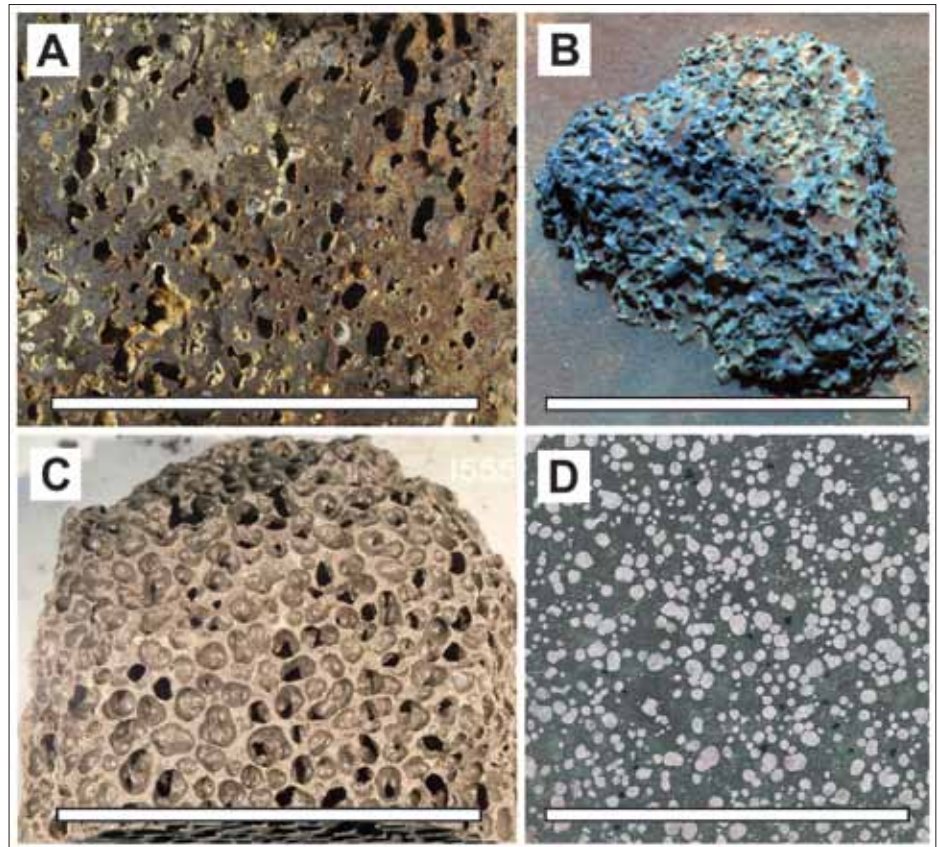


The habitability of vesicles in martian basalt

Sean McMahon, John Parnell
Joanna Ponicka, Malcolm Hole
and Adrian Boyce argue that
cavities in martian volcanic
rocks are a good place to look for
microbial life on Mars.

Several arguments suggest that the most hospitable environments for life on present-day Mars are likely to occur in the subsurface. In order to colonize any environment, microbes need a combination of tolerable pressure and temperature, nutrients, energy sources, space for growth, and at least small amounts of liquid water. Liquid water is thermodynamically unstable at the low temperatures (mean ~210 K) and pressures (mean ~0.6 kPa) on the surface of Mars, but could be present or even abundant at the higher temperatures and pressures below the cryosphere (e.g. Clifford *et al.* 2010). The subsurface is also protected from the high surface doses of sterilizing cosmic and solar radiation (e.g. Dartnell *et al.* 2007) and from oxidants likely to destroy biomolecules (Benner *et al.* 2000). Finally, rocks and their reactions with circulating water in the subsurface could provide a broad palette of metabolic substrates and essential nutrients (Boston *et al.* 1992, Fisk and Giovanoni 1999). Geologically recent microbial activity in this habitat could have produced distinctive fossils and biosignatures, which may be available for sampling on the surface.

