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The Petrochemistry of Jake_M: A Martian Mugearite

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"Jake_M," the first rock analyzed by the Alpha Particle X-ray Spectrometer instrument on the Curiosity rover, differs substantially in chemical composition from other known martian igneous rocks: It is alkaline (>15% normative nepheline) and relatively fractionated. Jake_M is compositionally similar to terrestrial mugearites, a rock type typically found at ocean islands and continental rifts. By analogy with these comparable terrestrial rocks, Jake_M could have been produced by extensive fractional crystallization of a primary alkaline or transitional magma at elevated pressure, with or without elevated water contents. The discovery of Jake_M suggests that alkaline magmas may be more abundant on Mars than on Earth and that Curiosity could encounter even more fractionated alkaline rocks (for example, phonolites and trachytes).

Rock "Jake_M" [(JM); named for Jet Propulsion Laboratory engineer Jake Matijevic] was the first sample imaged with the Mars Hand Lens Imager (MAHLI) and analyzed with the Alpha Particle X-ray Spectrometer (APXS) on the Mars Science Laboratory (MSL) (*1*, *2*). Although the rock is an isolated fragment lacking field context (encountered ~282 m from the Bradbury landing site and analyzed on sols 46 and 47, where 1 sol is a martian day), its dark color and apparently fine-grained texture suggested, before analysis, that it was a relatively homogeneous (on a millimeter-to-centimeter scale) igneous rock and thus an appropriate sample with which to initiate the APXS analytical program and to analyze with ChemCam (*3*) using laser-induced breakdown spectroscopy (LIBS). Here, we report chemical analyses of JM and an interpretation of their meaning for its petrogenesis.

Results and Discussion

Petrography

Jake_M is roughly pyramidal in shape (~50 cm on each of its three base edges and ~50 cm tall) (Fig. 1). The rock is dark gray and thinly coated by light-toned, reddish-brown dust. Its upper surfaces have rounded hollows that are probably due to wind erosion and <1- to 3-mm pits that could be vesicles. The lowest ~2 cm of the rock has smoother surfaces that may reflect primary layering or the effects of wind erosion. Near-vertical fractures (~10 cm long) project upward from the base. Feldspar microphenocrysts have been tentatively identified in MAHLI images (*4*), but individual mineral grains could not otherwise be distinguished in optical images, perhaps due to the dust cover and/or polish by wind. Compositional variations among the 14 individual locations (see Fig. 1 and fig. S1) analyzed by LIBS using ChemCam show that the rock is heterogeneous on a length scale of ~0.5 mm. The heterogeneities observed by LIBS analyses suggest the presence of plagioclase (broadly consistent with oligoclase), Ca-rich pyroxene, olivine, and Fe-Ti-rich oxide(s) (*3*) (see also figs. S1 to S4).

Bulk Composition and Classification

The three APXS analyses (Table 1) were collected on two different spots; the listed uncertainties on the average [calculated after normalizing each analysis to 100 weight % (wt %), excluding SO_3, Cl, and trace elements] are due to variations between the three analyses that may partially reflect real differences between the two analyzed spots. The surface of JM was not brushed or abraded before analysis [in the supplementary materials, we compare the JM analyses to both unbrushed (i.e., "as is") and physically abraded rock surfaces analyzed by the Mars Exploration Rovers (MERs)]. The CIPW norms (*5*) (Table 1) are based on the average JM composition and were calculated using molar Fe^{3+}/(total Fe) ratios of 0 and 0.15. Although this range of Fe^{3+}/(total Fe) ratios brackets the ratios expected in basaltic melts at the estimated oxygen fugacity (fO_2) values of basaltic shergottites [e.g., (*6*)], recent modeling suggests that mantle melting at higher fO_2s may have occurred early in the planet's history (*7*). However, even for a Fe^{3+}/(total Fe) value of 0.3, normative nepheline is still ~15 wt %.

