H. and Antonietti, M.: Crystal design of calcium carbonate microparticles using](#)
 501 [double-hydrophilic block copolymers. Langmuir, 14, 582–589, doi: 10.1021/la970765t, 1998.](#)
 502 [Cölfen, H. and Antonietti, M.: Mesocrystals: inorganic superstructures made by highly](#)
 503 [parallel crystallization and controlled alignment. Angew. Chem. Int. Ed., 44, 5576–5591, doi:](#)
 504 [10.1002/anie.200500496, 2005.](#)
 505 Davies, B. J., Glasser, N.F., Carrivick, J. L., Hambrey, M. J., Smellie, J. L., [and](#) Nývlt, D.:
 506 Landscape evolution and ice-sheet behavior in a semi-arid polar environment: James Ross
 507 Island, NE Antarctic Peninsula. Special publication. Geological Society of London, doi:
 508 10.1144/SP381.1, 2013.
 509 Davey, M. C.: The effect of freezing and desiccation on photosynthesis and survival of
 510 terrestrial Antarctic algae and cyanobacteria. Polar Biol., 10:–, 29–36, 1989.
 511 Davey, M. C., Pickup, J., [and](#) Block, W.: Temperature variation and its biological
 512 significance in fellfield habitats on a maritime Antarctic island. Antarct Sci., 4:–, 383–388,
 513 1992.
 514 De Wever, A., Leliaert, F., Verleyen, E., Vanormelingen, P., Van der Gucht, K., Hodgson, D.
 515 A., Sabbe, K., [and](#) Vyverman, W.: Hidden levels of phylodiversity in Antarctic green algae:
 516 further evidence for the existence of glacial refugee. P. Roy. Soc. B-Biol. Sci., 276:–, 3591–
 517 3599, doi: 10.1098/rspb.2009.0994, 2009.
 518 Effenberger, H., Mereiter, K., [and](#) Zemann, J.: Crystal structure refinements of magnesite,
 519 calcite, rhodochrosite, siderite, smithsonite and dolomite, with discussion of some aspects of
 520 the stereochemistry of calcite-type carbonates. Z. Kristallogr., 156:–, 233–243, 1981.
 521 Elster, J.: Ecological classification of terrestrial algal communities of polar environment, [in](#):
 522 GeoEcology of terrestrial oases, [edited by](#): (Beyer, L., [and](#) Boelter, M., [eds](#)), pp. 303–319.
 523 Ecological Studies, Springer-Verlag, Berlin, Heidelberg, 2002.
 524 Elster, J., [and](#) Benson, E. E.: Life in the polar terrestrial environment with a focus on algae
 525 and cyanobacteria, [in](#): Life in the frozen state, [edited by](#): (Fuller, B., Lane, N., [and](#) Benson
 526 E. E., [eds](#)), pp. 111–149. Taylor and Francis, London, doi: 10.1201/9780203647073.ch3,
 527 2004.

528 Elster, J., Degma, P., Kováčik, L., Valentová, L., Šrámková, K., [and](#) Pereira, A. B.: Freezing
529 and desiccation injury resistance in the filamentous green alga *Klebsormidium* from the
530 Antarctic, Arctic and Slovakia. *Biologia*, 63:—, 839–847, doi: 10.2478/s11756-008-0111-2,
531 2008.

532 Fairchild, I. J., Bradby, B., [and](#) Spiro, B.: Carbonate diagenesis in ice. *Geology*, 21, 901–904,
533 doi: 10.1130/0091-7613(1993)021<0901:CDII>2.3.CO;2, 1993.

534 [Fan, Y.W. and Wang, R.Z.: Submicrometer-sized vaterite tubes formed through nanobubble-](#)
535 [templated crystal growth. *Adv. Mater.*, 17, 2384–2388, doi: 10.1002/adma.200500755, 2005.](#)

536 Jacob, A., Wiencke, C., Lehmann, H., [and](#) Krist, G. O.: Physiology and ultrastructure of
537 desiccation in the green alga *Prasiola crispa* from Antarctica. *Bot. Mar.*, 35:—, 297–303, doi:
538 10.1515/botm.1992.35.4.297, 1992.

539 Johnson, J. S., Bentley, M. J., Roberts, S. J., Binnie, S. A., [and](#) Freeman, S. P. H. T.:
540 Holocene deglacial history of the northeast Antarctic Peninsula – A review and new
541 chronological constraints. *Quaternary Sci. Rev.*, 30:—, 3791–3802, doi:
542 10.1016/j.quascirev.2011.10.011, 2011.

543 Hawes, I., Smith, R., Howard-Williams, C., [and](#) Schwarz, A. M.: Environmental conditions
544 during freezing, and response of microbial mats in ponds of the McMurdo Ice Shelf,
545 Antarctica. *Antarct. Sci.*, 11:—, 198–208, 1999.

546 Hawes, I., Howard-Williams, C., [and](#) Vincent, W. F.: Desiccation and recovery of Antarctic
547 cyanobacterial mats. *Polar Biol.*, 12:—, 587–594, 1992.

548 Hawes, I., Moorhead, D., Sutherland, D., Schmeling, J., [and](#) Schwarz, A. M.: Benthic primary
549 production in two perennially ice-covered Antarctic lakes: pattern of biomass accumulation
550 with a model of community metabolism. *Antarct. Sci.*, 13:—, 18–27, 2001.

551 Komárek, J. [and](#) Elster, J.: Ecological background of cyanobacterial assemblages of the
552 northern part of James Ross Island, NW Weddell Sea, Antarctica. *Pol. Polar Res.*, 29:—, 17–32,
553 2008.

Formatted: Font: Not Italic

554 Komárek, J., Nedbalová, L., [and](#) Hauer, T.: Phylogenetic position and taxonomy of three
555 heterocytous cyanobacteria dominating the littoral of deglaciated lakes, James Ross Island,
556 Antarctica. *Polar Biol.* 35: 759–774, doi: 10.1007/s00300-011-1123-x, 2011.

557 Komárek, J., Bonaldo, G. D., Fatima, F. M., [and](#) Elster, J.: Heterocytous cyanobacteria of the
558 Ulu Peninsula, James Ross Island, Antarctica. *Polar Biol.* 38: 475–492, ~~DOI~~doi:
559 10.1007/s00300-014-1609-4, 2015.

560 Kopalová, K., Veselá, J., Elster, J., Nedbalová, L., Komárek, J., [and](#) Van de Vijver, B.:
561 Benthic diatoms (Bacillariophyta) from seepages and streams on James Ross Island (NW
562 Weddell Sea, Antarctica). *Plant Ecol. Evol.* 145: 1–19, doi: 10.5091/plecevo.2012.639,
563 2012.

564 Kopalová, K., Nedbalová, L., Nývlt, D., Elster, J., [and](#) Van de Vijver, B.: Diversity, ecology
565 and biogeography of the freshwater diatom communities from Ulu Peninsula (James Ross
566 Island, NE Antarctic Peninsula). *Polar Biol.* 36: 933–948, doi: 10.1007/s00300-013-1317-
567 5, 2013.

568 Kremer, B., Kaźmierczak, J., [and](#) Stal, L. J.: Calcium carbonate precipitation in cyanobacteria
569 mats from sandy tidal flats of the North Sea. *Geobiology* 6: 46–56, doi: 10.1111/j.1472-
570 4669.2007.00128.x, 2008.

571 Láska, K., Barták, M., Hájek, J., Prošek, P., [and](#) Bohuslavová, O.: Climatic and ecological
572 characteristics of deglaciated area of James Ross Island, Antarctica, with a special respect to
573 vegetation cover. *Czech Polar Reports* 1: 49–62, 2011a.