Speculation about a deep biosphere on Mars has been encouraged by evidence of active microbial populations in diverse environments several kilometres below the Earth's surface. Endoliths (organisms that live in rock) have been found in continental aquifers up to 5.3 km deep (Szewzyk *et al.* 1994), in oil and gas reservoirs up to 2.8 km deep (Onstott *et al.* 1998), in marine sediments up to 1.6 km below a 4.5 km-deep seafloor (Roussel *et al.* 2008), and in the rocky basement of the oceanic crust up to 1.3 km below a 1.6 km-deep seafloor (Mason *et al.* 2010). The sub-seafloor biosphere has been extensively sampled over many decades by the International Ocean Drilling Programme and its predecessors. Sub-seafloor microbes are metabolically diverse; among the more abundant groups are autotrophic and heterotrophic methanogens, acetogens, aerobic and anaerobic



1: Basalt from Earth, Mars and the Moon containing vesicles – frozen-in bubbles. Vesicular basalt has a high internal surface area where microbes can live, a high porosity and permeability for fluid and cell transport, and a high compressive strength, allowing vesicles to remain open at great depths. (a) Sample from a lava flow in the Columbia River Basalt, a continental flood basalt province in the USA. Some vesicles are lined or partially filled by zeolite minerals. (Sample courtesy of A Ebinghaus) (b) Vesicular basalt *in situ* on Mars, photographed in false colour by Spirit in Gusev Crater. Vesicles may have been enlarged by wind abrasion. Scale bar ~20 cm (McSween 2009). (NASA/JPL-Caltech) (c) Lunar basalt sample 15556, collected by Apollo 15 astronauts. Scale bar ~6 cm. (NASA) (d) Section through formerly vesicular Ordovician basalt in which percolating fluids have precipitated secondary carbonates, forming amygdales. Sgavoch Rock, Ayrshire, Scotland. Scale bar ~4 cm.

methane-oxidizers, sulphate-reducing bacteria and nitrate-reducing bacteria. Fossilized fungi have also been discovered at two locations in the Pacific crust, respectively 51 m and 150 m below the seafloor under a ~5 km water column (Schumann *et al.* 2004, Ivarsson *et al.* 2012).

Why basalt is good for life on Earth

Much of the Earth's deep biosphere occupies pores and fractures in the fine-grained volcanic rock basalt, which is compositionally the dominant rock type on the surface of Earth and on Mars (Taylor and McLennan 2009). Basalt offers several advantages for endolithic life. It is a ready source of redox couples for metabolism, and typically contains elemental macronutrients in sufficient abundance to support millions of

cells per gram of rock (Fisk and Giovanoni 1999, Bailey *et al.* 2009). Moreover, basaltic facies commonly offer a high porosity and internal surface area for biological colonization, and a high permeability for fluid migration.

Endolithic microorganisms with diverse modes of life have apparently populated basalts since the Archaean (Furnes *et al.* 2004). In the terminology of Golubic *et al.* (1981), *euendoliths* bore into basaltic glass, *chasmoendoliths* populate fractures, and *cryptoendoliths* occupy vesicles (gas bubbles commonly pervasive in basaltic glass) and other primary pores. Euendoliths are postulated to have produced microtubular cavities that may count among the earliest evidence of life on Earth (Furnes *et al.* 2004), although their biogenicity may

reasonably be doubted (Brasier *et al.* 2006, McLoughlin *et al.* 2007). Multi-micron-scale filamentous and coccoidal structures have been reported from secondary minerals filling vesicles and fractures, and have been interpreted as fossilized chasmoendoliths and cryptoendoliths, including fungi as well as prokaryotes (e.g. McKinley *et al.* 2000, Hofmann *et al.* 2008, Schumann *et al.* 2004, Ivarsson *et al.* 2012).

In our solar system, basalt is a major component of the surfaces of Mercury, Venus, Io, the Moon, Vesta and some smaller asteroids as well as the Earth and Mars (Moskovitz *et al.* 2008, Wilson 2009). It is probably abundant on silicate planets and moons throughout the universe; the formation of a basaltic “secondary crust” is thought to be an important early heat-loss mechanism for rocky planets following the formation of the “primary crust” by initial differentiation (Taylor 1989). To a first approximation, the surface of Mars reveals a “basaltic planet” (Taylor and McLennan 2009); the southern highlands appear to consist mostly of basalt erupted between ~3 and ~4 Gyrs ago, while the northern lowlands were resurfaced less than ~3 Gyrs ago with either basaltic andesite (a slightly more silicic rock) or basalt that subsequently weathered (Wyatt and McSween 2002). Large regions of alkaline lavas and smaller areas of more differentiated volcanics have also been identified (Taylor and McLennan 2009). There is evidence of continued volcanism on a small-scale until the late Amazonian, and perhaps as recently as 2 million years ago (e.g. Werner 2009, Neukum *et al.* 2004).