Based on either its calculated norm or inspection of its major-element composition, JM has a basaltic composition, and it is probably an igneous rock (although we cannot tell whether it is from a lava flow, an intrusion, a pyroclastic flow, or a

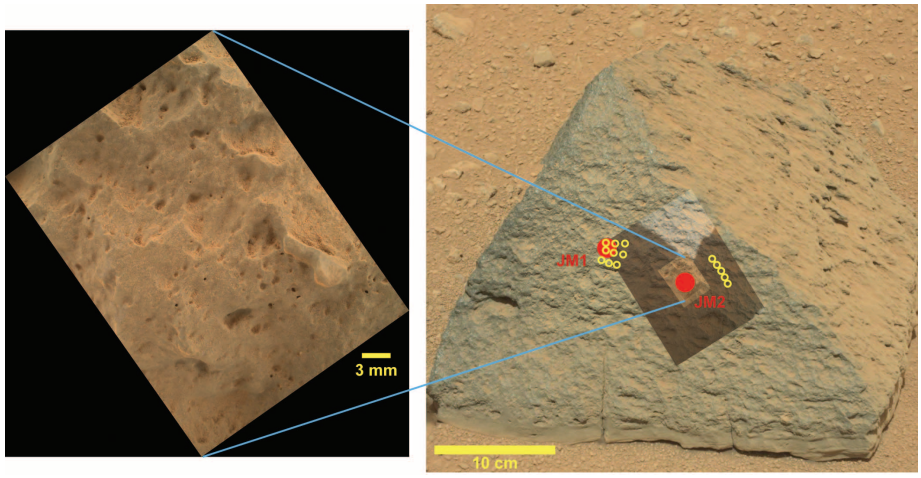

Fig. 1. Raw image of Jake_M taken by the left mast camera (mastcam) (identification number 0046ML0212000000E1) with overlain images from MAHLI at 26.9-, 6.9-, and 4.4-cm offsets from the front of the lens. The MAHLI projection on the left was taken at 4.4 cm (identification number 0047MH0011002000E1). Shadowing by the turret reduced the contrast in the inset MAHLI images, causing color differences with the mastcam image. The solid red circles labeled JM1 and JM2 indicate the locations of the two APXS spots (1.7-cm diameter). ChemCam raster spots are represented by yellow open circles; actual spot sizes are ~0.45 mm. [Credit: NASA/Jet Propulsion Laboratory–Caltech/Malin Space Science Systems]

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volcaniclastic sediment deposited after minimal fractionation or alteration of primary igneous materials). Moreover, with its ~16 to 17% normative nepheline (Table 1) and its position on an alkali-silica diagram (Fig. 2), JM is an alkaline rock [with an alkalinity index (8) higher than other known martian rocks]. JM is also evolved (likely due to crystal fractionation) relative to most other known martian igneous rocks (Fig. 3): It has a low MgO content (4.4 wt %), albitic normative plagioclase (oligoclase, ~An_{15}), a molar $Mg/(Mg+Fe_{total})$ ratio of ~0.43, ~40 parts per million (ppm) Ni, and ~270 ppm Cr (Ni and Cr values are from the two long-duration analyses listed in Table 1). Based on its MgO content, JM is more fractionated than most other martian rocks—of the analyses plotted in Fig. 3, only the basaltic shergottite Los Angeles (9), the rocks Wishstone and Champagne analyzed by the MERs (10), and the two estimated soil-free Pathfinder rock compositions (11, 12) have similar or lower MgO contents.

For terrestrial igneous rocks, chemical composition is generally not the sole criterion for classification. For JM, we have no other information and although it plots slightly above the nominal mugearite field on the alkali-silica diagram (this field is shown as the blue polygon in Fig. 2), the composition of the normative plagioclase (i.e., oligoclase; broadly consistent with the ChemCam results), the substantial normative nepheline and orthoclase, and the fact that it overlaps compositionally with many terrestrial rocks that have historically been called mugearites (Fig. 2B and fig. S5) lead us to classify JM as a mugearite (13). Mugearites are well-defined and widely distributed, though relatively uncommon, intermediate (i.e., fractionated) members of the terrestrial alkali-olivine basalt, hawaiite, mugearite, benmoreite, trachyte-phonolite magma series found in locations such as ocean islands and continental rifts (14–16). They generally contain normative nepheline, but nepheline as a phenocryst phase is relatively rare (14), so the absence of a nepheline signature in the ChemCam results is not inconsistent with JM's normative composition. Although JM actually plots in the nominal phonotephrite field in Fig. 2, in other respects the compositional comparison of JM to terrestrial rocks that have been called phonotephrites is no better (and arguably worse) than to rocks called mugearites (figs. S5 and S6).

