CRUSTAL DIFFERENTIATION ON MARS: INSIGHTS FROM ROCKS ANALYZED BY THE MER ROVER SPIRIT.
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Introduction: After formation of the primary martian crust as the result of some extent of early planet-wide partial melting, the crust likely underwent further evolution upon input of magmas from the martian mantle to form a secondary crust [1]. As magmas were variably emplaced and extruded, a thin primary crust would have evolved compositionally towards the bulk composition of the ascending mantle-derived magmas, and the surface composition would increasingly reflect the new bulk crust composition. This is similar to what is seen in oceanic regions of Earth where a relatively homogeneous crust is formed. However, on Mars, the primary and secondary crusts are considered to be quite thick. Even the earliest crust formed at 4.5 Ga has been proposed to be 20-30 km thick [2, 3], with a secondary crust 33-81 km thick [4] produced in the subsequent few million years [3]. Magmatism on Earth that requires ascent through thick crust is confined primarily to continental hotspot magmatism and the processes at work there may have direct relevance to martian magmatism and crustal evolution.

High crustal thickness would have made it likely that mantle-derived magmas underwent a protracted and probably sporadic period of ascent on Mars, that is, ascent punctuated by periods of ponding and crystallization. Evidence from liquid lines-of-descent of bulk lava compositions and mineral compositions in continental hotspot suites on Earth, show pervasive evidence of polybaric histories involving such steps, with fractionation at the base of the continental crust, loss and ascent of residual liquids, further ponding steps at intermediate levels within the crust until a final cooling and crystallization stage at shallow levels prior to eruption [5, 6] (shown schematically in **Fig. 1)**.

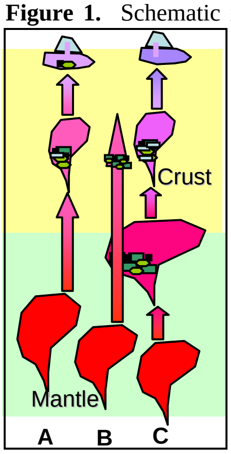

Figure 1. Schematic illustrating polybaric fractionation of magma ascending from the mantle though thick crust. Periods of ponding and crystallization may be punctuated by ascent of residual liquid. In this way the deep crust becomes enriched in cumulate material and the shallow crust in evolved magma compositions. Path **A** involves cooling and ascent to mid-crustal levels, crystallization and ascent of residual melt; Path **B** involves ascent of mantle-derived magma with the addition of cumulate xenoliths; Path **C** involves multiple ponding stages near the deep crust and at intermediate levels.

Without mixing processes such as plate margin-related orogenesis, such a crystallization history would result in crustal stratification with a preponderance of cumulus material at depth and residual liquids in shallower levels. The nature of any such stratified crustal heterogeneity is of particular current importance in light of the recent efforts to use surficial data from the gamma ray spectrometer onboard the 2001 Mars Odyssey spacecraft to assess the bulk secondary crust compositional characteristics (e.g., [7]). However, beyond the anticipated effects on Mg#, it is difficult to predict which chemical changes would characterize this stratification, as this depends upon knowing the liquid line-of-descent and mineral crystallization history of Martian melts.

We have undertaken an experimental investigation in order to assess the nature of possible cumulus material and residual liquids that would arise if magma compositions represented by the martian surface lithologies analyzed by the MER Rover Spirit (which show minimal weathering and clear igneous texture) fractionated at deep, intermediate, and shallow levels of the martian crust. Such studies emulate the processes of Fig. 1 and can provide information on possible igneous stratification of the crust. This information is being coupled with that provided by the SNC meteorites in order to develop a comprehensive view of martian magmatism and the compositional evolution of the martian deep and shallow crust. Comparison of the results with terrestrial hot-spot magmas may provide insights into the nature of the less-evolved magmas, as it is anticipated that, as on Earth, in regions of thick continental crust, primitive magmas are exceedingly rare and access to information regarding their source region is limited.

