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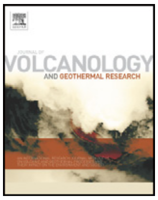

Glaciovolcanic hydrothermal environments in Iceland and implications for their detection on Mars

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ABSTRACT

Volcanism has been a dominant process on Mars, along with a pervasive global cryosphere. Therefore, the interaction between these two is considered likely. Terrestrial glaciovolcanism produces distinctive lithologies and alteration terrains, as well as hydrothermal environments that can be inhabited by microorganisms. Here, we provide a framework for identifying evidence of such glaciovolcanic environments during future Mars exploration, and provide a descriptive reference for active hydrothermal environments to be utilised for future astrobiological studies. Remote sensing data were combined with field observations and sample analysis that included X-ray diffraction, Raman spectroscopy, thin section petrography, scanning electron microscopy, electron dispersive spectrometer analysis, and dissolved water chemistry to characterise samples from two areas of basaltic glaciovolcanism: Askja and Kverkfjöll volcanoes in Iceland. The glaciovolcanic terrain between these volcanoes is characterised by subglacially-erupted fissure swarm ridges, which have since been modified by multiple glacial outburst floods. Active hydrothermal environments at Kverkfjöll include hot springs, anoxic pools, glacial meltwater lakes, and sulphur- and iron-depositing fumaroles, all situated within ice-bound geothermal fields. Temperatures range from 0 °C–94.4 °C, and aqueous environments are acidic–neutral (pH 2–7.5) and sulphate-dominated. Mineralogy of sediments, mineral crusts, and secondary deposits within basalts suggest two types of hydrothermal alteration: a low-temperature (<120 °C) assemblage dominated by nanophase palagonite, sulphates (gypsum, jarosite), and iron oxides (goethite, hematite); and a high-temperature (>120 °C) assemblage signified by zeolite (heulandite) and quartz. These mineral assemblages are consistent with those identified at the Martian surface. *In-situ* and laboratory VNIR (440–1000 nm) reflectance spectra representative of Mars rover multispectral imaging show sediment spectral profiles to be influenced by $Fe^{2+/3+}$-bearing minerals, regardless of their dominant bulk mineralogy. Characterising these terrestrial glaciovolcanic deposits can help identify similar processes on Mars, as well as identifying palaeoenvironments that may once have supported and preserved life.

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1. Introduction

Hydrothermal environments driven by volcanism are prime targets for astrobiological exploration on Mars (for a review see Schulze-Makuch et al., 2007), and have many well-documented terrestrial analogues, *e.g.* Yellowstone National Park, USA (Bishop et al., 2004; Hellman and Ramsey, 2004; Marion et al., 2011), Cerro Negro volcano, Nicaragua (Hynek et al., 2011), and Iceland (Griffith and Shock, 1997; Nelson et al., 2005; Warner and Farmer, 2010). Fundamental to the generation of these environments is water, either as liquid ground water or seawater (as typical on Earth), or frozen water ice as found within the cryosphere of Mars (Clifford et al., 2010). Hydrothermal systems that are associated with fissure and hot spot basaltic volcanism in particular are analogous to past environments on Mars.

However, despite the ubiquity of both volcanism and a widespread cryosphere on Mars, widespread glaciovolcanic terrains have yet to be definitively identified (Keszthelyi et al., 2010). If these two processes have both occurred concurrently, then it is a

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challenge for future exploration to find unequivocal or diagnostic topographic, geomorphological, sedimentological and/or mineralogical evidence of glaciovolcanic interactions. Glaciovolcanism is proposed to have been widespread on Mars throughout its past (*e.g.* Chapman et al., 2000; Head and Wilson, 2002, 2007) ranging from lava flows that have interacted with ground ice, *e.g.* rootless cones in Athabasca Valles (Fagents and Thordarson, 2007; Jaeger et al., 2007) to volcanic eruptions into glaciers, *e.g.* tuya constructs at Chryse/Acidalia Planitia (Martínez-Alonso et al., 2011) and moberg ridges at Pavonis Mons (Head and Wilson, 2007). Glacial processes themselves have been widely documented on Mars throughout its history (Kargel and Strom, 1992; Neukum et al., 2004; Dickson et al., 2008), much of which has been in association with volcanic regions (Head and Wilson, 2002; Cousins and Crawford, 2011 and references therein). Likewise, it has been recently proposed that low-albedo sediments covering large areas ($>10^7$ km^2) of the northern lowlands of Mars are dominated by basaltic glass (Horgan and Bell, 2012), implying widespread explosive volcanism, such as that found during volcano–ice interaction (Horgan and Bell, 2012). One recent terrestrial example of this process is the 2010 Ejafjallajokull eruption in southern Iceland, which generated large volumes of ash as fine glass particles (Dellino et al., 2012).

Glaciovolcanic terrains are of relevance to astrobiology, as such systems may have provided a past habitat for microbial life on Mars due to the coupling of liquid water and geochemical disequilibria (Gaidos et al., 2008; Cousins and Crawford, 2011). In terrestrial systems this liquid water exists as subsurface cycling of hydrothermal fluids throughout the volcanic edifice, or as large volumes of subglacial meltwater (Björnsson, 2002). If released catastrophically this subsurface water forms a type of glacial outburst flood known as a “jökulhlaup” (Björnsson, 2002), of which the deposits and erosional features form a major indicator of glaciovolcanic activity. Aqueous floods have certainly played a major role in Mars surface processes (*e.g.* Warner et al., 2009), although the origin of these floods is often contested or uncertain (Baker et al., 1991; Baker, 2001). The megaflood features of Athabasca Valles in particular are temporally and spatially associated with volcanotectonic fissures (Burr et al., 2002), highlighting the important relationship between dike emplacement and the release of aquifers (Burr et al., 2002). Likewise, the formation of Aromatum Chaos and Mangala Fossa has been attributed to volcano-ice interaction and subsequent release of subsurface water (Leask et al., 2006, 2007). However, the Athabasca Valles floods and other chaos terrains (*e.g.* Iani Chaos) have alternative, non-volcanogenic explanations (Burr et al., 2005; Warner et al., 2011).

