

**CRYOGENIC ORIGIN FOR MARS ANALOG CARBONATES IN THE BOCKFJORD VOLCANIC COMPLEX, SVALBARD (NORWAY).** H.E.F. Amundsen<sup>1</sup>, L. Benning<sup>2</sup>, D.F. Blake<sup>3</sup>, M. Fogel<sup>4</sup>, D. Ming<sup>5</sup>, M. Skidmore<sup>6</sup>, A. Steele<sup>4</sup> and the AMASE team, <sup>1</sup>Earth and Planetary Exploration Services, Oslo, Norway, ha@epx.no; <sup>2</sup>Univ. of Leeds, Leeds, UK; <sup>3</sup>NASA Ames Research Center, Moffet Field, CA, USA; <sup>4</sup>Geophysical Laboratory, Carnegie Inst. Washington, DC, USA; <sup>5</sup>ARES NASA Johnson Space Center, Houston TX, USA. <sup>6</sup>Montana State Univ., Bozeman MT, USA.

**Introduction:** The Sverrefjell and Sigurd fjell eruptive centers in the Bockfjord Volcanic Complex (BVC) on Svalbard (Norway) formed by subglacial eruptions [1] ca. 1 Ma ago. These eruptive centers carry ubiquitous magnesian carbonate deposits including dolomite-magnesite globules [2] similar to those in the Martian meteorite ALH84001 [3, 4]. Carbonates in mantle xenoliths are dominated by ALH84001 type carbonate globules that formed during quenching of CO<sub>2</sub>-rich mantle fluids [2, 4].

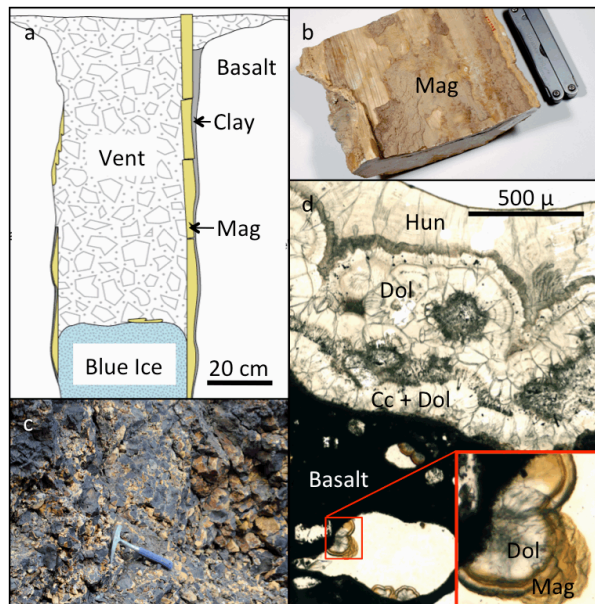


Figure 1: (a) Cross-section of Sverrefjell vent lined with massive layered magnesite (b) protruding into clear blue ice. (c) Carbonate cemented basalt breccia at Sverrefjell. (d) Thinsection image of calcite + dolomite + huntite lining basalt clast in (c) and ALH84001 type dolomite magnesite globules lining basalt vesicles.

Lava hosted carbonates include ALH84001 type carbonate globules occurring throughout lava vesicles and microfractures and massive carbonate deposits associated with vertical volcanic vents. Massive carbonates include  $\leq 5$  cm thick magnesite deposits protruding downwards into clear blue ice within volcanic vents (Fig. 1a,b) and carbonate cemented lava breccias associated with volcanic vents (Fig 1c). Carbonate cements comprise layered deposits of calcite, dolomite, huntite, magnesite and aragonite [5] associated with

ALH84001 type carbonate globules lining lava vesicles (Fig. 1d). Combined Mössbauer, XRD and VNIR data show that breccia carbonate cements at Sverrefjell are analog to Comanche carbonates at Gusev crater [6].

**Fluid Sources During Deposition of Lava Hosted Carbonates:** Degassing of primitive alkali basalts during subglacial eruptions would have produced enormous amounts of CO<sub>2</sub> and glacial meltwater, with volcanic vents and porous lava breccias acting as a plumbing system during circulation of fluids. Figure 2 illustrates a phase diagram for the carbonate system combined with hydrochemistry of fluids likely present during deposition of lava hosted carbonates at BVC. Blue ice trapped in Sverrefjell vents have relatively high Mg/Ca values (Fig. 2) similar present day glacial meltwaters on Svalbard (Ref). Carbonate deposition during degassing of CO<sub>2</sub> from high Mg/Ca glacial meltwater and/or basalt aquifers would lead to deposition of calcite followed by dolomite, huntite and magnesite similar to layered carbonate cements in BVC breccias.

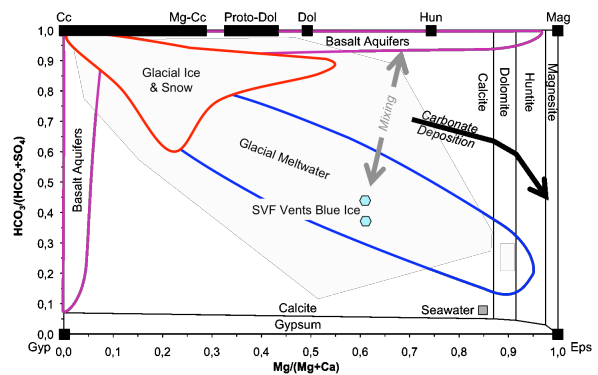


Figure 2: Phase diagram for the carbonate system (modified after [7]). Hexagons denote composition of blue ice in Sverrefjell vents. Hydrochemistry of seawater, glacial ice and snow, Svalbard meltwaters [8] and basalt aquifers from Iceland [9] are shown for comparison. Black arrow illustrates fluid evolution during progressive carbonate deposition from mixture of basalt aquifer and glacial meltwater.

