



Recrystallized microbial trace fossils from metamorphosed Permian basalt, southwestern Japan

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ABSTRACT

Microbial trace fossils on terrestrial basalts can be used as an analogue in the search for traces of life on other terrestrial planets. This study reports on microbial trace fossils within Permian greenstones in the Maizuru Terrane, southwest Japan, which is recognized as back-arc basin oceanic crust that consists mainly of metabasalt and metagabbro. The trace fossils have been studied by means of morphology, mineralogy, elemental mapping, and carbon isotope analysis. Although minute original textures of trace fossils are recrystallized in these rocks, *Granulohyalichnus vulgaris* isp., *Tubulohyalichnus spiralis* isp., and *Tubulohyalichnus annularis* isp. were identified. Significant concentration of C within the trace fossils implies these are organic remnants from microbes. The $\delta^{13}\text{C}_{\text{PDB}}$ values $< -7\text{‰}$ of calcite within the greenstones indicates that the bacterial activity took place prior to the formation of calcite veins. The results support that microbial trace fossils within low-grade metamorphic basalt can be reliably identified based on their morphology and chemical composition, as revealed by elemental mapping. In this context, glassy Martian basalt may be the best rock type to investigate in terms of searching for signs of microbial activity on Earth and other planets.

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1. Introduction

Microbial trace fossils on terrestrial basalts can be used as an analogue in the search for traces of life on other terrestrial planets. The study of microbial trace fossils within basaltic rocks gives insights into early life (Furnes et al., 2004; Banerjee et al., 2006), the diversity and evolution of subsurface life (Thorseth et al., 2001), biochemical cycling (Cavalazzi et al., 2011), and life searching by remote rovers on Mars (Izawa et al., 2010). Because most ancient oceanic basalts on Earth have experienced metamorphism (e.g., Liou and Ernst, 1979), the evaluation of microbial trace fossils from ancient oceanic basalt is critical. Because basaltic rocks are the main component of the Martian crust (e.g., Allen et al., 1981; Wyatt and McSween, 2002), and given their low-grade metamorphism (e.g., Ehlmann et al., 2011), the study of microbial fossils within metamorphosed basalts could contribute to the search for Martian biosignatures at present and in the past.

Microbial trace fossils in basaltic glass are mostly associated with modern oceanic crust. Nonetheless, few examples are described from ancient oceanic crust (e.g., Fisk et al., 1998, 2000; Fliegel et al., 2012; Furnes et al., 1999, 2002, 2005, 2007; Knowles et al., 2013; Staudigel et al., 2008; Torsvik et al., 1998). Based on a compilation of occurrences

and morphology, microbial trace fossils were divided into two ichnogenera and five ichnospecies (McLoughlin et al., 2009). Most of the original morphological characteristics of microbial trace fossils are well-preserved in non-metamorphosed basaltic rocks. Thus, the microbial trace fossils from in-situ oceanic basalts could be readily identified based on the diagnosis of ichnogenera and ichnospecies. On the other hand, many microbial trace fossils in ancient oceanic basalts lose their original morphological, mineralogical, and geochemical features because of metamorphic processes (Banerjee et al., 2006). Although a number of previous studies considered the alteration textures from in-situ oceanic basalts (e.g., Alt and Mata, 2000), only few of them have investigated the relation between ambiguous, recrystallized alteration textures and low-grade metamorphism. The aim of this study is to characterize morphology and chemical properties of putative bioalteration textures within metabasalts of dismembered early-middle Permian Ibara ophiolite (Koide, 1986) of Maizuru Terrane, southwest Japan. This is performed by morphological, petrographical and carbon isotope analyses and by elemental mapping.

2. Geologic setting and materials

2.1. Geology and metamorphic conditions

The Ibara metabasalts in the Ibara greenstones are found north of Ibara city, southwest Japan, in Maizuru Terrane. Based on petrography, geological, and geochemical features, the Ibara metabasalts are

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recognized as back-arc basin oceanic crust that forms the basement to the Permian Maizuru Group (Koide, 1986; Koide et al., 1987). The related metabasalts in Maizuru Terrane are considered member of the Permian Yakuno ophiolite (Ishiwatari, 1978, 1985a, 1985b). Rocks in the study area comprise Late Paleozoic metamorphosed greenstone complex that mainly consists of metabasalts and metagabbros with lesser serpentinite, chert, and siliceous red shale (Koide, 1986). The metabasalts have a wide distribution, and consists of hyaloclastites, vesicle-poor pillow lavas, and massive lavas, and doleritic dykes. Chert xenoliths and evidence of flowage of the siliceous red shale are often seen in the pillow and massive lavas in the northeastern and mid-western parts of the Ibara greenstones. The latter contain well-preserved original structures and textures.

The stratigraphic sequence is reconstructed by the field observations, mapping, and the corresponding metamorphic grade of the Ibara greenstones (Fig. 1). The Ibara greenstones are divided into four zones (I–IV) in ascending order of metamorphic grade. The representative mineral assemblages are prehnite + pumpellyite + chlorite ± epidote in zone I, prehnite + actinolite + epidote + plagioclase + chlorite in zone II, actinolite + epidote + plagioclase + chlorite in zone III, and hornblende + plagioclase in zone IV. The mineral assemblages and mineral chemistry suggest that rocks of all four zones have been subjected to low-grade ocean-floor metamorphism (Sugawara et al., in preparation).