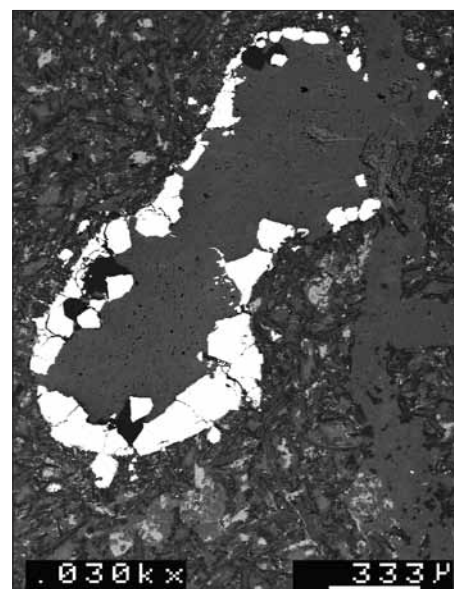
Basalt is widely discussed as a potential substrate for a present-day deep martian biosphere (e.g. Boston *et al.* 1992, Stevens and McKinley 1995, Fisk and Giovannoni 1999, Cousins and Crawford 2011). However, given the prevalence of basalt in the martian crust and the limited capacity for sample return or *in situ* analysis, it is necessary to focus the search for recent life more narrowly. Vesicles in basalt and other igneous rocks are frozen-in bubbles formed by the exsolution of supersaturated volatiles, primarily H₂O and CO₂. Vesicular basalt combines a high internal surface area for microbial colonization, a high porosity and permeability for subsurface fluid and cell transport, and a high compressive strength, allowing vesicles to remain open at greater depths than pores in sedimentary rocks. Biosignatures in volcanic vesicles on Earth have previously encouraged suggestions that they could provide evidence of past life on Mars (e.g. Hofmann *et al.* 2008, Farmer *et al.* 2011). This paper argues that any present-day martian deep biosphere is likely to occupy basalt vesicles, and that mineralized vesicles in basalt exhumed from deep settings should be a preferred target in the search for evidence of geologically recent life on Mars.

Vesicles in basalt

Vesicles in basalt may be interconnected or isolated, spherical or irregular, equant or elongate, and sometimes show preferred orientations. The size and abundance of vesicles depends on many factors, including the composition of the melt and the style of the volcanic activity.

Vesicles generally occur more abundantly at the margins of lava flows than in their centres. Although flow morphology and internal structure can vary widely between different styles of eruption and emplacement, Self (1997) found that lava flows in the Columbia River Basalt (CRB) of the Western USA (figure 1a) – probably the best-studied of Earth’s continental flood basalt (CFB) provinces – commonly share a tripartite internal structure with flows in Hawaii, Iceland, the Deccan Traps (a CFB in India), and elsewhere. In Self’s (1997) terminology, this structure comprises an upper crust (40–50% of flow thickness), a lava core (40–60% flow thickness) and a smaller basal zone (<1 m thick in the CRB). The upper crust, having cooled relatively rapidly in air, is somewhat glassy and highly vesicular, with vesicularity decreasing and vesicle size increasing from the top of the flow downwards. Superimposed on this pattern are thin horizontal sheets of vesicles. The upper crust is irregularly jointed at the flow top, with longer cooling joints lower down. The lava core contains more regular cooling joints which may outline large polygonal columns. This layer cooled more slowly and so is dominantly crystalline with very few vesicles, although large (5–30 cm) cavities can form when gas is trapped below the earlier-solidifying upper crust. The basal zone is mostly glassy with sparse vesicles that become more abundant towards the base of the flow. Meteoroid impacts can also generate vesicles in shocked target rocks. Although negligible on Earth, this may be a significant source of vesicular glass on the present-day surface of Mars (Fike 2003, Schultz and Mustard 2004).