574 Láska, K., Budík, L., Budíková, M., [and](#) Prošek, P.: Method of estimating of solar UV
575 radiation in high—latitude locations based on satellite ozone retrieval with improved
576 algorithm. *International J. Journal of Remote Sensing* 32: 3165–3177, doi:
577 10.1080/01431161.2010.541513, 2011b.

578 [Lepot, K., Compère, P., Gérard, E., Namsaraev, Z., Verleyen, E., Tavernier, L., —Hodgson](#)
579 [D. A., Vyverman, W., Gilbert, B., and Javaux, E. J. : Organic and mineral imprints in fossil](#)
580 [photosynthetic mats of an East Antarctic lake. *Geobiology*, 12, 424–450, doi:](#)
581 [10.1111/gbi.12096, 2014.](#)

582 Nakai, N., Wada, H., Kiyoshu, Y., [and](#) Takimoto, M.: Stable isotope studies on the origin and
583 geological history of water and salts in the Lake Vanda area, Antarctica. *Geochem. J.*, 9, 7–
584 24, 1975.

585 Nedbalová, L., Nývlt, D., Kopáček, J., Šobr, M., [and](#) Elster, J.: Freshwater lakes of Ulu
586 Peninsula, James Ross Island, north-east Antarctic Peninsula: origin, geomorphology, and
587 physical and chemical limnology. *Antarct. Sci.*, 25:—, 358–372, doi:
588 10.1017/S0954102012000934, 2013.

589 ~~Nedbalová, L., Elster, J., Komárek, J., Medová, H., Vrba, J., Fott, J., Kopalová, K., Van de~~
590 ~~Vijver, B.: Freshwater lakes of Ulu Peninsula (James Ross Island, NE Antarctic Peninsula):~~
591 ~~II. Planktic and benthic assemblages. *Antarct. Sci.* (in prep), 2015.~~

592 Ng, F. [and](#) Hallet, B.: Patterning mechanisms in subglacial carbonate dissolution and
593 deposition. *J. Glaciol.*, 48:—, 386–400, 2002.

594 Nývlt, D., Košler, J., Mlčoch, B., Mixa, P., Lisá, L., Bubík, M., [and](#) Hendriks, B. W., H.: The
595 Mendel Formation: evidence for late Miocene climatic cyclicity at the northern tip of the
596 Antarctic Peninsula. *Palaeogeogr. Palaeoclimatol.*, 299:—, 363–394, 10.1016/j.palaeo.2010.11.017,
597 2011.

598 Olivero, E. B., Scasso, R. A., [and](#) Rinaldi, C. A.: Revision of the Marambio Group, James
599 Ross Island, Antarctica. Instituto Antartico Argentino, Contribución, 331, 1–28, 1986.

600 ~~O'Neil, J. R.: Hydrogen and oxygen isotope fractionation between ice and water. *J. Phys.*~~
601 ~~*Chem.* 72, 3683–3684, 1968.~~

602 Øvstedal, D. O., [and](#) Lewis Smith, R. I.: Lichens of Antarctica and South Georgia: A guide to
603 their identification and ecology. Studies in Polar Research, Cambridge University Press,
604 Cambridge, [411 pp.](#), 2001.

605 Pechar, L.: Use of acetone:methanol mixture for the extraction and spectrophotometric
606 determination of chlorophyll a in phytoplankton. *Archiv für Hydrobiologie/Supplement,*
607 *Algological Studies*, 46:—, 99–117, 1987.

608 [Pedley, M., Rogerson, M., and Middleton, R.: Freshwater calcite precipitates from in vitro](#)
 609 [mesocosm flume experiments: a case for biomediation of tufas. *Sedimentology* 56, 511-527,](#)
 610 [doi: 10.1111/j.1365-3091.2008.00983.x, 2009.](#)

611 [Pichrtová, M., Hájek, T., and Elster, J.: Osmotic stress and recovery in field populations of](#)
 612 [Zygnema sp. Zygnematophyceae, Streptophyta\) on Svalbard \(High Arctic\) subjected to](#)
 613 [natural dessication. *FEMS Microbiol. Ecol.*, 89, 270–280, doi:10.1111/1574-6941.12288,](#)
 614 [2014.](#)

615 Rabassa, J., Skvarca, P., Bertani, L., [and](#) Mazzoni, E.: Glacier inventory of James Ross and
 616 Vega Islands, Antarctic Peninsula. [Annals of Glaciology](#), 3, 260–264, 1982.

617 Reid, P., Dupraz, C., Visscher, P., [and](#) Sumner, D.: Microbial processes forming marine
 618 stromatolites, [in: Fossil and recent biofilms – a natural history of life on Earth, edited by:](#)
 619 [\(Krumbein, W.E., Peterson, D.M., and –& Zavarzin, G.A., eds\), pp. 103–118. Kluwer](#)
 620 [Academic Publishers, London, 2003.](#)

621 [Riding, R.: Microbialities, stromatolites, and thrombolites, in: Encyclopedia of Geobiology,](#)
 622 [edited by: Reitner, J. and Thiel, V., 635–654, Encyclopedia of Earth Science Series, Springer,](#)
 623 [Heidelberg, 2011.](#)

624 Rybalka, N., Andersen, R. A., Kostikov, I., Mohr, K. I., Massalski, A., Olech, M., [and](#) Friedl,
 625 T.: Testing for endemism, genotypic diversity and species concepts in Antarctic terrestrial
 626 microalgae of the Tribonemataceae (Stramenophiles, Xanthophyceae). *Environ. Microbiol.*,
 627 11, 554–565, doi: 10.1111/j.1462-2920.2008.01787.x, 2009.

628 Šabacká, M., [and](#) Elster, J.: Response of cyanobacteria and algae from Antarctic wetland
 629 habitats to freezing and desiccation stress. *Polar Biol.*, 30, 31–37, doi: 0.1007/s00300-006-
 630 0156-z, 2006.

631 Shao, Y. ~~(2008)~~: Physics and Modelling of Wind Erosion. Atmospheric and Oceanographic
 632 Sciences Library 37. 2nd Edition. Springer, Heidelberg. 456 pp, [2008.](#)

633 Schieber, J.: Microbial mats in terrigenous clastics: the challenge of identification in the rock
 634 record. *Palaios*, 14, 3–12, doi: 10.2307/3515357, 1999.

635 Schmidt, N. H. and Olensen, N. O.: Computer-aided determination of crystal-lattice
636 orientation from electron-channeling patterns in the SEM. *Can. Mineral.* 28: 15–22, 1989.

637 Schneider, S. and Le Campion-Alsumard, T.: Construction and destruction of carbonates by
638 marine and freshwater cyanobacteria. *Eur. J. Phycol.* 34: 417–426, doi:
639 10.1017/S0967026299002280, 1999.

640 Schneider, J., Niebuhr, B., Wilmsen, M., and Vodrážka, R.: Between the Alb and the Alps –
641 The fauna of the Upper Cretaceous Sandbach Formation (Passau region, southeast Germany).
642 *Bull. Geosci.* 86: 785–816, doi: 10.3140/bull.geosci.1279, 2011.

643 Škaloud, P., Nedbalová, L., Elster, J., and Komárek, J.: A curious occurrence of *Hazen*
644 *broadyi* spec. nova in Antarctica and the review of the genus *Hazen* (Ulotrichales,
645 Chlorophyceae). *Polar Biol.* 36: 1281–1291, doi: 10.1007/s00300-013-1347-z, 2013.

