Research Paper

Iron-Magnesium Silicate Bioweathering on Earth (and Mars?)

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ABSTRACT

We examined the common, iron-magnesium silicate minerals olivine and pyroxene in basalt and in mantle rocks to determine if they exhibit textures similar to bioweathering textures found in glass. Our results show that weathering in olivine may occur as long, narrow tunnels (1–3 μm in diameter and up to 100 μm long) and as larger irregular galleries, both of which have distinctive characteristics consistent with biological activity. These weathering textures are associated with clay mineral by-products and nucleic acids. We also examined olivine and pyroxene in martian meteorites, some of which experienced preterrestrial aqueous alteration. Some olivines and pyroxenes in the martian meteorite Nakhla were found to contain tunnels that are similar in size and shape to tunnels in terrestrial iron-magnesium silicates that contain nucleic acids. Though the tunnels found in Nakhla are similar to the biosignatures found in terrestrial minerals, their presence cannot be used to prove that the martian alteration features had a biogenic origin. The abundance and wide distribution of olivine and pyroxene on Earth and in the Solar System make bioweathering features in these minerals potentially important new biosignatures that may play a significant role in evaluating whether life ever existed on Mars. Key Words: Bioweathering—Biosignature—Olivine—Pyroxene—Dunite—Nakhlite. Astrobiology 6, 48–68.

INTRODUCTION

Microorganisms interact with their environment in a variety of ways that may leave biosignatures (evidence of their presence or activity) in the geological record. For example, cells may form biominerals, such as magnetite (Bazylinski, 1996) and pyrite (Popa et al., 2004a), and microbial bioweathering has been found in carbonates, oxides, and silicates (e.g., Fortin et al., 1996; Fisk et al., 1998). Biosignatures may result from mineral formation or alteration that benefits the cell, or the mineral transformations may be incidental to cellular activity (Lowenstam, 1981). Microbial biosignatures also include body fossils, stromatolites, trace fossils (burrows, tunnels, footprints, or other marks or impressions), reduced or oxidized minerals, alteration of geo-

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chemical cycles, fractionation of stable isotopes, chirality, metabolic byproducts, and organic molecules such as polysaccharides, nucleic acids, amino acids, fatty acids, polyaromatic hydrocarbon compounds, enzymatic cofactors, and pigments (e.g., Schopf, 1993; Furnes et al., 2002; Patwardhan and Clarson, 2002; Cady et al., 2003; Fisk et al., 2003).

McKay et al. (2003) established a classification system for biosignatures that ranks them on the basis of what is known about possible abiotic mechanisms that can produce similar signatures. Category I biosignatures are defined as unambiguous evidence of life such as living forms, fossils, or DNA (McKay et al., 2003). Category II biosignatures are not known to be produced by abiotic processes and resemble biotic products such as complex forms, isotopic fractionation, or organic compounds. Category III biosignatures are known to be produced by life but can also be produced by abiotic processes. Recently detected methane in the martian atmosphere, for example, could be of geothermal origin or a metabolic product (Duxbury et al., 2004; Krasnopolsky et al., 2004) and, therefore, is characterized as a Category III biosignature. Microbial trace fossils such as those described here are interpreted as Category II biosignatures because they are complex forms and there are no known abiotic processes that produce them.

Biosignatures in terrestrial rocks

Many examples of distinctive features attributed to microbial alteration (biotic alteration) of volcanic rocks have been reported (e.g., Thorseth et al., 1992; Fisk et al., 1998, 2003; Furnes et al., 2001a; Banerjee and Muehlenbachs, 2003; Storrie-Lombardi and Fisk, 2004). Biotic alteration takes on many forms, three of which are present in Fig. 1. In this image the original fractures in volcanic glass are sharply defined, and small threadlike tunnels (1 μm in diameter and about 3 μm long) and large tunnels (3 μm wide up to 40 μm long) extend from this boundary into the glass. Larger galleries, which in this case are 5–10 μm in di-

FIG. 1. Plane polarized light photomicrograph of a 30-μm-thick petrographic thin section of an oceanic basalt (Ocean Drilling Program Sample 183, 1140A-26-1-84). The tan mottled area is fresh basalt glass. A fracture filled with yellowish-orange smectite clay runs diagonally through the photo. White material at the left of the photograph is a second fracture filled with zeolites and clay. The basalt is 30 million years old and was buried by 134 m of sediment and 4 m of igneous rock.
ameter and 20 μm long and have undulating walls, also start at the edge of fractures. Additional biotic alteration forms are found in other samples (e.g., Furnes et al., 1996; Giovannoni et al., 1996; Fisk et al., 1998). A common feature of biotic alteration is that the tunnels emerge from a glass or mineral surface that has been in contact with water, and the host mineral or glass is replaced with hydrous minerals that are identified chemically by electron microprobe (e.g., Furnes et al., 1996; Giovannoni et al., 1996; Storrie-Lombardi and Fisk, 2004). Additional common features of biotic alteration are: the dark brown to black boundary between the glass and the fracture-filling clay (Fig. 1); the localized, nonuniform distribution of tunnels along fractures or mineral edges; the uniform size and shape of tunnels in a single sample; and the uniform diameter along the length of individual tunnels.

This biotic alteration morphology can be distinguished from abiotic alteration in thin sections because abiotic alteration of glass produces an unembayed, smooth (at the 1 μm scale) alteration front that affects the whole glass surface (e.g., Fisk et al., 1998, Fig. 1a; Fisk et al., 2003, Fig. 2c and d). Smooth alteration fronts have been generated in abiotic experiments (Crovisier et al., 1983), but tunnels and galleries like those illustrated in Fig. 1 have not been produced in either biotic or abiotic laboratory experiments (Staudigel et al., 1995; Thorseth et al., 1995a).

Localized concentrations of nucleic acids, C, N, and P, and in some cases cell-like bodies are associated with the biotic alteration of glass such as that illustrated in Fig. 1 (e.g., Thorseth et al., 1995b; Furnes et al., 1996, 2001a,b; Giovannoni et al., 1996; Torsvik et al., 1998; Fisk et al., 2003). The DNA of novel microorganisms has been extracted from rocks that contain the gallery and tunnel features such as those described here (Fisk et al., 2003; C.A. Di Meo-Savoie et al., manuscript in preparation), and no abiotic mechanism has been demonstrated that produces such a variety of tunnel features. However, this circumstantial evidence does not prove that the tunnels and galleries are produced by microorganisms. This proof awaits the production of tunnels and galleries by microbes in laboratory cultures.