Once cooled, vesicles provide surfaces, transport conduits, and habitable pore space for colonization by crypto- and euendolithic organisms. Vesicles in sub-seafloor basalts host both prokaryotes and eukaryotes (e.g. Schumann *et al.* 2004). Studies of subaerially exposed vesicular basalts have also shown bacteria adhering to vesicle walls and infilling vesicle space (Holman *et al.* 1998, Cockell *et al.* 2009). The terrestrial record of basalt vesicle-colonization reaches back at least to the Devonian (Peckmann *et al.* 2008) and includes probable filamentous fossils in mineralized vesicles (Hofmann *et al.* 2008, Peckmann *et al.* 2008) and microtubules propagating radially into vesicle walls, which are suggested to represent euendolithic borings (Furnes *et al.* 2007, Cousins *et al.* 2009). In both ancient and modern basalts, isotopes of carbon and sulphur in vesicle-filling carbonates and sulphides (e.g. figure 2) respectively show evidence



2: Biologically processed sulphide in an ancient basalt vesicle. Pyrite (white) in this Ordovician basalt vesicle from Noblehouse, near Edinburgh, UK, has a biogenically light sulphur isotope composition. SEM image with enhanced contrast. Empty vesicles are uniform grey; basalt groundmass is cross-hatched by crystals. Note 333 μm scale bar.

of biological fractionation (Krouse *et al.* 1977, Demény and Harangi 1996, Rouxel *et al.* 2008). Vesicle-lining clays in ~1 km-deep Hawaiian basalt have yielded a range of biosignatures including RNA, DNA, microtubules and high phosphorus concentrations (Fisk *et al.* 2003).

Vesicular basalts are expected to be common in the solar system and have been photographed on Mars and collected by astronauts from the Moon (figure 1b, c). Their presence has been inferred on Venus from radio and thermal emission data (Bondarenko 2010). Meteorites derived from Vesta also show a vesicular texture believed to have formed deep within the asteroid (McCoy *et al.* 2006). On Mars, both Viking 2 and Pathfinder photographed pitted rocks interpreted as vesicular (Mutch *et al.* 1977, McSween *et al.* 1999). Spirit encountered several clear and distinct vesicular textures in lava in the Gusev crater (figure 1b), some of them extremely vesicular (McSween *et al.* 2004, McSween 2009).

The lower and upper margins of martian lava flows are expected to contain vesicular zones like those found on Earth, although they should be somewhat thinner because of the difference in atmospheric pressure (Crumpler *et al.* 2002). Successive ancient lava flows have formed deep accumulations of layered basalt on Mars, particularly in the large equatorial volcanic region, Tharsis. Layered rocks in the walls of the Valles Marineris rift system have been interpreted as Late Noachian (~4 Ga) flood basalts (McEwen *et al.* 1999) although they may include sedimentary strata (Malin and Edgett 2000) and layered intrusions (Williams *et al.* 2003). The rift exposes a cumulative thickness of “at least

8 km” (McEwen *et al.* 1999), which is similar to the average thickness of the Earth’s oceanic crust. The lateral extent of these Late Noachian flows is unknown. The northern lowlands were formed ~3.5 Ga when another 0.8–1 km of lava flows resurfaced heavily cratered basaltic Noachian basement (Head *et al.* 2002).

Besides layered flows, the interaction of erupting lava with the ancient martian cryosphere and hydrosphere may also have produced vesicular pillows and hyaloclastite breccias similar to those formed by submarine and englacial eruptions on Earth; many geomorphological features on Mars have been identified that closely resemble the results of volcano–ice interaction on Earth, although pillow basalts have yet to be identified on Mars (see Cousins and Crawford 2011 for review). On Earth, emergent and extrusive styles of glaciovolcanism commonly produce highly vesicular glass, e.g. in Antarctica (Smellie and Hole 1997), Iceland (Steinthorsson *et al.* 2000) and Canada (Edwards and Russell 2002).

Aquifers in vesicular basalt

Internal heat is likely to maintain liquid water below the martian cryosphere (Clifford *et al.* 2010), although the abundance and distribution of this water have yet to be determined. On Earth, organisms in pores and fractures in oceanic basalt and deep basalt aquifers are supplied with nutrients and energy sources by low rates of water circulation and attendant geochemical reactions; hydrothermal systems in the flanks of mid-ocean ridges circulate ocean water under an area exceeding 50% of the seafloor (Huber *et al.* 2006). Analogous environments on Mars could be similarly replenished by groundwater convection if liquid water is stable at depths where sufficient porosity, permeability, and hydraulic connectivity are available (Boston *et al.* 1992, Travis *et al.* 2003).

