INTENSIVE AND BULK COMPOSITIONAL CONTROLS ON HYDROTHERMALLY ALTERED MAFIC ROCKS - IMPLICATIONS ON THE STUDY OF MARTIAN HYDROTHERMAL METAMORPHISM

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The occurrence of hydrothermally altered rocks on Mars has important implications with regard to exobiology [1,2]; the planetary CO₂ budget [3] and petrology. It is highly probable that hydrothermally altered Martian rocks will contain mineral assemblages similar to those found in metamorphosed mafic rocks on Earth and could be assigned to the zeolite-, prehnite-pumpellyite-, prehnite-actinolite-, pumpellyite-actinolite-, or greenschist-facies. The mineralogy of metamorphosed mafic rocks is very sensitive to changes in their intensive conditions, such as pressure (P) and temperature (T). Unfortunately, most terrestrial metamorphosed mafic rocks contain high-variance assemblages (phase-rule degrees of freedom > 3) that can not be used individually to estimate P or T. When Martian samples are returned to Earth during the early part of the next century, it is highly probable that they will contain high-variance assemblages. Fruitful interpretation of these samples will require that they be placed in petrological context with their terrestrial counterparts. Fortunately, the terrestrial high-variance assemblages typically exhibit a systematic correspondence between effective bulk composition and mineral assemblage, and can be used to interpret the P, T and fluid composition during metamorphism [4,5,6].

Terrestrial Analogs

A highly illustrative and useful way to study metamorphosed mafic rocks is to represent the compositions of coexisting phases that show variation in their chemical composition (such as pumpellyite (Pmp), chlorite (Chl), actinolite (Act), and prehnite (Prh)) by projecting their compositions from isocompositional and ubiquitous phases. Typically the ubiquitous phases are epidote (Epi), quartz, albite, and water. Mineral assemblages are projected onto the composition plane MgO - FeO - (Al₂O₃ + Fe₂O₃ - 0.75CaO - Na₂O). Assemblages from various localities around the Earth can be grouped into four basic chemographies that represent different intensive conditions of metamorphism (see Figure 1). These chemographies can be characterized by the Mg# (MgO/(MgO+FeO) of Chl and its coexisting phases. Group 1 assemblages contain Chl + Pmp over a wide range of Mg# (0.4 to 0.8). Group 2 assemblages contain Chl + Pmp in Mg-poor bulk compositions (Mg# < 0.6) and Chl + Act in Mg-rich bulk compositions (Mg# > 0.6) and a very narrow or vanishing field of Chl + Pmp + Act at intermediate Mg#. Group 3 assemblages have a wide 3-phase field of Chl + Pmp + Act. Group 4 assemblages also contain Chl + Pmp + Act and are differentiated from Group 3 by containing Al-rich Pmp. Crossing tie-lines and mass balance calculations indicate that each group represents different intensive conditions of metamorphism. Group 1 samples occur in metamorphosed ophiolites or arc ophiolites that have undergone sub-seafloor hydrothermal metamorphism at relatively low pressures. Group 2 and 3 samples occur in rocks of varied provenance that have been traditionally assigned to the pumpellyite-actinolite facies. Group 4 samples occur in blueschist terrains such as the high P, Sanbagawa Belt of Japan, and most likely represent the highest P of metamorphism.

Martian Hydrothermal Metamorphism

Various authors have proposed, based on physiochemical modeling, remote sensing or the study of Martian simulants, that rocks and minerals on Mars have been hydrothermally altered [7-12]. It is highly probable that Martian metamorphism may have occurred under comparable P and T conditions as some of the terrestrial analogs described above. However, there may be two significant compositional differences 1) bulk-rock Mg# and 2) the chemical potential of carbon dioxide in the fluid (μCO₂). The chemical composition of Martian fines, analyzed by the Viking landers, is iron-rich and bulk rock Mg# may be as low as 0.2, depending on ferrous-ferric ratios [13]. SNC meteorites are equally iron rich. Treiman [14] has inferred a parent magma for the Nakhla meteorite, based on magmatic inclusions, that plots (on the Epi-projection) in the
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Chl + Pmp field for all four groups \( (\text{AF}^* = -0.07, \text{Mg}^\# = 0.17) \). Gooding [15] has proposed that the aqueous fluid phase responsible for preterrestrial precipitation of salts and clays in SNC meteorites was oxidizing and contained dissolved C, S, and Cl (and probably Na, Mg, P, K, and Ca). Interaction of such a fluid with a Martian basalt would increase ferric iron content and bulk-rock Mg\(^\#\) permitting actinolite to be stable. The stability of mineral assemblages in hydrothermally altered mafic rocks are very sensitive to the CO\(_2\) content of the aqueous fluid. Zeolite-, prehnite- or pumpellyite-bearing assemblages are typically stable when \( \mu \text{CO}_2 \) is very low [16].

Our present day understanding of Martian metamorphism is highly speculative. However, recent advances in our knowledge of the low-temperature metamorphism of terrestrial basalt provide useful models to help in interpreting very limited Martian data, analogous to the fashion in which terrestrial igneous rocks (e.g. komatites) are interpreted in the model of SNC meteorites.


Figure 1. Epidote projection of metamorphosed mafic rocks; \( \text{AF}^* \) is \( (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - \text{Na}_2\text{O} - 0.75\text{CaO}) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - \text{Na}_2\text{O} - 0.75\text{CaO} + \text{MgO} + \text{FeO}) \); group one is from the Macuchi Formation of Ecuador [17]; group two is from the Smartville Complex of California [18]; group three is from the paratectonic Caledonides of Wales [19]; group four is from the Sanbagawa metamorphic belt of Japan [20].