Volcano–ice interaction:

The interaction between volcanism and ice on Earth provides numerous habitats for exploitation by microbial life – and may have created potential islandsof habitability on Mars, argues Claire Cousins.

The search for life on Mars is inherently rooted in our understanding of life and environments here on Earth. As the only currently known planet inhabited by what we identify as modern day biology, life on Earth provides us with the blueprint on which we can base the search for life elsewhere. A major avenue of this terrestrial-based research has been the investigation into environments believed to be analogous to either past or present environments on Mars. These environments are wide-ranging, both in scale and physicochemical conditions, and provide us with a natural laboratory within which to understand the biological processes that may have once operated on Mars. Crucially, we can find out how life within these environments not only survives, but also how it changes the environment itself – producing biosignatures within the rock record.

Mars, like the Earth, has a geologically diverse terrain, suggesting the planet was once much more dynamic and active than its current quiet state. The original view of Mars as a vast windswept and pock-marked terrain has been comprehensively swept aside as orbital and *in situ* data gathered during the past decade have revealed complex valley networks, past hydrothermal activity, delta plains, and evidence of glaciological processes. Likewise, orbital hyperspectral data from OMEGA and CRISM have shown Mars also to be mineralogically diverse, highlighting the potential for a wide range of palaeoenvironments – some of which may well have once been habitable.

Analogue environments

There are many well-studied and valuable analogue terrains within the context of searching for life on Mars. Environments such as the Atacama Desert (Navarro-Gonzalez *et al.* 2003), Antarctic Dry Valleys (Wierzchos *et al.* 2005), acid mine drainage sites (Amils *et al.* 2007), and evaporites (Rothschild 1990) have all been found to host a resilient array of microbial life. In particular, life in such extreme environments is closely associated with the local geology, an interaction that is not only directly related to metabolism and survival, but also fundamental to the production of biosignatures. For example, the UV-shielding properties of gypsum crystals at the Haughton impact crater are used by photosynthetic bacteria, which in turn alter the local geochemistry of the mineral deposits by their activity (Cockell *et al.* 2010). Similar examples can be found in the Antarctic Dry Valleys, where the cold, desiccating winds are avoided by microorganisms who seek refuge within porous rock substrates, and at acid mine drainage sites where redox coupling between iron and sulphur drive bacterial metabolisms (Amils *et al.* 2007). While all these environments are relatively clement in comparison to present-day conditions on Mars, there is the distinct possibility that past climatic and geological conditions here allowed the formation of such environments, and it is therefore imperative to understand the geobiological processes that take place within these systems on Earth.

Mars is predominantly volcanic, and it is widely observed that a continuous global cryosphere has been present for much of its history, with the vast majority of water currently frozen at the poles (Clifford 1993, Hvidberg 2005). The past interaction between this cryosphere and volcanic activity may have produced a variety of habitable environments (Schulze-Makuch *et al.* 2007), the deposits of which could be suitable targets in the search for martian life (Boston *et al.* 1992, Hovius *et al.* 2008).

Volcano–ice interaction

The interaction between volcanic activity and ice can manifest itself in many forms, and ranges from the flow of lava over ice-rich ground, to the production of whole volcanic edifices beneath a glacier. These volcanic edifices can be built entirely subglacially within a zone of meltwater above the eruption site (figure 1a). Alternatively, where the eruption is long-sustained or the ice thinner, the continual transference of geothermal heat will eventually melt the ice, resulting in a subaerial eruption. In these cases, basaltic volcanic edifices typically display a sequence of basal pillow lavas, overlain by volcaniclastic deposits (e.g. hyaloclastite, hyalotuff) as the eruption becomes more explosive due to reduced overlying pressure from the glacier (Jakobsson and Gudmundsson 2008). Where the edifice has emerged completely through the ice, it will often be capped by horizontal subaerial lavas (see figure 1b). Examples of such past and present volcano–ice interaction can be found in places such as Iceland, British Columbia and Antarctica.