The average geothermal gradient (rate of temperature increase with depth) can be approximated by the ratio of the average heat flux, q , through the martian surface to its average thermal conductivity, K . K is temperature-dependent; the average value for basalt in the temperature range 210 K (the average surface temperature of Mars) to 263 K (a hypothetical “average Mars salinity” freezing point of water) is close to $2.5 \text{ W m}^{-1} \text{ K}^{-1}$ (Clifford *et al.* 2010). Estimates for martian average q range from 0.015 to 0.040 W m^{-2} (Travis *et al.* 2003, Zegers *et al.* 2010). These estimates place the average global thickness of the cryosphere between 3.3 and 8.8 km. Regional variations of several kilometres are expected with latitude, crustal composition and structure, and heat flux (Travis *et al.* 2003, Clifford *et al.* 2010). The water table should lie directly below the cryosphere or several kilometres below it depending on the size of the inventory (Clifford 1993).

In some places, convection should allow liq-

uid water to be stable at much shallower depths than predicted by this simple one-dimensional conductive model. Travis *et al.* (2003) found that convection cells driven solely by the background geothermal gradient could bring liquid water within 0.3 km of the surface of Mars in local upwellings on roughly million-year timescales. Local magmatic intrusions could also drive convecting plumes but the Mars Odyssey thermal emission survey (THEMIS) found no evidence of local magmatically elevated temperatures (Christensen *et al.* 2003).

Highly porous basalts have a lower thermal conductivity and hence a higher rate of temperature increase with depth, favouring shallower aquifers. Empirical measurements at 2 kbar and 35 °C show that a water- or air-saturated basalt with a bulk porosity of 75% has a thermal conductivity about $\frac{2}{3}$ that of a basalt with a bulk porosity of 50%, which would correspond to a proportional increase in geothermal gradient (Robertson and Peck 1974). Thus, highly vesicular or otherwise porous rock sequences should be expected to maintain shallower aquifers than less porous rocks. Clifford *et al.* (2010) also observe that gas hydrates are thermodynamically stable in martian subsurface conditions and would further lower the average thermal conductivity if present in pore spaces.

On the whole, it appears likely that water tables should reach within 8 km of much of the martian surface, i.e. within the range of depths where flood basalts have so far been tentatively identified (McEwen *et al.* 1999). The maximum thickness of these putative aquifers is a vexed question, with estimates ranging up to 20 km (Hanna and Phillips 2005). On Earth, uncompacted vesicular basalts typically have porosities up to 75% and permeabilities of 10^{-14} to 10^{-10} m^2 (Freeze and Cherry 1979, Al-Harthi *et al.* 1999, Saar and Manga 1999, Petford 2003). In any type of rock, however, porosity and permeability decrease with depth because of elastic compaction under lithostatic pressure. The greater compressive strength of igneous rocks means that their high porosity and permeability can be preserved during burial while sedimentary rocks become compacted (Petford 2003). Consequently, vesicular basalts make good aquifers (e.g. Kulkarni *et al.* 2000, Russell and Rodgers 1977). However, controls on the depth at which pore closure blocks basalt aquifers are poorly understood. Vesicles in basalt on Earth can remain open down to at least 1.7 km (Dannowski and Huenges 2002), corresponding to an overburden pressure that would be encountered at ~4.5 km on Mars. Elastic compaction, however, is not the only process involved in pore closure. Pressure solution gradually dissolves minerals from grain contacts, which re-precipitate in less stressed cavities. Hydrothermal circulation also fills fractures and vesicles with secondary miner-