**Carbonate Deposition Mechanism:**  $\delta^{18}\text{O}$  (SMOW) and  $\delta^{13}\text{C}$  (PDB) data for lava hosted carbonates are illustrated in Figure 3 together with published

data for cryogenic cave carbonates and aufeis [10] as well as marine-, evaporative lake- and basalt hosted caliche- and amygdale carbonates. Both massive magnesite, breccia cements and globules in basalt vesicles show similar C-O isotope signatures with very low  $\delta^{18}\text{O}$  values between -3 and +3 ‰. C-O isotope data on lava hosted carbonates are only matched by data on cryogenic cave carbonates formed during closed system freezing [10] with kinetic isotope fractionation leading to very low  $\delta^{18}\text{O}$  values. Using  $\delta^{18}\text{O}$  data on blue ice in a Sverrefjell vent as a starting point (-16.9 ‰) the initial carbonate to form during freezing would have a  $\delta^{18}\text{O}$  value of ca 11.3 ‰ with progressive isotope fractionation during closed system freezing leading to  $\delta^{18}\text{O}$  values down to ca -2 ‰ similar to observed values for the lava hosted carbonates (Fig. 3).

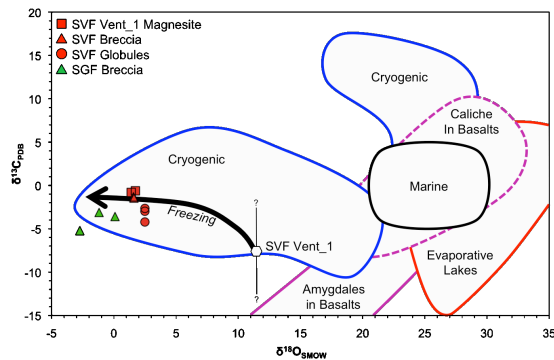


Figure 3:  $\delta^{18}\text{O}$  (SMOW) and  $\delta^{13}\text{C}$  (PDB) data for BVC carbonates. Open hexagon indicates estimated  $\delta^{18}\text{O}$  of carbonate that would form by initial freezing of water present as blue ice in Sverrefjell vents. Modelled evolution of carbonate  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  during progressive closed system freezing is modified from [11]. Data on cryogenic cave carbonates and aufeis [10], as well as marine-, evaporative lake- and basalt hosted caliche- and amygdale carbonates are shown for comparison.

A possible link between the blue ice trapped in Sverrefjell vents and the fluid(s) depositing the lava hosted carbonates remains speculative. However, the C-O isotope signatures with very low  $\delta^{18}\text{O}$  values indicate that the carbonates were deposited by cryogenic rather than hydrothermal processes. A rare combination of events with  $\text{CO}_2$  rich volcanic eruptions melting glacial ice and permafrost under very cold ambient conditions may have culminated in cryogenic deposition of carbonates throughout BVC. Remobilisation of Mg-rich carbonates initially deposited from primary mantle fluids [2, 4] may have been an additional important factor.

**Implications for ALH84001- and Comanche Carbonates:** A possible cryogenic origin for carbonates in ALH84001 have been suggested by [12, 13] based on C-O isotope data and experimental deposition of hydrothermal and cryogenic carbonates. A low temperature origin for BVC carbonate globules was proposed by [3], and the close textural and mineralogical similarity between carbonate globules in ALH84001 and BVC [3,4] may support a common (i.e. cryogenic) depositional mechanism. However, carbonate mineralogy similar to BVC globules and breccia cements (dolomite + huntite + magnesite) can form from progressive carbonate deposition (cfr. Fig. 2) in a range of different environments including evaporative lakes [14] and hydrothermal alteration of ultramafic rocks. Thus the similar mineralogy and geological setting for BVC, ALH84001 and Comanche carbonates does not by itself imply identical temperature conditions (i.e. cryogenic vs hydrothermal) during carbonate deposition.

**References:** [1] Skjelkvåle B. L. et al. (1987) *J. Volc. Geoth. Res.* 37, 1-19 [2] Amundsen H. E. F. (1987) *Nature*, 327, 692-695. [3] Treiman A. H. et al. (2002) *EPSL* 204, 323-332. [4] Steele A. et al. (2007) *Meteorit. Planet. Sci.* 42, 1549-1566. [5] Blake D. et al. (2011) This Volume. [6] Morris R. et al. (2011) This Volume. [7] Nesbitt H. W. (1990) *Geochem. Soc. Spec. Publ.* 2, 355-371. [8] Wadhams J. L. et al. (2000) *Hydrol. Process.* 14, 1767-1786. [9] Arnorsson S. et al. (2002) *GCA* 66, 4015-4046. [10] Zak K. et al. (2007) *Quat. Int.* 187, 84-96. [11] Zak K. et al. (2004) *Chem. Geol.* 206, 119-136. [12] Socki R. A. et al. (2003) *LPSC* 34, Abstract # 1938. [13] Niles P. B. et al. (2004) *Sec. Conf. Early Mars*, Abstract # 8043. [14] Camur M. Z. and Mutlu H. (1996) *Chem. Geol.* 127, 313-329.