Humphrey-like liquids: The Gusev picrobasalts Humphrey, Mazatzal, and Adirondack appear to be relatively unweathered olivine-rich basalts [8, 9]. In spite of their olivine-rich nature they are considered by some to represent liquids and even primitive liquids (e.g., [10]). Although questions have been raised regarding these interpretations (e.g., [11]), experiments were conducted on the Humphrey composition assuming that it represents a magma composition. These experiments focused on determining the liquid line-of-descent and the nature of possible cumulus minerals forming under "dry" conditions (<0.1 wt% water) and with 1 wt% dissolved water crystallizing during fractionation near the base of the martian crust. Experiments conducted under "dry" conditions [12] have shown that olivine and chromite precipitate out early and by the time 20% crystallization takes place, pigeonite would join the fractionation assemblage (**Table 1, Fig. 2**). The liquid by this stage would still be basaltic, but would show significant decreases in silica and MgO abundance, and increases in FeO, alkalis, CaO, alumina, TiO_2, and P_2O_5 (**Fig. 3**) contents. Ascent of residual liquid at 1200°C or lower would result in significant compositional differences between the material added to the lower vs. upper crust. Importantly, even after 80% crystallization, the residual liquid is basaltic and not andesitic or rhyolitic (**Fig. 3**).

Table 1. Phases formed during crystallization of liquid of Humphrey composition "dry" at 9.3 kbar pressure.

Temperature	Phases
1200	Olivine (Fo_{65}) Spinel (Cr-Al-Fe) Pigeonite ($En_{58}W_{18}Fs_{23}$) Glass
1150	Olivine (Fo_{53}) Spinel (Cr-Al-Fe) Pigeonite($En_{55}Wo_{15}Fs_{30}$) Plagioclase ($An_{45}Ab_{54}Or_1$) Glass
1120	Olivine (Fo_{47}) Spinel Pigeonite ($En_{43}Wo_{25}Fs_{32}$) Plagioclase ($An_{43}Ab_{56}Or_1$) Glass

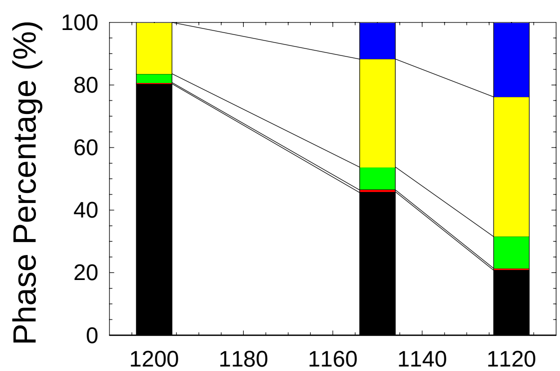

Figure. 2. Experimentally determined phase abundances at the temperatures of Table 1 (*phases*: **olivine**, **pigeonite**, **plagioclase,** **melt).**

The Fe-enrichment evidenced in residual liquids of Humphrey crystallized "dry" is also observed on Earth in the fine-grained FTP (Fe-Ti-P-enriched) plutonic rocks of the anorthosite complexes (e.g., of the Laramie Anorthosite Complex, [13]) with as much as 22 wt% FeO_T and in lavas of the Snake River Plain (e.g., [14, 15]). As shown by [16], Fe-rich liquids with Fe-contents of 17 wt% can be generated from ordinary continental tholeiite with 11 wt% Fe by crystallization at the base of the terrestrial crust. This Fe-enrichment and silica depletion is very pressure sensitive and was obtained experimentally at 7.3 and 9.3 kbar, but not at 4.3 kbar. Ascent of such liquid to shallow levels involves leaving a more Fe-Ti-P-poor, silica-rich residue of olivine, clinopyroxene, and plagioclase in the lower crust. If a significant amount of tholeiitic magma with less than ~0.4 wt% H_2O ponded at the base of the crust or in the lower crust on Mars, a highly stratified deep and shallow crust could be produced.

Experiments at higher water content are ongoing. As anticipated, based on experiments on terrestrial compositions [17], with 1 wt% water, residual liquids are not Fe-enriched.