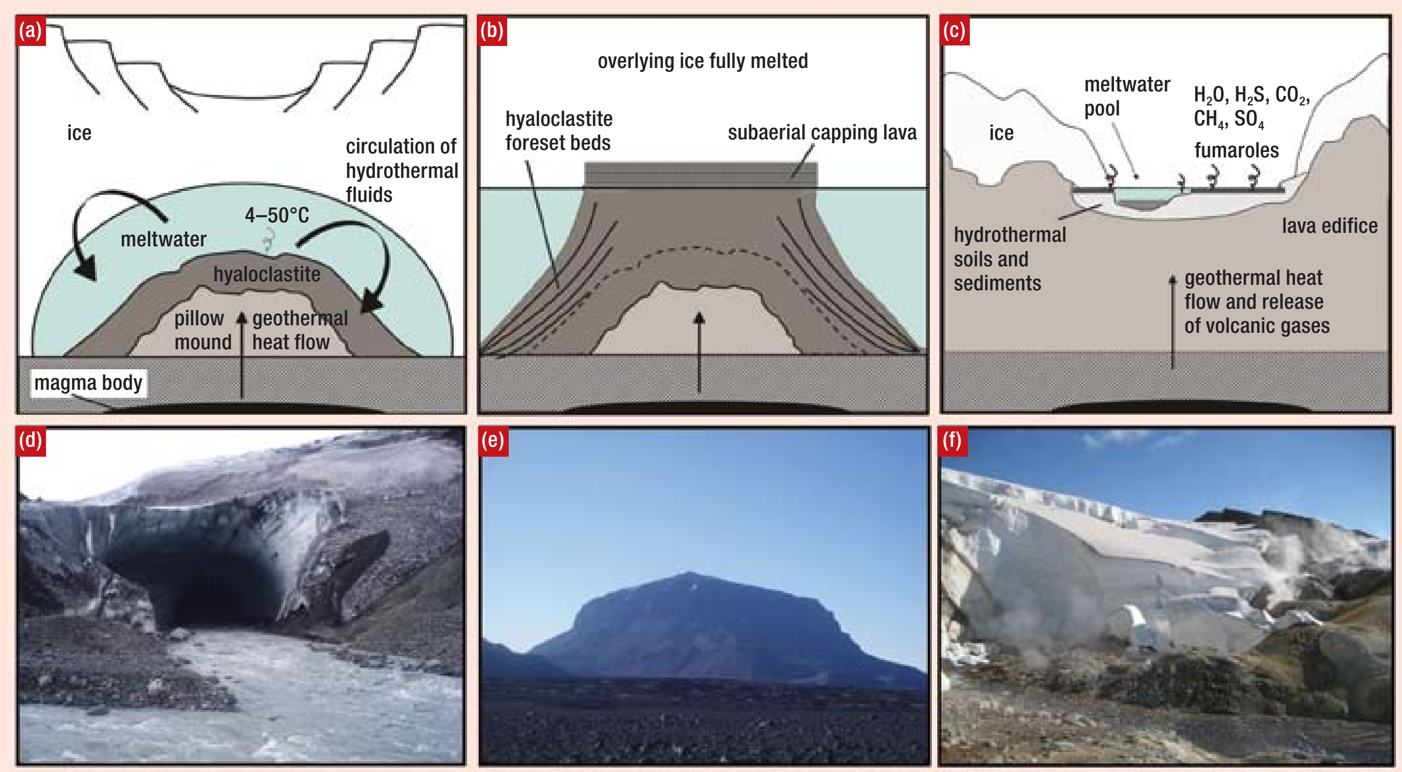
The melting of so much glacial ice inevitably leads to the generation of liquid water. This water can be stored within the confines of the glacier, forming a meltwater lens that cycles through the lava edifice and mixes with hydrothermal fluids (Björnsson 2002). Eventually this meltwater zone becomes unstable, and is commonly released from the glacier as a catastrophic outflow flood – termed a *jökulhlaup* – depositing volcanic sediments and ice across an outwash plain. These "sandur" plains are characteristic features of volcano–ice terrain in Iceland, where they take their name (*jökulhlaup* means "glacier burst"); similar large-scale features have been identified on Mars.

Iceland and Mars

The volcanic country of Iceland lies on a high point of the Mid-Atlantic Ridge (figure 2). This unique geological setting, while being responsible for the production of Iceland in the first place, leads to ongoing and often intense volcanic activity, much of which is highly analogous to Mars surface processes. Due to the near-Arctic latitude at which Iceland lies, much of the volcanism here is in direct interaction with glacial activity. Indeed, the elevated topography of the currently dormant volcanoes leads to increased glaciation of volcanic centres, despite their relatively high heat flow. Vatnajökull – Europe's largest glacier – overlies seven volcanic centres (figure 2), including those associated with the hot spot. Similarly, much of Iceland's glaciers coincide with the active volcanic zones that cut through the centre of the island. The relatively small eruption of Eyjafjallajökull in southern Iceland earlier this year is a recent example of this volcano–ice interaction. Here, an initially subglacial eruption quickly became subaerial as the overlying ice was melted away (Gudmundsson *et al.* 2010). Previous to this were the eruptions at Grimsvotn in 1998 and 2004 (Jakobsson and Gudmundsson 2008), and Gjalp in 1996 (Gudmundsson *et al.* 1997), all beneath Vatnajökull.

