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Volcanic rocks of the oceanic crust as habitat for recent to Paleoarchean microbial life: A review

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ABSTRACT

Submarine alteration of basaltic glass in pillow lavas and hyaloclastites result in (1) abiotic *palagonite* with smooth interface between the fresh and altered glass, and (2) biogenically-produced irregular *granular* and *tubular* textures. In the upper oceanic crust, the bio-generated textures are dominant, but become progressively less abundant downwards into the volcanic pile to finally disappear at ca. 550 m depth, contemporaneously with the increase in palagonite alteration. The bio-related granular and tubular alteration structures can be found in originally basaltic glass of pillow lavas dating back to ca. 3.5 Ga, providing information of the earliest life on Earth. Element mapping of these bio-related textures show traces of carbon even in the oldest examples. Further, carbon isotope data of the glassy pillow rims and crystalline material exhibit significantly lower $\delta^{13}C_{\text{carbonate}}$ of the former than the latter. Thus, both the carbon signatures and the C-isotope signatures are consistent with microbial influence during alteration of the basalt glass.

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Research Highlights

- Extensive bio-generated alteration of the upper *in-situ* oceanic crust
- Mapping the oceanic biosphere
- Bioalteration and history of early life

1 Introduction

The upper part of the oceanic crust consists predominantly of basaltic lava, of which pillow lavas and associated hyaloclastites may be a major part, particularly at ridges with slow to intermediate spreading rate (e.g., Bonatti and Harrison, 1988). These lithologies consists partly of basaltic glass, which are prone to alteration. The alteration of basaltic glass (sideromelane) has traditionally been considered as a purely physical process in which

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hydrothermal processes convert basaltic glass to palagonite (Honnorez, 1972), an amorphous and hydrated heterogeneous, material consisting of clay minerals and iron oxides (e.g., Honnorez, 1972; Furnes and El-Anbaawy, 1980; Thorseth et al., 1991). In a study of palagonite from one of the subglacial pillow lava/hyaloclastite deposits in Iceland, it became evident that microbes had contributed to the alteration of the sideromelane in the outermost 6–7 mm of the exposed surface (Thorseth et al., 1992). Several recent studies further demonstrated that microbial activity, both at the surface (e.g., Deming and Baross, 1993; Jannasch, 1995) and inside the oceanic crust (e.g., Thorseth et al., 1995; Furnes et al., 1996; Fisk et al., 1998; Furnes and Staudigel, 1999) plays a significant role in the alteration process. Investigating the glassy material of some of the deepest drill holes in the oceanic crust (DSDP Sites 417D, 418A in the Atlantic Ocean, and DSDP/ODP Sites 504B and 896A at the Costa Rica Rift), revealed that biogenerated alteration-textures could be traced as deep as ca. 550 m into the oceanic basement (Furnes and Staudigel, 1999). The microbial interaction process between rocks and micro-organisms has an important influence on the chemical exchange between ocean water and the oceanic crust, and thus, the oceanic crust can be considered as a giant bioreactor (Staudigel et al., 2004).

In this paper the significance of trace fossils, as revealed by micro-biological activity, such as (1) textures; (2) elemental signatures, and (3) C-isotopes, will here be briefly reviewed. The main results of the studies related to these three objectives will be summarized, as well as stressing their importance in the alteration process of the volcanic rocks of the oceanic crust. For the more extensive, detailed and in-depth descriptions and discussions of the various bio-related alteration phenomena, as well as isotopic dating of the alteration process, the reader is directed to the following papers: Thorseth et al., 1992, 1995; Torsvik et al., 1998; Furnes and Staudigel, 1999; Furnes et al., 2001a,b, 2007, 2008; Banerjee et al., 2006, 2007; Staudigel et al., 2008, 2014, 2015; McLoughlin et al., 2009, 2010; Fliegel et al., 2010, 2011, 2012.

2 Material investigated

The investigated material that makes the basis for this review of the papers dealing with bio-alteration of basaltic glass, consist of pillow lava and hyaloclastites from *in-situ* oceanic crust, Phanerozoic ophiolites and Precambrian greenstone belts. The samples from the *in-situ* oceanic crust are dominantly DSDP/ODP samples from the Atlantic Ocean.Lau Basin, Costa Rica Rift and the Ontong Plateau, as well as from Icelandic subglacial samples, spanning the age range of 0–170 Ma. The ophiolites from which samples were collected range in age from Cretaceous to middle Proterozoic, and the samples from the greenstone belts range in age from rom Proterozoic to early Archean. The DSDP/ODP sections, ophiolite and greenstone belt complexes are listed in Table 1, while comprehensive descriptions and illustrations are provided in Furnes et al. (2008) and Staudigel et al. (2008).

***in-situ* oceanic crust**
1. Icelandic hyaloclastite
2. Knipovich. Kolbeinsey, and Mohns ridges
3. 648B Mid-Atlantic Ridge
4. 411 Mid-Atlantic Ridge
5. 409 Reykjanes Ridge
6. 410A Central Atlantic
7. 396B Central Atlantic
8. 559 Mid Atlantic
9. 561 Mid Atlantic
10. 407 Reykjanes Ridge
11. 417B Bermuda Rise
12. 418A Bermuda Rise
13. 1026 Juan de Fuca Rift
14. 504B Costa Rica Rift
15. 8976A Costa Rica Rift
16. Hawaii Scientific Drilling Project
17. 807 Ontong Java Plateau
18. 801C East of the Mariana trench
19. 834B Lau Basin
20. Dredged samples – Australian Antarctic Discordance
21. 187 Australian Antarctic Discordance
Phanerozoic ophiolites
22. Troodos ophiolite, Cyprus
23. Mirdita ophiolite, Albania
24. Franciscan Complex, California
25. Meta-pillow basalt, Corsica
26. Kizildag ophiolite, Turkey
27. Solund-Stavfjord ophiolite complex, Norway
Precambrian ophiolites and Greenstone belts
28. Jormua ophiolite, Finland
29. Pechenga greenstone belt, Russia
30. Wutai Group, China
31. Pilbara Craton, West Australia
32. Barberton greenstone belt, South Africa
33. Isua, Greenland

Table 1. Sample localities.