646 Smellie, J. L., Johnson, J. S., McIntosh, W. C., Esser, R., Gudmundsson, M. T., Hambrey, M.
647 J., and Van Wyk de Vries, B.: Six million years of glacial history recorded in volcanic
648 lithofacies of the James Ross Island Volcanic Group, Antarctic Peninsula. *Palaeogeogr.*
649 *Palaeoclimatol.* 260: 122–148, doi: 10.1016/j.palaeo.2007.08.011, 2008.

650 Strunecký, O., Elster, J., and Komárek, J.: Molecular clock evidence for survival of Antarctic
651 cyanobacteria (Oscillatoriales, *Phormidium autumnale*) from Paleozoic times. *FEMS*
652 *Microbiol. Ecol.* 82: 482–490, doi: 10.1111/j.1574-6941.2012.01426.x, 2012.

653 Sutherland, D. and Hawes, I.: Annual growth layers as proxies for past growth conditions for
654 benthic microbial mats in a perennially ice-covered Antarctic lake. *FEMS Microbiol. Ecol.* 67:
655 279–292, doi: 10.1111/j.1574-6941.2008.00621.x, 2009.

656 Švábenická, L., Vodrážka, R., and Nývlt, D.: Calcareous nannofossils from the Upper
657 Cretaceous of northern James Ross Island, Antarctica. *Geol. Q.* 56: 765–772, doi:
658 10.7306/gq.1053, 2012.

659 Svojtka, M., Nývlt, D., Muramaki, M., Vávrová, J., Filip, J., and Mixa, P.: Provenance and
660 post-depositional low-temperature evolution of the James Ross Basin sedimentary rocks
661 (Antarctic Peninsula) based on fission track analysis. *Antarct. Sci.* 21: 593–607, doi:
662 10.1017/S0954102009990241, 2009.

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663 [Tashyreva, D. and Elster, J.: The limits of desiccation tolerance of Arctic Microcoleus strains](#)
 664 [\(Cyanobacteria\) and environmental factors inducing desiccation tolerance. Front. Microbiol.](#)
 665 [doi: 10.3389/fmicb.2015.00278, 2015.](#)

666 Taton, A., Grubisic, S., Brambilla, E., de Wit, R., [and](#) Wilmotte, A.: Cyanobacterial diversity
 667 in natural and artificial microbial mats of Lake Fryxell (McMurdo Dry Valleys, Antarctica): a
 668 morphological and molecular approach. *Appl. Environ. Microb.* 69:—, 5157–5169, doi:
 669 10.1128/AEM.69.9.5157-5169.2003, 2003.

670 Turner, J., Barrand, N. E., Bracegirdle, T. J., Convey, P., Hodgson, D. A., Jarvis, M., Jenkins,
 671 A., Marshall, G., Meredith, M. P., Roscoe, H., Shanklin, J., French, J., Goosse, H.,
 672 Guglielmin, M., Gutt, J., Jacobs, S., Kennicutt, M. C., Valerie Masson-Delmotte, II.,
 673 Mayewski, P., Navarro, F., Robinson, S., Scambos, T., Sparrow, M., Summerhayes, C.,
 674 Speer, K., [and](#) Klepikov, A.: Antarctic climate change and the environment: an update. *Polar*
 675 *Rec.* ~~ord~~, 50, 237—259, doi: 10.1017/S0032247413000296, 2014.

676 Vincent, W. F. [and](#); Laybourn-Parry, J. ([Eds.](#)): Polar lakes and rivers. Oxford University
 677 Press, Oxford, [346 pp.](#) doi: 10.1093/acprof:oso/9780199213887.001.0001, 2008.

678 Vincent, W. F.: Cyanobacterial dominance in polar regions, [in:](#) —The Ecology of
 679 Cyanobacteria, [edited by:](#) —(Whitton B. A. [and](#) Potts, M., ~~eds~~), [pp.](#)—321–340. Kluwer
 680 Academic Publishers, the Netherlands, 2000.

681 Vodrážka, R.: A new method for the extraction of macrofossils from calcareous rocks using
 682 sulphuric acid. *Palaeontology*, 52:—, 187–192, doi: 10.1111/j.1475-4983.2008.00829.x, 2009.

683 Vogt, T. [and](#)—Corte, A. E.: Secondary precipitates in Pleistocene and present cryogenic
 684 environments (Mendoza Precordillera, Argentina, Transbaikalia, Siberia, and Seymour Island
 685 Antarctica). *Sedimentology*, 43, 53—64, doi: 10.1111/j.1365-3091.1996.tb01459.x, 1996.

686 Wadham, J. L., Tranter, M., [and](#) Dowdeswell, J. A.: Hydrochemistry of meltwaters draining a
 687 polythermal-based, high-Arctic glacier, south Svalbard: II. Winter and early ~~s~~Spring. *Hydrol.*
 688 *Process.*, 14:—, 1767—1786, doi: 10.1002/1099-1085(200007)14:10<1767: AID-
 689 HYP103>3.0.CO;2-Q, 2000.

690 | Wagner, B., Cremer, H., Hulzsch, N., Gore, D., [and](#) Melles, M.: Late Pleistocene and
691 | Holocene history of Lake Terrasovoje, Amery Oasis, East Antarctica, and its climatic and
692 | environmental implications. *J. Paleolimnol.* [32](#)–[321](#)–[339](#), doi: 10.1007/s10933-004-0143-8,
693 | 2004.

694 | Walter, M.: *Stromatolites*. Elsevier Science Ltd., Amsterdam, the Netherlands, 1976, [790 pp.](#)

695 | Wharton, R. A., Parker, B. C., Simmons, G. M., [and](#) Love, F. G.: Biogenic calcite structures
696 | forming in Lake Fryxell, Antarctica. *Nature*, [295](#)–[403](#)–[405](#), doi: 10.1038/295403a0, 1982.

697 | Wharton, R.: Stromatolitic mats in Antarctic lakes, [in](#): *Phanerozoic Stromatolites, II*, [edited](#)
698 | [by](#): (Bertrand-Safari, J. [and](#) Monty, C., eds), pp. 53–70, Springer, New York, USA, doi:
699 | 10.1007/978-94-011-1124-9_3, 1994.

700 | Yamamoto, A., Tanabe, K., [and](#) Isozaki, Y.: Lower Cretaceous freshwater stromatolites from
701 | northern Kyushu, Japan. *Paleontol. Res.* [13](#)–[139](#)–[149](#), 10.2517/1342-8144-13.2.139, 2009.

702 | ~~Žák, J., Urban, J., Čížek, V., Hereman, H.: Cryogenic cave calcite from several Central~~
703 | ~~European caves: age, carbon and oxygen isotopes and a genetic model. *Chemical Geology*~~
704 | ~~206: 119–135, doi: 10.1016/j.chemgeo.2004.01.012, 2004.~~

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719 Table 1. Physico-chemical characteristics and chlorophyll-a concentrations in lake water.
720 Samples were collected from surface of lakes. ND – not determined, ANC – acid
721 neutralization capacity, PN – particulate nitrogen, DP – dissolved phosphorus, PP –
722 particulate phosphorus, SRP – dissolved reactive phosphorus, DOC – dissolved organic
723 carbon, PC – particulate carbon, * – laboratory values.

