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Filamentous microbial fossil from low-grade metamorphosed basalt in northern Chichibu belt, central Shikoku, Japan



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ABSTRACT

The past two decades have seen the reporting of microbial fossils within ancient oceanic basalts that could be identical to microbes within modern basalts. Here, we present new petrographic, mineralogical, and stable isotopic data for metabasalts containing filamentous structures in a Jurassic accretionary complex within the northern Chichibu Belt of the Yanadani area of central Shikoku, Japan. Mineralized filaments within these rocks are present in interstitial domains filled with calcite, pumpellyite, or quartz, and consist of iron oxide, phengite, and pumpellyite. $\delta^{13}C_{PDB}$ values for filament-bearing calcite within these metabasalts vary from -2.49‰ to 0.67‰. A biogenic origin for these filamentous structures is indicated by (1) the geological context of the Yanadani metabasalt, (2) the morphology of the filaments, (3) the carbon isotope composition of carbonates that host the filaments, and (4) the timing of formation of these filaments relative to the timing of low-grade metamorphism in a subduction zone. The putative microorganisms that formed these filaments thrived between eruption (Late Paleozoic) and accretion (Early Jurassic) of the basalt. The data presented here indicate that cryptoendolithic life was present within water-filled vesicles in pre-Jurassic intraplate basalts. The mineralogy of the filaments reflects the low-grade metamorphic recrystallization of authigenic microbial clays similar to those formed by the encrustation of prokaryotes in modern iron-rich environments. These findings suggest that a previously unusual niche for life is present within intraplate volcanic rocks in accretionary complexes.

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1. Introduction

Recent advances in planetary science have changed a number of fundamental assumptions about the possible existence of life in the universe, increasing the number of potentially habitable zones in the solar system and on planets orbiting other stars, and furthering the search for extraterrestrial microbial life. One possibility is that life may have developed on Venus, Mars, Jupiter's moon Europa, Saturn's moons Titan and Enceladus, and extrasolar planets, such as Gliese 581 d, a recently discovered planet that has a mass similar to Earth mass, located in a star's habitable zone, and may potentially contain liquid water (e.g., Kempe and Kazmierczak, 2002; Schulze-Makuch and Irwin, 2002; McKay and Smith, 2005; Horneck and Rettberg, 2007; von Bloh et al., 2007; Postberg et al., 2011).

One of the primary scientific objectives of the Viking lander mission was to search for biosignatures on Mars. The 1976 Viking lander experiments appeared to discount the possibility of life on Mars (Mazur et al., 1978); however, a team of researchers studying the Martian meteorite ALH84001 found evidence of polycyclic aromatic hydrocarbons (PAHs) and traces of bacteria-like structures, both of which have Martian origins (McKay et al., 1996). This finding triggered a discussion on the possibility of life on Mars, including during the early water-present stage of the evolution of the Martian surface, based on the signatures of life and its habitats on Earth (Cabrol et al., 2007). This was further supported by the 26 November 2011 launch of the NASA Mars Science Laboratory mission with its Curiosity rover, which carried instruments designed to examine the past or present habitability of Mars (http://mars.jpl.nasa.gov/msl/mission/overview/).

The discovery of a vast expanse of deep sub-seafloor biosphere as a significant feature of Earth's ocean crust has led to the identification of fossilized microorganisms within crust intercepted during deep drilling; these microorganisms are generally granular and tubular ichnofossils that appear to have grown within the original volcanic glass (Thorseth et al., 1992; Furnes and Staudigel, 1999; Furnes et al., 2001a, 2001b, 2007, ; Banerjee et al., 2004; Santelli et al., 2008; McLoughlin et al., 2009; Fliegel et al., 2011), and corresponding body fossils have been identified (e.g., Hofmanna and Farmer, 2000; Schumann et al., 2004; Ivarsson et al., 2008a, 2008b). Both ichnofossils and body fossils are located

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within or are associated with veins and vesicles in which the microorganisms migrated through the rock. The eventual filling of these veins and vesicles with secondary minerals, such as carbonates, quartz, clays, or zeolites, trapped the microorganisms; samples with these petrographic alteration textures also generally have very low δ^{13} C values (e.g., Furnes and Staudigel, 1999; Furnes et al., 2001a; Banerjee and Muehlenbachs, 2003), elevated concentrations of C, N, P, K, and S (e.g., Furnes et al., 2001b; Banerjee and Muehlenbachs, 2003), and, in younger samples, may contain DNA (e.g., Torsvik et al., 1998; Furnes et al., 2001a; Banerjee and Muehlenbachs, 2003). These characteristics strongly suggest that these ichnofossils and body fossils have biogenic origins.