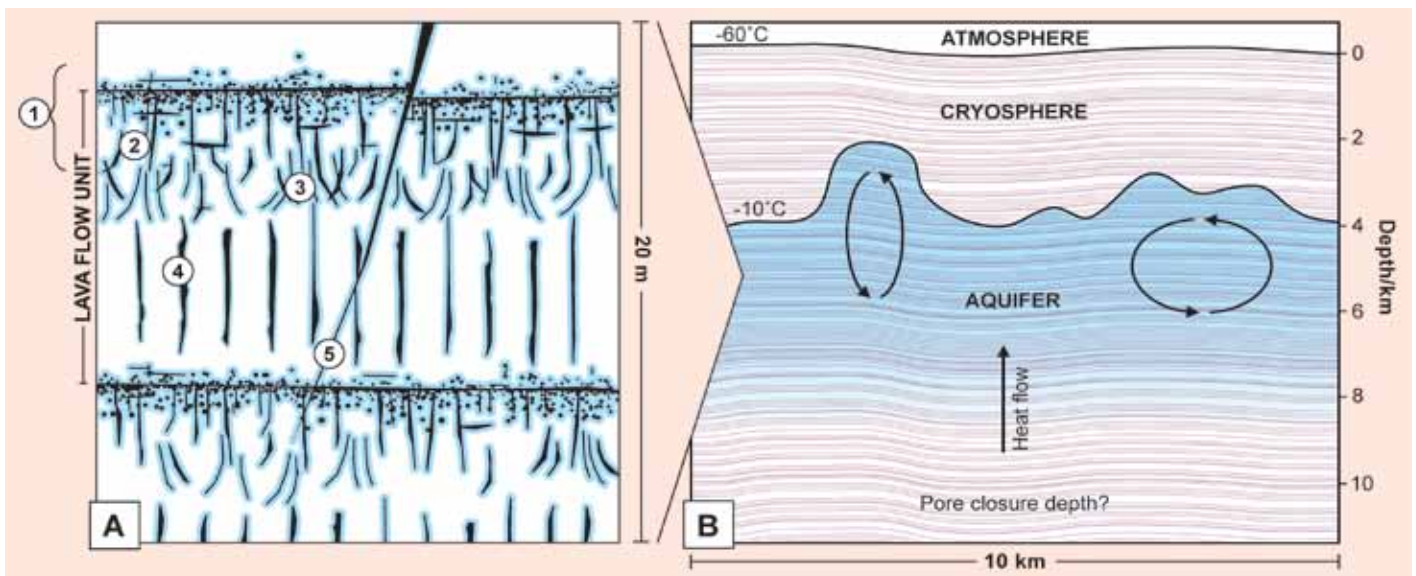
als (chiefly calcite, quartz, chalcedony, clays and zeolites) precipitated progressively over millions of years. As a result, “younger basalts are more likely to host ... unfilled vesicles than older ones” (Helm-Clark *et al.* 2004), although it is unclear whether all vesicles through which hydrothermal fluids migrate are eventually occluded in this way. High pressure at depth favours the dissolution of vesicle-fills, creating secondary porosity. The Deep Sea Drilling Programme has sampled Early Cretaceous vesicular basalts containing vesicles both partially filled and unfilled despite, presumably, 120 million years of continuous hydrothermal circulation (Donnelly *et al.* 1977).

The Columbia River Basalt contains regionally important aquifers known to support anaerobic lithotrophic microorganisms (e.g. Stevens and McKinley 1995). The CRB comprises more than 300 individual lava flows erupted between 17 and 6 Ma, stacking up to a maximum of ~4 km in thickness and thinning outwards to cover a total area of $\sim 1.6 \times 10^5 \text{ km}^2$ (Tolan *et al.* 1989, McGrail *et al.* 2006). Flow units range from ~0.1 to 100 m thick, and average about 30 m (Hansen *et al.* 1994). The sparsely fractured interiors of the flows tend to serve as impermeable caps, confining groundwater to the vesicular and sometimes rubbly margins of adjacent flows (interflow zones), although vertical cooling joints allow limited fluid migration (Gégo *et al.* 2002, McGrail *et al.* 2006). Columnar cooling joints have also been observed in flood basalts on Mars (Milazzo *et al.* 2009), where additional hydraulic connectivity between interflow zones may be available from impact fractures in the heavily cratered crust.

Pillowed glaciovolcanic and hydrovolcanic basalt deposits are less well stratified than trap lavas but can contain rubbly horizons and metre-scale internal voids that might also represent locally important conduits, when buried, for subsurface fluids on Mars (e.g. Graettinger *et al.* 2012). The fact that isolated vesicles in unfractured basalt are often filled by secondary minerals (forming amygdalae, figure 1d) suggests that the permeability of basaltic groundmass is also slightly above zero. Major sources of porosity and permeability in a hypothetical martian layered basalt aquifer are summarized in figure 3.