Iceland shares many similarities with martian volcanism, and volcanic systems here are often used as analogues for those on Mars (e.g. Keszthelyi *et al.* 2004). As far as volcano–ice interaction is concerned, numerous localities on Mars have been suggested to be the result of subglacial volcanism or magma–cryosphere coupling. These are found both at the poles (such as in the Dorsa Agentea Formation, see Head and Pratt 2001), as well as the equatorial regions (e.g. Kadish *et al.* 2008), and at major volcanic centres (such as Elysium, see Pedersen *et al.* 2010). As such, the environmental conditions

a haven for life on Mars?



1 (a–c): Examples of volcano–ice interaction processes and associated environments. (a) Edifice growth during a subglacial eruption within a zone of meltwater. (b) Continual edifice growth leading to the development of a subaerial tuya. (c) Manifestation of geothermal activity at the glacier surface. (d–f): Present-day volcano–ice interaction environments as observed in Iceland. (d) Ice cave and subglacial outflow stream. (e) Herðubreið basaltic tuya. (f) Hydrothermal activity at the glacial surface induced by underlying volcanic heat.

generated by this activity warrant investigation with regards to their potential for life.

Subaerial and subsurface habitats

The key to volcano–ice interaction habitability lies principally in the generation of liquid water and geothermal heat. Taking Iceland as a model, both subaerial and subsurface environments exist that are exploited by microbial life. One of the most exciting of all these environments are the subglacial "caldera lakes". These exist beneath the glacier surface, maintained by high geothermal heat between eruptions (Björnsson 2002), and are confined by the surface topography of the underlying volcanic caldera or edifice. Despite the thermal input, these lakes are generally cold, and have been found to be inhabited by psycrotolerant and chemotrophic bacteria (Gaidos *et al.* 2008). Equivalent environments are thought to have existed on Mars, where the geometry of the volcano Ceraunius Tholus, for example, would favour similar meltwater accumulation from the geothermal melting of summit snowpack (Fassett and Head 2007).