Lake		Green 1		Green 2
Date		22.2.2008	5.1.2009	12.1.2009
Temperature	°C	3.5	ND	12.3
O ₂	mg L ⁻¹	13.1	ND	13.7
O ₂ saturation	%	98.7	ND	128.0
pH		7.9	7.4*	8.6
Conductivity (25 °C)	µS cm ⁻¹	54	48*	97
ANC	mmol L ⁻¹	236	246	455
Na ⁺	mg L ⁻¹	4.7	5.9	12.5
K ⁺	mg L ⁻¹	0.24	0.29	0.60
Ca ²⁺	mg L ⁻¹	2.12	1.26	2.32
Mg ²⁺	mg L ⁻¹	1.24	0.77	1.65
SO ₄ ²⁻	mg L ⁻¹	1.74	1.33	2.60
Cl ⁻	mg L ⁻¹	5.3	5.1	10.6
NO ₃ -N	µg L ⁻¹	<5	11	<5
NO ₂ -N	µg L ⁻¹	0.6	0.2	0.1
NH ₄ -N	µg L ⁻¹	6	<5	<5
PN	µg L ⁻¹	20	50	73
DP	µg L ⁻¹	7.8	20.2	30.4
PP	µg L ⁻¹	4.6	5.9	11.7
SRP	µg L ⁻¹	4.0	11.6	19.3
DOC	mg L ⁻¹	1.25	1.13	2.17
PC	mg L ⁻¹	0.13	0.41	1.33
Si	mg L ⁻¹	1.45	0.87	2.85
chl- <i>a</i>	µg L ⁻¹	0.9	ND	6.0

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Figure captions

Figure 1. Location of lake 1 and 2 and air temperature measurements (ASW) in the Solorina Valley.

Figure 2. Bathymetric parameters of lake 1 (a) and 2 (b) together with marked lines of water level and maximum extent of the photosynthetic microbial mat littoral belt in lake 1.

Figure 3. a – annual variation of daily mean water temperature in lake 1 (L1water) and annual variation of daily mean air temperature ~~2-m above ground~~ in the Solorina Valley (SV air), b – diurnal temperature amplitudes in lake 1 (L1 water) and diurnal air temperature amplitudes in the Solorina Valley (SV air), respectively. c – daily mean global radiation at Mendel Station. All parameters measured from February 2009 to November 2010.

Figure 4. [Dominant species in the photoautotrophic mats.](#)

[a – *Calothrix elsteri*.](#)

[b – *Hazenia broadyi*](#)

Figure ~~65~~. Photoautotrophic mats in lakes 1 and 2.

a,b – rapid development of the mat in January 2009 (lake 1). The two photos show the mat at a one week interval, note the growth of gelatinous clusters of densely agglomerated filaments of the green alga *Hazenia broadyi*,

c,d – fully developed mats with mosaic-like structures on the surfaces of stones in the littoral zone of lake 2,

e,f – detail,

g – drying of the mat in the littoral zone leaves a characteristic structure on the surface of stones,

h – calcium carbonate spicule in situ (arrowed)

Figure 6. Photoautotrophic mat covering a stone visualized using imaging fluorometry.

a – upper view.

b – lateral view

Figure 7. SEM macrographs showing the structure of the dried mat in the lakes.

a – transversal section of the mat with visible cyanobacterial filaments,

b – surface structure of the mat, the position of cyanobacterial filaments incorporated within mucilaginous matrix is indicated by arrows,

c – general view of the surface structure of the mat with the net formed by mucilage (compare with Fig. 7d),

d – detail of the same mucilaginous structure

Figure 8. Perpendicular thin sections of rock substrate ~~covered~~overgrown by dry biofilms (recorded under cross polars). Note that biofilms are partly detached from the surface of the rock due to complete drying of the sample.

a – conspicuous U-shaped empty void (arrowed "2") near the surface of basaltic rock partly infilled with crystals of feldspathoids (tectosilicate minerals, arrowed "1"); empty void is bridged by biofilm (arrowed "3") with partly incorporated mineral clasts, represented by semi-rounded quartz grains (arrowed "4"),

b – rather thick biofilm with numerous incorporated mineral grains. Note that close to the rock substrate the angular grains of plagioclase (feldspar group) and augite (pyroxene group) dominate, being derived from basaltoids, whereas close to the surface rounded grains of quartz occur (arrowed),

c – in situ calcium carbonate spicule penetrating biofilm and surrounded by incorporated grains of feldspars (two arrows on the left) and pyroxene (arrow on the right),

d – close up of the same calcium carbonate spicule with a cyanobacterial filament in its centre

781 Figure 9. SEM macrographs showing the morphology of partly recrystallized calcium
782 carbonate spicules. Spicules were washed away from the living tissue and collected directly
783 from the surface of biofilms, although residence time on the bottom cannot be determined.

784 a – calcareous spicule showing specific surface texture intensively (“worn surface”) and
785 complete recrystallization of the spicule interior. The spicule shows crystal facets on the
786 surface and cleavage (crystallographic structural planes) in the interior (arrowed) – i.e. typical
787 characteristics of calcium carbonate monocrystal,

788 b – detail of previous image; two parallel systems of deep furrows on the surface are
789 crystallographic structural planes of calcite monocrystal; remnants of a superficial layer of
790 microcrystalline calcite are, however, preserved in places on the surface of the crystal
791 (arrowed),

792 c–f – poorly recrystallized spicule, formed mainly by microcrystalline calcite,

793 c – lateral view of the spicule,

794 d – detail of the surface showing corrosion of needle-like calcite microcrystals with distinct
795 layering,

796 e – parallel needle-like calcite microcrystals on the surface of the central part of the spicule,

797 f – tops of parallel needle-like calcite microcrystals on the surface of the terminal part of the
798 spicule; the view is perpendicular with respect to the previous macrograph

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800 Figure 10. FSD image of a transversely sectioned, partly recrystallized calcite spicule
801 acquired in (a) chemical contrast, (b) orientation contrast

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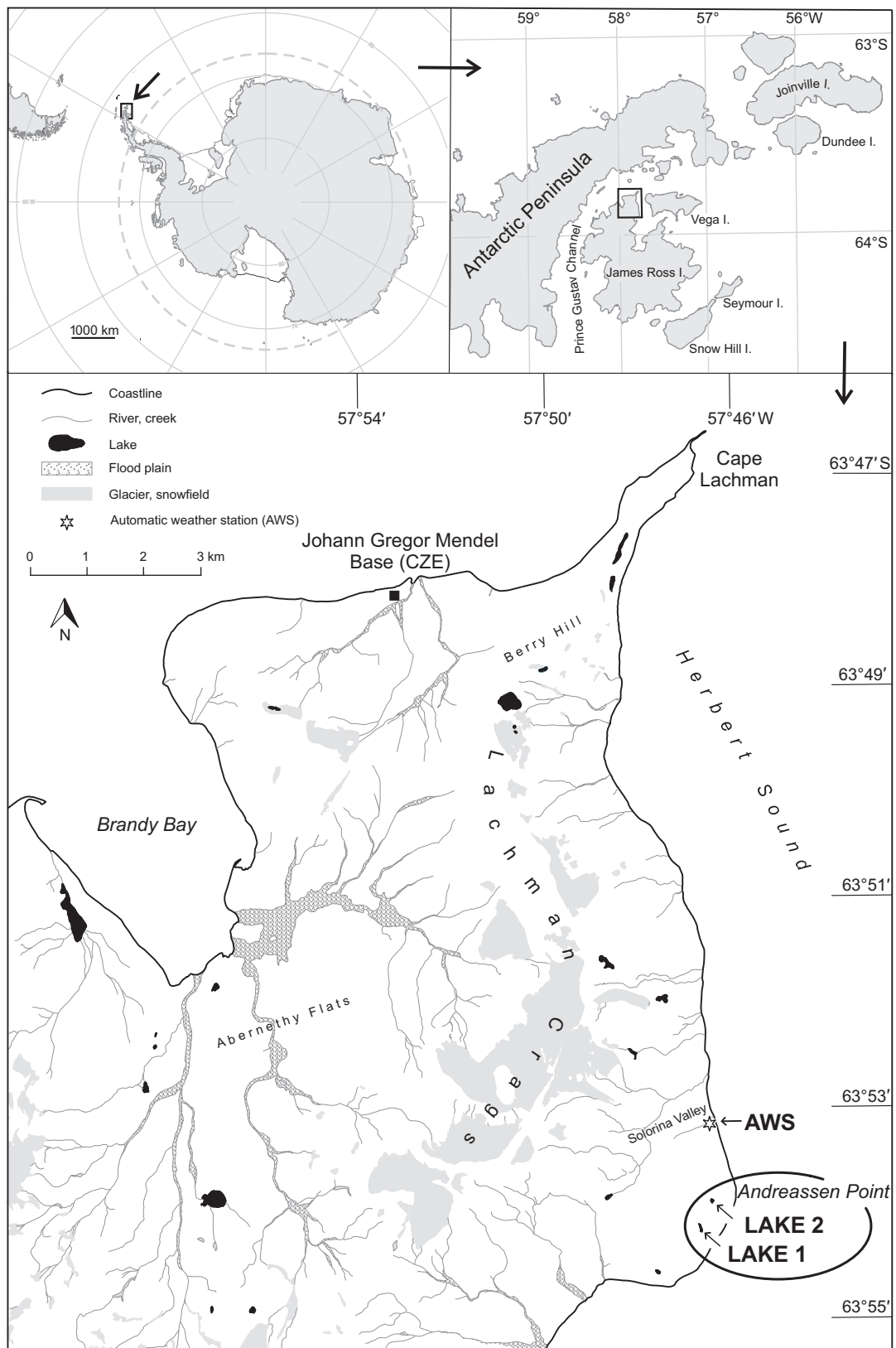


