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LETTER

The Mars/Earth dichotomy in Mg/Si and Al/Si ratios: Is it real?

JUSTIN FILIBERTO,* HANNA NEKVASIL, AND DONALD H. LINDSLEY

[1]Department of Geosciences, SUNY Stony Brook, Stony Brook, New York 11794-2100, U.S.A.

ABSTRACT

The apparent dichotomy of Mg/Si and Al/Si ratios between terrestrial rocks and Martian meteorites has been interpreted as indicative of major differences between the terrestrial and Martian magma source regions. We suggest that this apparent dichotomy is not robust when compared with partly cumulate and non-cumulate terrestrial igneous material. Terrestrial cumulate intra-plate nodules with similar mineralogy to the SNC meteorites plot in the SNC field in this compositional space and far removed from the "terrestrial geochemical fractionation" line (Earth's crust line) of Jagoutz et al. (1979). As is the case for terrestrial partly cumulate igneous rocks, the bulk compositions of cumulate SNC meteorites such Chassigny and Nakhla are dominated by the chemical characteristics of the accumulated minerals, minerals compositionally similar to those found in terrestrial intra-plate magmas. Therefore, the minor amounts of liquid involved play an insignificant role in the Mg/Si and Al/Si signature and no special Martian chemical characteristics can be identified. SNC meteorites considered as possibly representative of liquid compositions are similar in composition and Mg/Si and Al/Si to terrestrial ferropicrites, suggesting that even "liquid" compositions within the SNC space are not uniquely Martian. Therefore, the Mg/Si and Al/Si ratios cannot clearly distinguish Martian from terrestrial rocks.

Keywords: Meteorite, Martian, igneous petrology, Mg/Si vs. Al/Si, lunar and planetary studies, Mars, major and minor elements, Mars rocks

INTRODUCTION

Numerous workers have noted significant differences in chemistry between Martian SNC meteorites and terrestrial rocks. However, recent Spirit data on Martian basalts (McSween et al. 2004) and TES Surface Types I and II (McSween et al. 2003) show compositions more terrestrial than the SNC meteorites, suggesting that these differences may not hold true for all Martian rocks. These observations are consistent with the moment of inertia calculations of Bills (1990) and Bills and James (1999) as well as melting experiments of Agee and Draper (2004) that suggest a less Fe-rich and more terrestrial-like Martian mantle than the Dreibus and Wänke (1982) model Mars. The possibility that some Martian magmas may have more terrestrial characteristics demands a revisiting of the often used discrimination diagrams to assess whether or not the observed differences between Martian and terrestrial rocks are as robust as they have long been held to be.

One commonly used discriminant is the variation in Mg/Si with Al/Si ratios. Figure 1 shows the deviation of the Martian meteorites and the "Martian crust line" from the Earth's geochemical fractionation line when plotted in this compositional space. The "Earth's crust line" was adopted from the geochemical fractionation line of Jagoutz et al. (1979). The geochemical fractionation line was originally developed from carefully selected ultramafic peridotite xenoliths from the Earth's mantle that were globally diverse, unaltered, and had high concentrations of Ca and Al, and Sr isotope values that suggest closed systems for more than 3.6 b.y. (Jagoutz et al. 1979). This line was used to infer the Earth's bulk mantle composition based on its intersection with unfractionated meteorites, and continues to be used for terrestrial rocks. For example, Drake and Righter (2002) used this diagram to constrain the composition of the Earth's primitive mantle (i.e., PUM, the Earth's mantle immediately after core formation). They suggested that magma extraction processes on Earth tend to raise the Mg/Si and lower the Al/Si ratio in mantle materials from which magma has been extracted because of the compatible nature of Mg and incompatible nature of Al, thereby supporting the negative slopes of the Earth's geochemical fractionation line (Burbine and O'Brien 2004). If the extracted liquids rise and are added to the crust, then the Al-rich region of this trend can be considered as reflective of the Earth's crust, albeit crust derived from primitive mantle.

