IMPACT-GENERATED HYDROTHERMAL SYSTEMS IN MAFIC TO ULTRAMAFIC NOACHIAN CRUST ON MARS.

S. P. Schwenzer[1] and D. A. Kring[1], [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston, TX 77058, USA; schwenzer@lpi.usra.edu; kring@lpi.usra.edu.

Introduction: Frequent impacts [e.g., 1-3] reworked the crust of Mars during the Noachian [4]. The energy of those impacts created thousands of prominent heat sources that supported long-lived, deep-reaching hydrothermal systems [5,6]. In this paper, we investigate how those systems altered the chemistry and mineralogy of Noachian crust.

Previous work and motivation for this study: We previously examined secondary minerals formed by the alteration of the plutonic lherzolithic shergottite LEW 88516 [8-9]. As the Martian crust contains diverse lithologies, we extended our calculations to compositions of more feldspathic shergottites (Dhofar 378) and olivine-rich dunites (Chassigny) [10]. Here we present the missing piece: pyroxenitic compositions that are represented by Nakhla, whose chemistry is taken from [11] with FeO/Fe_2O_3 partitioning as suggested by [12]. The initial fluid composition is a Ca-Mg-Fe-brine that is in equilibrium with Nakhla. We also considered a brine with sufficient K^+ to charge balance SO_4^{2-} at a water/rock (W/R) value of unity. Furthermore, we considered a brine with ~5 times this amount of K^+ (and SO_4^{2-}) to evaluate its affect on alteration assemblages. We calculated results for five temperatures: 13 °C (which is the minimum temperature at 1 km depth according to the geothermal gradient of Mars after [13]) and 50 °C for the low temperature part of the system, i.e., the radially most-distant parts of the system beneath the crater at any time and also the last stage of the system before it returns to ambient thermal conditions. The high-T steps are 150, 200, and 300 °C. Figure 1 displays the 150 °C results.

Results: From the pyroxene-rich Nakhla protolith, pyroxene and/or amphibole (re-)precipitates at the lowest W/R values and from all fluid compositions. Nontronite is an abundant product at intermediate W/R values (Fig. 1).

Nakhla alteration vs. that of other protoliths. Alteration at 150 °C (110 bar) and W/R of 1 creates secondary pyroxene ($Dio_{31.9}Hed_{68.1}$) and amphibole ($Rie_{20.4}Trem_{32.7}Act_{46.9}$) accompanied by serpentine, chlorite, and garnet (andradite). At an intermediate W/R of 1000 the dominating phases are hematite and clay (Mg-nontronite), which are accompanied by quartz and pyrite. If the W/R is very high (100000), hematite dominates the precipitate with pyrite and traces of diaspore.

This pyroxene-rich alteration is unlike that produced from other mafic and ultramafic protoliths (Fig.
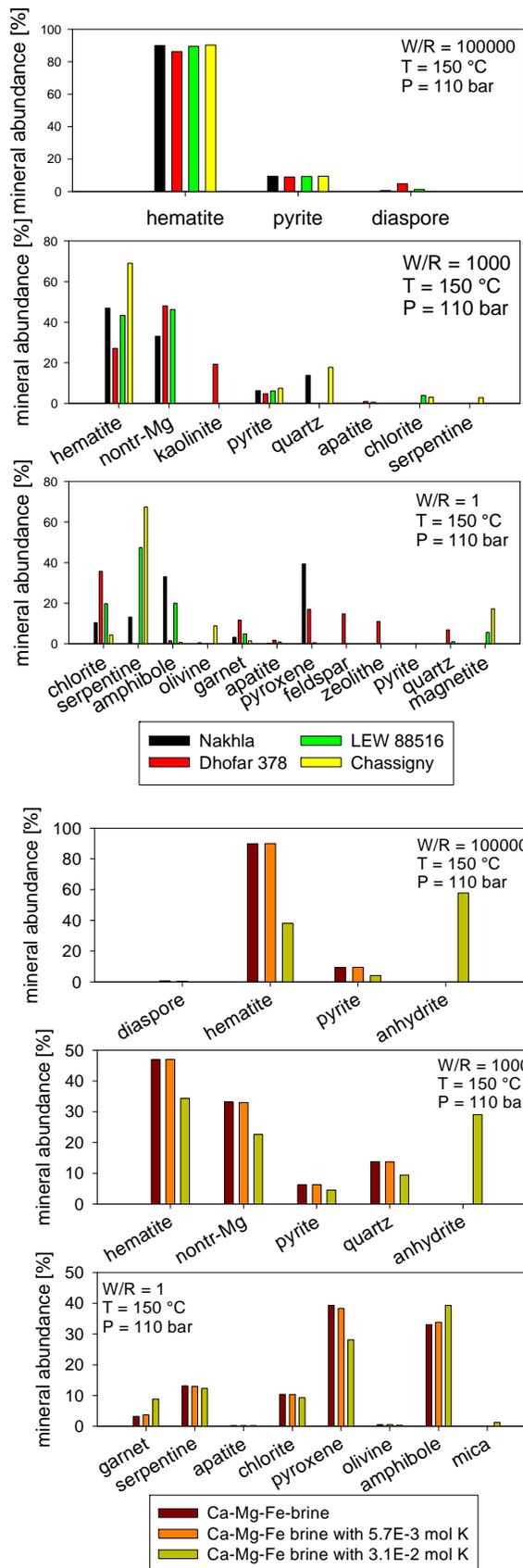
1). At W/R of unity, 28 wt.-% of the alteration assemblage is iron-dominated pyroxene. At this W/R the olivine-rich Martian rock compositions (LEW 88516, Chassigny) form serpentine as the dominating phase, while a more feldspar- (i.e., Al-) rich composition (Dhofar 378) forms chlorite as the dominating phase. Also, the pyroxene in the Dhofar 378 alteration assemblage is more Ca-rich ($Dio_{41.8}Hed_{58.2}$) than that produced by alteration of Nakhla.