Comparison to Other Martian Igneous Rocks

Although there is overlap in some oxide concentrations, taken as a whole, the JM composition is distinct from all other known martian igneous rocks (Figs. 2 and 3). In particular, compared with JM's Na_2O and K_2O contents of ~7 and ~2.1 wt %, respectively (Table 1), all martian meteorites and martian igneous rocks analyzed by Pathfinder and the MERs are considerably lower in sodium and potassium: The highest previously analyzed Na_2O contents are only ~4 to 5 wt % [Backstay, Humboldt Peak, Northwest Africa (NWA) 7034 meteorite, Wishstone, Champagne, and one of the estimated soil-free Pathfinder compositions) (Fig. 3F), and the highest K_2O contents of relatively unaltered martian rocks (17) are only ~1 wt % (Backstay, Humboldt Peak, Madeline English, and the soil-free Pathfinder compositions) (Fig. 3G). However, there is evidence from the nakhlite meteorites of K-rich martian liquids: (i) the presence of K-rich kaersutite in melt inclusions (18), (ii) highly fractionated glassy mesostasis in the nakhlites (19), and (iii) K-rich bulk melt-inclusion compositions (20). Most martian meteorites and analyzed martian igneous rocks have higher MgO and FeO* contents and lower Al_2O_3 contents than JM (Fig. 3, C and D) [see also (21)]. Although there are exceptions for individual elements (e.g., the soil-free Pathfinder compositions, Wishstone, Champagne, and Los Angeles for MgO; Backstay, Wishstone, Champagne, and NWA 7034 for FeO*; and Wishstone and Champagne for Al_2O_3), no known martian rock overlaps JM in all three of these elements. The Ni (22 to 59 ppm) and Cr (~270 ppm) contents of JM are among the lowest values for an unbrushed rock surface found on Mars to date; moreover, because martian dust is typically enriched in Ni by ~10 times the JM values (22), JM probably contains even lower Ni than is suggested by the APXS analyses.

Although some Gusev samples are alkaline [i.e., they plot above the alkaline-subalkaline boundary curve in Fig. 2 (23) and have normative

Table 1. Composition and CIPW norms of Jake_M. 1 and 2 after JM indicate the two locations analyzed on the rock (see Fig. 1); 2n indicates the nighttime analysis on spot 2. Values in parentheses for JM1, JM2, and JM2n are assessments of 2σ uncertainty based on counting statistics and data reduction in terms of the least number of units cited [i.e., 50.7(6) = 50.7 ± 0.6]; for further details see (2). n.d., not detected; N/A, not applicable. The average represents the unweighted mean of the three compositions, each normalized to 100% excluding SO_3, Cl, and trace elements; values in parentheses are the standard deviations. Norm, normative minerals in weight %. The column labeled "0 Fe^{3+}" shows the calculated CIPW norm, assuming that all Fe in the average bulk composition is Fe^{2+}; the column labeled "0.15 Fe^{3+}" shows the calculated CIPW norm, assuming Fe^{3+}/(total Fe) = 0.15. Normative constituents: Pl, plagioclase (sum of normative anorthite and albite); Or, orthoclase; Ne, nepheline; Cpx, sum of normative diopside and hedenbergite; Ol, sum of normative forsterite and fayalite; Ilm, ilmenite; Mt, magnetite; Ap, apatite; Chr, chromite; %An, 100 × $Ca/(Ca + Na)_{molar}$ in the normative plagioclase; Mg# ol and Mg# cpx = 100 × $Mg/(Mg + Fe)_{molar}$ in normative olivine and high-Ca pyroxene, respectively; $(Mg\#)^{ol}$ = 100 × $Mg/(Mg + Fe)_{molar}$ of the liquidus olivine calculated using an olivine-liquid $K_{D,Fe^{2+}\text{-}Mg}$ $[(FeO/MgO)^{ol}/(FeO/MgO)^{liquid}]$ of 0.34 (80, 81).

