

Modeling low-grade metamorphic phases on Mars as a function of oxygen fugacity

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1. Introduction

Some of the spectrally observed hydrous minerals on Mars, such as prehnite, epidote, and serpentine are indicative of low-grade metamorphic conditions [1]. Therefore, they must have formed at elevated temperatures, either along a geothermal gradient or as a result of impact- or volcanic-induced hydrothermal activity [2,3]. We investigated the conditions required for the formation of these lowgrade metamorphic phases via phase equilibria calculations, and concluded that at least 2.5 wt % H₂O in the whole-rock composition is required to form prehnite [4]. We have also shown that Ca-Al silicates are very sensitive to even small amounts of CO₂ in the fluid phase, stabilizing carbonates and quartz instead of prehnite and zeolites [5]. Here, we build on these previous works to investigate how variations in oxygen fugacity (fO2) influence metamorphic phase stability fields. Martian basaltic rocks (shergottites and surface basalts) show a large variety of fO_2 ranging from -3.8 to 0.5 Δ QFM (quartz-fayalite-magnetite) [6-8]. The oxygen fugacity during metamorphism is significantly influenced by the oxidation state of the protolith.

2. Methods

1.1 Model parameters

Phase diagrams are calculated with the Gibbs free energy minimization software Perple_X 6.8.4 [9] and an internally consistent thermodynamic data base [10]. The oxides MnO, Cr_2O_3 , and P_2O_5 were excluded from our calculations because of their low abundances and/or limitations of solid solution models. Based on previous studies showing that prehnite and zeolites are not stable in CO₂-rich environments [5], we use H₂O as the only fluid component. All fluid properties are calculated by a Compensated-Redlich-Kwong equation of state [10]. The oxygen fugacity in our model is fixed at the quartz-iron-fayalite (QIF), the quartz-fayalitemagnetite (QFM), and magnetite-hematite (MH) buffers to cover the whole range of redox conditions. We use the following solid solution models: clinopyroxene (Cpx) [10], actinolite (Act). pumpellyite (Pmp), and stilpnomelane (Stp) [11], chlorite (Chl) and white mica (muscovite, Ms) [12], K-feldspar (Ab) [13], plagioclase (Pl) [14], epidote (Ep) [15], biotite (Bt) [16], and ilmenite (Ilm) [17]. Prehnite (prh), stilbite (stlb), laumontite (lmt), wairakite (wrk), quartz (qz), titanite (ttn), rutile (rt), zoisite (zo), and lawsonite (lws) are treated as pure phases.

1.2 Input parameters

We use the composition of Bounce Rock [18], which was analysed by the Mars Exploration Rover Opportunity on Meridiani Planum. It is similar to basaltic shergottite meteorites in texture, mineralogy, and chemistry (composition in wt %: 51.6 SiO₂, 0.74 TiO₂, 10.5 Al₂O₃, 14.4 FeO, 6.8 MgO, 12.1 CaO, 1.7 Na₂O, 0.1 K₂O).

3. Results

Figure 1 shows the calculated phase assemblages for the composition of Bounce Rock at water-saturated conditions and the three oxygen buffers. At fO_2 fixed at the QIF buffer (Fig 1a), the prehnite stability field is the largest, extending to both higher temperatures and pressures than at conditions of the QFM buffer (Fig 1b). At even more oxidizing conditions equivalent to the MH buffer (Fig. 1c), prehnite is not stable, while epidote stability is increased significantly towards both higher and lower temperatures.



Figure 1: Modeled phase stability fields for the composition of Bounce rock at water-saturated conditions and oxygen fugacities fixed at the following buffers: (a) QIF, (b) QFM, and (c) HM. Black solid lines represent possible Martian geotherms. Colors represent the following phase fields: yellow – prehnite; red – pumpellyite; blue – epidote.

4. Discussion and Conclusions

A limited amount of Al in prehnite can be replaced with Fe³⁺, which is currently not considered as a solid solution model and can therefore not be accounted for in our modeling approach. However, both pumpellyite and epidote have the ability to accommodate more Fe³⁺ in their mineral structures than prehnite and their stability fields will therefore always be increased at more oxidizing conditions. In contrast, more reducing conditions are more favorable for the formation of prehnite. The detection of prehnite hence implies metamorphic formation conditions equivalent to \pm QFM or more reducing fO_2 suggesting less oxidized conditions for the protoliths than previously modeled for Martian surface basalts [19].

References

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