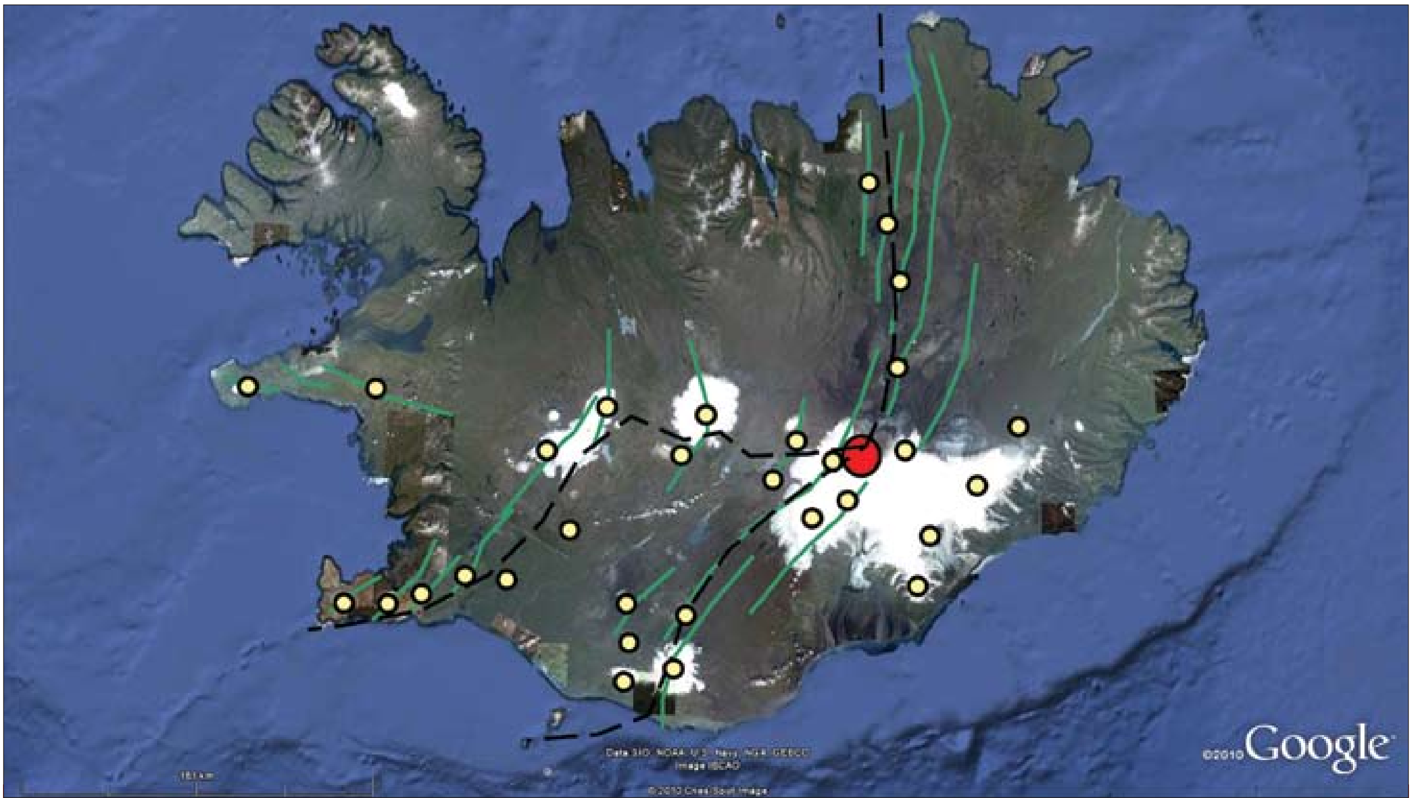
While meltwater can be ponded to form subglacial lakes, in other cases it is released gradually via fissures and drainage tunnels within the ice. Where the meltwater eventually is released at the edge of the glacier, it can form a substantial cave network within the ice. Ice caves have been observed in Iceland (figure 1d) and at Mount Rainier, USA, where fumaroles produced caves over 1.5 km long (Zimbelman *et al.* 2000). These caves provide a sheltered, water-rich environment, and are likely to have formed on Mars wherever geothermal heat flow coincided with overlying ice deposits. In addition, such subglacial drainage networks have the potential to link nearby caldera lake systems.

In contrast to the aqueous and hydrothermal habitats is the lava edifice itself. Basaltic lava has proven to be an environment widely exploited by microbial life on Earth, both within a subaqueous setting and in cold volcanic deserts. Combined with hydrothermal activity, the basaltic edifice has the potential to be colonized by a variety of chemosynthetic life (Boston *et al.* 1992). Basaltic pillow lavas and hyaloclastite erupted at the seafloor from mid-ocean ridge systems is rapidly colonized by bacterial and archaeal communities (Santelli *et al.* 2008). Likewise, terrestrial basaltic lava habitats include those within the deep subsurface (McKinley and Stevens 2000) and now-exposed subglacially erupted lavas in Iceland (Herrera *et al.* 2009). Therefore, any microbiota with volcano–ice systems on Mars would probably exploit the basaltic lava edifice along with its surrounding aqueous and hydrothermal environments.

Finally, while most environments likely to have once been habitable lie in the subsurface, volcano–ice interaction also has surface manifestations (figure 1c), in the form of large glacial meltwater lakes, fumaroles and hot springs (figure 1f). These environments form isolated "islands" of habitability within an otherwise barren terrain, and can also be found in places such as the Atacama, Antarctica and Iceland.

Finding life

In the same way that the variety of environments created by volcano–ice interaction provides a wide-range of putative microbial habitats, geological deposits are equally diverse, and provide several opportunities for the preservation of biosignatures. In particular, the possibility for the preservation of biomolecules within extensive *jökulhlaup* deposits would mean large, expansive flood plains accessible to rover exploration could be searched for evidence of life. Additionally, the clay-rich nature



2: Google Earth satellite image of Iceland, showing the Icelandic Rift Zone (black dashed line), with associated fissure systems (green) and central volcanoes (yellow). (Adapted from http://gullhver.os.is/website/hpf/orkustofnun_english/viewer.htm)

of *jökulhlaup* deposits is conducive to the preservation of organic molecules (Ehlmann *et al.* 2008). Recently, Warner and Farmer (2010) demonstrated how visible to near-infrared and shortwave-infrared remote-sensing data can be used to identify hydrothermal minerals (such as clays) within Icelandic *jökulhlaups*.