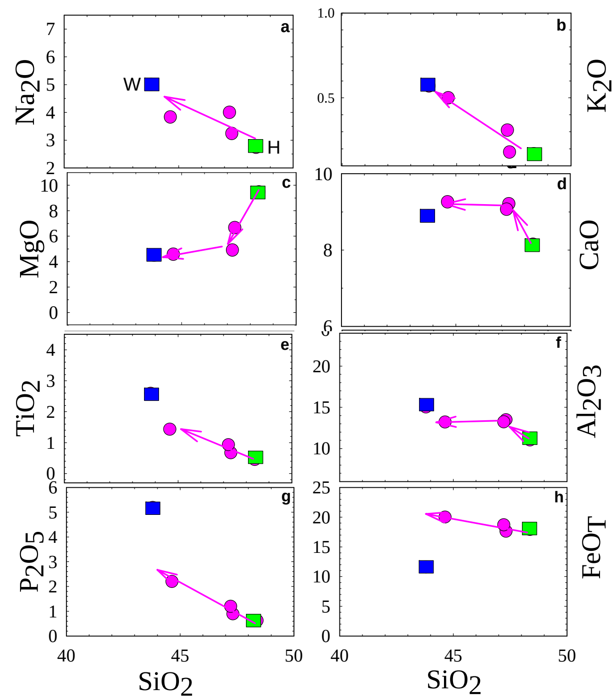

Figure 3. Experimental residual liquids from an initial liquid with Humphrey composition (H) crystallized at 9.3 kbar "dry". Arrows point in the down-temperature direction. Wishstone composition (W) is shown for comparison.

Backstay-like liquids: Backstay is an aphanitic rock from the Columbia Hills that shows a high probability of reflecting a liquid composition. [9, 18] noted that Backstay shows strong compositional similarities to hawaiite from the sodic silica-saturated alkalic hotspot suites on Earth. Such hawaiite is compositionally evolved relative to the picrobasalts of Gusev Crater and Irvine of the Columbia Hills [9] and not likely reflective of a primitive composition. Nonetheless, it can give access to the nature of evolved materials that could be added to the upper crust. On Earth, such suites fractionate from mantle-derived magma primarily at the base of the crust and show evidence of some low-pressure crystallization of residual liquid, perhaps in the shallow subvolcanic regime. Experiments conducted on terrestrial hawaiite [5] indicate that the presence of >0.4 wt% water in a terrestrial tholeiite and crystallization at pressures between 7 and 11 kbars is necessary to produce the overall sodic silica-saturated alkalic path. Crystallization experiments under these conditions on melt with Backstay composition have been conducted. These experiments yielded residual liquids that evolve towards Fe-depletion and alkali and silica enrichment (**Fig. 4**) when fractionating at the base of the crust. With about 50% crystallinity the liquid has evolved to 60% silica. Small degrees of silica-rich melt will likely form at lower temperatures. Addition of the residual liquids to the upper crust would not increase Fe content but primarily alkali and silica contents. Importantly, if the Earth can be considered an analog to Mars, such alkalic magmas are volumetrically minor on Mars.

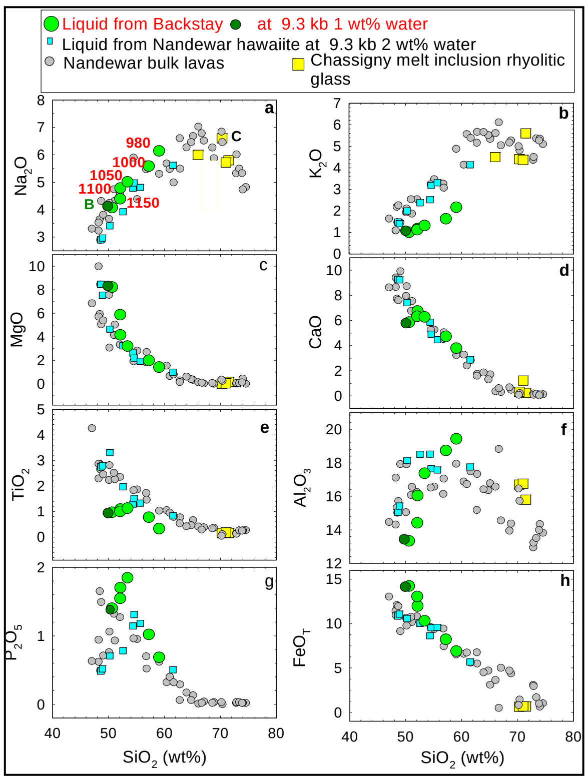

Figure 4. Liquid line-of-descent of Backstay (B) composition liquid crystallized at 9.3 kbar and 1 wt% bulk water (green circles) compared with lavas from the Nandewar volcano (gray circles, [19]). Experimental residual liquds from a Nandewar hawaiite [5] (blue squares) and rhyolite glass from Chassigny (C) melt inclusions (yellow squares) are shown for comparision.

Table 2 shows the mineral assemblages crystallizing from Backstay melt. If the residual liquids leave a cumulus assemblage beind in the lower crust, this assemblage would be dominated by olivine, pyroxene, and chromite.

Table 2. Experimental assemblage at the temperatures indicated in **Fig. 4**.