Features such as those shown in Fig. 1, which are referred to as microbial trace fossils, can endure for many millions of years if the host rock is not highly metamorphosed or destroyed by physical weathering. These Category II biosignatures are found in seafloor rocks as old as 170 million years (Fisk et al., 1999) and in ophiolites (ocean crust uplifted and exposed above sea level) in Cyprus, Norway, and the Barberton Greenstone Belt of South Africa, which are 60, 220, and 3,400 million years old, respectively (Furnes et al., 2001b, 2002, 2004). In the older two of these ophiolites, the rocks have experienced low-grade metamorphism and mild chemical alteration, yet the distinct microbial alteration remains recognizable.

In addition to volcanic glass, silicate minerals such as olivine, pyroxene, feldspar, and hornblende have been altered by microorganisms in laboratory and field studies (Rogers et al., 1998; Kalinowski et al., 2000; Santelli et al., 2001).

**Olivine and pyroxene as potential hosts of microbial biosignatures**

**Olivine.** Olivine is the most abundant terrestrial mineral, making up 3–5% of the basaltic crust and more than 50% of the upper mantle. It is an orthorhombic silicate with major constituents Si, Fe(II), Mg, and O, and minor constituents Al, Ca, Mn, Cr, Co, and Ni. Other elements are present at less than 0.1% (wt/wt). Fe(II) and Mg substitute freely for each other, and olivine compositions range from the pure iron end member Fe2SiO4 (fayalite) to the magnesium end member Mg2SiO4 (forsterite). Accordingly, the atomic ratio Mg/[Mg+Fe(II)] in olivine can vary from 0.0 to 1.0 (i.e., an atomic ratio of 0.80 would be reported as Fo80 or forsterite 80). Typical values for olivine in basaltic magmas on Earth are Fo50–Fo90. Cumulate rocks may have values from Fo0 to Fo100, though extreme values are rare. On Mars, the compositional range is shifted toward iron-rich values, generally from Fo14 to Fo70 (some examples are shown in Table 1).

Olivine is unstable in aqueous environments, and in the presence of organic acids, such as oxalic and salicylic acid, it is more soluble than other silicate minerals (Barman et al., 1992). During the alteration of olivine, Fe(II) and Mn(II) are commonly oxidized to Fe(III) and Mn(IV), and because of the multiple oxidation states of Fe and Mn, they may act as electron donors or acceptors. At least one microorganism, Acidithio-bacillus ferrooxidans, can oxidize Fe(II) in olivine...
Pyroxene. Pyroxene is typically 10–40% of basalts and mantle rocks. It is a single-chain silicate with the generic formula (M1M2T2O6), where M1, M2, and T are crystallographically distinct sites. The major constituents of pyroxene in igneous rocks are usually Si, Mg, Fe(II), Ca, Al, and O. The T site (surrounded by four oxygens) is primarily occupied by Si or Al, and M2 (the larger of the two M sites) accommodates the larger Ca ion. Fe(II) and Mg cations occupy either M1 or M2. Minor constituents are Fe(III), Mn, Na, Ti, and Cr, though a number of other elements may also be present above the 0.01% (wt/wt) level. As in olivine, Fe(II) and Mg freely substitute for each other.

Although pyroxene is unstable in aqueous environments, it is altered at a significantly lower rate than olivine in terrestrial environments (Goldich, 1938; Brantley, 2003) because of its more highly structured silicate lattice. Therefore pyroxene often appears unaltered after olivine has been completely transformed to secondary minerals. For this reason, pyroxene is more suited for observing bioalteration in rocks that have experienced large degrees of alteration, whereas olivine would be more suited for observing bioalteration in slightly altered rocks. As martian meteorites have experienced only minor amounts of aqueous alteration, they are probably best compared with terrestrial rocks that have undergone only slight aqueous alteration. Characteristics of olivine and pyroxene that make them suitable for microbial alteration studies include the following:

- Olivine and pyroxene are transparent when viewed in thin section (30 μm thick) and are distinguished from their alteration products by color and other optical properties. This provides a good opportunity to observe alteration at the micrometer scale in three dimensions when using techniques such as confocal microscopy and image deconvolution.
- Olivine and pyroxene contain Fe(II), an electron donor for biologically mediated redox reactions. Abiotic alteration can release the iron, thus making it available to microorganisms.
- Iron is often present as Fe(III) in the common alteration products of olivine and pyroxene, such as clays, Fe oxides and Fe oxyhydroxides, and laihunite [Fe(III)-bearing olivine].
- Crystallographic planes and preferred alteration orientations can be observed in thin section.
- The biologically relevant elements C, N, P, and H are trace constituents of olivine and pyroxene so chemical analyses of organic matter on or in these silicate minerals have a high signal-to-background ratio.
- The native ultraviolet-excited fluorescence of the minerals is at a different wavelength than that of many nucleic acid dyes and complex organic compounds such as aromatic amino acids.
- In addition, laboratory abiotic and biotic alteration of olivine produces different and distinguishable alteration textures (Longazo et al., 2001, 2002; Santelli et al., 2001; Welch and Banfield, 2002).

The biotic alteration of olivine and pyroxene is of particular importance to the astrobiology of Mars because pyroxene is present in most and olivine is present in many martian meteorites. Some of these meteorites underwent aqueous alteration while still on Mars (Gooding et al., 1991; Treiman et al., 1993; Treiman, 2005).

### Table 1. Olivine Abundance and Composition in Nakhlites

<table>
<thead>
<tr>
<th>Meteorite name</th>
<th>Olivine (%)</th>
<th>Olivine composition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governador Valadares</td>
<td>7–13</td>
<td>Fo22–Fo34</td>
<td>Berkley et al. (1980)</td>
</tr>
<tr>
<td>Lafayette</td>
<td>7–20</td>
<td>Fo23–Fo35</td>
<td>Berkley et al. (1980), Bunch and Reid (1975)</td>
</tr>
<tr>
<td>MIL 03346</td>
<td>3</td>
<td>Fo22–Fo33</td>
<td>Treiman (2005)</td>
</tr>
<tr>
<td>Nakhla</td>
<td>5–14</td>
<td>Fo23–Fo35</td>
<td>Bunch and Reid (1975), Weinke (1978), Gooding et al. (1991)</td>
</tr>
<tr>
<td>NWA 817</td>
<td>10–15</td>
<td>Fo14–Fo44</td>
<td>Sautter et al. (2002)</td>
</tr>
<tr>
<td>NWA 998</td>
<td>10</td>
<td>Fo26</td>
<td>Treiman (2005), Irving et al. (2002)</td>
</tr>
<tr>
<td>Yamato 000593</td>
<td>10–12</td>
<td>Fo22–Fo38</td>
<td>Mikouchi et al. (2002)</td>
</tr>
</tbody>
</table>