3 Textural development during alteration

3.1 *in-situ* ocean floor

Before introducing the bio-generation textures that develop during alteration of basaltic glass and its scope and significance, it is necessary to address the characteristic features of abiotically-developed textures that may develop before, or contemporaneously with those of biotic origin. The abiotic alteration of basaltic glass (sideromelane) produces a pale yellow to brown material known as palagonite. This phenomenon is a physical-chemical activity and continuous aging process that involves incongruent and congruent dissolution accompanied by precipitation, hydration and chemical exchange occurring during low to high temperatures (e.g., Thorseth et al., 1991; Stroncik and Schmincke, 2001; Walton et al., 2005). Thus, alteration of basalts during low – to high temperature hydrothermal activity results in different directions of elemental changes, i.e., gain of some elements (f. ex. U, Mg, and Pb), while other elements (f. ex. K, Rb, and Ba) suffer loss (e.g., Fowler and Zierenberg, 2016).

The resulting palagonite occurs around the rims of the glassy shards and as banded material on either side of fractures with a relatively smooth interface between the fresh and altered glass (e.g., Furnes et al., 2008), and as shown in Fig. S1.

The bio-generated textures appear as two distinct types, i.e., a *granular* type, and a *tubular* type, both filled with cryptocrystalline and/or fine-grained phyllosilicates. The granular type appear as spherical bodies, 0.1–1.5 µm (most commonly ca. 0.5 µm) in diameter, that have developed in connection with fractures in glassy basaltic material (sideromelane). At the beginning stage of development, they occur as individual bodies (Fig. 1A and B), whereas at progressive alteration stages they coalesce to define granular aggregates, generally most pronouncedly developed at the intersection of fractures (Fig. 1C and D). In some cases, one can observe an initial alteration stage of non-biological development adjacent to fractures, and subsequent overgrowth of granular textures (Fig. 1E and F).

The tubular type, like the granular type, is also rooted in fractures, and are generally filled with the same type of material. They may occur as straight or curved individual bodies (Fig. 2), that may develop into dense bundles of thin, long tubes. The diameter of the tubes varies between ca. 0.4–6 µm, most commonly between 1–2 µm, whereas the length may be $>$100 µm (Furnes et al., 2007). The tubes commonly propagate perpendicular to the alteration front, and some exhibit segmentation. In cases of varioles and/or vesicles, the tubes can be observed to have grown radially into the fresh glass (sideromelane).

As demonstrated by distinct abiotic and bio-generated alteration types (granular and tubular), it is possible to make some estimate of the relative significance between the various alteration types (biotic versus abiotic) of the upper part of the oceanic crust. A study by Furnes and Staudigel (1999) in which 74 samples from the drill holes 396B, 407, 410A, 418A in the Atlantic Ocean, Holes 504B and 896A from the Costa Rica Rift in the Pacific Ocean, and hole 834B in the Lau Basin were investigated for this purpose. The results of this study demonstrate that in the upper part of the volcanic sequence (dominated to by pillow lavas), and at a low temperature, the alteration is dominated by granular textures. The tubular textures, on the other hand, are volumetrically of minor extent, and are not observed at the surface and below ca. 350 m into the crust, being most abundant around the upper 200 m at a temperature of ca. 80 ℃. With increasing depth and temperature, the proportion of the granular texture type continuously decreases while abiotic alteration (palagonite) increases. Thus, at a depth of ca. 500 m and a temperature of ca. 115 ℃, abiotic alteration is completely dominant (Fig. 3).

3.2 Phanerozoic ophiolites

Pillow lava and hyaloclastites from three Phanerozoic ophiolite complexes (Troodos – Cyprus; Mirdita – Albania; Solund-Stavfjord – West Norway) have been investigated for bioalteration textures (see detailed description in Furnes et al., 2008). They all displayed typical biotextures, but the best-preserved examples are exposed in the glassy rims of the pillow lavas of the Troodos ophiolite, and some of which will be presented here. As presented above, the most common bio-generated texture is the granular type. The most spectacular are, however, represented by the tubular textures. Abundant examples of straight, as well as curves tubes may reach lengths of 100 µm, and the most spectacular types define a spiral form (Fig. S2). Another larger tubular type, reaching length of 500 µm and diameters of 20 µm, exhibit well-defined segmentations with 5–10 µm spacings (Fig. S2). More extensive and detailed descriptions and illustrations of these bioalteration textures are found in Furnes et al. (2008) and McLoughlin et al. (2010).

3.3 Precambrian ophiolites and greenstone belts

Even though Precambrian pillow lava sequences, in some cases referred to as *Greenstone Belt*, may represent ophiolites (Furnes et al., 2015), here we retain the term “greenstone belt”. For the search of Precambrian trace fossils in the originally glassy rims of pillows, samples from the following sequences were collected and investigated: The Early Proterozoic (1.95 Ga) Jormua ophiolite (Furnes et al., 2005); the Middle Proterozoic Pechenga greenstone belt (Kola Peninsula, Russia), the Neoarchean Wutai Complex China, the Paleoarchean Barberton greenstone belt (South Africa) and the Pilbara Craton (Western Australia), and the PaleoArchean Isua supracrustal belt in southwestern Greenland (see Furnes et al., 2008 and references therein for description of each complex). In the pillow rims and hyaloclastites from the Pechenga, Wutai, Pilbara and Barberton, titanite-filled tubes, interpreted as mineralized microbial-produced textures, were found (Furnes et al., 2004; Banerjee et al., 2006, 2007; Staudigel et al., 2006). As for the *in-situ* oceanic examples shown in Figs. 1 and 2, these tubular textures (Fig. 4) are also rooted in, and extend away from mineral-filled fractures. These tubular

