

# Characterization of Bockfjord Volcanic Complex Carbonates: Implications for Formation Process and Potential as Martian Analog

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Carbonates in igneous rocks from the Bockfjord Volcanic Complex (BVC), Spitsbergen Island, are a potential terrestrial analog for Martian carbonates because they include globular, chemically zoned deposits similar to those found in the Martian meteorite Allan Hills 84001 [1]. BVC carbonates as Martian analogs can potentially help improve our understanding of the habitability of ancient Mars because carbonates are closely related to both aqueous environments and the atmosphere [2], but the availability of Noachian Martian carbonate samples is limited to ALH 84001, a unique meteorite without geological context. However, detailed studies of BVC carbonates are limited and their formation mechanism is still under debate [1,3]. In this study, the mineralogy and alteration fluid condition (redox potential and acidity) of a sample of carbonate-bearing basaltic breccia from the BVC are characterized with the aim to reconstruct the formation process and environment and to evaluate their validity as a Martian analog. Mineralogy was determined from elemental composition measured using scanning electron microscope and energy-dispersive X-ray spectroscopy (SEM-EDS). The analysis revealed a complete set of mineral record of the carbonate formation process: unaltered host rock containing mainly clinopyroxene crystals, some larger olivine and orthopyroxene crystals, and magnetite grains in a feldspathic mesostasis; carbonate globules with different Fe contents but usually Fe-rich rims; and silicate byproducts including a silica phase, zeolite, and talc. The silicate byproducts are better preserved than the trace amount present in ALH 84001 [4], and their location between the host rock and carbonates suggests that they deposited before the carbonates (Fig. 1).

The oxidation state of S, a redox-sensitive element, in the carbonates was measured as a proxy for the redox condition of the alteration fluid using X-ray absorption near-edge structure (S-XANES). Linear combination fitting (LCF) of the collected spectra with those of reference materials (Fig. 2, Tab. 1) indicates that carbonate-associated sulfate is the dominant S species in the carbonate globules, which is consistent with previous S-XANES results from ALH 84001 carbonates [5]. Our XANES data suggest that carbonates in the two samples formed under similar fluid conditions. Reduced S species are also found in the BVC carbonate sample. Iron sulfide grains are widely distributed in the alteration phases but not in the host rock, suggesting a secondary origin. Organic sulfides are found in the Fe-rich rims of carbonate globules (Fig. 3), possibly associated with magnetite in magnetite-macromolecular carbon assemblages previously reported in both ALH 84001 and xenolith BVC carbonates [6].

[4] recently reported a talc-like phase, silica, and magnetite in ALH 84001. Our results suggest BVC carbonates are a good analog for Martian carbonates beyond similarity in appearance since similar formation fluid conditions and silicate byproducts possibly mean a similar formation process. We also identified the sequence of deposition of alteration products as: silicates → carbonates → Fe-rich phase (possibly magnetite) and reduced, S-bearing organics. The sequence records the evolution of the formation environment during water-rock interaction.

## References

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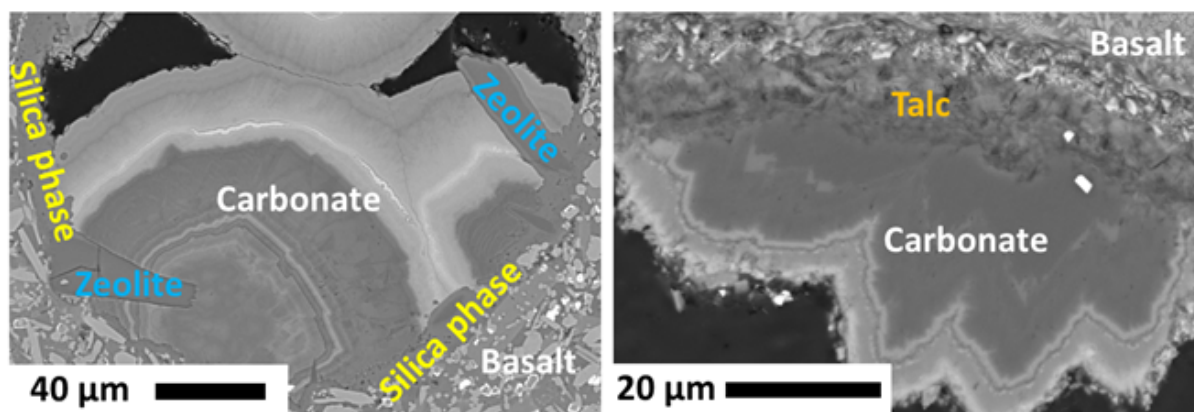


Fig. 1: Silicate byproducts located between the host rock and the carbonates.