*The generic formula of olivine is (Mg, Fe)2SiO4. The Fo subscript is the atomic percentage of Mg relative to Mg + Fe.*
Energy considerations. Iron in olivine and pyroxene is predominantly Fe(II), and microorganisms such as Leptothrix ochracea, Gallionella ferruginea, and A. ferrooxidans are capable of using Fe(II) as an electron donor. The energy available to chemolithotrophic microorganisms that oxidize Fe(II) depends on the electron acceptor utilized (for example, O$_2$, NO$_3^-$, or SO$_4^{2-}$), the concentration of the electron acceptor, temperature, and very likely the abundance of Fe in the mineral. Oxidation of Fe(II) from Fe-poor minerals may provide less energy than it costs the microorganism to degrade the crystal lattice, and therefore biotic degradation of iron-bearing minerals may be dependent on iron content. Alternatively, abiotic aqueous weathering of olivine and pyroxene can release Fe(II) into solution at no cost to microorganisms. This iron, whose supply is dependent on the rate of silicate weathering, is a source of electrons that can be used for the reduction of O$_2$, NO$_3^-$, or SO$_4^{2-}$.

HYPOTHESIS AND OBJECTIVES

We postulate that, if life existed on Mars, subsurface organisms would have left biosignatures similar to those found in silicate minerals on Earth. These biosignatures could be biological residues, mineral deposits, or microtextural features, e.g., pits, tunnels, or galleries, on mineral surfaces and along fractures within minerals. In the event that such biosignatures exist in silicate rocks on Mars, they may be better preserved than on Earth because liquid water, a key ingredient in low temperature alteration on Earth, seems to have been mostly lost from the martian surface early in the planet’s history (Carr, 1996; Malin and Edgett, 2001). Desiccation would slow, or stop, biosignature-erasing alteration. Martian meteorites (volcanic rocks from the martian surface and shallow subsurface) are potential carriers of fossil evidence of past life on Mars (McKay et al., 1996; Gibson et al., 2001). Our goal has been to investigate olivine in terrestrial basalts and olivine and pyroxene in peridotites for evidence of alteration in the presence of water that could be attributed to microorganisms. If terrestrial alteration is associated with biomarkers, such as DNA, we can compare the nature of such bioalteration with mineral alteration observed in martian meteorites. We recognize that association of DNA with mineral alteration does not constitute proof that microorganisms caused the alteration. We further recognize that morphology of trace fossils (tunnels) may not be a suitable indication of biogenicity, just as morphology of “microfossils” without comparative anatomy is not a suitable criterion for biogenicity (Ruiz et al., 2002).

MATERIALS AND METHODS

Sample locations and descriptions

Numerous terrestrial samples and 12 martian meteorites were examined by petrographic microscopy, and four terrestrial samples and the martian meteorite Naklıa were then selected for detailed study. The terrestrial rocks were: (1) a deep subsurface basaltic lava from Hawaii (R401-2.85), (2) a surface-weathered dunite (a rock with more than 90% olivine and some pyroxene) from central Oregon (BM2), (3) a surface-weathered dunite from northern California (NFSR2), and (4) a dunite from the Tonga trench (BMRG8-16-1-17). These four rocks were weathered in four different terrestrial environments. Naklıa experienced aqueous alteration in the martian subsurface (Treiman, 2005).

Basalt R401-2.85. A sample of olivine-rich basalt (olivine phenocrysts 0.1–5 mm in length) was obtained from the Hawaiian subsurface at 19°43.0′N, 155°3.3′W near Hilo, HI by the Hawaiian Scientific Drilling Program in 1999. The rock, which erupted above sea level about 400,000 years ago, has since subsided to 960 m below sea level (Stolper et al., 2000) and is in a zone saturated with salt water that is presently 8°C (Thomas et al., 1996).

Dunite BM2. Dunite BM2 from the Canyon Mountain ophiolite [260 Ma (Leeman et al., 1995)] was sampled from an outcrop near the top of Baldy Mountain in the Strawberry Mountain Wilderness, south of John Day, OR (latitude 44°20.1′N, longitude 118°47.8′W, elevation 2,167 m). The site has an average January temperature of −6°C and an average August temperature of 22°C, and precipitation is approximately 0.8 m/year.

Dunite NFSR2. The second dunite was exposed by erosion and collected along the Smith River near Gasquet, CA. The sample is from the Josephine ophiolite, a Jurassic island arc (about
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150 million years old) that was accreted to North America (Harper et al., 1994). The rock was originally part of the mantle beneath the island arc. The sample is a stream-rounded boulder that was embedded in calcite cement in an alkaline spring on the river bank (41°51.7’N, 123°57.8’W, elevation 120 m). Seasonal temperature variation is from 2° to 24°C, and annual precipitation is 2.2 m.

Tonga forearc seafloor dunite BMR8-16-1-17. North of New Zealand, between the Tonga Ridge and the Tonga Trench, is a submerged ophiolite sequence (Bloomer et al., 1996). The dunite for this study was collected from the base of this sequence in about 8,000 m of water (17°25’S and 172°24’W). The dunite is most likely part of the island arc basement and about 45 million years old (S.H. Bloomer, personal communication). It was exposed on the seafloor by fracturing of the ocean crust due to sinking of the Pacific Plate into the subduction zone, and once exposed it would have been in continuous contact with sea water.

Martian meteorites. Thirty-five martian meteorites (the SNC meteorites, so named for three type examples, Shergotty, Nakhla, and Chassigny) are known at this time. Thin sections of SNC meteorites (ALHA77005, ALH84001, Chassigny, EETA79001, Lafayette, Los Angeles, MIL03346, Nakhla, NWA 998, QUE94201, Shergotty, and Zagami) were examined for this study. In some cases more than one thin section was studied from a single meteorite. Seven of the SNC meteorites are classified as nakhlites (Table 1) because their mineralogy and composition are similar to those of Nakhla, a meteorite that fell in Egypt in 1911. One feature the nakhlites have in common is the presence of 3–20% olivine that is Fe-rich (Fo15–Fo45) relative to most terrestrial volcanic rocks (Treiman, 2005). Another feature of nakhlites is that they have experienced hydrous alteration and the formation of a secondary mineral assemblage of iron oxides and clays (informally referred to as iddingsite). The iddingsite has been demonstrated to be preterrestrial in origin (Gooding et al., 1991). Nakhla solidified from a magma about 1,300 million years ago, but the alteration appears to have formed more recently (Swindle and Olson, 2004). The previously reported date of a single alteration event for Nakhla of about 620 million years ago (Shih et al., 1998, 1999; Swindle et al., 2000) is not supported by more recent measurements (Swindle and Olson, 2004). New results suggest multiple alteration events occurred on Mars, possibly signaling episodic wetting of Nakhla. In this study, we examined four examples of the nakhlites: Lafayette, MIL03346, Nakhla, and NWA 998, all of which contain aqueous alteration.