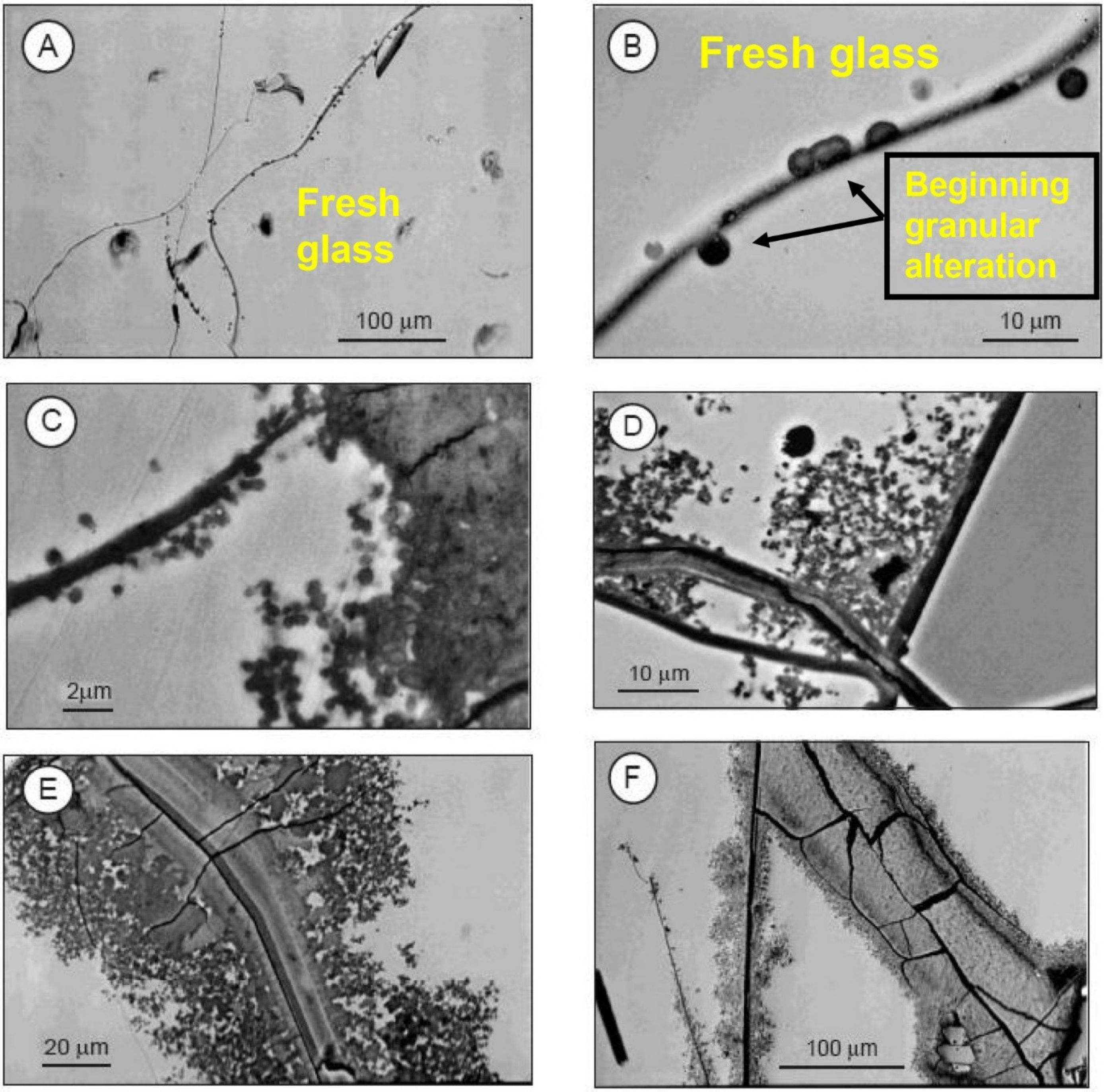

Fig. 1. Granular textures showing incipient stage of development along fractures (A and B), to more advanced stage along fracture (C), at intersection between fractures (D), to advanced stages (E and F). Adjacent to the fracture in (E) is a palagonite rim, and different stages of alteration along the fractures in (F). The images are from the following samples: (A) ODP Site 648B-1R-1, unit 3, piece 7, 37–40 cm; (B) detail from A (central fracture); (C) DSDP Site 418A-52-5, 75–80 cm; (D) DSDP/OPD (Leg 70) Site 504B-46-3, unit 30A, piece 803, 105–106 cm; (E) DSDP Site 417D, 30-6, 20–24 cm; (F) DSDP Site 418A-55-4, 112–114 cm. Modified from Furnes et al. (2007).