Fig. 1

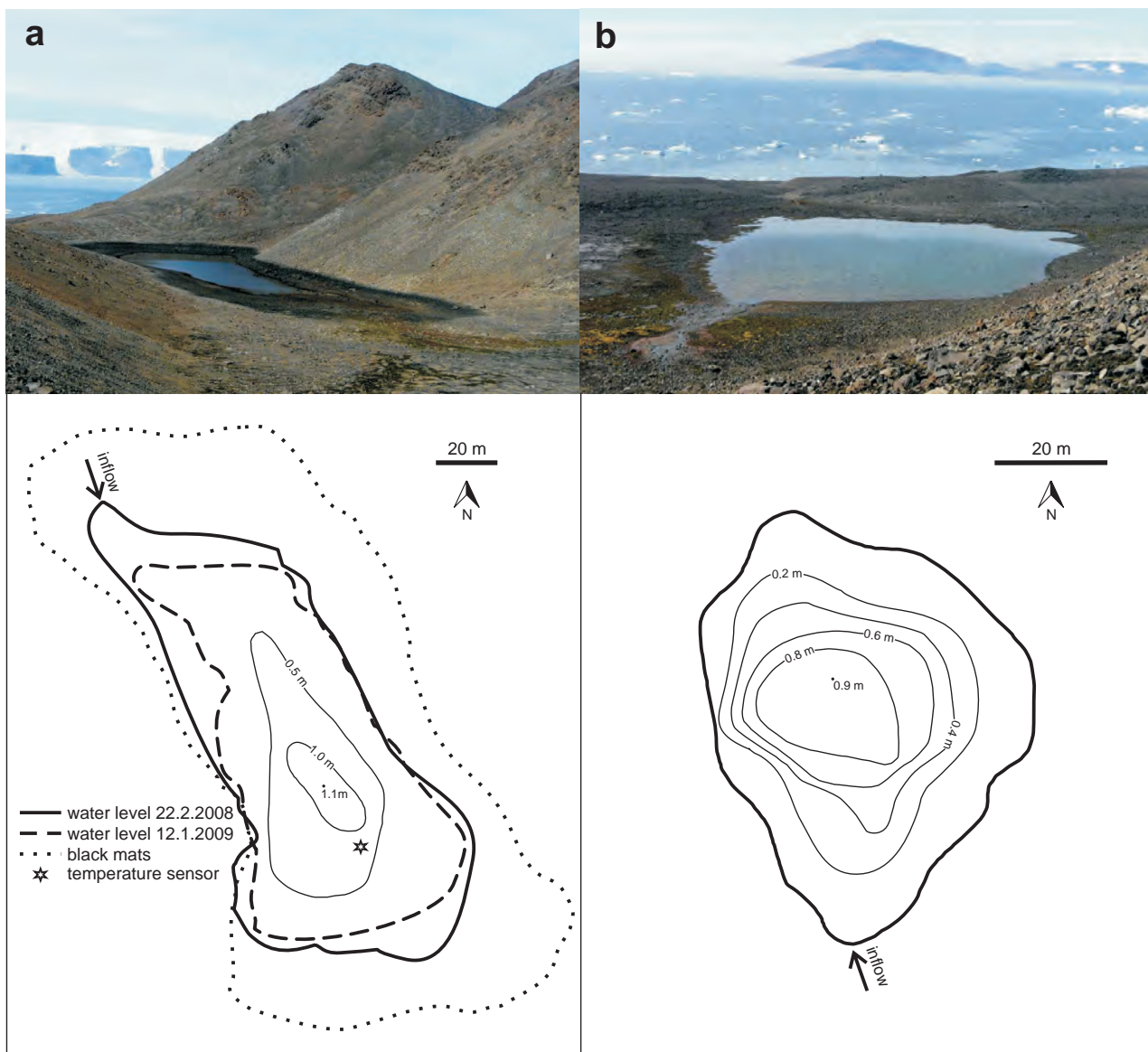


Fig. 2

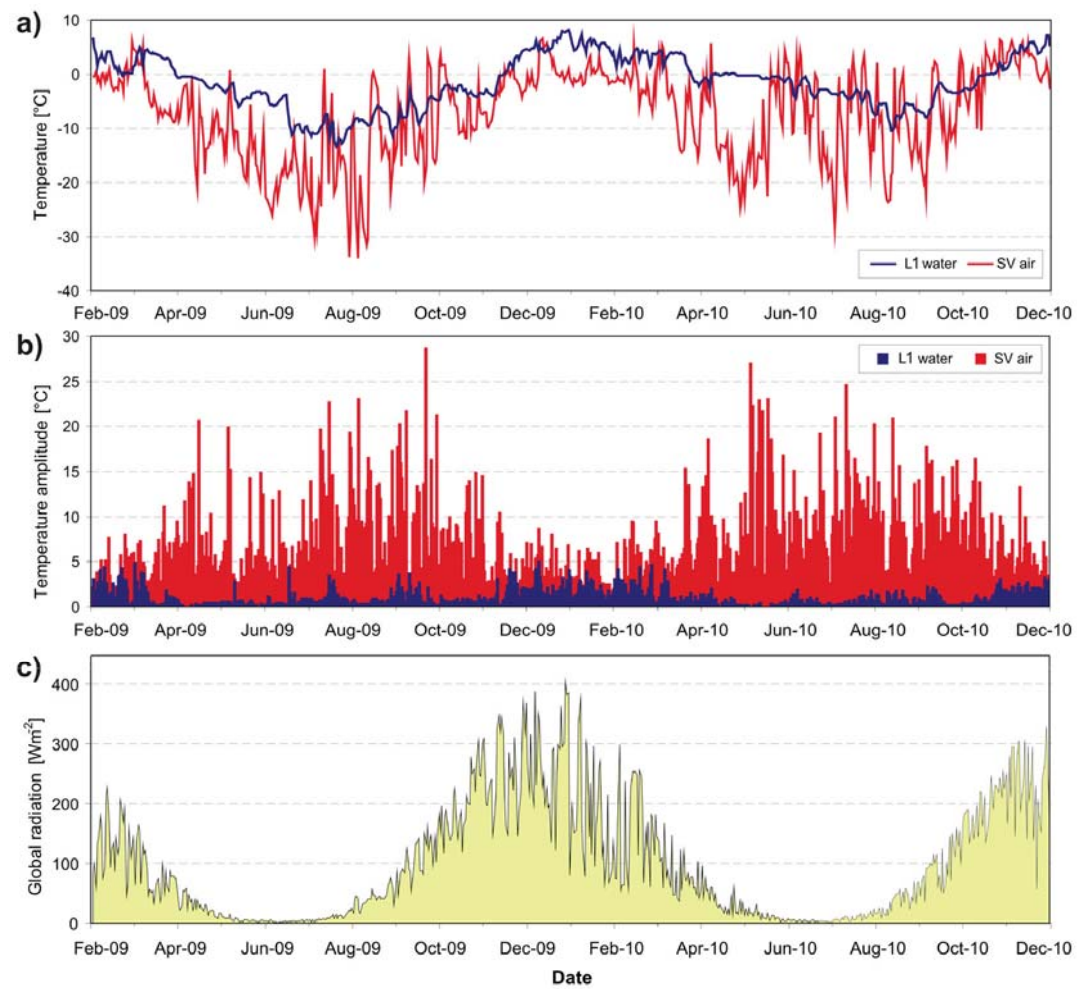


Fig. 3

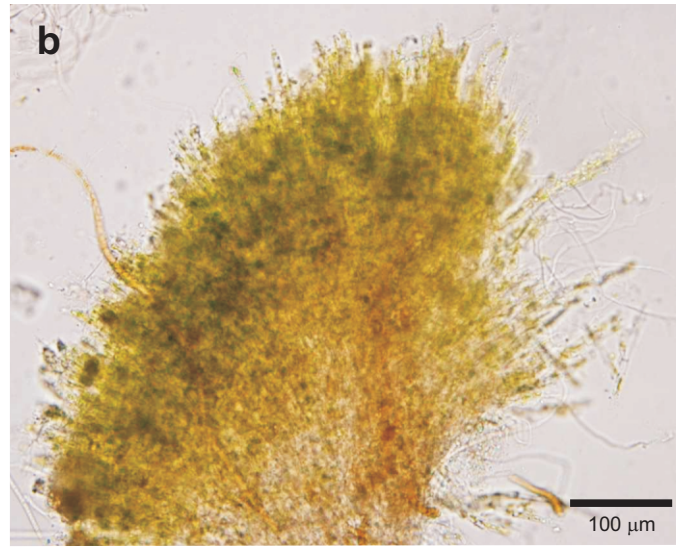
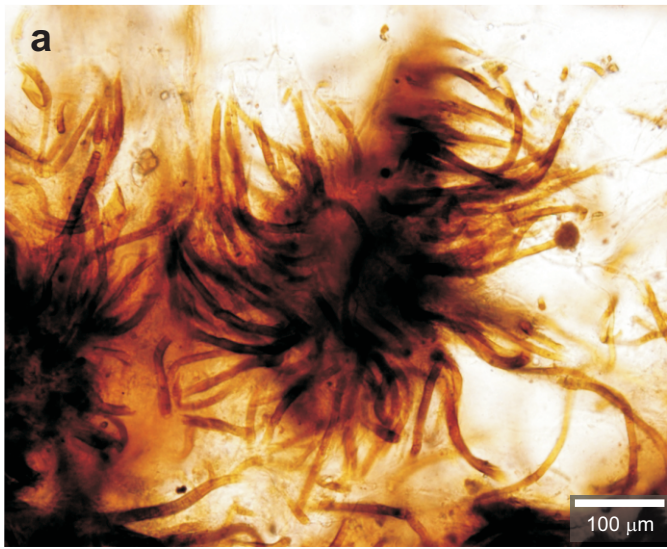