Weight %	JM1	JM2	JM2n	Average	Norm	0 Fe^{3+}	0.15 Fe^{3+}
SiO_2	50.7(6)	49.3(9)	48.9(5)	51.6(9)	Pl	32.3	34.4
TiO_2	0.50(3)	0.65(6)	0.73(3)	0.65(12)	Or	12.5	12.5
Al_2O_3	16.1(5)	14.6(7)	14.6(2)	15.7(9)	Ne	17.4	16.2
Cr_2O_3	0.03(1)	0.09(3)	0.04(1)	0.04(1)	Cpx	20.0	19.8
FeO	9.44(7)	10.61(11)	10.94(9)	10.8(8)	Ol	14.9	11.6
MnO	0.14(1)	0.17(2)	0.21(1)	0.18(4)	Ilm	1.2	1.2
MgO	3.6(4)	4.6(7)	4.60(12)	4.4(6)	Mt	N/A	2.6
CaO	6.09(7)	6.54(11)	6.78(8)	6.7(4)	Ap	1.6	1.6
Na_2O	7.1(3)	6.6(5)	5.59(14)	7.0(3)	Chr	0.06	0.06
K_2O	2.22(4)	2.01(6)	1.89(3)	2.12(17)	%An	15.2	14.2
P_2O_5	0.50(7)	0.60(12)	0.85(4)	0.68(19)	Mg# ol	43.0	49.7
SO_3	2.46(9)	3.05(16)	2.81(8)	N/A	Mg# cpx	43.0	49.7
Cl	0.88(3)	1.03(5)	0.95(3)	N/A	$(Mg\#)^{ol}$	68.0	71.6
Total	99.80	99.80	99.90	N/A	N/A	N/A	N/A
Ni (ppm)	22(17)	n.d.	59(17)	N/A	N/A	N/A	N/A
Zn (ppm)	216(13)	341(25)	318(15)	N/A	N/A	N/A	N/A
Br (ppm)	88(8)	94(11)	107(7)	N/A	N/A	N/A	N/A
Temp	−3°C	−2°C	−55°C	N/A	N/A	N/A	N/A
Duration	30 min	12 min	30 min	N/A	N/A	N/A	N/A

nepheline; e.g., Humboldt Peak] or transitional (i.e., they plot near the boundary curve and have only small amounts of either normative nepheline or hypersthene; e.g., Backstay, NWA 7034), no relatively unaltered samples are as alkali-rich relative to the alkaline-subalkaline boundary curve in Fig. 2 or as rich in normative nepheline as JM. Note that despite their positions in Fig. 2, Wishstone and Champagne are not nepheline-normative, due to their extremely high bulk P_2O_5 contents of 5.2 to 5.3 wt %. Only if P_2O_5 were ~1 wt %, a value more typical of Gusev crater rocks, would these rocks be as strongly nepheline-normative as their positions on Fig. 2 might suggest. [See also (24) for a discussion of how changing the normative phosphate-bearing mineral from apatite to Ca-merrillite affects the proportions of the other normative components.]

Comparison to Terrestrial Compositions

As shown by a comparison between JM and lavas from Tenerife (one of the Canary Islands), there is an excellent correspondence between JM and fractionated alkaline basaltic rocks on Earth (Fig. 3 and figs. S5 to S8). JM lies on or near the oxide-MgO trends for Tenerife for all oxides except TiO_2. As is the case for JM, when compared with Tenerife lavas with the same MgO content, nearly all of the martian rocks plotted in Fig. 3 have substantially lower TiO_2 contents than the Tenerife lavas, and this low TiO_2 appears to be a characteristic of martian rocks generally. Nevertheless, even the TiO_2 content of JM is not outside the range of fractionated terrestrial alkaline igneous rock compositions (fig. S7A), and both JM and nonalkaline martian rocks overlap with terrestrial tholeiites in TiO_2-MgO space (fig. S7B). Although JM is slightly elevated in total alkalis relative to the Tenerife trend (Fig. 2) and at the upper end of the field defined by mugearite lavas (reflecting JM's high Na_2O content) (Fig. 3F and fig. S5F), terrestrial alkaline suites span a wide range of total alkali contents at a given silica (or MgO) content, with some being lower than that of JM [e.g., St. Helena (25)] and others being higher [e.g., Tristan da Cunha (25)].

The chemical similarity between JM and terrestrial igneous rocks is surprising given that the chemical compositions of SNC (Shergotty, Nakhla, and Chassigny) meteorites and of igneous rocks analyzed using APXS on the surface of Mars (after correction for or removal by brushing or abrasion of surface-correlated components such as dust) differ systematically, in many respects, from those of terrestrial igneous rocks [e.g., (26, 27); see also (21)]. These distinctions remain even when martian meteorites are compared with Fe-rich terrestrial lavas (28). However, even JM's Fe/Mn ratio is within the range of comparable terrestrial igneous rocks [fig. S8; terrestrial and martian bulk rock and olivine and pyroxene Fe/Mn ratios have historically been considered diagnostic of each planet (29–32)]. Overall, if JM had been found on Earth, we would be hard pressed to tell from its whole-rock chemical composition that it is martian. In the discussion below, we use the fact that JM plots essentially on the alkaline rock series from Tenerife (Figs. 2 and 3) as an aid to understanding one possible model for its petrogenesis.