Habitability of martian vesicular basalt

A broadly consistent general model for a present-day martian deep biosphere has emerged over the past two decades (e.g. Boston *et al.* 1992, Fisk and Giovanonni 1999, Parnell *et al.* 2010). In this scenario, water maintained by geothermal heat and replenished by melting ice supports chemoautolithotrophic endoliths in pores and fissures, which use locally favourable redox reactions to fix inorganic carbon anaerobically. Nutrients and redox couples are provided by water–rock reactions, magmatic



3: Water in layered basalt aquifers. (Left): Schematic cross-section through lava flows showing subsurface water, with (1) highly permeable interflow zone of vesicular glass and rubble; (2) vesicular flow top (vesicles sizes exaggerated); (3) curved interior cooling joints (entablature); (4) columnar cooling joints; (5) faults and fractures. (Right): Proposed aquifers in martian basalt. Saline liquid water is stable below the depth where the temperature exceeds freezing point. The depth of the aquifer top varies with variations in local heat flux and convection cells (Travis *et al.* 2003). Porosity decreases with depth.

outgassing, downward transport of atmospheric oxidants and/or other geochemical or geobiological processes, and circulated hydrothermally through the crust. This scenario is consistent with current knowledge of Mars and the terrestrial deep biosphere.

Several mechanisms plausibly generate H_2 , a powerful electron donor, in the martian subsurface. H_2 produced by the low-temperature hydration of olivine and pyroxene (serpentinization) appears to drive primary productivity (e.g. methanogenesis) in terrestrial basalt aquifers (Stevens and McKinley 1995, 2000, although Anderson *et al.* 1998 take an opposing view) and possibly some parts of the sub-seafloor biosphere (e.g. Hellevang 2008). Reactive surface area is an important control on the rate of H_2 -production by water-rock reactions, which ought therefore to be higher in more vesicular or otherwise porous rocks. Both methanogenesis and serpentinization have been proposed to account for martian atmospheric methane (Formisano *et al.* 2004, Krasnopolsky *et al.* 2004, Mumma *et al.* 2009). One alternative is magmatism-related hydrothermal activity, which would also entail the production of H_2 (Lyons *et al.* 2005). H_2 can also be produced in biologically significant quantities by the radiolysis of water and by earthquake-induced frictional grinding of silicate rocks (Lin *et al.* 2005, Hirose *et al.* 2011). Other electron donors on Mars could include Fe(II) and Mg(II) abundant within basalt itself (e.g. Popa *et al.* 2012).

Electron acceptors could be indigenous to the basalt (e.g. Bailey *et al.* 2009) or transported from nearer Mars's oxidizing surface, e.g. SO_4^{2-} , NO_3^- , ClO_4^- , photochemically produced superoxides, and indeed CO_2 , which constitutes over 95% of the martian atmosphere and is also a common product of subsurface geochemical

reactions. Macronutrients (C, H, N, O, P, S) are also available directly from basalt, typically in sufficient abundance to support $\sim 10^6$ cells per gram, with P limiting (Fisk and Giovanonni 1999).

Habitable environments are not necessarily inhabited. Even if microbes once occupied porous rocks on Mars, they could have been driven to extinction by the occlusion of local pore space by secondary minerals; by shutdown of local hydrothermal circulation caused by changes in heat flux, venting of water to the atmosphere or redistribution of water away from old, mineralizing fractures and along sterile new ones without accompanying transport of cells; or by local chemical equilibration, which is accelerated by microbial metabolic activity. Nevertheless, the general scenario outlined above provides a plausible account of how a martian biosphere could have survived after the surface became uninhabitable. If this scenario is correct, we suggest that water, nutrients, redox reactants and microbial cells should be preferentially transported and concentrated in the highly porous and permeable vesicular interflow zones of layered flood basalts and perhaps also in the pillowed and brecciated intervals of less stratified glacio/hydrovolcanic deposits. Thus, if present, a high proportion of any present-day or geologically recent martian subsurface biosphere should reside in basalt vesicles.

Sampling and astrobiological analysis of vesicular basalt

Sedimentary rocks laid down in the early warm, wet phase of martian history have traditionally been emphasized as good targets for astrobiological research, representing a plausible habitat with high preservation potential. Drilling deeply enough to sample deep aquifers on

Mars for present-day life is not feasible in the near future, although a mission scenario has been described in detail (Mancinelli 2000). It has also been proposed that relatively young hydrothermal minerals and serpentinites might host fossil and chemical evidence of a geologically recent deep biosphere (Parnell *et al.* 2010). The scenario discussed above predicts that several kinds of evidence for geologically recent life might be available in vesicular basalts now exposed at the martian surface, especially amygdaloidal basalts (those with mineral-filled vesicles) excavated from deep settings by rifting, erosion, or impact cratering.