At intermediate W/R, hematite is a major phase produced from Nakhla, similar to that from Chassigny. The pyroxene cumulate, however, also forms abundant clay (Mg-nontronite). These abundances (33 wt.-%) are significant, but less than those formed from LEW 88516 (46 wt.-%) and Dhofar 378 (48 wt.-%).

At W/R = 100000 the system is dominated by two factors: the fluid composition and solubility of the least soluble and/or most dominant elements. With all iron-rich protoliths, these assemblages are dominated by hematite and pyrite. If the protolith has sufficient Al, diaspore forms.

Potassium-enriched starting fluid. At W/R = 1 and 150 °C, pyroxene and/or amphibole dominate the alteration assemblage produced from Nakhla (Fig. 2). The pyroxene composition changes from $Dio_{31.9}Hed_{68.1}$ to $Dio_{32.4}Hed_{67.6}$ and $Dio_{35}Hed_{65}$ with increasing K^+ concentration. The amphibole's tremolite content increases, also, while the actinolite content decreases: $Rie_{20.4}Trem_{32.9}Act_{46.9}$ for a K-free brine, and $Rie_{20.5}Trem_{33.0}Act_{46.4}$ and $Rie_{19.3}Trem_{35.8}Act_{44.9}$ for the K^+-enriched brines, respectively. Serpentine is formed at higher temperatures and mica (Fe-celadonite) takes up K at 150 °C.

At W/R = 1000 and T=13 °C the only difference between the K-free and K-bearing solutions is the nontronite that is formed: Mg-nontronite for the K-free brine and K-nontronite for the K-containing brines. At 150 °C (Fig. 2), Mg-nontronite is the product for all starting fluids and anhydrite precipitates from the brines with the highest K^+ (thus SO_4^{2-}). At 300 °C all three brines form anhydrite, with the amount depending on the SO_4^{2-} content of the solution. All three systems also form hematite as a dominating phase, with the hematite decreasing with increasing K^+ and SO_4^{2-} content (80, 62, and 36 wt.-%, respectively). Serpentine shows the opposite behaviour and increases with increasing K^+ and SO_4^{2-} content (~8 in the first two runs, and 35 wt.-% in the most K^+-rich run).

Figure 1 (top of opposite column). Comparing alteration minerals formed from Nakhla with alteration minerals formed from Dhofar 378, LEW88516, and Chassigny.

Figure 2 (bottom of opposite column). Comparing alteration minerals formed from Nakhla with a K-free Ca-Mg-Fe brine with alteration minerals formed from Nakhla with K-bearing brines.

At W/R = 100000 the dominating phase is goethite (13 °C) or hematite (150 and 300 °C). The K ion is bound in nontronite at 13 °C: while the alteration products of Nakhla with our K-free starting fluid form Mg-nontronite, the clay phase is K-nontronite in the calculations with higher potassium concentrations. At higher temperatures K^+ stays in solution; however, the higher SO_4^{2-} concentration causes anhydrite to form where the K^+ (and thus SO_4^{2-}) concentration is highest.

Conclusion: At low W/R, altered pyroxenites form secondary pyroxene and amphibole, rather than the chlorite- and serpentine-rich assemblages produced from other protoliths. Smectite (including nontronite) forms from all mafic and ultramafic lithologies at W/R values of order 10^2. If significant K^+ and SO_4^{2-} occur in the fluid, then anhydrite precipitates at W/R of a few hundred to 100000. Hematite is abundant at the highest W/R values. These alteration assemblages are similar to those deteced by OMEGA and CRISM. We also note that secondary pyroxene may be a product of alteration and, thus, that it may contribute to the total amount of pyroxene found on Mars [14].

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