

**CARBONATE CEMENTS FROM THE SVERREFJELL AND SIGURDFJELL VOLCANOES, SVALBARD NORWAY: ANALOGS FOR MARTIAN CARBONATES.** D.F. Blake,<sup>1</sup> A.H. Treiman,<sup>2</sup> R. Morris<sup>3</sup>, D. Bish,<sup>4</sup> H.E.F. Amundsen,<sup>5</sup> A. Steele<sup>6</sup> and the AMASE team. <sup>1</sup>MS 239-4, NASA Ames Research Center, Moffett Field, CA 94035 USA, david.blake@nasa.gov; <sup>2</sup>Lunar and Planetary Institute, Houston, TX; <sup>3</sup>Johnson Space Center, Houston, TX; <sup>4</sup>Department of Geological Sciences, Indiana University; <sup>5</sup>Earth and Planetary Explorations Services, Oslo, Norway; <sup>6</sup>Geophysical Laboratory, Carnegie Institution of Washington.

**Introduction:** The Sverrefjell and Sigurdfjell volcanic complexes erupted at ~1Ma on Svalbard, Norway. Sverrefjell is a cone of cinders, pillow lavas and dikes; Sigurdfjell is elongate in outcrop and may represent a fissure eruption [1]. The lavas of both volcanos were volatile rich. The volcanos erupted under ice and were subsequently dissected by glaciation (glacial erratics are present on most of Sverrefjell, even on its summit). Eruption beneath an ice sheet is inferred, based on the presence of pillow lavas from near sea level to ~1000 m above sea level. Sverrefjell contains the largest fraction of ultramafic xenoliths of any volcanic complex in the world, in places accounting for as much as 50% of the volume of the outcrop. The Sverrefjell and Sigurdfjell volcanos contain carbonate cements of several varieties:

(1) Amundsen [2] reported Mg-Fe-rich carbonate in sub-mm globules in basalts and ultramafic xenoliths from the volcanos. These globules are the best terrestrial analogs to the carbonate globules in the Mars meteorite ALH84001 [3].

(2) Thick (1-3 cm) coatings of carbonate cement drape the walls of vertical volcanic pipes or conduits on the flanks and near the present summit of Sverrefjell. Similar occurrences are found on Sigurdfjell.

(3) Breccia-filled pipes or vents occur on Sverrefjell and Sigurdfjell in which the breccia fragments are cemented by carbonate. The fragments themselves commonly contain carbonate globules similar to those found in the basalts and ultramafic xenoliths.

**Sverrefjell and Sigurdfjell Carbonates as Analogs to Martian Carbonates:** Morris et al. [4] describe carbonate cements on Mars that, on the basis of [3,5], are interpreted to be hydrothermal in origin. The occurrence of volcanic hydrothermal features hosting iron and magnesium carbonates is relatively rare on Earth but may have been common on early Mars. Morris et al. [6] report Mössbauer and infrared spectroscopy data that show the Sverrefjell breccia carbonate cements to be the closest terrestrial analogs to the Martian examples [4]. A petrologic investigation of the Sverrefjell and Sigurdfjell carbonates should give insight into how the Martian carbonates were formed.

**Field Relationships, Mineralogy and Petrology of the Carbonates:** Carbonate-containing volcanic conduits,

that occur both at Sverrefjell and Sigurdfjell, are 1-10 meters in diameter with hollow or breccia-filled interiors [7-8]. Millimeter- to centimeter-thick coatings of carbonate occur on interior surfaces of the conduits and permeate fractures in the rock. The carbonates change cation content and mineralogy from the basaltic wall rock outward, presumably following the chemistry of the solutions from which they precipitated. A typical (but generalized) sequence might include high-Mg calcite, huntite, magnesite, dolomite or ankeritic dolomite, siderite and minor aragonite. A third ventlike locality on Sverrefjell, the "ice cave," contains predominantly magnesite.

These carbonate cements are not forming today, and most of the localities are exposed to the air. Ice cave is a narrow vent filled with blue ice; however carbonate is not presently being deposited. The volcanic pipes or conduits stand meters above the volcanos slopes because the surrounding scree is less resistant to erosion than the cemented pipe walls. Brecciated basalts in intimate contact with the cements appear pristine, with no sign of weathering or dissolution.

A section of carbonate from a Sigurdfjell volcanic vent is shown in Figure 1. Quantitative X-ray diffraction analysis of the outer layer of the cement yields 4% dolomite, 74% magnesite and 22% siderite, with some substitution of Mg in siderite and Fe in magnesite. However, in the inner-



*Fig. 1. Polished cross-section of carbonate-cemented breccia from a Sigurdfjell volcanic pipe. The translucent outer layer consists of well-crystallized dolomite, magnesite and siderite whereas the inner milky layer consists of (from EMPA, see fig. 2) alternating mg-calcite, huntite, dolomite and Ca-magnesite. Slab is approximately 4 cm. across*

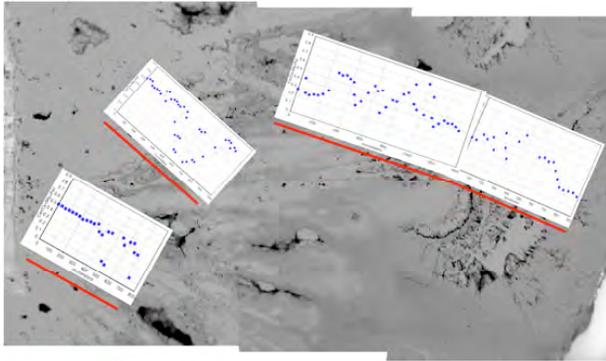


Fig. 2. BSE image of the Sigurdssjell breccia carbonate shown in Fig. 1, with superimposed EMPA transects and  $Ca/(Ca+Mg+Fe)$  plots. Field of view is approximately 4 mm.