Treatment of samples

Previously prepared and new thin sections (30 μm thick) were examined by petrographic microscopy. About 200 thin sections (mostly peridotites) were examined. New singly polished thin sections of R401-2.85 (from Hawaii) were prepared with the low-fluorescence resin EPO-TEK 301-2FL (Epoxy Technology, Billerica, MA) to reduce autofluorescence. Native fluorescence was determined before using fluorescent stains to locate biosynthetic molecules. Previously prepared samples from Oregon, California, and Tonga and from Nakhla were made with standard petrographic thin section epoxy resin.

Thin sections were stained with dyes specific for nucleic acids as described below and examined by epifluorescence microscopy. We used the 4,6-diamidino-2-phenylindole (DAPI) stain on the thin sections from Hawaii (Basalt R401-2.85) and propidium iodide (PI) to stain thin sections of the Oregon dunite (Dunite BM2) and Nakhla. The DAPI stain is distinguishable from olivine autofluorescence and unlikely to give a false-positive (Huber et al., 1985). In addition, native fluorescence of the alteration was determined before staining and found not to be significant. Because PI only stains cells with damaged membranes, it is generally used in combination with other stains to differentiate living from dead cells (Schumann et al., 1994). PI has the advantage of indicating dead bacteria as well as traces of DNA (Schumann et al., 2003). PI has the advantage of indicating dead bacteria as well as traces of DNA (Tobin et al., 1999). However, the disadvantage of using PI is that its potential to bind with minerals has not been systematically studied, and false-positives in samples of mixed mineralogy are possible. As with the DAPI staining, the thin sections were examined with the epifluorescent microscope before staining to determine that no native fluorescence occurred in the regions of interest. Before staining, each petrographic thin section was rinsed with 10 ml of 75% (vol/vol) ethanol and then air-dried in a clean hood for 5 min. Each thin section was then stained with 30 μl of a 1:500 dilution of filter-sterilized (0.2 μm pore size)
0.1% (wt/vol) DAPI or 0.1% (wt/vol) PI, which was dissolved in autoclaved phosphate-buffered saline solution (pH adjusted to 7.4) (Sambrook et al., 1989). To stain microbial cells or cell remnants in channels that intersected fractures in the olivine, DAPI stain was forced into the fractures and pore spaces by cycling the pressure from 1 atmosphere to partial vacuum (3.3 kPa for 2 min) while the samples were submerged in the stain. The thin sections were subsequently incubated with PI at 37°C for 0.5 h. Following incubation, the thin sections were rinsed with repeated washes of 50 ml of filter-sterilized phosphate-buffered saline solution buffer, pH 7.4. During washing, the samples were also cycled to partial vacuum and back to atmospheric pressure to remove unbound stain.

RESULTS

Most of the altered olivine we examined has morphologies that are similar to naturally weathered olivine (Delvigne et al., 1979; Smith et al., 1987). However, in some samples the size, shape, and location of the alteration were different from previously described mineral alteration and were similar to textures typical of biotic weathering found in volcanic glass (Fisk et al., 1998, 2003; Furnes and Staudigel, 1999; Furnes et al., 2001a; Storrie-Lombardi and Fisk, 2004).

Hawaii basalt

All but the shallowest lavas cored at the Hilo, HI site were from horizons that were saturated with fresh or salt water (Thomas et al., 1996). Within the salt water-saturated zone (where sample R401-2.85 was cored) we observed both pristine and partially altered olivine. DNA, amino acids, cells, and novel microorganisms have been found in olivine-bearing samples from the salt water aquifer from this site (Fisk et al., 2003).

Olivine alteration in R401-2.85 was selected for investigation because it is similar in size and distribution to microbially generated tunnels found in volcanic glass. This alteration is illustrated in a transmitted light photomicrograph of the Hawaiian Scientific Drilling Program Core sample R401-2.85 (Fig. 2a). Tunnels 1–3 μm in diameter (Table 2) and up to 100 μm long emerge from some areas of a fracture that contains iddingsite, an oxidized secondary mineral assemblage. The tunnels are curved [some formed spirals and double spirals (Popa et al., 2004b)] and are not confined to crystallographic directions. They also have undulating margins and a limited range of diameters.

In another view of R401-2.85 (Fig. 2b), irregular tunnels 1–3 μm in diameter extend from the fracture into the interior of a single olivine phenocryst. Staining with DAPI (Fig. 2c) indicated that nucleic acids were located at discrete points within the fractures at the approximate location of the tunnel intersections with the fracture. Nucleic acids were not detected inside the tunnels in the olivine, nor was DAPI fluorescence observed in pits in the sample surface that were formed during sample preparation.

Oregon dunite

The exterior of sample BM2 is moderately weathered to a depth of 20 mm, and within this rim much of the olivine has been replaced by a veined network of serpentine (Fig. 3a). The remaining olivine displays either smooth surfaces adjacent to serpentine or surfaces with pitting and embayments (tunnels and galleries). The galleries are 10 μm or less in diameter at the surface of the olivine, extend up to 20 μm into olivine (Table 2), and decrease in diameter with depth into the olivine. The tunnels are about 3 μm in diameter, extend up 20 mm into the olivine, and maintain about the same diameter along their lengths.

Two areas of the BM2 thin section were stained with PI (Fig. 3b). The smooth gallery-free altered surface of olivine between galleries and the surrounding serpentine did not fluoresce in either stained area, but the surface of olivine with galleries fluoresced intensely (Fig. 3b). The interiors of galleries also fluoresced (Fig. 3b). Fluorescing cell-sized rods occurred in some galleries.