In addition to *jökulhlaups*, the hydrothermal activity associated with volcano–ice interaction can lead to the deposition of concentrated mineral deposits. As with many hydrothermal and hot spring systems, these mineral deposits have the potential to produce biosignatures, through the fossilization and preservation of microbiota. The subglacially erupted volcano Sigurdfjellet in Svalbard is rich in hydrothermally deposited carbonate, and is indeed a good analogue for the carbonate globules in martian meteorite ALH84001 (Treiman *et al.* 2002); it provides an example of the mineralogical deposition that could potentially preserve biosignatures. Alternatively, subsurface silica-charged hydrothermal fluids have been found to precipitate amorphous silica upon freezing when they are erupted into a sub-zero environment (Channing and Butler 2007) and it has been suggested such precipitation would simultaneously silicify any microbial life present. In particular, this mechanism of fossilization would provide a window into any subsurface microbial communities brought up by the erupting spring fluid.

Lastly, basaltic lavas themselves have the potential to yield signs of past microbial activity. Basaltic lavas on the seafloor are often riddled with so-called "bioalteration" textures, thought to be traces of microbial life burrowing into volcanic glass (Furnes *et al.* 2007). Such textures have been putatively identified in Archaean rocks on Earth, clearly lending themselves to long-term survival within the rock record. However, little is known regarding the generation of these features – biogenic or otherwise – and indeed those lavas from subglacial environments do not always display these textures in the abundance with which they are found in seafloor lavas (Cousins *et al.* 2009).

Summary

Active volcano–ice systems and their associated environments can potentially provide all the ingredients for life, including protection from the harsh surface extremes present on Mars. In addition the geological processes in themselves produce a number of mineralogical and sedimentary deposits that are potentially conducive to the preservation of biosignatures. Much work needs to be done to uncover the true value of present-day volcano–ice systems as a martian analogue environment, including the microbial life that resides within them. ●

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References

Amils R *et al.* 2007 *Plan. and Space Sci.* **55** 370–381.
Björnsson H 2002 *Global and Planetary Change* **35** 255–271.
Boston P J *et al.* 1992 *Icarus* **95** 300–308.
Channing A and Butler I B 2007 *Earth Plan. Sci. Letts* **257** 121–131.
Clifford S M 1993 *J. Geophys. Res.* **98** 10973–11016.
Cockell C S *et al.* 2010 *Geobiology* **8** 293–308.
Cousins C R *et al.* 2009 *Int. J. Astrobiology* **8** 37–49.
Ehlmann B L *et al.* 2008 *Nature Geoscience* **1** 355–358.
Fassett C I and Head J W 2007 *Icarus* **189** 118–135.
Furnes H *et al.* 2007 *Precambrian Res.* **158** 156–176.
Gaidos E *et al.* 2008 *ISME Journal* **3** 486–497.
Gudmundsson M T *et al.* 1997 *Nature* **389** 954–957.
Gudmundsson M T *et al.* 2010 *Geophysical Research Abstracts* **12** EGU2010-15762.
Head J W and S Pratt 2001 *J. Geophys. Res.* **106** 12275–12299.
Herrera A *et al.* 2009 *Astrobiology* **9** 369–381.
Hovius N *et al.* 2008 *Icarus* **197** 24–38.
Hvidberg C S 2005 in Tetsuya Tokano (ed.) *Adv. Astrobiol. Biogeophys.* 129–152.
Jakobsson and Gudmundsson M T 2008 *Jökull* **58** 179–196.
Kadish S J *et al.* 2008 *Icarus* **197** 84–109.
Keszthelyi L *et al.* 2004 *Geochem. Geophys. Geosyst.* 5.
McKinley J P and Stevens T O 2000 *Geomicrobiology Journal* **17** 43–54.
Navarro-Gonzalez R *et al.* 2003 *Science* **302** 1018–1021.
Pedersen G B M *et al.* 2010 *Earth Plan. Sci. Letts* **294** 424–439.
Rothschild L J 1990 *Icarus* **88** 246–260.
Santelli C M *et al.* 2008 *Nature* **453** 653–657.
Schulze-Makuch D *et al.* 2007 *Icarus* **189** 308–324.
Treiman A H *et al.* 2002 *Earth Plan. Sci. Letts* **204** 323–332.
Warner N H and Farmer J D 2010 *Astrobiology* **10** 523–547.
Wierzchos J *et al.* 2005 *Environmental Microbiology* **7** 566–575.
Zimbelman D R *et al.* 2000 *J. Volcanol. Geotherm. Res.* **97** 457–473.