Wänke et al. (1984) used the only known samples of the Martian surface at the time, that is, the five Martian (SNC) meteorites Chassigny, Zagami, Shergotty, ALHA 77005, and EETA 79001 lithology A and B, to obtain the Martian fractionation line ("Martian crust line") of Figure 1. For these samples it was not possible for Wänke et al. (1984) to apply the same stringent criteria used by Jagoutz et al. (1979) in selecting ultramafic xenoliths likely representative of the Earth's undepleted mantle, and no direct evidence remains that these meteorites represent either samples of the Martian mantle or residual mantle material after partial melting. As the population of SNC meteorites have grown (McSween 2002) it is now clear that many Martian meteorites do not actually fall on this "Martian crust line" (Fig.

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* E-mail: Justin.Filiberto@sunysb.edu

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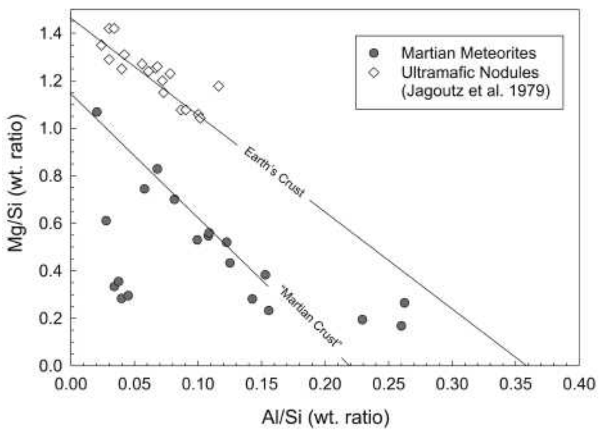

FIGURE 1. Mg/Si vs. Al/Si (wt. ratio) variation of the terrestrial geochemical fractionation line (Earth's crust line; Jagoutz et al. 1979) and the "Martian crust line" (SPB line; Wänke et al. 1984). Also plotted are peridotite nodules used by Jagoutz et al. (1979) and SNC meteorite bulk compositions (Greshake et al. 2004; Lodders 1998; McSween 1985; Wänke et al. 1984).

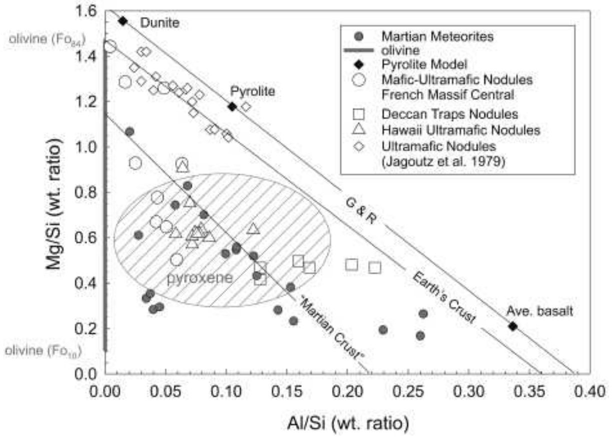

FIGURE 2. Mg/Si vs. Al/Si variation of terrestrial cumulate nodules from intraplate magmas (French Massif Central, Féménias et al. 2003; Deccan Traps, Dessai et al. 2004; Hawaii, Bohrson and Clague 1988) compared with the SNC meteorites (sources as in Fig. 1). Also shown are the compositional spaces of olivine (Fo_{84}-Fo_{10}) and Al-bearing pyroxene. A mixing line constructed from (Green and Ringwood 1963; G&R) pyrolite, average basalt, and dunite is shown for comparison with the Earth's crust line (Jagoutz et al. 1979).

1) and in fact, lie in a broad field to the low Al/Si side of the Earth's geochemical fractionation line, yet still displaced from the Earth's line. Is this deviation from the Earth's geochemical fractionation line unique to Martian igneous rocks? To answer this, intraplate nodules on Earth with cumulate characteristics and mineralogy similar to the cumulate SNC meteorites, as well as ferropicrites similar in texture and mineralogy to the SNC meteorites thought to be representative of liquids (i.e., Y980459, Dalton et al. 2005; QUE94201, McSween et al. 1996), have been compared with the SNC meteorites.

