PETROLOGICAL EXPLANATIONS FOR THE MAGNETIC ANOMALIES DETECTED ON MARS.

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Introduction: The discovery of crustal magnetization in some locations on Mars [1,2], particularly the southern highlands, has major implications for the early evolution of Mars. The east-west-trending linear features in the southern highlands with alternating polarity may be the result of an early seafloor spreading process similar to that seen on Earth today [2]. The larger magnetization of the martian crust compared to the Earth can be attributed to its higher Fe content [3,4] and the proposed minerals associated with this magnetization are multidomain hematite and pyrrhotite [2]. In this study, we discuss the petrological evolution of basalts on Earth and Mars and suggest processes that may enhance crystallization of magnetic minerals in the martian rocks, thereby accounting for their intense magnetic properties.

Fractionation of Terrestrial Basalts: There are two major types of basalts on Earth: (1) those formed by mantle plumes, such as Hawaii, and (2) midocean ridge basalts (MORB) characteristic of seafloor spreading. The general crystallization sequence in MORB is olivine±spinel, olivine+plagioclase±spinel, and plagioclase+clinopyroxene±olivine. MORB represent the partial melting of lherzolite (ol+opx+cpx) mantle, which has previously undergone a partial melting. Iron enrichment occurs as the magma follows the so-called tholeiitic differentiation trend whereby the early crystallization of olivine and plagioclase increases the FeO content of the residual melt. Eventually, magnetite crystallizes as a result of the increase in FeO content and its appearance causes an increase in the SiO_2 content of the residual liquid. In contrast, Hawaiian tholeiites are compositional distinct from MORB and they are controlled more by olivine crystallization versus olivine+plagioclase in MORB. Hawaiian basalts form by partial melting in an ascending plume, probably beginning at the core-mantle boundary (D'' layer) and therefore, they represent more enriched, less depleted melts than MORB. Alkali and nephelinite basalts are also erupted at Hawaii and they result from small amounts of melting of peridotite under high pressures, compared to larger degrees of melting under intermediate pressures for the Hawaiian tholeiites.

Iceland represents an unusual volcanic setting. Located along the Atlantic spreading ridge, it is a thermal anomaly that produces significant quantities of basalt to create the island. Anorogenic Icelandites are andesitic rocks that form here by fractional crystallization of basalts, in contrast to andesites associated with subduction zones. The composition of sulfur-free rocks measured by the Mars Pathfinder rover APXS instrument is best approximated by these Icelandites [5]. More evolved rocks are also produced at Iceland, including rhyolites; these evolved magmas are best explained as products of partial melting in the crust where water is brought into the deep crust by hydrothermal circulation systems [6].

Two points about these terrestrial basalts and their differentiates are particularly relevant to Mars volcanism and the magnetic anomalies: (1) All of these terrestrial basalts begin with about 10 wt% FeO and 12-16 wt% Al_2O_3; if differentiation occurs dry and at low oxygen fugacities it can build the FeO up to 20 wt%, but only after much of the original magma volume has crystallized (e.g., the Fe-Ti basalts of Iceland [7]). (2) Normally a MORB contains 1-2% Fe-oxides, but it is possible to crystallize greater amounts of an Fe-oxide (at the expense of Fe-silicates) if the magma either contains water or is oxidized or both during differentiation [8].

Martian Basalts and Their Differentiates: Martian basalts, as represented by the SNC meteorites and the parent melts to the cumulate SNC rocks, are relatively low in Al_2O_3 (~8 wt %) and the melts contain from 18 to 25 wt% FeO (i.e., [4]). Crystallization of these melts dry and at low oxygen fugacities produces abundant Fe-pyroxenes and plagioclase later in the crystallization sequence because of the low Al_2O_3 [5, 9]. However, if these magmas could be oxidized, hydrated, or both before crystallization occurred or during crystallization, the amounts of Fe-oxide produced would be greatly increased. This scenario in the basalt eruption environment on Mars could enhance the amount of magnetite by a factor of 4 if just half the FeO were oxidized, and consequently increase the intensity of any magnetic signature relative to what could be obtained from a MORB. Under extreme oxidizing conditions, hematite would be produced, further increasing the magnetization. Interestingly, the S content possible in basaltic magmas also increases with increasing Fe content, and so the Fe-rich martian magmas would also be capable of carrying and crystallizing large quantities of FeS which would enhance the size of the magnetic anomaly. However, to our knowledge there is no indication that the SNC basalts were saturated with FeS near their liquidus, and it would be difficult to have an eruption environment that produced large amounts of Fe-oxides under oxidizing conditions and at the same time produced FeS. Instead, as basaltic magmas become more oxidized, the reduced S which could have crystallized as FeS is oxidized to sulfates and/or a gas phase.