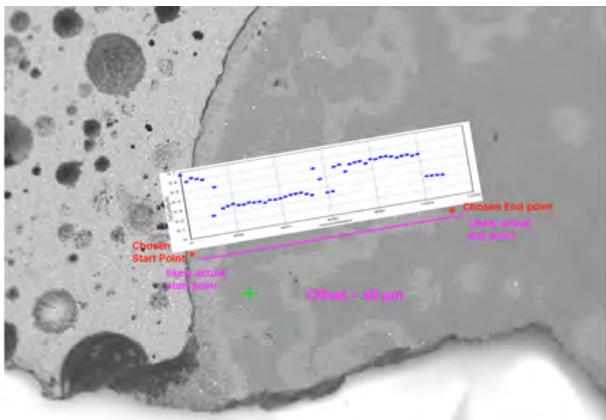


Fig. 3. BSE image of the Sverrefjell breccia carbonate [6], with superimposed EMPA transects and  $Ca/(Ca+Mg+Fe)$  plots. Mamillary texture is reminiscent of carbonate globules found in matrix basalt. Field of view is approximately 2 mm.

most layer, the [104] carbonate peak is exceptionally broad, indicating multiple phases, changes in solid solution in the carbonates, or both. Quantitative XRD of the inner layer yields about 16% dolomite, 54% siderite and 30% magnesite.

Electron microprobe data and backscattered electron images (EMPA/BSE) reveal fine-scale alternation of cements, starting at the basalt/carbonate interface. Fine-scale alternations of (by composition) high-Mg calcite, dolomite, huntite and Ca-magnesite, with textures of deposition and dissolution, suggest a rapid, non-equilibrium process after initial nucleation (e.g., fig. 2). The outer, more coarsely crystalline carbonates, which are more or less stoichiometric, could have precipitated under less supersaturated, more stable conditions. At the basalt/carbonate interface in this cement and more obviously in the Sverrefjell breccia carbonate (e.g., fig. 3), multiple nucleation points are apparent which in their initial growth have the appearance of the carbonate globules described in [3] and which are also found within the basalt matrix in internal gas bubbles and cavities.

**Conditions of formation of the carbonates.** Because the volcanic vents are near the tops of the peaks, there is currently no hydrostatic head to cause fluids to flow through the conduits. Thus cementation must have occurred during or soon after the volcanic eruptions, but not after the end of glaciation (a thick ice sheet above the volcano could itself create a hydrostatic head that could cause flow). The system must have been open, as dissolved  $CO_2$  would have to escape freely in order to maintain pH and alkalinity conditions that would permit the deposition of carbonate cements. Furthermore, cementation must have occurred in the shallow subsurface as vesicles are common in many of the brecciated basalt fragments (i.e., Fig. 3).

The rocks immediately adjacent to the vents appear to have been heated to higher temperatures than the rest of the cindercone. This could reflect eruption of high temperature vents through relatively cold and wet volcanic deposits and/or focused mobilization of high temperature fluids associated with the vents. The vents at least began their existence as high temperature magma conduits and may later have acted as a plumbing system for fluid transport.

**Conclusions:** Conditions such as those described above could have existed on early Mars as a result of eruptive activity in the presence of surface or subsurface fluids. In the absence of vulcanism, hydrothermal activity could also have occurred as a result of large impacts into wet or frozen terrane which would create subsurface hydrothermal cells from the heat of impact.

The detailed study and analysis of a terrestrial volcanic terrane which hosts carbonate cements should provide great insight into the possible origin(s) of similar carbonate cements on Mars. The large variations in carbonate chemistry and petrology at this site suggest that we shouldn't over-interpret individual observations of Martian carbonates that lack regional context (i.e., ALH84001) or that sample only the upper few tens of microns of surface material (i.e., Mössbauer and infrared spectroscopy). Rather, these observations are valuable guideposts to what must have been a rich and varied carbonate geochemistry on early Mars.

**References:** [1] Harland, W.B. (1997). *Memoir 17, Geol. Soc. of London* (521 pp.). [2] Amundsen, H.E.F. (1987) *Nature*, 327, 692–695. [3] Treiman, A.H. et al. (2002) *EPSL*, 204, 323–332. [4]. Morris, R. V., et al. (2010) *Science*, 329, 421–424. [5]. Golden, D. C., et al. (2000). *Meteorit. Planet. Sci.*, 35, 457–465. [6]. Morris, et al. (this conference). [7]. Blake et al. (2010). AbSciCon abstr. # 5119. [8]. Mahaffy et al. (2010). AbSciCon abstr. # 5306.