CUMULATE SNC METEORITES

Figure 2 shows the bulk compositions of cumulate nodules from several intra-plate regions on Earth (Hawaii, Bohrson and Clague 1988; Deccan Traps, Dessai et al. 2004; the French Massif Central, Féménias et al. 2003) characterized by minerals more Fe-rich than those of the peridotite considered by Jagoutz et al. (1979) and similar in composition to the minerals of the SNC meteorites. These terrestrial cumulates plot well off the geochemical fractionation line of Jagoutz et al. (1979), and in the field of the Martian meteorites, yet are clearly from Earth.

This deviation of terrestrial cumulate materials from the geochemical fractionation line (Earth's crust line) clearly calls into question its usefulness as a unique indicator of terrestrial characteristics. In fact, for rocks dominated compositionally by accumulated minerals, chemical characteristics reflect primarily the nature of the accumulated phases rather than unique planetary characteristics.

Along the Earth's geochemical fractionation line extracted magma and residue will be co-linear with the selected mantle composition. Thus, this line is a simple mixing line that can be used to consider accumulation processes. Bulk rock compositions will be displaced from liquid compositions toward higher Mg contents along this line during the accumulation of mafic minerals that lie along the line. As with any mixing line, however, the slope and intercepts will change depending upon the nature of the liquids and accumulated phases. Figure 2 shows the mixing line between dunite and the basalt used by Green and Ringwood (1963) to formulate pyrolite. This line is displaced from the Jagoutz et al. (1979) line because of the more olivine-rich nature of a dunite compared with a pyroxene-bearing peridotite. Increasing pyroxene content of the accumulating phases, or in the residual mantle after partial melting, will move the Mg/Si-intercept to lower values because of the location of the pyroxene field (Fig. 2) in this compositional space. Similarly, the more evolved (i.e., Fe-rich) the accumulated olivine (Fig. 2), the lower the value of the Mg/Si intercept. If the cumulate and partly cumulate SNCs compositions reflect varied degrees of accumulation of fractionated magmatic mineral assemblages, could the accumulated mineral assemblages have coexisted with typical terrestrial magmas or are they more consistent with liquids along the "Mars crust line"?

Terrestrial intra-plate magmatic suites are of most relevance to this question as the magmas in such suites have been generated simply by thermal anomalies (plume activity) without tectonic processes. Figure 3 shows a composite of the main compositional trends of lavas from the primary types of silica-saturated intraplate suites extending from basalt through rhyolite. The most magnesian (parental) lavas of each of these suites fall well beyond the geochemical fractionation line of Jagoutz et al. (1979), that is, at lower MgO and higher Al_2O_3 contents. Intermediate and felsic members of the suites cross the geochemical fractionation line and trend toward the "Mars crust line" at low Mg/Si ratios. Thus, neither terrestrial cumulate rocks nor fractionated magmas are constrained to the geochemical fractionation line.

Plotted in Figure 3 are the bulk compositions and cumulate phase compositions of two clearly cumulate SNC meteorites, Chassigny and Nakhla. These meteorites consist primarily of accumulated olivine and pyroxene, respectively. Based on

