MODELING LOW-GRADE METAMORPHIC PHASES OF SEDIMENTARY ROCKS AT GALE CRATER, MARS.

S. Benaroya[1,2] and J. Semprich[1], [1] Lunar and Planetary Institute, Universities Space Research Association, Houston, TX 77058, [2] Department of Earth and Planetary Science, Rutgers University, Piscataway, NJ 08854.

Introduction: The majority of hydrous minerals on Mars are associated with surficial processes [1, 2]. However, phases detected from orbit such as prehnite, epidote, and serpentine are indicative of low-grade metamorphic conditions [1]. The higher temperatures required for their formation could have derived from an elevated geothermal gradient or volcanic/impact-induced hydrothermal systems [3,4]. A better understanding of the formation conditions of alteration phases is crucial to identify areas with high water activity and hence possible habitable environments on Mars.

Previous studies have applied phase equilibria to model the detected low-grade metamorphic minerals for basaltic and ultramafic conditions [4,5]. Here, we study mineral assemblages for a larger compositional range using three bulk rock compositions from Gale Crater, which could be representative for hydrothermal alteration of sedimentary rocks elsewhere on Mars. We investigate the effects of variations in pressure, temperature, water content, and fluid composition.

Methods: Phase diagrams are calculated using the Gibbs free energy minimization software Perple_X 6.8.6 [6] and an internally consistent thermodynamic data set [7]. MnO, P_2O_5, Cr_2O_3, SO_3, and Cl are excluded due their relatively low abundances and/or incomplete set of solid solution models. The sum of all considered oxides is normalized to 100 % by Perple_X. We compute phase equilibria for three different compositions at 0-0.5 GPa and 150 °C – 450 °C. Fluid is either treated as pure H_2O or as a mixture of H_2O and CO_2. All fluid properties are defined by a Compensated-Redlich-Kwong equation of state [7]. The amount of Fe^{3+} is represented by the O_2 content, which is set to 0.15 wt. %. The following solid solution are included: Actinolite (Act), White Mica (Ms), Stilpnomelane (Stp), Pumpellyite (Pmp) [8], Clinopyroxene (Cpx), Orthopyroxene (Opx), Magnesite (Mgs), Dolomite (Dol), Olivine (Ol) [7], Epidote (Ep) [9], Chlorite (Chl) [10], Spinel (Spl) [11], K-feldspar (Kfsp) [12], Plagioclase (Pl) [13], Biotite (Bt) [14], Serpentine/Antigorite (Atg) [15], and Ilmenite (Ilm) [16]. Talc (Tlc) was treated as ideal solution while analcime (anl), laumonite (lmt), stilbite (stb), wairakite (wrk), prehnite (prh), titanite (ttn), quartz (qz), lawsonite (lws), rutile (rt), and nepheline (nph) were added as pure phases. Vesuvianite and garnet end-members were excluded. We calculated mineral assemblages for the starting compositions of three analyses from MSL Curiosity in Gale crater on Mars (Table 1) with highly variable oxide contents. The Windjana (WJ) sample is a very fine sand-, silt- or mudstone [17]. The Mount Remarkable (MR) sample has been identified as a massive coarse sandstone [18]. Buckskin (BK) is a light-colored fine to medium grade mudstone/siltstone [19].

Table 1: Bulk Compositions

	Windjana[16]	Mount Remarkable[17]	Buckskin[18]
SiO_2	39.3	47.1	68.1
TiO_2	1.15	0.8	1.51
Al_2O_3	5.69	11.4	6.1
FeO	26.50	19.4	4.4
MgO	12.67	8.4	3.45
CaO	4.91	5.9	3.87
Na_2O	0.4	1.7	2.2
K_2O	3.65	5.3	0.82

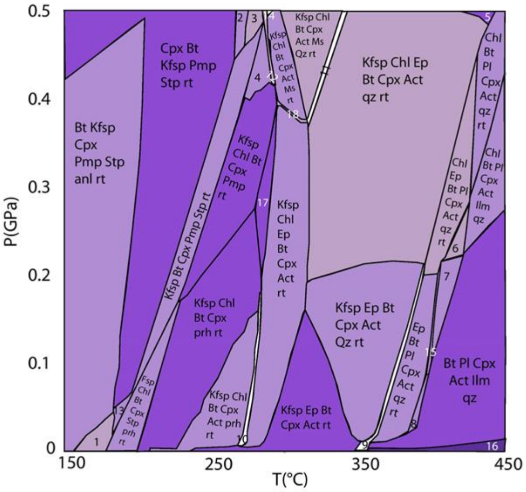

Figure 1: P-T pseudosection for Mount Remarkable composition at water saturated conditions.