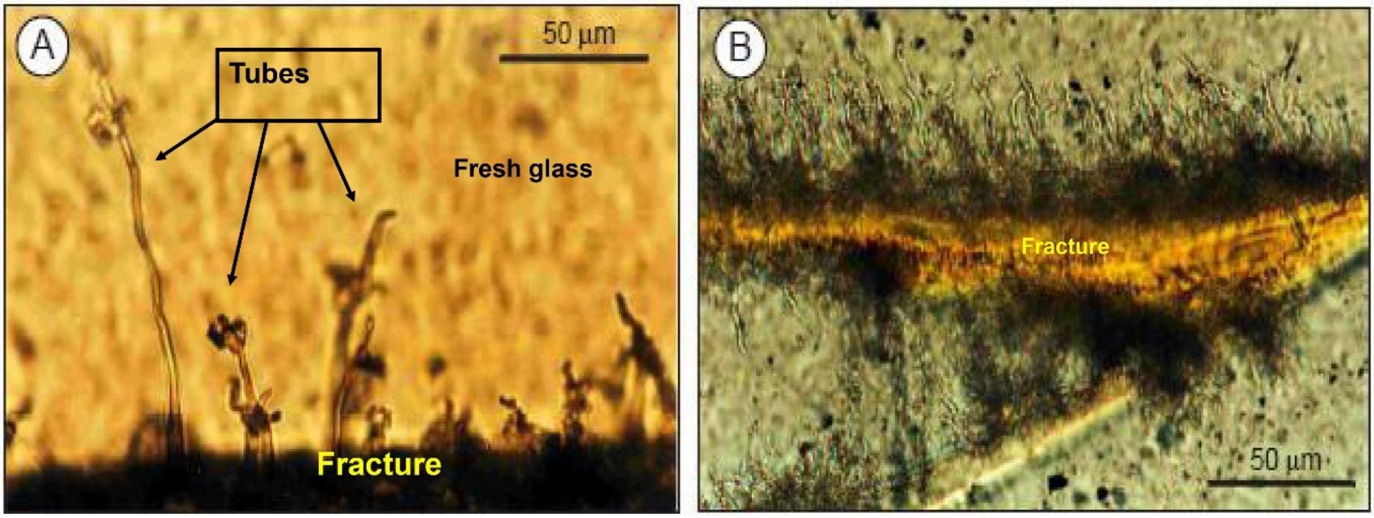

Fig. 2. Tubular textures at various stages of growth (A) in basaltic glass, to dense population of tubes overgrowing dark brown granular textures (B). Picture A: From DSDP samples 70-504B, 35-1, 24, piece 106–113 cm, Picture B: from DSDP sample 46-396B, 20R-4, piece 5, 32–40 cm. Modified from Furnes et al. (2007).

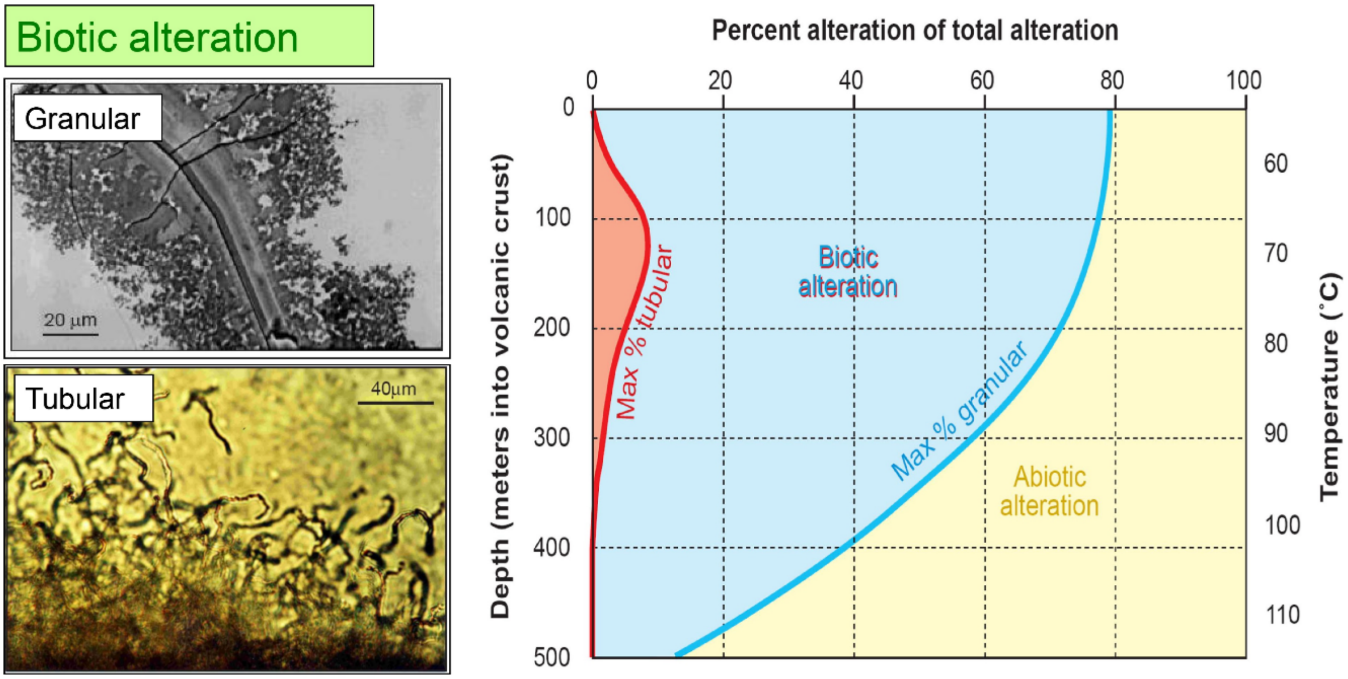

Fig. 3. The upper left and lower left photos show granular and tubular alteration textures, respectively. The right diagram shows the fraction of biotic and abiotic alteration versus depth of the oceanic crust and temperature (modified from Furnes and Staudigel, 1999).