In addition, the microbial colonization of basaltic glass appears to have occurred during the early history of the Earth, as part of a deep subsurface biosphere (Thorseth et al., 1995; Fisk et al., 1998; Furnes and Staudigel, 1999; Furnes et al., 2001b, 2004, 2007; Edwards et al., 2005; Staudigel et al., 2006, 2008). Research focusing on pillow lavas within ancient oceanic crust, such as ophiolites and greenstone belts, has confirmed that similar microorganism-rock interactions have occurred within formerly glassy volcanic rocks since the Mesoarchean (Furnes and Muehlenbachs, 2003; Furnes et al., 2004, 2008; Banerjee et al., 2006). Fossilized cryptoendolithic microorganisms that originally inhabited fluid-filled cavities of basaltic rocks also have been recently identified within ocean-floor basalts, seamounts, and green rocks (Schumann et al., 2004; Peckmann et al., 2008; Eickmann et al., 2009; Cavalazzi et al., 2011). This research has provided a new search tool for the earliest signs of life on Earth and other planets (McLoughlin et al., 2007), and provides evidence of ancient microbiota within poorly investigated microenvironments that are relevant to our understanding of Mars.

Accretionary complexes within the circum-Pacific, as exemplified by those of the Japanese Islands, contain low-grade metamorphosed oceanic basaltic rocks of varying ages and environments of formation. These rocks provide an important evidence on subsurface microbial eco-systems that existed during the Phanerozoic. Here, we report new data from a putative cryptoendolithic community located within the interstitial matrix of a pre-Jurassic basaltic rock from the low-grade metamorphosed Jurassic northern Chichibu accretionary complex of central Shikoku, Japan.

2. Geology of the study area and outcrop description

The Chichibu Belt in Japan is dominated by Permian–Early Cretaceous accretionary complexes, and extends approximately 1500 km from the Kanto Mountains across Shikoku Island to the Okinawa Islands (Isozaki, 1987; Yamakita, 1988; Hada and Kurimoto, 1990; Matsuoka et al., 1998). This belt is geologically divided into the northern Chichibu, Kurosegawa, and southern Chichibu belts. The northern Chichibu Belt is an accretionary complex that formed during Late Permian–Early Jurassic northwards subduction of the Kula–Izanagi Plate.

The northern Chichibu Belt on Shikoku Island, in southwest Japan, hosts a Jurassic accretionary complex that contains voluminous low-grade metamorphosed basaltic rocks, the majority of which are alkaline or mildly alkaline and have intraplate affinities (e.g., Umeki and Sakakibara, 1998; Ishizuka et al., 2003). Volcanism in the study area peaked during the Late Carboniferous and Late Permian (Matsuoka et al., 1998), and the accretionary complex is thought to have been deformed during seamount collision and accretion (Tsuji and Sakakibara, 2009).

The Yanadani area, within the southernmost northern Chichibu Belt of central Shikoku, is characterized by a pelitic mélange that contains blocks of greenstone, chert, limestone, basalt, and sandstone, in addition to coherent sequences. Pelitic rocks in this area



onto Belt

Shi

likab

Southern

Fig. 1. Simplified geologic map of Shikoku showing the sample locality (black star) in Japan.

Kurosegawa Belt

are weakly foliated, but sandstone, chert, and basalt are generally massive (Tsuji and Sakakibara, 2009).

The sample analyzed in this study was collected from a basaltic block within pelitic mélange in a riverside outcrop in the Yanadani area (Fig. 1 ; 39°30'4.2"N, 132°56'44.7"E), approximately 700 m east of Komi Village in Kumakougen Town, Ehime Prefecture. This outcrop contains massive basaltic lava with minor amounts of basaltic hyaloclastite, and the pelitic mélange in this area has undergone lower prehnite–pumpellyite facies metamorphism (Tsuji and Sakakibara, 2009).

3. Analytical methods

Greenrock & limestone

Filamentous structures within the Yanadani basalt and their constituent minerals were analyzed using a JEOL JSM-6510 LV scanning electron microscope (SEM) with an Oxford Instruments X-Max X-ray energy dispersive spectrometer system with a 50-mm² silicon drift EDS detector at the Department of Earth Science, Ehime University, Japan. A ZAF correction procedure was used during data reduction, and all Fe was assumed to be ferrous. Low-grade metamorphic minerals were analyzed with a beam current of 4×10^{-9} Å, an accelerating voltage of 15 kV, and an acquisition time of 50 s to avoid the volatilization of light elements. Analytical accuracy and precision were verified using anorthoclase and KH-1 clinopyroxene standards (Kilbourn Hall,

N?

50km

Izumi Group

Ryoke Belt

Sanbagawa Belt

33° W-

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