California dunite

This dunite (NFSR2) has two sets of crosscutting fractures that contain different minerals (Fig. 4a), which indicates two episodes of fracturing. The first fractures (nearly horizontal in Fig. 4a) are 10–30 μm wide, contain reddish-tan clay (probably a mixture of serpentine and iron oxides), and are rimmed with opaque minerals. The second set of fractures are thin (5 μm) and con-
FIG. 2.  a: Photomicrograph of the interior of an olivine phenocryst in sample R401-2.85 from the Hawaiian Drilling Program hole. b and c: Pair of photomicrographs of a second region of R401-2.85. b: Viewed in plain light (bright-field), the broad dark bands are fractures, and thin tunnels extend from the fractures. c: Same area as (b) viewed with an epifluorescence microscope to show the location of DAPI stain.
**Table 2. Environment and alteration styles of Earth and Mars samples with Category II biosignatures (classification after McKay et al., 2003)**

<table>
<thead>
<tr>
<th>Sample number, sample type, phase</th>
<th>Environment</th>
<th>Contact with water</th>
<th>Temperature (°C) (in situ)</th>
<th>Alterationa</th>
<th>Diameter (μm)</th>
<th>Length (μm)</th>
<th>Biotic confirmationb</th>
<th>Fig</th>
</tr>
</thead>
<tbody>
<tr>
<td>1140A-26-1-84, ocean basalt, glass</td>
<td>Earth, subsurface basalt</td>
<td>Continuous</td>
<td>~5</td>
<td>Small tunnels</td>
<td>1</td>
<td>3</td>
<td>P</td>
<td>1</td>
</tr>
<tr>
<td>R401-2.85, Hawaiian olivine basalt, olivine</td>
<td>Earth, subsurface basalt</td>
<td>Continuous</td>
<td>15</td>
<td>Large tunnels</td>
<td>3</td>
<td>Up to 40</td>
<td>P</td>
<td>2</td>
</tr>
<tr>
<td>BM2, Oregon dunite, olivine</td>
<td>Earth, surface outcrop</td>
<td>Episodic (seasonal)</td>
<td>~6 to 22, freeze-thawing</td>
<td>Galleries</td>
<td>5-10</td>
<td>20</td>
<td>P</td>
<td>2</td>
</tr>
<tr>
<td>NFSR2, California dunite, olivine</td>
<td>Earth, surface outcrop</td>
<td>Continuous</td>
<td>2 to 24, &gt;freezing</td>
<td>Galleries</td>
<td>5-10</td>
<td>20</td>
<td>T</td>
<td>3a,b</td>
</tr>
<tr>
<td>BMRG8-16-1-1, Tonga dunite, olivine</td>
<td>Earth, ocean floor outcrop</td>
<td>Continuous</td>
<td>~2</td>
<td>Tunnels</td>
<td>2-3</td>
<td>20</td>
<td>T</td>
<td>2a</td>
</tr>
<tr>
<td>NMNH 426-7, Nakhla SNC meteorite, olivine</td>
<td>Mars, subsurface</td>
<td>Single event or episodic</td>
<td>?</td>
<td>Tunnels</td>
<td>1</td>
<td>10</td>
<td>N</td>
<td>4b</td>
</tr>
<tr>
<td>NMNH 426-7, Nakhla SNC meteorite, pyroxene</td>
<td>Mars, subsurface</td>
<td>Single event or episodic</td>
<td>?</td>
<td>Tunnels</td>
<td>1-2</td>
<td>10-20</td>
<td>N (NFSR2)</td>
<td>4c</td>
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aWhere two or more alteration styles are present, an alteration diameter and length are given for each style.

bBiotic confirmation indicates whether nucleic acids were found in association with tunnels and galleries: P, yes in previous work; T, yes, this work; I, no but inferred to be biotic based on similarity to samples with confirmed association of DNA and tunnels; N, no confirmation of nucleic acids. For Nakhla the biogenic confirmation lists terrestrial samples with similar alteration morphology.
tain serpentine, Mg₃Si₂O₅(OH)₄. Though tunnels were found to be associated with both sets of fractures, they were much more prevalent along the second stage fractures (Fig. 4a). Here long tunnels (5–15 μm) that are oriented nearly perpendicular to the fractures penetrate the olivine (Fig. 4a). The bases of the tunnels are dark, and some tunnels contain cell-sized objects.

**Tonga forearc dunite**

The dunite from the Tonga forearc (BMRG8-16-1-1) is heavily altered with about 25% of the olivine replaced with serpentine. Along some margins of fractures we observed wide, rounded galleries that extended into the olivine (Fig. 5) and other fractures that are nearly free of embayments.
The martian meteorites Lafayette, MIL03346, Nakhla, and NWA 998

Although four nakhlites were examined, biogenic-like tunnels were found only in olivine and pyroxene in Nakhla (Figs. 3c–g and 4b). In one area of Nakhla, we found thin (1–2 μm) 10-μm-long tunnels with dark interiors that extended from a zone of alteration that contains iddingsite (Fig. 4b). In another area of Nakhla, which includes a pyroxene enclosed by olivine, we found two types of tunnels (Fig. 3c): (1) straight, pointed tunnels (1 μm in diameter and 10 μm long) that protrude from the red alteration zone into the pyroxene; and (2) round tunnels (2 μm in diameter and 20 μm long) that curve from the surface of the thin section down and to the right toward the red alteration zone and a void space that may have contained fluid (Fig. 3c). Figure 3d–g consists of photomicrographs taken with the microscope focused on adjacent planes that are about 2 μm apart. The arrows indicate the same two tunnels at each level in the thin section. Using the narrow depth of field and focusing within the thin section shows that the tunnels curve down and toward the alteration zone. PI staining of Nakhla did not reveal any fluorescence associated with the tunnels or the clays shown in Figs. 3c and 4b.

DISCUSSION

Similarity of olivine and glass alteration

The characteristics of glass alteration that appear to be related to biological activity are: (1) tunnels emerging from the glass–clay boundary; (2) an irregular glass–clay boundary and localized, nonuniform distribution of tunnels along the boundary; (3) numerous tunnels that are of the same size and shape, such as the repeating hourglass undulating walls; (4) uniform tunnel diameter along their lengths; (5) dark mineral precipitates at the glass–clay boundary; (6) organic compounds associated with tunnels; and (7) cell-sized objects in tunnels or at tunnel entrances. These features are in contrast to the smooth (at the 1 μm scale) glass–clay boundary and the absence of tunnels and organic compounds in abiotic alteration [e.g., Fisk et al., 1998 (Fig. 1a), 2003 (Fig. 2c and d)]. We examined olivine and pyroxene from four different terrestrial environments to evaluate the similarities and differences of the morphology of grain boundary alteration with the morphology of putative biotic alteration of volcanic glass.

Hawaiian basalt, R401-2.85. The alteration of olivine phenocrysts in the Hawaiian basalt (Fig. 2) exhibits a number of biotic morphologic features of volcanic glass. The tunnels (center of Fig. 2a) start at a fracture that contains oxidized secondary minerals, and the tunnels cluster along some segments of the fracture and are absent from others. All tunnels have similar diameters and shapes (repeating hourglass shape), and diameters are relatively constant from start to end.