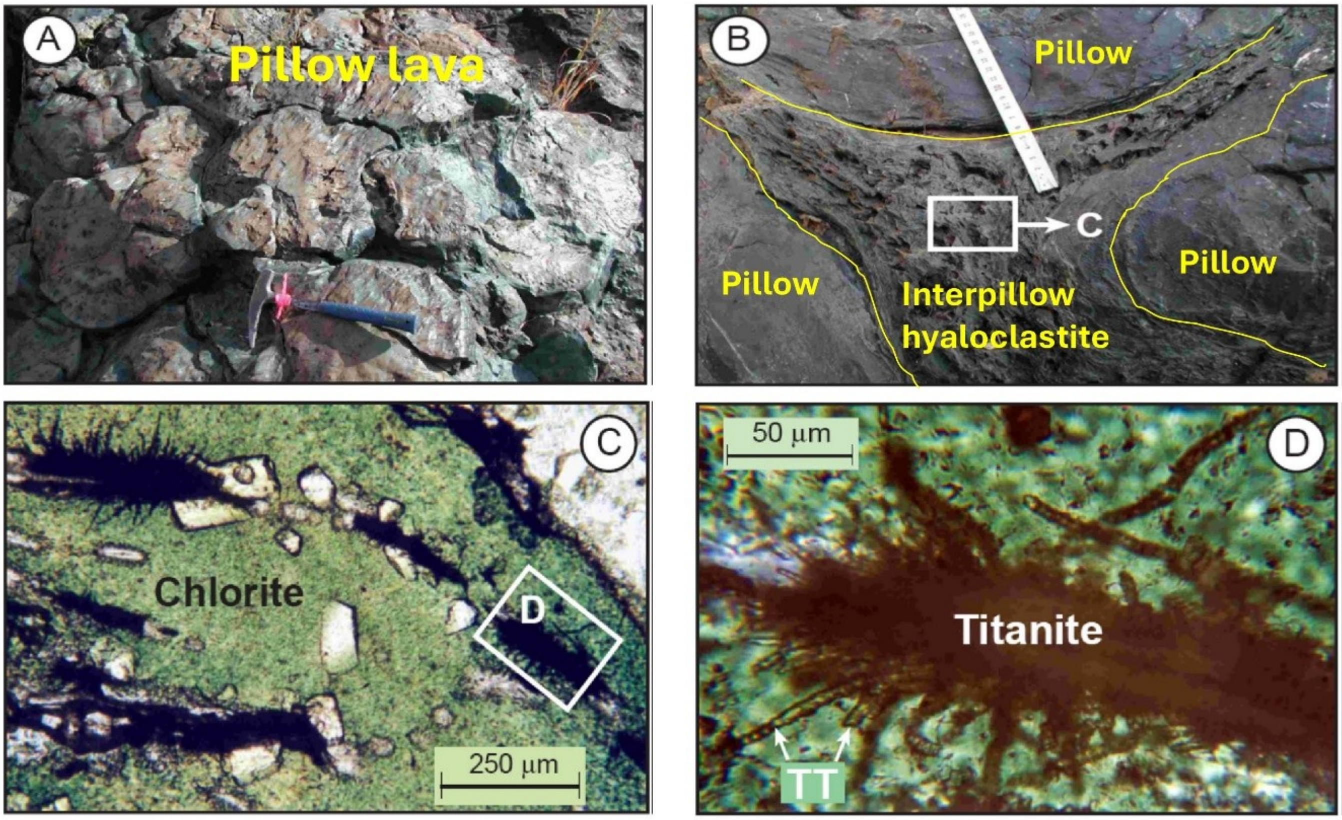

Fig. 4. Pillow lava (A), inter-pillow hyaloclastite (B) showing location of titanite-filled tubular textures developed along fractures (C) and enlarged picture (D) of tubes. Sample from 3.47 Ga of the Barberton greenstone belt (see Furnes et al., 2004).

features, some of which exhibit segmentation, may reach lengths of 200 µm, and width 1–9 µm (Fig. S3).

The importance of the titanite ($CaTiSiO_5$)-filled tubes, taken as a trace fossil, is that it can be isotopically dated, and thus provide a minimum age for the microtunnelling process. This has been successfully achieved for the titanite of the 3.47 Ga South African Barberton pillows, yielding an U-Pb age of 3.342 ±0.068 Ga (Fliegel et al., 2010). For the Australian 3.35-3,31 Ga Euro Basalt of the Pilbara Craton, direct U-Pb dating of titanite (2921 ±110 Ma) also demonstrate an Archan age (Banerjee et al., 2007).

4 Geochemistry

4.1 Element mapping

X-ray mapping of glassy or originally glassy pillow margins of several samples of all ages as described above, of which granular and tubular textures can be demonstrated, have been performed on a large number of pillow lava and hyaloclastite samples from the *in-situ* oceanic crust, Phanerozoic ophiolites and the Precambrian greenstone belts, and the method and applied instrument have been described in Banerjee et al. (2006). For the supporting evidence of microbial origin of these textures, particular attention has been given to the elements carbon and nitrogen. Elevated concentrations of carbon, particularly along the margins of these textures (Fig. S4) have been registered in several cases on samples of all ages, including the 3.47 Ga samples from the Barberton pillows (Fig. S5). The N/C ratios of the analysed samples from Site 896A at the Costa Rica range from 0.08 to 0.25 (Torsvik et al., 1998), comparable to those of marine bacteria (Fagerbakke et al., 1996).

4.2 C-isotope data

Samples of the glassy rim and crystalline interior of individual pillows of all ages (recent to Archean) containing granular and tubular textures have been analysed for $\delta^{13}C$ on, disseminated carbonate, and compared with that of unaltered basalt from *in-situ* oceanic crust (Furnes et al., 2001a). The results of these analyses show that the glassy rims with granular and tubular textures in general have lower $\delta^{13}C$ than the crystalline parts (Fig. S6) devoid of these textures. The compiled $\delta^{13}C$ (‰) versus wt.%