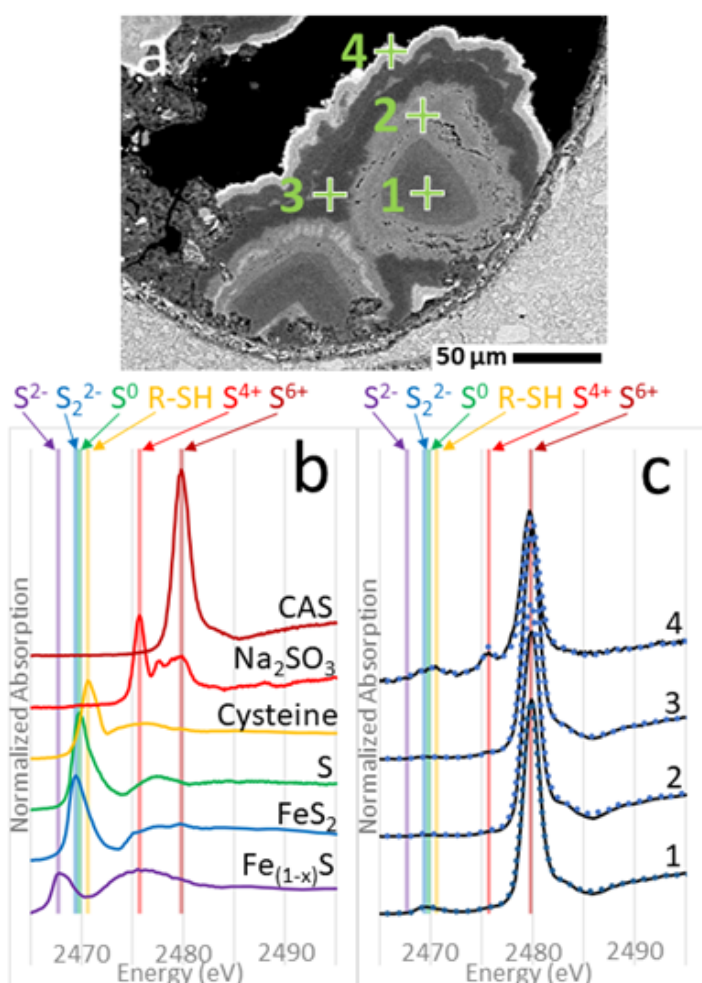


Fig. 2: (a) Backscattered electron image of a carbonate globule with EDS analysis spots labelled. (b) X-ray absorption spectra of reference materials. (c) X-ray absorption spectra (black solid curves) and LCF spectra (blue dotted curves) of the analysis spots in (a).

Tab. 1: LCF results for the analysis spots in Fig. 2 (a)

Spot	1	2	3	4
CAS	93%	96%	96%	60%
Na <sub>2</sub> SO <sub>3</sub>	0%	2%	1%	19%
Cysteine	0%	0%	0%	3%
S	3%	0%	1%	7%
FeS <sub>2</sub>	4%	2%	0%	1%
Fe <sub>(1-x)</sub> S	1%	0%	2%	10%
R value	0.373	0.246	0.166	0.924

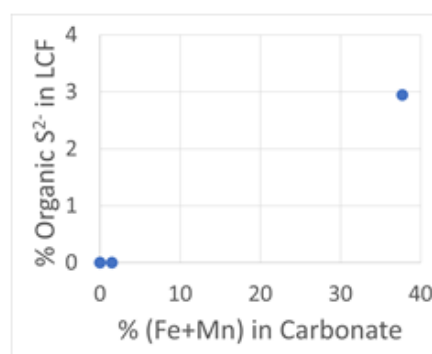


Fig. 3: Plot of the share of organic sulfide (represented by cysteine) in the LCF result against the molar share of Fe and Mn in carbonate cations (Ca, Mg, Fe, Mn).