Fig. 4

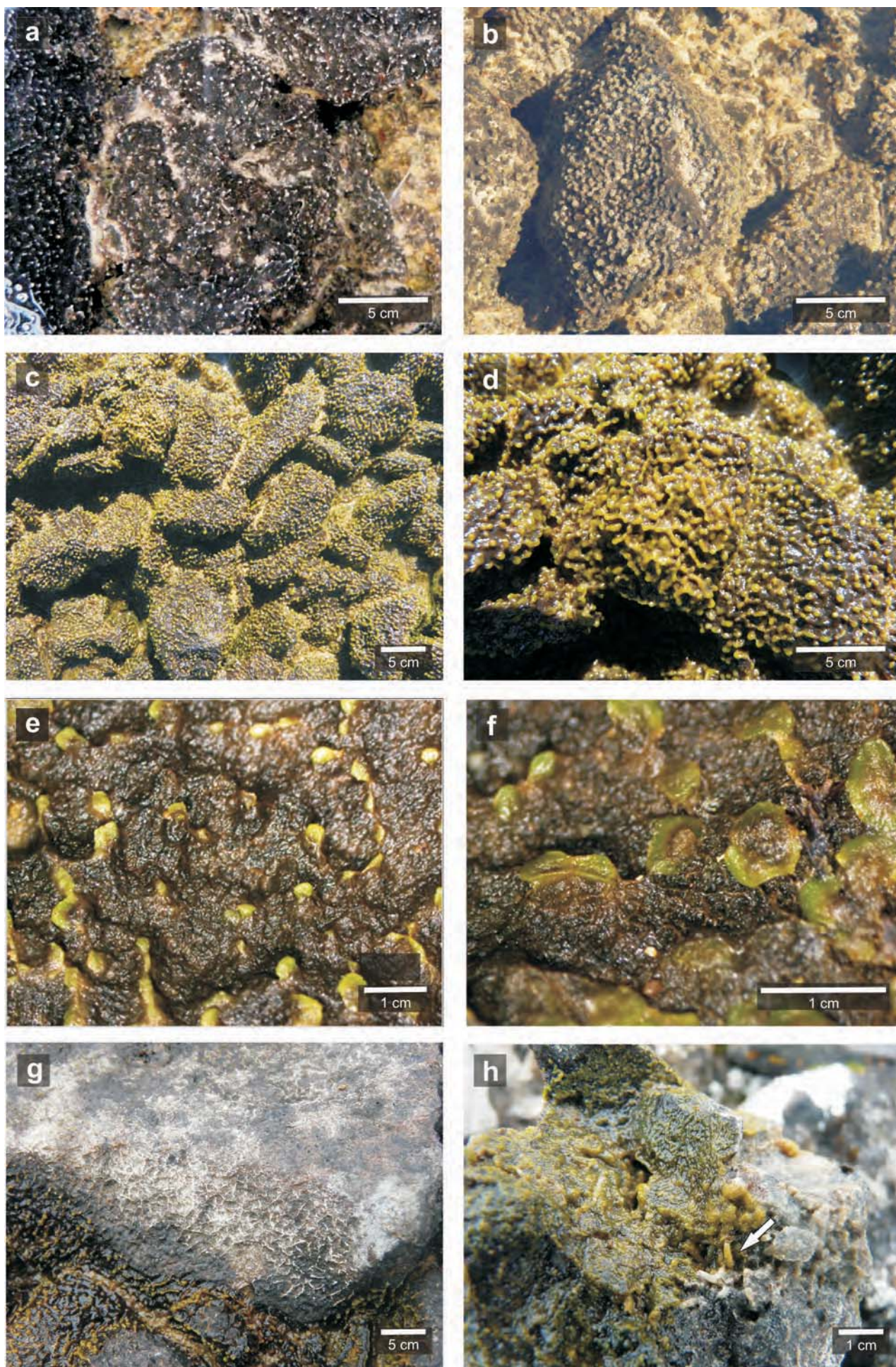


Fig. 5

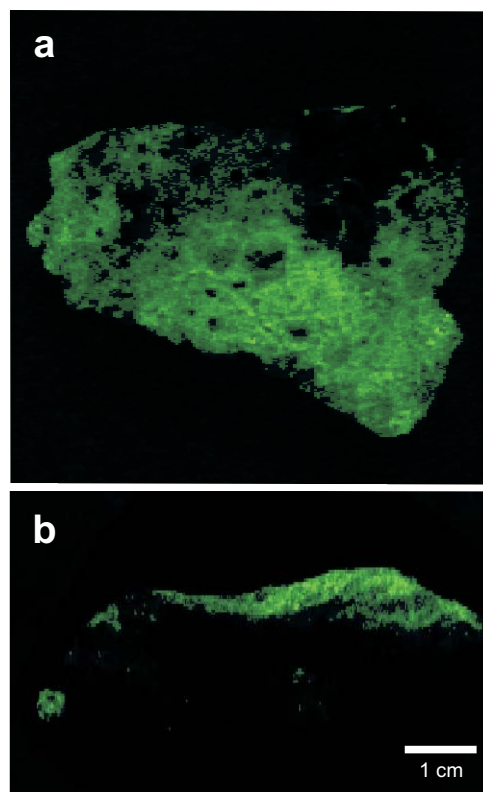


Fig. 6

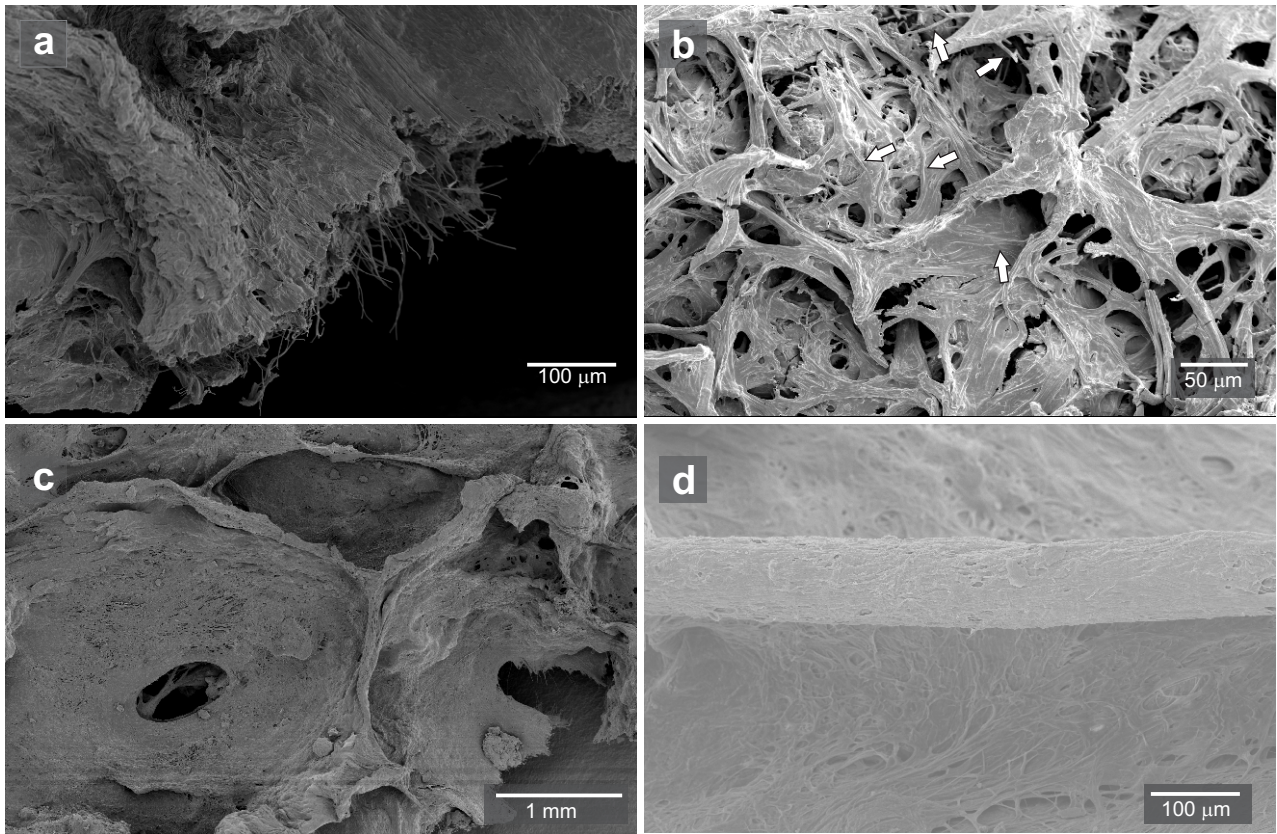


Fig. 7