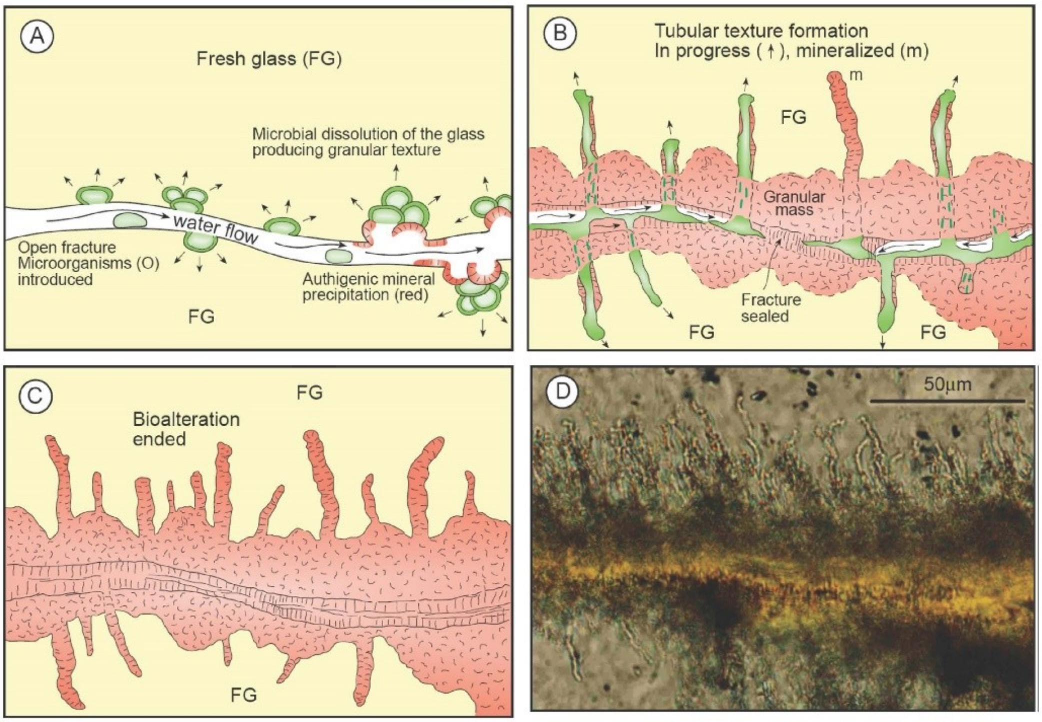

Fig. 5. Model depicting bioalteration producing granular and tubular textures. Picture (A) shows initial colonization of individuals to aggregates of microbes causing dissolution of the basalt glass and beginning authigenic mineralization to produce granular textures. In picture (B) increased authigenic mineralization has stopped granular growth, while hyphal-like cell extension may penetrate the fresh glass producing tubular textures. In picture (C) all circulation of fluids is cut off and the alteration process has stopped. Picture (D) shows a sample (DSDP site 396B, 20R-4, piece 5, 32–40 cm) with granular and tubular textures from which the model has been developed. Modified from Staudigel et al. (2008).

carbonate results from *in-situ* oceanic crust, and ophiolite/greenstone belts, shown in (Fig. S7) show the shift in the $\delta^{13}C_{\text{carbonate}}$ of the glassy pillow rim samples towards more negative values than for the crystalline pillow core samples. By taking the $\delta^{13}C_{\text{carbonate}}$ value of $-7‰$ as the lower limit for magmatic values (e.g., Thorseth et al., 1995; Hoefs, 1997) the percentages of crystalline (pillow core) and glassy (pillow rim) samples from the *in-situ* oceanic crust that exhibit $\delta^{13}C_{\text{carbonate}}$ values lower than $-7‰$, are ~14% and 52%, respectively. The pillow lavas of the ophiolites and greenstone belts show value broadly comparable with those seen for *in-situ* oceanic crust: i.e. the percentages of crystalline and glassy samples that define $\delta^{13}C_{\text{carbonate}}$ values lower than $-7‰$, are ~15% and 35%, respectively, a phenomenon that is attributed to the microbial alteration process (see Thorseth et al., 1995; Furnes et al., 2001a, 2008).

Microbial oxidation of organic matter produces ^{12}C-enriched CO_2. This may subsequently be precipitated in carbonate depleted in ^{13}C (negative $\delta^{13}C$), thus giving $\delta^{13}C_{\text{carbonate}}$ values lower than those for unaltered basalts. Positive $\delta^{13}C_{\text{carbonate}}$ values, on the other hand, can result from lithotrophic utilization of CO_2 by methanogenic Archaea. These microorganisms produce methane from H_2 and CO_2 preferentially producing ^{12}C-enriched methane and leaving the remaining CO_2 enriched in ^{13}C, which will be recorded in any precipitated carbonate" (for more detailed explanation, see Torsvik et al., 1998; Furnes et al., 2008).

5 Syngenicity and antiquity

For the establishment of syngenicity of the granular and tubular textures and thus exclude an origin of modern organisms, they should be seen to predate cross-cutting fractures, veins and cements, as well as metamorphic mineral overgrowth of the old candidates (e.g., McLoughlin et al., 2013). The similarity in the alteration textures in basaltic glass of any age as outlined above provide ample evidence of bioalteration, titanite-filled tubular structures of the Barberton and Pilbara pillow lavas are morphologically similar to trace fossils of young examples. Further, the $\delta^{13}C$ values (less than -7) of carbonates in the Barberton pillow lavas are consistent with microbial fractionation, and X-ray element mapping reveals carbon enrichment along the wall of the tabular structures. This supports the presence of primitive microbial life in the same regions, as also reported from cherts (Westall et al., 2001).

6 Alteration model

The granular alteration texture has been explained by colonizing microbes along open fractures that dissolve the glass they settle and gradually form the sponge-like interconnected network of micron-sized cavities along glass surfaces. This microbial-glass interaction process, originally proposed by Thorseth et al. (1992), creates a microenvironment with local and different pH-value than that of the surrounding seawater, leading to dissolution of the glass. During glass dissolution the cell may absorb nutrient components from the glass, and important components may be Fe (II) and Mn (II) as electron donors (Staudigel et al., 2008). Tubular alteration texture, on the other hand, is more likely to have been created by filamentous cell extensions in a process similar to fungal tunneling of soil feldspars and marine carbonates (for more explanation, see Staudigel et al., 2008). A model for the granular and tubular alteration textures is shown in Fig. 5.