This sample also contains complex organic matter (nucleic acids) at the intersection of the tunnels with the fracture (Fig. 3c), which is the same location as nucleic acids in some basalt glass (Furnes et al., 2001a; Fisk et al., 2003). (Nucleic acids are also found inside tunnels in glass, which is not the case for tunnels in olivine.) The localization of DAPI fluorescence near tunnel entrances and the absence of DNA within the tunnels are consistent with a hypothesis that it would be energetically favorable for microbes to reside outside the tunnels. A microbe positioned at a tunnel opening in an oxidizing environment could exploit the reducing power of Fe(II) released from olivine into the tunnel by chemical or biological weathering.

The energy available from the oxidation of the Fe(II) in 100–200 cell volumes of olivine would support the growth and replication of one cell if one assumes (1) 40% efficiency of the oxidation by oxygen of Fe(II) from typical olivine phenocryst (Fo86) with a cell volume of 0.2 μm³ and (2) that 2–4 kJ are needed to create 1 g of cells. A small tunnel (Fig. 2a) is about 150 cell volumes, so the olivine in the Hawaiian basalt appears to be able to support a small population of microbes. Novel archaea were extracted from one Hawaiian basalt from this site (Fisk et al., 2003). Their metabolic needs, however, are unknown, and their relationship to tunnel formation has not been demonstrated.

Oregon dunite, BM2. Some tunnels in the Oregon dunite (Fig. 3a) have variable diameters (about 3 μm) and are similar in size and shape to the labeled “large tunnels” in glass (Fig. 1 and Table 2). Galleries in BM2 are larger in diameter
FIG. 4.  

(a) NFSR2 

Photomicrograph of a thin section of dunite NFSR2 in plane polarized light. Olivine (white) contains a near vertical fracture from which a high concentration of tunnels extends.

(b) Nakhla 

Reddish iddingsite alteration of olivine in Nakhla photographed in plane polarized light showing fractures filled with iddingsite and tunnels extending from some fractures.
than the tunnels and have irregular walls. The tunnels and galleries are localized along some mineral edges and absent from others, and dark precipitates have formed at the mineral boundary, especially where tunnels and galleries are present. The presence of complex organic compounds as evidenced by PI staining and the location of a cell-sized rod in one gallery (near the tip of the middle arrow in Fig. 3b) are additional similarities between the altered olivine and biotically altered glass.

The absence of fluorescence in the serpentine that surrounds the olivine and along the smooth gallery free margins of olivine (Fig. 3b) indicates that nucleic acids are present only in the vicinity of the galleries, an observation consistent with the hypothesis that biological activity is associated with the formation of galleries. The validity of an alternate hypothesis—that nucleic acids were concentrated at the entrances of abiotically formed galleries—would depend on whether a mechanism exists by which DNA is trapped in the galleries in olivine but not in the porous serpentine that surrounds the olivine.

California dunite, NFSR2. In the California dunite, the different orientation and different minerals filling of the two sets of fractures in NFSR2 suggest that the physical and chemical conditions evolved between the fracturing events. The second set of fractures may have formed in the shallow crust before the rock was eroded from its outcrop along the Smith River, and it is this second set of fractures that exhibits the tunnels with darkened bases. The darkened bases, similar tunnel diameters and lengths, and the distribution of tunnels are attributes similar to those observed in small tunnels in glass (Fig. 1). The NFSR2 tunnels are nearly all parallel to each other, which suggests crystallographic control of their orientation, a feature not common in glass (which is amorphous) or in the Oregon dunite.

The tunnels in Fig. 4a also appear similar to a previously described natural alteration of olivine (Delvigne et al., 1979) in which dark, fine-denticulated shaped invasions of olivine are made of iron oxides and clay. Also, Eggleton (1984) showed 0.1–0.2-μm-wide and 1-μm-long pipe-like channels at the edge of olivine, which are filled with iddingsite. These channels, however, are much smaller than the tunnels in the California dunite. Also, in these two examples, the weathering occurred in nature, so it is not known whether this is bioweathering or abiotic chemical weathering.

Tonga forearc dunite, BMRG-16-1. The galleries that are 5–10 μm in diameter and up to 20 μm deep (Fig. 5 and Table 2) have some similarities to the galleries in volcanic glass (Fig. 1). These similarities include the localized distribution of the galleries along one side of a fracture and their absence on the other side (Fig. 5b), which suggest slight differences in physical or chemical conditions on opposite sides of the fractures. The potential that biological activity was involved in the formation of the galleries also cannot be excluded. The galleries are not constrained to a single orientation, and they all have a similar form and size. They also have about the same diameter from start to end. These galleries are similar to only a few of the tunnels in the Oregon dunite and are unlike tunnels found in the California dunite. These features are also dissimilar to those of naturally altered olivine (Delvigne et al., 1979; Smith et al., 1987) and olivine that was altered via biotic and abiotic mechanisms experimentally (Longazo et al., 2001, 2002; Santelli et al., 2001; Welch and Banfield, 2002). The structures are interpreted as a style of alteration not seen in weathering of olivine on land but may be characteristic of deep sea alteration associated with permanent exposure to seawater.

Nakhla. Four thin sections of Nakhla, along with thin sections of other nakhlites, were thoroughly examined. We only observed, however, the two styles of alteration described here in one thin section (USNM426-7) within a few millimeters of each other. Though rare, these alterations in Nakhla appear similar to alterations seen in terrestrial glass and olivine.

One form of alteration within this small area of USNM426-7 consists of aligned, dark tunnels (1 μm in diameter and up to 10 μm long) that extend into olivine from fractures that contain hydrous alteration (Fig. 4b). The tunnels are localized along some fractures and absent from others, and their diameters are the same as the small tunnels in the glass (Fig. 1). The size, distribution, and dark color of the tunnels are similar to those in the California dunite (NFSR2; Fig. 4a and Table 2). They are different from the tunnels in the basalt glass and NFSR2 in that the bases of the tunnels are not dark. In this sense they are more
like the tunnels in the Hawaiian basalt, which start at a fracture that contains iddingsite (Fig. 2). A similar style of tunnel has been previously described in Nakhlite (Gooding et al., 1991; McKay et al., 2001) and in the nakhlite, Lafayette (Treiman et al., 1993). In Lafayette 0.5-μm-wide veinlets were observed between pyroxene and feldspar (Treiman et al., 1993), and in Nakhlite 0.1-μm-wide elongate masses of smectite were found in olivine (Gooding et al., 1991). The different host mineralogy in the study of Treiman et al. (1993) and the smaller width of the features in the study of Gooding et al. (1991) suggest that these are not the same types of features as the tunnels in Fig. 4b. The features (tunnels) in Nakhlite (Gooding et al., 1991; McKay et al., 2001) are less than 3 μm in length and much smaller than those in Fig. 4b.