***T* (oC)**	***EXPERIMENTAL ASSEMBLAGE of** BACKSTAY **hawaiite 9.3kbar; 1 wt% H_2O***
1150	**Olivine** (Fo69) **Chromite**
1100	**Olivine** (Fo64) **Chromite** **Pigeonite** (En59Wo13Fs28) **Orthopyroxene** (En67Wo4.5Fs29)
1050	**Olivine** (Fo60) **Chromite** **Orthopyroxene (**En63Wo4.5Fs33) **Clinopyroxene** (En50Wo28Fs22)
1000	**Olivine** (Fo54) **Orthopyroxene** (En58Wo4.8Fs37) **Ti-amphibole** **Plagioclase** An38Ab60Or2
980	**Olivine** (Fo49) **Orthopyroxene** (En57Wo4Fs39) **Ti-amphibole** **Plagioclase** An35Ab63Or2 **Apatite**

Evidence for crystal accumulation in the deep Martian crust: Is there any direct evidence for a cumulus mineral-enriched lower crust? The SNC meteorites contain a variety of cumulate rocks that range from dunites to pyroxenites to wehrlites. But evidence for the depth at which they crystallized is elusive.

Extensive study of the Chassigny meteorite has provided some pressure constraints [20]. We propose that the Chassigny meteorite is a fragment of a cumulus layer that formed in the lower crust by a fractionating magma which was incorporated as a cognate nodule or xenolith im ascending magma and brought to shallow levels (path B of Fig. 1). Permissive evidence for this is three-fold. First, experiments conducted on Backstay suggest that a magma of Backstay composition could represent the kind of liquid that was trapped in the Chassigny melt inclusions only if crystallization took place in the lower crust. At such depths, Backstay is saturated in the cumulus minerals of the Chassigny meteorite (see liquidus assemblage of **Table 2**.). Furthermore, Backstay can produce the observed melt inclusion mineral assemblage (**Table 2**) during further crystallization only at such depths. (By about 30 km depth on Mars this assemblage is no longer obtained.) Second, the observations of [20] indicate that the Al/Ti ratios in the interstitial and melt inclusion augite are consistent with pressures between 7 and 9 kbar. And third, the observations of [20, 21] that the Chassigny melt inclusion feldspars are consistent with low solidus temperatures and that both pyroxene and feldspars show continued compositional changes at subsolidus temperatures suggest conditions deep enough for high volatile solubilities as well as for slow cooling.

If the Chassigny dunite was produced by a typical fractionation process in the lower crust of Mars, then the lower crust may contain a significant amount of accumulated material and be compositionally quite distinct from the upper crust. The accumulated minerals may be quite magnesian as evidenced by the cumulus phases of meteorites such as NWA2737.

Implications: If the meteorites and martian surface lithologies primarily reflect evolved rather than primitive compositions and evolution took place primarily by fractionation within the crust of "dry" tholeiitic magma then

- application of the Fe content obtained from GRS data would be restricted to the upper crust as this Fe content would not be reflective of the cumulate-rich Fe-poor lower crust.
- high FeO content is not required of either the liquids parental to the Fe-rich residual melts or the mantle source region since high FeO_T contents are readily obtained from "ordinary" tholeiitic basalts with 11 wt% FeO_T..
- the differences between the martian meteorite and surface GRS compositions for the crust may reflect heterogeneity of the crust and a primary origin of the meteorites at depth which includes incorporation of variable amounts of accumulated material
- the surface lithologies can be exclusively basaltic with low silica contents and high Fe, Ti, and P contents even though they have undergone significant extents of fractionation and are thus "highly evolved".
- cumulate nodules could be commonplace on the surface brought up with ascending residual magmas.
- primitive magmas would be rarely found on the surface, most of them having undergone differentiation to some extent before reaching the surface. Such residual liquids would make poor probes into the martian mantle magmatic source regions
- martian magmatism can be compared most reasonably with terrestrial continental hotspot/early rift magmatism rather than MOR or subduction zone magmatism.
- addition of residual liquids from fractionation of magmas with >~0.5 wt% water will primarily enrich the upper crust in alkalis and silica. Since the the crust is primarily basaltic, alkalic magmatism on Mars is likely rare.
- any martian dichotomy in crustal thickness would suggest more Fe-enriched surface materials in regions of thicker crust and less Fe-enrichment in regions of thinner crust since Fe-enrichment of residual melts increases with depth of fractionation.

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