7 Summary

Important results of the investigation of bio-generated textures in glassy (or originally glassy) rocks of *in-situ* oceanic crust (0–170 Ma), Phanerozoic ophiolites and Precambrian greenstone belts are:

- Bio-generated alteration of basaltic glass (of pillow lavas and hyaloclastites) of the oceanic crust develops distinct alteration textures, i.e., granular and tubular types.
- The possibility to quantitatively estimate the extent of bio-alteration with depth in the is-situ oceanic crust.
- When basalt glass is dissolved during generation of the granular and tubular textures, this process results in an exchange of chemical components between seawater and the crust. The oceanic crust is thus a giant bioreactor.
- The bio-generated textures that are filled with metamorphic minerals, as for example titanite, can be isotopically dated, and thus add information to the history of early life.

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Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary material

Supplementary information for this article can be found online at https://doi.org/10.63335/j.hp.2025.0001.

References

Banerjee, N.R., Furnes, H., Muehlenbachs, K., Staudigel, H., de Wit, M., 2006. Preservation of ca. 3.4-3.5 ga microbial biomarkers in pillow lavas and hyaloclastites from the Barberton Greenstone Belt, South Africa. Earth Planet. Sci. Lett. 241, 707–722.

Banerjee, N.R., Simonetti, A., Furnes, H., Muehlenbachs, K., Staudigel, H., Heaman, L., Van Kranendonk, M.J., 2007. Direct dating of Archean microbial ichnofossils. Geology 35(6), 487–490. doi:10.1130/G23534A.1.

Bonatti, E., Harrison, C.G.A., 1988. Eruption styles of basalt in oceanic spreading ridges and seamounts: effects of magma temperature and viscosity. J. Geophys. Res. 93, 2967–2980.

Deming, J.W., Baross, J.A., 1993. Deep-sea smokers, windows to a subsurface biosphere? Geochim. Cosmochim. Acta 57, 3219–3230.

Fagerbakke, K.M., Heldal, M., Norland, S., 1996. Content of carbon, nitrogen, oxygen, sulphur and phosphorous in native auatic and cultured bacteria. Aquat. Misrobial. Ecol. 10, 15–27.

Fisk, M.R., Giovannoni, S.J., Thorseth, I.H., 1998. The extent of microbial life in the volcanic crust of the ocean basins. Science 281, 978–979.

Fliegel, D., Knowles, E., Wirth, R., Templeton, A., Staudigel, H., Muehlenbachs, K., Furnes, H., 2012. Characterization of alteration textures in Cretaceous oceanic crust (pillow lava) from the N-Atlantic (DSDP Hole 418A) by spatially-resolved spectroscopy. Geochim. Cosmochim. Acta 96, 80–93. doi:10.1016/j.gca.2012.08.026.

Fliegel, D., Kosler, J., McLoughlin, N., Simonetti, A., de Wit, M.J., Wirth, R., Furnes, H., 2010. In-situ dating of the Earth's oldest trace fossils at 3.34 Ga. Earth Planet. Sci. Lett. 299, 290–298. doi:10.1016/j.epsl.2010.09.008.

Fliegel, D., Wirth, R., Simonetti, A., Schreiber, A., Furnes, H., Muehlenbachs, K., 2011. Tubular textures in pillow lavas from a Caledonian west Norwegian ophiolite: a combined TEM, LA-ICP-MS, and STXM study. Geochem. Geophys. Geosyst. 12(2). doi:10.1029/2010GC003255.

Fowler, A.P.G., Zierenberg, R.A., 2016. Elemental changes and alteration recorded by basaltic drill core samples recovered from in situ temperatures up to 345 ℃ in the active, seawater-recharged Reykjanes geothermal system, Iceland. Geochem. Geophys. Geosyst. 17. doi:10.1002/2016GC6595.

Furnes, H., Banerjee, N.R., Muehlenbachs, K., Kontinen, S., 2005. Preservation of biosignatures in metaglassy volcanic rocks from the jormua ophiolite complex, finland. Precamb. Res. 136, 125–137.

Furnes, H., Banerjee, N.R., Muehlenbachs, K., Staudigel, H., de Wit, M.J., 2004. Life recorded in archean pillow lavas. Science 304, 578–581.

Furnes, H., Banerjee, N.R., Staudigel, H., Muehlenbachs, K., McLoughlin, N., de Wit, M., Van Kranendonk, M., 2007. Comparing petrographic signatures of bioalteration in recent to mesoarchean pillow lavas: tracing subsurface life in oceanic igneous rocks. Precamb. Res. 158, 165–176.

Furnes, H., Dilek, Y., de Wit, M., 2015. Precambrian greenstone sequences represent different ophiolite types. Gondwana Res. 27, 649–685.

Furnes, H., El-Anbaawy, M.I.H., 1980. Chemical changes and authigenic mineral formation during palagonitization of a basanite hyaloclastite, Gran Canaria, Canary Islands. N. Jb. Mineral. Abh. 139(3), 279–302.

Furnes, H., McLoughlin, N., Muehlenbachs, K., Banerjee, N., Staudigel, H., Dilek, Y., de Wit, M., Van Kranendonk, M., Schiffman, P., 2008. Oceanic pillow lavas and hyaloclastites as habitats for microbial life through time -a review, in: Dilek, Y., Furnes, H., Muehlenbachs, K. (Eds.), Links Between Geological Processes, Microbial Activities & Evolution of Life. Springer Science + Business Media B.V.