Results:. Pseudosections were computed for all three compositions. Fig. 1 illustrates the stable mineral assemblages for the water-saturated Mount Remarkable composition. Pumpellyite is stable from 150-250 °C at all pressures. Prehnite is present at higher temperatures (200-250 °C) and is restricted to pressures below 0.25 GPa. In WJ serpentine is stable only at temperatures below 300 °C, but at all pressures. In BK pumpellyite is restricted to temperatures of 200-250 °C and pressures of 0.25-0.45 GPa. Zeolites are stable at all pressures but restricted to lower temperatures (150-250 °C). At higher T (>250 °C), epidote is stable at all pressures. Fig. 2

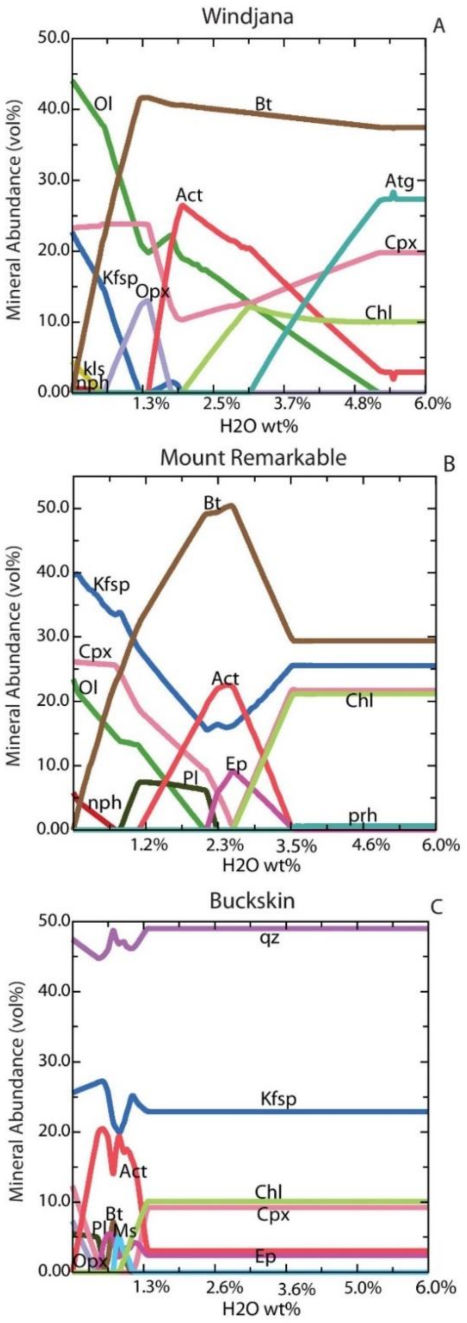

Figure 2: Mineral proportions (vol%) for the Windjana (A), Mount Remarkable (B) and Buckskin (C) compositions at 250 °C (13 °C/km geotherm).

shows mineral proportions as a function of water content at a temperature of 250 °C (and P of ~0.2 GPa) on a 13 °C/km geotherm. The WJ composition is dominated by olivine and clinopyroxene at low water content before transitioning to biotite, actinolite, and serpentine at higher water contents. MR is primarily K-feldspar, clinopyroxene and olivine at water-poor conditions. Actinolite, chlorite and small amounts of prehnite occur at higher water contents. The BK composition is dominated by quartz and K-feldspar with chlorite, epidote and actinolite at water-rich conditions. A small amount of CO_2 added to the fluid leads to the precipitation of a significant amount of carbonates in all compositions.

Discussion and conclusions:

Our calculations assume complete equilibrium, which is not always achieved in geological processes, in particular at low temperatures. Martian rocks, however, may only be partially altered depending on water availability and temperature. We report similar hydrous phases for Martian sedimentary rocks as in previous studies of basaltic and ultramafic compositions [4,5]. However, their abundance and assemblages vary. WJ has silica contents comparable to ultramafic rocks but also increased K_2O and is therefore dominated by biotite and serpentine at high water content. Prehnite forms only in MR (similar to Martian basalts) and requires >3.5wt.% H_2O, as well as >250°C. The formation of prehnite is strongly dependent on composition, temperature, and water content. Serpentine requires at least 3 wt.% H_2O and is only stable in WJ due to its silica-poor composition. Epidote forms in both MR and BK in the range of 0.6-6 wt.% H_2O depending on temperature and is therefore not only present at greenschist facies conditions. Actinolite is a major phase in all modeled compositions and is stable at varying water contents. Actinolite has only been identified in one spectral study [20] but it has spectral features that may make it difficult to be detected from orbit [5]. In accordance with previous studies [4, 21], we find that even small amounts of CO_2 in metamorphic fluids stabilize carbonates, feldspar, quartz, and mica at the expense of other hydrous minerals. The presence of prehnite and zeolites hence implies that they formed in a CO_2-poor environment either not in contact with the Martian atmosphere or during early Mars.

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