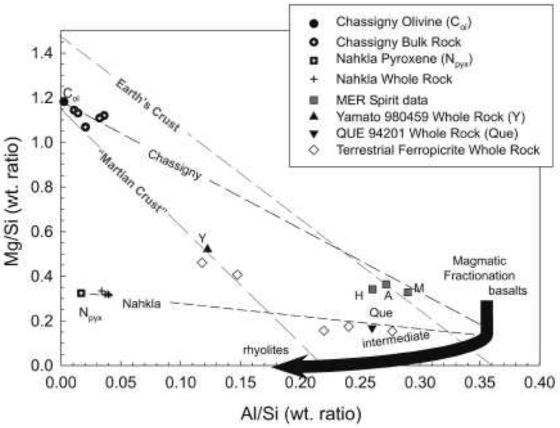

FIGURE 3. Mixing lines constructed for the Chassigny bulk meteorite composition and cumulate olivine (Floran et al. 1978), and for the Nahkla bulk composition and cumulate pyroxenes (Bunch and Reid 1975; Dreibus and Wanke 1982; Lodders 1998; McCarthy et al. 1974) extended to terrestrial liquids along a composite fractionation path. The fractionation path (heavy arrow) was constructed as a composite of intraplate magmatic suites containing lavas that range from basalt through rhyolite, specifically the Nandewar silica-saturated alkalic suite (Stolz 1985), the Snake River Plain/Craters of the Moon suite (Leeman et al. 1976; Stout and Nicholls 1977), Thingmuli tholeiitic suite (Carmichael 1964). Also plotted are the MER abraded bulk compositions of Adirondack (A), Humphrey (H), and Mazatzal (M) (McSween et al. 2004), Yamato980459 whole rock composition (Y; Greshake et al. 2004), QUE 94201 whole rock composition (Que; Lodders 1998), and selected terrestrial ferropicrite whole rock data (Hanski and Smolkin 1995; Stone et al. 1995). Sources for Earth's crust and "Martian crust" lines are as in Figure 1.

tie-lines shown between the bulk composition and the mineral phase accumulated, the Chassigny bulk composition (Floran et al. 1978) in this compositional space could be readily produced by a mixture of less than 10% typical terrestrial silica-saturated hawaiite, instead of liquid along the "Martian crust line", and over 90% olivine of Fo_{68} composition. (In fact, the experiments of Nekvasil et al. (2003) produced precisely this olivine composition in equilibrium with pyroxenes from a hawaiite.) The Nakhla bulk rock composition (Dreibus and Wanke 1982; Duke 1968; Jérome 1970; McCarthy et al. 1974; Stolper and McSween 1979) could consist of 15% liquid on the "Mars crust line" or similarly ~10% terrestrial melt (albeit a more evolved one than for Chassigny, e.g., a trachyandesite) and accumulated pyroxene (Treiman 1993). Clearly, the small amount of liquid represented in these meteorites shows that it is the mineral compositions that primarily affect the compositional characteristics of these meteorites. Since such minerals are also found in terrestrial cumulates and even lavas, these cumulate meteorites cannot be used to identify any uniquely Martian melts.

MARTIAN "LIQUID" COMPOSITIONS

Recently it has been suggested that some of the SNC meteorites (i.e., Yamato 980459, Dalton et al. 2005, and QUE 94201, McSween et al. 1996) may represent liquids. Their bulk compositions lie off of the terrestrial geochemical fractionation line and in the field of the other SNC meteorites. However, terrestrial ferropicrites with similar mineralogy, texture, and geochemistry also plot off the terrestrial fractionation line and in the same region in this compositional space (Fig. 3). The location of both the "liquid" SNC meteorites and terrestrial ferropicrites in the same compositional region precludes using the Mg/Si and Al/Si ratios of such SNC meteorites to indicate unique Martian chemical characteristics.

It has also been suggested that the Gusev basalts might represent liquid compositions (McSween et al. 2004). As shown in Figure 3, these basalts appear to preclude involvement of any liquids along the "Mars crust line" in their composition regardless of whether they represent liquids or partial cumulates. Their location close to the terrestrial geochemical fractionation line indicates that in this compositional space they could not be identified as uniquely Martian.

In summary, the Al/Si and Mg/Si ratios of the bulk compositions of igneous rocks that have undergone accumulation of minerals reflect primarily the compositional characteristics of the accumulated minerals. For this reason Mg/Si and Al/Si ratios cannot be used to uniquely distinguish between Martian and terrestrial cumulate rocks. The similarity of terrestrial ferropicrites to the "liquid" Martian meteorites likewise precludes the use of Al/Si and Mg/Si ratios to discriminate between Martian and terrestrial magmas, and further precludes use of deviations from the terrestrial geochemical fractionation as indicative of unique Martian mantle characteristics.

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