Martian Basalts and Their Eruption Conditions: The data presented above suggests that if SNC magmas are representative of basalts being extruded on Mars during its earliest volcanic history (i.e., prior to 4 Ga when the magnetic field was active [1]), then there are certain sets of eruption conditions where it would be possible to produce very large (by terrestrial MORB standards) magnetic signatures. In order to determine the potential importance of this idea, we must first demonstrate that the SNC magmas were typical of this period of volcanism as well as volcanism later in the history of Mars. Secondly, it is necessary to demonstrate that either water or oxidized conditions could develop in martian basalts as they crystallized at this time. Neither point can be made conclusively, but the one Mars meteorite with a crystallization age >4 Ga, ALH84001, is composed of predominantly low-Ca pyroxene which is similar in composition to Fe-Mg silicates in other primitive SNC meteorites. Therefore, we tentatively suggest that SNC magmas are representative of both old and young Mars basalt volcanism. However, all of these SNC magmas appear to require a fractionation event very early in Mars history, probably associated with core formation, and hence, SNC magmas would not be representative of this earliest period of volcanism.

Are there ways to produce the observed large magnetic anomalies on Mars without requiring a 30 km thick basalt layer? The size of the magnetic anomaly expected from basaltic magmas extruded on the surface of Mars would be enhanced by the high FeO composition indicated for these basalts, but it would also increase with increases in the oxidation state of these magmas as they crystallize. The data from SNC meteorites suggests a Mars oxidation state similar to those in magmas near the Earth's surface, ~QFM oxygen buffer. Although there is some discussion of both higher and lower oxidation states [10, 11], the QFM estimate seems well established. Could higher oxidation states have been induced in some basalts early in the volcanic history of Mars? We can envision this happening if basalt interacted with near-surface ice or water, or with oxidized surface rocks during eruption. Assimilation of either material would increase the oxidation state of the basalt, although energetically assimilation of oxidized surface rocks would be difficult. These scenarios would thus require that either or both the present day oxidized surface and the Mars surface water existed at greater than 4 Ga. Given the geological evidence for the presence of near-surface ice/water and possible water-magma interactions [12, 13, 14], we consider it very plausible to suggest that Mars basalts interacted with this ice- and water-rich, near-surface region during their eruption. In contrast to submarine eruptions on Earth, there probably was not enough water in the martian crust that it served to quench the magma before it could react with the oxidizing water environment.

Discussion: To account for the intensity of these magnetic lineations, a plate thickness of 30 km was calculated based upon the assumption that the composition was that of MORB with similar magnetic properties [2]. There are serious problems with forming and cooling such a thick slab that could retain an intense magnetic signature [15]. It is also possible that the magnetic bands are thinner than the 200 km width assumed for the modeling [2]. MOC images reveal that the cratered highlands are layered [16, 17], which raises the intriguing possibility that there may have been numerous eruptions occurring in the location of the magnetic anomalies. As long as their was sufficient time to recharge the crust with water, the next eruption would interact with the water and lead to oxidized conditions and increased Fe-oxide crystallization. Magnetic sources detected in the northern region [1] could also be explained by similar processes as those we have described for the southern highlands. Eruption of magmas that did not encounter near-surface water would not have produced the required oxidized conditions and enhanced magnetic properties. Whether the east-west trending magnetic lineations are the result of a seafloor spreading mechanism or the interaction of magma with concentrations of near-surface water/ice remains to be shown. A study of surface features that correlate to the enhanced magnetic anomalies may provide insight into any association between likely water-rich regions and magnetic anomalies.

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