2.2. Sample description

Samples were collected for petrography, mineralogy, and geochemistry analyses. Samples of massive basalt with calcite veins, and glassy basalt from hyaloclastite and chilled margins of pillow lava were collected from zones I–III (Fig. 1). Samples of metagabbro were collected from zone IV. The locations of the samples with the most significant evidence for microbial trace fossils were marked in the lithological column (Fig. 1).

3. Analytical methods

3.1. Petrography and mineral chemistry

Thin sections of Ibara metabasalts and metagabbros were observed by using transmitted-light microscopy. The chemical

compositions of the minerals was determined using a JEOL-6500LV electron probe microanalyzer operated at an accelerating voltage of 15 kV, beam current of 8.00×10^{-10} A and beam diameter of 1 μ m. Cobalt was used as the standard material, and enstatite, K-feldspar, and clinopyroxene were also used as working standards to monitor the precision and accuracy of the analyses. The ZAF method was used for data correction. The transmitted-light microscopy and electron probe microanalyzer are housed at the Department of Earth Sciences, Ehime University, Japan.

Areas in thin sections with putative evidence for microbial trace fossils within altered glass in basaltic pillow lava were targeted for element mapping. Polished thin sections coated with platinum were analyzed using a JEOL JSM-6510LV scanning electron microscope (SEM) equipped with an Oxford Instruments energy dispersive X-ray spectrometer (EDS) at the Department of Earth Sciences, Ehime University, Japan. operated under high vacuum, equipped with an Oxford Instruments energy dispersive X-ray spectrometer (EDS), with the equipment housed at the Department of Earth Sciences, Ehime University, Japan. The SEM was operated under high vacuum, an accelerating voltage of 15 kV, a beam current of 3.00×10^{-9} A, and beam diameter of 1 μ m. Two-dimensional elemental maps were generated using the Oxford Inca Energy software.

3.2. Carbon isotope analysis

Powder samples of target calcite were obtained using a micro-drill from polished slabs of basaltic rocks. The powders were weighed and placed in glass vials, and then reacted with 100% phosphoric acid at 90 °C in vacuum. The released CO₂ was purified and analyzed for $\delta^{13}\text{C}$ using an IsoPrime isotope ratio mass spectrometer (IRMS) with a MultiPrep automated sample-preparation module at the Center of Marine Core Research, Kochi University, Japan. The results are expressed in relation to the VPDB (Vienna PeeDee Belemnite) standard. The estimated analytical precision was better than 0.05‰ for $\delta^{13}\text{C}$ measurements.

4. Results

4.1. Description of putative microbial trace fossils

At two locations in zone I (prehnite–pumpellyite facies), altered basaltic glass in the rims of pillow lavas contain granular and tubular alteration textures (Fig. 1) herein interpreted as microbial trace fossils. Granular trace fossils in the altered glass occur as irregular clusters along fracture walls, and in calcite or chlorite veins. These features are equidimensional (< 10 μ m in diameter) and consist of titanite (Fig. 2a and b).

Tubular trace fossils radiate away from the fracture walls and rims of altered glass. Some tubular trace fossils are discontinuous and isolated within the altered glass (Fig. 2b). These textures are divided into four types based on morphology: (1) unbranched tubes with terminal swelling; (2) branched tubes with terminal swelling; (3) unbranched tubes with spiral tubular texture around the tube (Fig. 2d–f); and (Fig. 4) unbranched tubes without terminal swelling or spiral tubular texture (Fig. 2c). All tubular trace fossils in the altered basaltic glass are < 20 μ m wide and < 400 μ m long.

4.2. Elemental mapping

Elemental mapping of a tubular microbial trace fossil was performed by SEM-EDS. The SEM-EDS analysis revealed local concentrations of C within and at the rim (Fig. 3). The significant concentrations of C within the tube show positive correlations

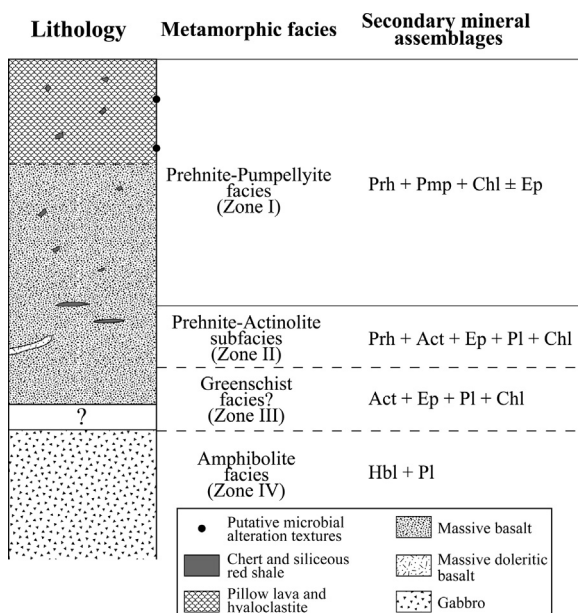


Fig. 1. Simplified lithological and metamorphic section of the Ibara greenstones. The stratigraphic column is not in scale.

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