Over 90% of loose rocks at Viking 2's Early Amazonian landing site show heavily pitted textures tentatively identified as vesicular (Mutch *et al.* 1977). Pathfinder also photographed vesicular rocks at its landing site on a Late Hesperian plain (McSween *et al.* 1999). Spirit encountered several clear vesicular textures in lava in the (Hesperian) Gusev Crater, some of them extremely vesicular, and a few containing possible amygdaloids and veins (figure 1b; McSween *et al.* 2004, McSween 2009). At least some of the blocks at these sites may be crater ejecta with impact-generated vesicles, rather than unshocked basalts with volcanic vesicles (Schultz and Mustard 2004).

Amygdaloidal basalt would provide an ideal target for *in situ* microscopy and chemical/isotopic analysis, and indeed for sample return. By analogy with similar rocks on Earth, amygdaloidal basalt is likely to have occupied a habitable subsurface environment and could contain a wide variety of signatures of past life:

- **Morphological fossils.** A range of minerals have been found to preserve multi- μm -scale spherical and tubular/filamentous structures believed to be morphological fossils of

prokaryotic and fungal cells in basalt amygdaloids and veins, including silica, sulphides, clays, carbonates and zeolite (McKinley *et al.* 2000, Schumann *et al.* 2004, Cavalazzi *et al.* 2011). However, abiotic mechanisms can produce similar structures (e.g. ambient inclusion trails; Lepot *et al.* 2011). Therefore, candidate microbial morphologies should be assessed against a range of criteria for biogenicity, including geological evidence for a habitable mineralizing environment, consistently microbe-like shapes, sizes and size distributions, association with carbonaceous matter and elevated nutrient concentrations, and other chemical and isotopic signatures of life; similar criteria are employed in verifying microbial fossils on Earth (e.g. Brasier *et al.* 2006).

● **Biogenic isotope compositions.** On Earth, vesicle-filling carbonates and sulphides (both ancient and modern) often show distinctively biogenic carbon and sulphur isotope compositions respectively, which might reflect either *in situ* microbial activity or the infiltration of fluid with a biogenic component (Demény and Harangi 1996, Krouse *et al.* 1977, Rouxel *et al.* 2008; figure 2). Nitrogen in whole-rock analyses of sub-seafloor basalt also shows a biogenic fractionation (Bebout *et al.* 2011). Although there are uncertainties about martian element cycling, strong isotopic fractionations in vesicles, especially if associated with elevated abundances of phosphorus, nitrogen, organic compounds, or other biosignatures, may record microbial activity in the habitat discussed here.

● **Bio-alteration textures.** Vesicle and fracture walls should also be imaged at the micron scale for the putatively biogenic tubular and granular alteration textures that have been observed in sub-seafloor, ocean-island and subglacial basalts on Earth (Thorseth *et al.* 1992, Fisk *et al.* 2003, Furnes *et al.* 2007). As with microbial body fossils, the possibility that candidate textures are abiogenic must be carefully considered (e.g. McLoughlin *et al.* 2007). Moreover, it remains unclear how, why, by which biota and in which optimal environmental conditions these structures are produced. Cousins *et al.* (2009) show that these textures are less abundant – though not absent – in lavas through which glacial meltwaters rather than seawater percolate, perhaps because of lower nutrient availability. These textures have yet to be described from continental aquifer basalts. They have, however, been identified in a Nakhla martian meteorite (Fisk *et al.* 2006), although here the evidence is insufficient to demonstrate biogenicity.

Conclusions

A subsurface martian biosphere, if present, is likely to be concentrated in pores and fissures at depths where temperatures and pressures permit liquid water to circulate. A review of the relevant literature suggests that highly vesicular

basalts provide a more likely substrate for such a habitat than sedimentary rocks and non-vesicular basalts and should be a preferred target in the search for life on Mars. In summary: (1) vesicular basalt is likely to be common in the depth range of liquid water stability on Mars; (2) vesicular basalt commonly occurs in laterally extensive layers suitable for sustaining aquifers; (3) vesicular basalt has a higher porosity and permeability than non-vesicular basalt, favouring fluid and cell transport; (4) vesicular basalt has a higher compressive strength than similarly porous sedimentary rocks, allowing pores to remain open at greater burial depths; (5) basalt vesicles provide a high surface area for microbial colonization and water–rock reactions. ●

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