The second type of alteration in USNM426-7 consists of two styles of tunnels (Fig. 3c–g). The box (Fig. 3c) encloses 1-μm (10-μm-long tunnels that extend from the red alteration zone into the pyroxene and are similar to those already described in the previous paragraph. Also shown in the box in Fig. 3c is a second style of tunnel (1–2 μm diameter and 20 μm long), which extends from the red zone of alteration into pyroxene. Note that two of these tunnels are traced by arrows at four depths within the thin section. This second style of tunnel is similar to (1) the tunnels observed in the volcanic glass that are hypothesized to be biogenic in origin (Fig. 1), (2) the Hawaiian olivine phenocryst (Fig. 2), and (3) the tunnels at the edge of olivine in the Oregon dunite (Fig. 3a). The similarities include the tunnels starting at the altered surface of the mineral, uniform tunnel diameters along their lengths, smooth and undulating margins, and not being confined to crystal planes. Unlike the tunnels in

**FIG. 5.** Photomicrographs of BMRG8 106-1-17, a dunite from the Tonga Trench in plane polarized light. a: Olivine (light gray) is cut by serpentine-filled fractures up to 50 μm wide. b: Region illustrates the contrast observed between smooth abiotic mineral surface with no galleries and biotic irregular margins that contain galleries.
the glass and the Oregon dunite, these Nakhla tunnels are not darkened where they intersect the red alteration. In this respect, they are similar to the tunnels in the Hawaiian olivine (Fig. 2). The absence of PI fluorescence near Nakhla tunnels indicates no cells or complex cell remnants were associated with them.

Biotic and abiotic production of tunnels

As mentioned above, neither abiotic nor biotic production of tunnels in glass has been demonstrated. In olivine, abiotic alteration has been identified as the cause of some tunnel-like features and tunnel morphology. The experimental conditions of abiotic tunnel formation and the size of these abiotic features, however, indicate that they are not equivalent to the features shown in Figs. 2–5. For example, tunnel-like features were produced by subjecting olivine to stress at temperatures of 1,200–1,400°C (Bai and Kohlstedt, 1992; Tingle et al., 1992). It has not been demonstrated that tunnels can be made at temperatures compatible with the low-temperature hydrous alteration associated with the tunnels in the terrestrial and martian igneous rocks studied here.

Tunnel-like features have also been found in natural and experimentally altered olivine. Pipe-like channels in naturally altered Fo82 (Eggleton, 1984; Banfield et al., 1990) are much smaller than the tunnels observed in olivines we studied. In biotic alteration experiments, where natural fayalite (Fo0) was incubated in sulfuric acid for 8 days in the presence of A. ferrooxidans, it was shown that microorganisms colonized the surface of the olivine but pits were not produced (Santelli et al., 2001; Welch and Banfield, 2002). In abiotic experiments with the same material and experimental conditions, scanning electron microscope images of the surfaces of olivine crystals revealed features that appear to be roughly similar in cross section to the fine tunnels (1 μm in diameter) found in NFSR2. The scanning electron microscope images did not reveal the depth of penetration of tunnels into the olivine or details of tunnel shape within the olivine, so it is difficult to make morphological comparisons with the tunnels characterized in our study by optical microscopy. Although the experimental studies (Santelli et al., 2001; Welch and Banfield, 2002) suggest that an abiotic process could produce tunnels, we propose that their observations are not directly comparable to what has been revealed in our images because of the differences between the conditions of the experiments and the in situ alteration conditions of our samples. Respectively, these differences are: reaction time of 8 days versus years, pH 2 versus 7 or greater, pure iron olivine versus nearly pure magnesium olivine, and a single microorganism (A. ferrooxidans) versus a possible consortium of microbes. At the present time, tunnels such as those found in our samples have not been produced experimentally under conditions similar to the natural environment, and certainly more abiotic and biotic experiments are needed.

Evidence of microbes in terrestrial olivine-rich rocks

At the present time, there is only limited evidence for bioweathering of peridotites. Fractures in completely altered peridotites have been found to contain mineralized filaments that mimic microbial shapes (Milliken, 2001). Also within these rocks the sulfur isotopic ratio ($^{34}$S) of secondary sulfides has been shifted to a value less than that of seawater, which suggests microbial sulfate reduction occurred in the rock (Alt and Shanks, 1998). In another study, nitrifying bacteria that were attributed with causing the dissolution of the host rock were extracted from heavily altered olivine-rich rocks and maintained in pure culture (Lebedeva et al., 1978), though follow-up studies to reproduce bioalteration of the rock were not pursued.

Conditions on Mars

The current surface conditions on Mars are adverse to life as we know it. Because of the low temperature (−121 to −53°C) and atmospheric pressure (0.7–1.0 kPa) (Hess et al., 1976; Owen, 1992; Zurek et al., 1992) only water vapor and ice can exist at the martian surface. Energetic solar and cosmic radiation oxidizes the surface and breaks down organic molecules in the soil. The Viking 1 and 2 instruments with detection limits of about one part in a billion did not detect organic material in the martian soil or evidence of metabolic activity (Biemann et al., 1977; Klein, 1977). Searching for organic biomarker compounds on the surface of Mars is, therefore, likely to be less productive than the microscopic examination of shallow subsurface rocks from Mars.
such as the nakhlites (Treiman, 2005). The discovery of ancient microbial life on Earth (Walter, 1976; Schopf and Packer, 1987) was based on optical light microscope investigations of microbial fossils rather than on the analysis of the chemical composition of microbial- or fossil-like objects. This was possible because of the temporal resilience of morphological biosignatures when compared with chemical biomarkers, which degrade with time.

Claims that the martian meteorite ALH84001 holds signatures of past life on Mars (McKay et al., 1996; Friedmann et al., 2001; Gibson et al., 2001) are based on the presence of polycyclic aromatic hydrocarbons, magnetosomes, a disequilibrium mineral assemblage, chemically zoned carbonates, and microbial fossil-like features observed in scanning electron microscope images. Substantive counter claims have cast doubt on the conclusion of McKay et al. (1996) that fossil life forms are the most likely explanation for this set of observations (e.g., Bradley et al., 1996; Treiman, 1999; Buseck et al., 2001; Golden et al., 2001). The strength of such counter arguments and the apparent absence of extant life on the martian surface do not, however, rule out the existence of life on Mars in a warmer and wetter past, and possibly in the subsurface today.