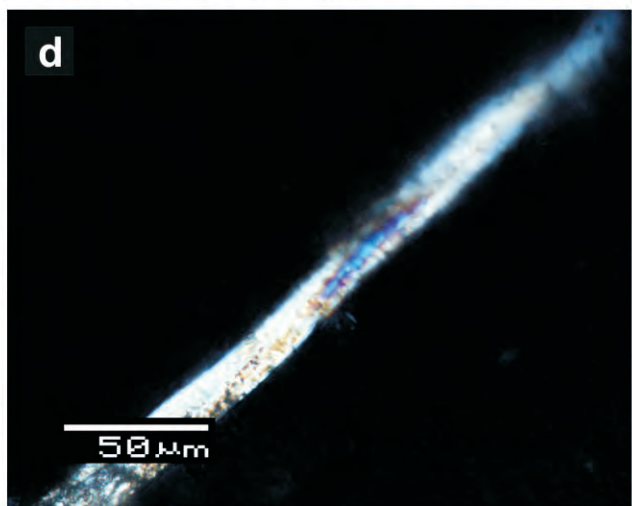
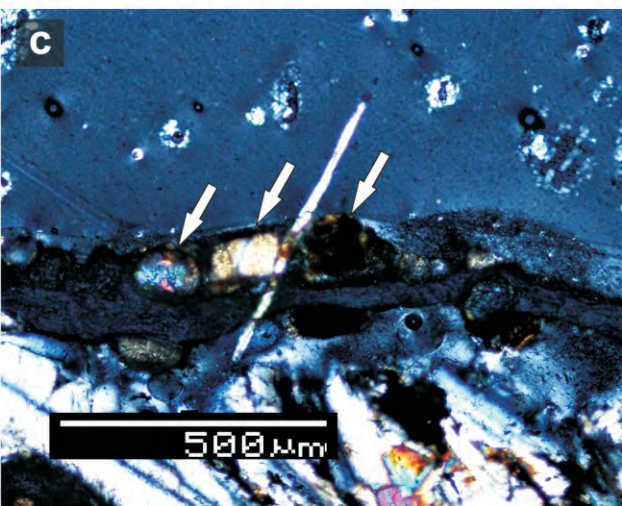
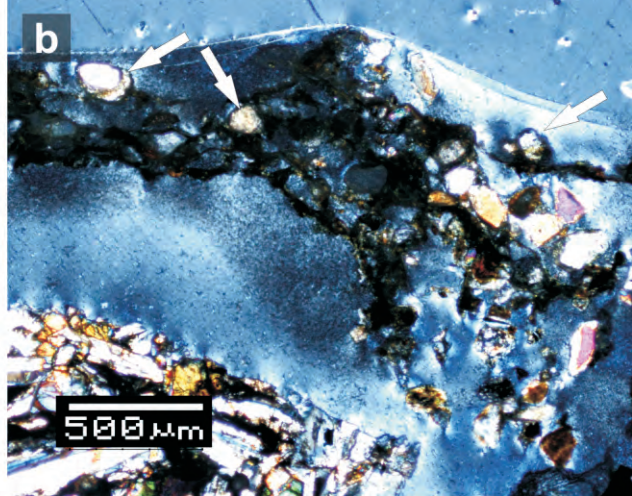
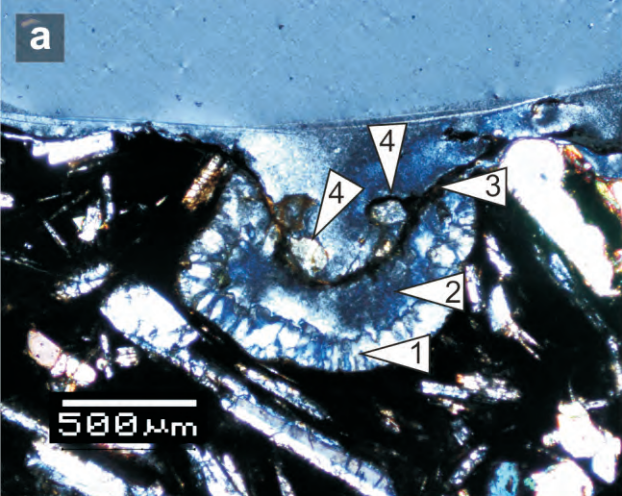