The mineral assemblages produced through glaciovolcanic hydrothermalism have yet to be fully incorporated into detection strategies. Mineral alteration terrains on Mars demonstrate a significant level of aqueous alteration of basaltic material, much of which may have been the result of hydrothermal activity (Bibring et al., 2006; Morris et al., 2008; Ehlmann et al., 2009). Mineral assemblages revealed by the instruments HiRiSE and CRISM (Bibring et al., 2006; Carter et al., 2010; Ehlmann et al., 2011; Weitz et al., 2011) suggest a variety of environmental conditions spanning acidic (typified by ferric oxides/oxyhydroxides and sulphates) to neutral–alkaline (typified by phyllosilicates and opaline silica) environments (Bibring et al., 2006; Chevrier et al., 2007; Ehlmann et al., 2011). Varying levels of water activity have also been proposed, ranging from ‘acid fog’ fumarole alteration (Tosca et al., 2004; Schiffman et al., 2006) to subsurface water circulation (Ehlmann et al., 2011). Terrestrial glaciovolcanism includes both of these contrasting mechanisms of hydrothermal alteration, and therefore alteration deposits associated with glaciovolcanic terrains have the potential to aid the future detection of such environments on Mars (Warner and Farmer, 2010), as well as provide a model for hydrothermal mineral deposition within cold, volcanic terrains.

Here, we assess (i) what specific mineral assemblages arise through the hydrothermal alteration of basaltic lithologies within glaciovolcanic environments, and how they correspond to the glaciovolcanic terrain in the Askja–Kverkfjöll region of Iceland, (ii) how these mineral assemblages compare to those on Mars, and (iii) the key environmental characteristics (temperature, pH, dissolved elemental chemistry) of the surface hydrothermal environments currently active at the Kverkfjöll volcano. Multi-instrument data products were acquired from natural glaciovolcanic deposits, including exposed pillow basalts and volcaniclastics, hydrothermal sediments, and hot spring mineral precipitates to provide a framework with which to identify glaciovolcanic terrains on Mars both remotely, and particularly with rover-deployed instruments. Combined, this study provides an overview of Askja and Kverkfjöll and their volcanic environments, with a call for these localities to be used as test grounds for future Mars research, from exploring microbiological processes to field-testing Mars rover instrumentation.

2. Regional setting

The Kverkfjöll and Askja volcanoes in Iceland, and the subglacially-erupted fissure swarm that lies between them (Fig. 1), represent both past and active hydrothermal environments and alteration. This region serves as an ideal Mars analogue for several reasons: (1) the region is dominated by basaltic volcanism and near-surface hydrothermal activity; (2) a rain shadow cast by the Vatnajökull ice cap results in little vegetation and surface water; (3) its geographical isolation has resulted in little disturbance by people, animals, and development; and (4) as a result of factors (2) and (3), the preservation of hydrothermal features allows for multi-scale studies of mineralogical and lithological deposits. Individual field areas are described below.

2.1. Askja

The Askja (65° 3.276′N; 16° 30.480′W) caldera lies within the Dyngjufjöll volcanic centre, and is dominated by a large subglacially-erupted hyaloclastite formation, comprised of basal pillow lavas, pillow breccias, and hyaloclastite tuffs (Brown et al., 1991; Sigvaldason, 2002). This subglacial terrain has been exposed by glacial retreat during the last 10,000 years (Sigvaldason, 2002), and has since been modified by more recent eruptions, including the explosive 1875 Plinian eruption producing Öskjuvatn (Askja lake) caldera (Hartley and Thordarson, 2012). The most recent activity at Askja was an eruption of subaerial basaltic lava to the north of the caldera (65° 3′ 44.88″N; 16° 36′ 58.61″W) in 1961 (Thorarinsson and Sigvaldason, 1962). Compositionally, eruptive products at Askja are largely basaltic, with the exception of rhyolite-producing eruptions at ~10 ka and in 1875 (Sigvaldason, 2002). The basaltic, glaciovolcanic terrain was the focus for this study.

2.2. Fissure swarm

A Holocene fissure swarm extends northeast of Kverkfjöll (Fig. 2A) towards Askja, and intrudes pre-Holocene bedrock (Hjartardóttir and Einarsson, 2012). Höskuldsson et al. (2006) infer that the pillow basalts within this fissure swarm were erupted beneath 1.2 to 1.6 km of ice during the last glacial maximum. These fissure swarms have since been eroded by catastrophic glacial outburst floods (jökulhlaups) originating from the northern Vatnajökull ice margin (Carrivick et al., 2004a; Carrivick and Twigg, 2005). Topography indicative of jökulhlaups includes a bedrock anastomosing channel pattern, which represents bifurcation of valleys separated by linear bedrock ridges or hills. Further evidence is provided by streamlining of these bedrock ridges *via* flank erosion and tail (down-valley) extension due to deposition of pendant bars.

2.3. Kverkfjöll

Kverkfjöll lies above the Icelandic mantle plume (Sigvaldason et al., 1974; Wolfe et al., 1997), and is situated within the northern volcanic zone (NVZ), which marks the mid-Atlantic plate boundary

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