Trace fossils, though they may be erased by metamorphism, alteration, or erosion, can be preserved for many millions of years. Given that the martian meteorites have experienced very little alteration and metamorphism, they may have preserved evidence of life from a time when liquid water was present in the rocks. In the case of nakhlites, this was less than 1,300 Ma (Swindle and Olson, 2004; Treiman, 2005).

Environmental conditions

The terrestrial samples in this study have experienced different environmental conditions than Nakhl, such as exposure to water, depth of burial, and temperature. Hydrous alteration of the nakhlites probably occurred intermittently after 1,300 Ma (Treiman, 2005), and BM2 was the only sample in our study with intermittent contact with water since the exposure of the outcrop, perhaps 10,000 years ago. Our other three terrestrial samples were exposed to water nearly continuously since their initial contact with water (Table 2). The Hawaiian basalt was submerged in fresh and salt water for most of its 400,000 years. When NFSR2 was last fractured, it was altered by ground water, and once it was exposed at the surface, it could have had nearly constant contact with fresh surface or ground water. Sample BMRG8-16-1-1 was continuously exposed to seawater. So BM2 is our only sample that had intermittent exposure to water as did Nakhl.

BM2 is also the only sample in our study that experienced seasonal and daily freeze–thaw cycles since its exposure at the Earth’s surface. The other three terrestrial rocks in our study were continuously above freezing. Nakhl, however, in its near surface environment may have been exposed to freeze–thaw cycles with seasonally or orbitally forced frequency.

The depth of burial at the time of alteration is different for BM2 and Nakhl. The oxidative bioweathering of BM2 occurred in the outer 2 cm of the rock and at the Earth’s surface. Nakhl, however, was altered in the martian subsurface, probably under low oxygen conditions. However, the two other terrestrial samples with tunnels like those in Nakhl (R401-2.85 and NFSR2) were altered in the subsurface, possibly under conditions with oxygen activity less than that of saturated surface water. Thus although present surface environmental conditions on Mars are different from those on Earth, the alteration of the nakhlites could have occurred at conditions that were similar to the conditions that prevailed when bioweathering occurred in the terrestrial samples in our study. The similarity of alteration styles of some terrestrial samples and Nakhl (whether the alteration is biotic or abiotic) may help to determine the subsurface conditions that Nakhl experienced when it was altered.

Contamination

It is difficult to find a rock on Earth (including meteorites such as Nakhl and those collected in Antarctica) that does not contain evidence of life (Steele et al., 2001; Toporski et al., 2001). Chemical biomarkers detected in meteorites, such as complex organic compounds, cell-like objects, and filaments, are most likely the result of terrestrial contamination. Because life is seemingly ubiquitous on the Earth’s surface, special care must be taken to document that the organic signs of life were present in situ and not introduced during sample collection and processing (Fisk et al., 2003).

Physical biosignatures (trace fossils) such as galleries and tunnels in minerals and glass are
clearly part of the rock matrix and not contamination. Trace fossil formation will cease when the minerals are removed from wet environments and placed in dry storage (as were the samples in this study). Dry storage of samples will also slow chemical alteration except for oxidation. Therefore, the trace fossils we observed in the silicates are not contaminants but were present at the time of collection. Exactly when the tunnels and galleries formed is not known; however, the presence of labile biomarkers such as amino acids in some samples (Fisk et al., 2003) suggests that life was present in some samples in the recent past. The biogenic-like features in Nakhla (Figs. 3c and 4b) represent features that appear to be contemporary with the hydrous alteration on Mars less than 1,300 million years ago.

**Category I, II, and III biosignatures**

Many of the delicate tunnel-like projections found along fractures in terrestrial olivines are different from microfractures and alteration features that follow crystallographic planes in olivine, which have been attributed to abiotic alteration. Santelli et al. (2001) and Welch and Banfield (2002) noted differences and similarities in the style of alteration produced biotically and abiotically, and Longazo et al. (2001, 2002) suggested that differences in the style of olivine alteration may be used to identify biotic alteration on Mars. In this paper, we have demonstrated that there are similarities in the alteration features found in terrestrial samples and those observed in martian samples. In some of our terrestrial samples, the alteration features were associated with biomarkers. We have not demonstrated, however, that microbes produced the tunnels and galleries we observed.

We propose that the presence of tunnels and galleries associated with nucleic acids in terrestrial olivine represents a Category II biosignature (i.e., complex forms that are associated with biomarkers and are not known to be produced by abiotic processes). In addition, we have shown that the galleries and channels of some terrestrial iron-magnesium silicates in basalts and dunites are similar to those found in iron-magnesium silicates in the martian meteorite Nakhla. It is possible that the channels and galleries we observe in olivine and pyroxene are the consequence of abiotic alteration. If these alteration textures can be produced experimentally in the absence of microorganisms, such “biosignatures” would be reclassified as Category III.

**CONCLUSIONS**

We have demonstrated that unusual styles of alteration (linear tunnels and irregular galleries) in olivine in a Hawaiian basalt and two dunites are similar to tunnels and galleries in basalt glass, which are thought to be created by microorganisms. In two cases, tunnels and galleries at the edges of olivine in a Hawaiian olivine basalt (Fig. 2a) and an Oregon dunite BM2 (Fig. 3a) tested positive for the presence of cellular material with DAPI and PI stains just as tunnels and galleries in glass in previous studies tested positive for DNA. This is the first demonstration of the association of nucleic acids with the pitting of olivine in field samples. Biogenicity of the tunnels and galleries has not yet been proven, but on the other hand abiotic mechanisms capable of generating tunnels of similar morphology and size have not been identified. We examined martian meteorites and found that only Nakhla contained tunnels and galleries in iron-magnesium silicate minerals similar in size, shape, and distribution to those found in terrestrial rocks. The evidence presented here is insufficient to claim that the alteration of Nakhla was the result of a biotic process. However, the similar styles of alteration, the potentially similar environments of terrestrial samples and Nakhla, and the presence of nucleic acids in the Earth samples suggest that further examination of such features, in both terrestrial and martian samples, is warranted.

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ABBREVIATIONS

DAPI, 4,6-diamidino-2-phenylindole; PI, propidium iodide; SNC, Shergotty, Nakhl, Chassigny, three type examples of meteorites. NASA Antarctic meteorite sample designations are ALH84001, ALHA77005, EETA79001, and QUE94201; BM2 is Oregon State University Oregon dunite sample designation; BMRG is the Oregon State University Tonga dunite sample designation; NMNH is the Smithsonian sample designation; NFSR2 is the Oregon State University California dunite sample designation; and NWA is the northwest Africa meteorite designation.

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