Fig. 8

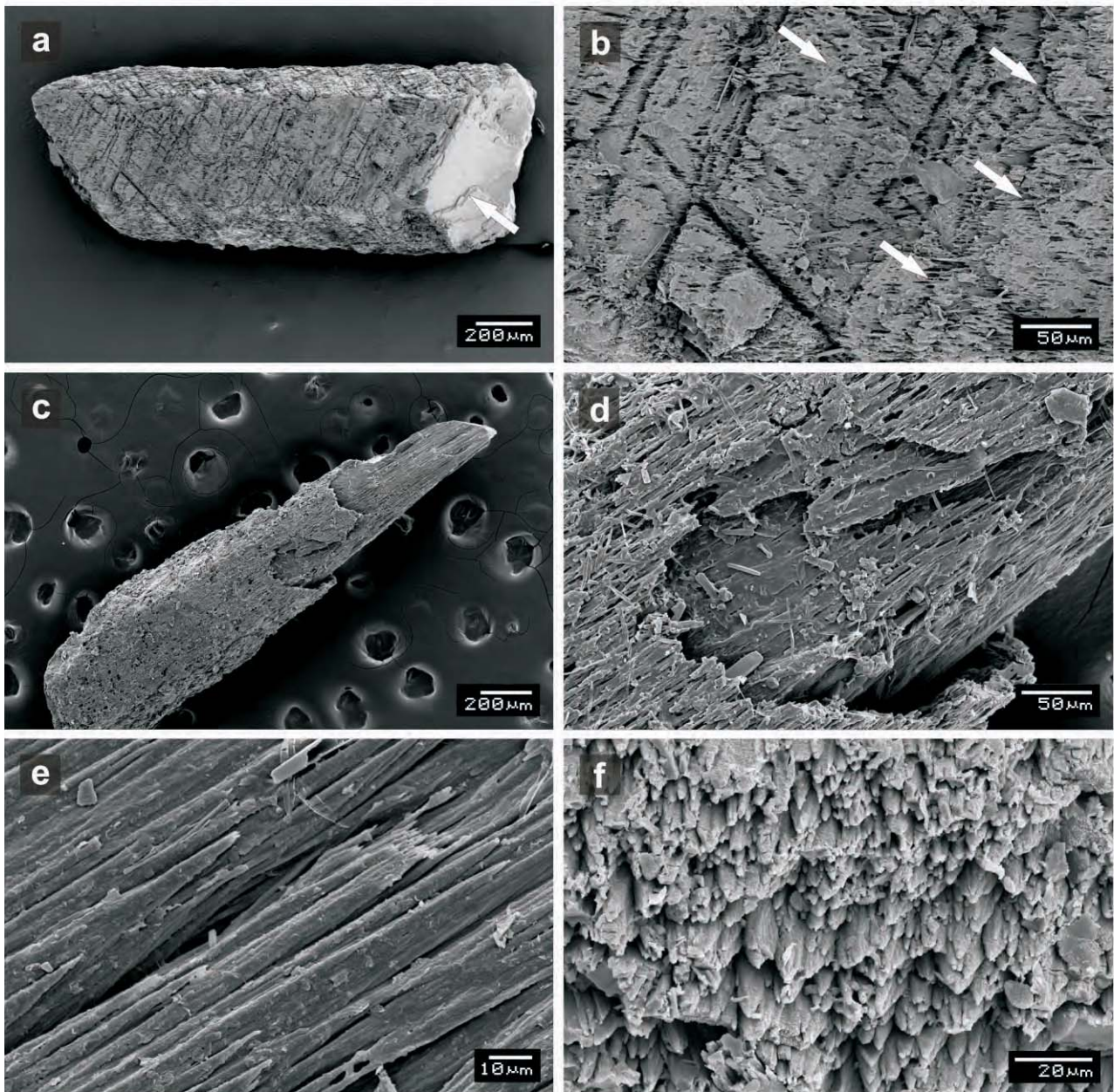


Fig. 9

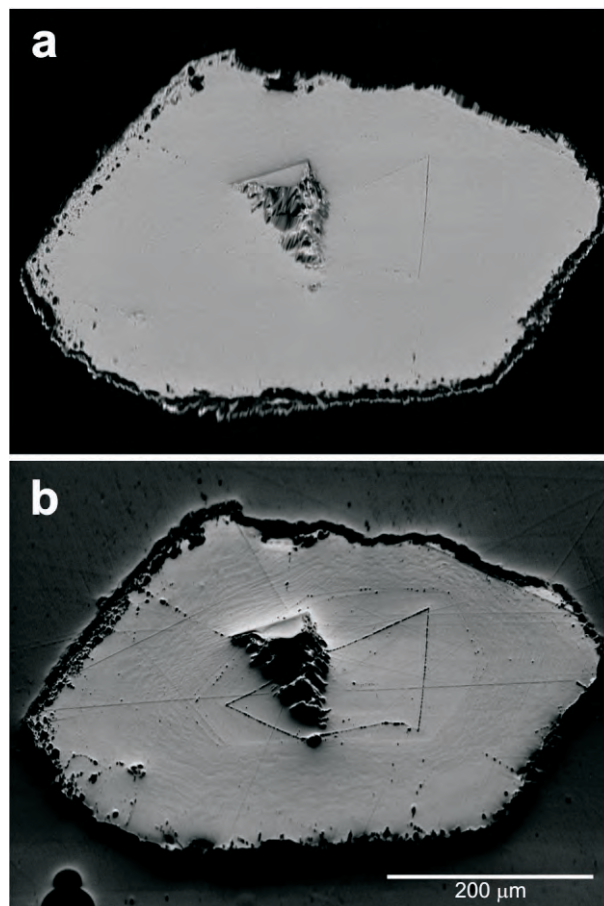


Fig. 10