Furnes, H., Muehlenbachs, K., Torsvik, T., Thorseth, I.H., Tumyr, O., 2001a. Microbial fractionation of carbon isotopes in altered basaltic glass from the Atlantic Ocean, Lau Basin and Costa Rica Rift. Chem. Geol. 173, 313–330.

Furnes, H., Staudigel, H., 1999. Biological mediation in ocean crust alteration: how deep is the deep biosphere? Earth Planet. Sci. Lett. 166, 97–103.

Furnes, H., Staudigel, H., Thorseth, I.H., Torsvik, T., Muehlenbachs, K., Tumyr, O., 2001b. Bioalteration of basaltic glass in the oceanic crust. Geochem. Geophys. Geosyst. 2, pap. no. 2000GC000150..

Furnes, H., Thorseth, I.H., Tumyr, O., Torsvik, T., Fisk, M.R., 1996. Microbial activity in the alteration of glass pillow lavas from Hole 896A, in: Alt, J.C., Kinoshita, H., Stokking, L.B., Michael, P.J. (Eds.), Proc-Ocean Drilling Prog. Sci. Results. Collage Station, Texas, pp. 191–206.

Hoefs, J., 1997. Stable Isotope Geochemistry. Springer, New York, 2091pp.

Honnorez, J., 1972. La palagonitisation, l'alter4ation sous-marine du verre volcanique basique de palagonia (Sicilie). Vulkaninstitut Immanuel Friedlander No. 9. Birkhausen Verlag, Basel.

Jannasch, H., 1995. Microbial interaction with hydrothermal fluids. AGU Geophys. Monogr. 91, 273–296.

McLoughlin, N., Furnes, H., Banerjee, N.R., Muehlenbachs, K., Staudigel, H., 2009. Ichnotaxonomy of microbial trace fossils in volcanic glass. J. Geol. Soc. London 166, 159–169. doi:10.1144/0016-76492008-049.

McLoughlin, N., Furnes, H., Hanski, E.J., Staudigel, H., 2013. Seeking trextural evidence of a palaeoproterozoic sub-seafloor biosphere in pillow lavas of the Pechenga Greenstone Belt, in: Melezhik et al. (Ed.), Reading the Archive of Earth's Oxygenation, Volume 3: Global Events and the Fennoscandian Arctic Russia – Drilling Early Earth Project. Springer-Verlag, Berlin Heidelberg, p. 1371–1393. doi:10.1007/978-3-642-29670-3_8.

McLoughlin, N., Staudigel, H., Furnes, H., Eickmann, B., Ivarsson, M., 2010. Mechanisms of cotunnelings in rock substrates: distinguishing endolithic biosignatures from abiotic microtunnels. Geobiology 8, 245–255. doi:10.1111/j.1472-4669.2010.00243.x.

Staudigel, H., Furnes, H., Banerjee, N.R., Dilek, Y., Muehlenbachs, K., 2006. Microbes and volcanoes: a tale from the oceans, ophiolites, and greenstone belts. GSA Today 16(10). doi:10.1130/GSAT01610A.1.

Staudigel, H., Furnes, H., McLoughlin, N., Banerjee, N.R., Connell, L.B., Templeton, A., 2008. 3.5 billion years of glass bioalteration: volcanic rocks as a basis for microbial life? Earth-Sci. Rev. 89, 156–176.

Staudigel, H., Furnes, H., Smits, M., 2014. Deep biosphere record of in situ oceanic lithosphere and ophiolites. Elements 10, 121–126. doi:10.2113/gelements.10.2.121.

Staudigel, H., Furnes, H., de Wit, M., 2015. Paleoarchean trace fossils in altered volcanic glass. Proc. Nat. Acad. Sci. (PNAS) 112(22), 6892–6897. URL: `www.pnas.org/cgi/doi/10.1073/pnas.1421052112`.

Staudigel, H., Tebo, B., Yayanos, A., Furnes, H., Kelley, K., Plank, T., Muehlenbachs, K., 2004. The oceanic crust as a bioreactor, in: The Subseafloor Biosphere at Mid-Ocean Ridges. Geophysical Monograph Series. volume 144, p. 325–341.

Stroncik, N., Schmincke, H.-H., 2001. Evolution of palagonite: crystallization, chemical changes, and element budget. Geochem. Geophys. Geosyst. 2(7). doi:10.1029/2000GC000102.

Thorseth, I.H., Furnes, H., Heldal, M., 1992. The importance of microbiological activity in the alteration of natural basaltic glass. Geochim. Cosmochim. Acta 56, 845–850.

Thorseth, I.H., Furnes, H., Tumyr, O., 1991. A textural and chemical study of Icelandic palagonite and its bearing on the mechanism of the glass-palagonite transformation. Geochim. Cosmochim. Acta 55, 731–749.

Thorseth, I.H., Torsvik, T., Furnes, H., Muehlenbachs, K., 1995. Microbes play an important role in the alteration of oceanic crust. Chem. Geol. 126, 137–146.

Torsvik, T., Furnes, H., Muehlenbachs, K., Thorseth, I.H., Tumyr, O., 1998. Evidence for microbial activity at the glass-alteration interface in oceanic basalts. Earth Planet. Sci. Lett. 162, 165–176.

Walton, A.W., Schiffman, L.P., Macperson, G., 2005. Alteration of hyaloclastites in the HSDP 2 Phase I Drill Core: 2. Mass balance of the conversion of sideromelane to palagonite and chabazite. Geochem. Geophys. Geosyst. 6(9). doi:10.1029/2004GC000903.

Westall, F., de Wit, M.J., Dann, J., van der Gaast, S., de Ronde, C.E.J., Gerneke, D., 2001. Early Archean fossil bacteria and biofilms in hydrothermally-influenced sediments from the Barberton greenstone belt, South Africa. Precamb. Res. 106, 93–116. doi:10.1016/S0301-9268(00)00127-3.