Based on the differences in S and Cl contents from undisturbed versus physically abraded martian rock surfaces, it is likely that much of the S and Cl in the APXS analysis of JM reflects a surficial component such as dust [after abrasion, SO_3 and Cl contents of Gusev crater rocks and outcrops generally drop by ~40 to 90% (10)]. However, there are haüyne-bearing terrestrial lavas, historically called "tahitites" (33), with major-element compositions that are broadly similar to JM and with elevated S and Cl contents. Analyses of such haüyne-bearing lavas (containing 50 to 58 wt % SiO_2 on a volatile-free basis) from the Georoc database (25) have 0.6 to 2.4 wt % SO_3 and up to 0.8 wt % Cl [and some phonolitic lavas from Tenerife contain haüyne; e.g., (34)]. Thus, although it cannot be quantified at this time, it is possible that non-negligible amounts of the S and Cl in the JM analysis are indigenous to the magma from which JM formed rather than a secondary, surface-correlated feature.

Petrogenesis of JM

Hypotheses for the origins of igneous rocks rarely rely on isolated chemical compositions but are constrained by field relations, petrography, and the compositional trends defined by related rocks. We lack these data for JM, but we are able to say with some confidence what its compositional features would signify if it formed by processes

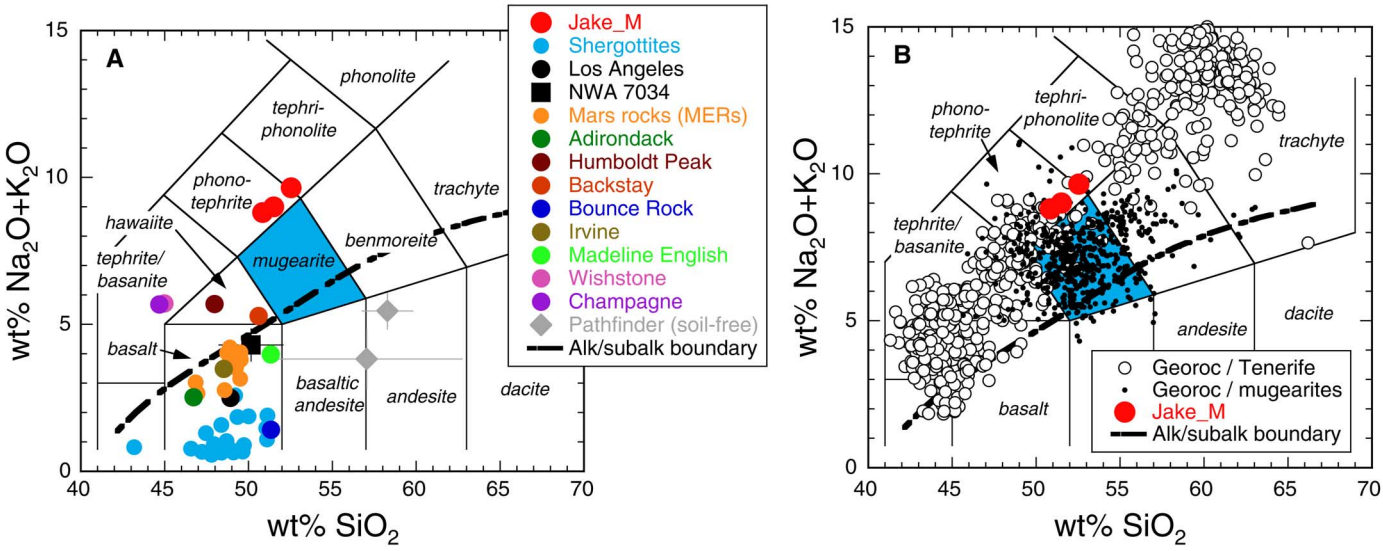

Fig. 2. Alkali-silica diagram. Compositional boundaries and rock names are from (72); the mugearite field is shown in blue. The dashed curve shows the alkaline-subalkaline boundary curve from Irvine and Baragar (23). (**A**) Colored symbols (see the key) show the three JM analyses (Table 1), normalized to 100 wt % without SO_3, Cl, and trace elements; basaltic martian meteorites [the shergottite "Los Angeles" (9, 73) and the basaltic breccia NWA 7034 (74) are shown as distinct symbols]; martian rocks analyzed by the MERs (10, 75–77) and interpreted as igneous (including volcaniclastics); and the two soil-free Pathfinder compositions calculated by Wänke *et al.* (11) and Foley *et al.* (12). Errors bars associated with the NWA 7034 and Pathfinder compositions reflect either 1σ uncertainties (NWA 7034) or the projection methods used to calculate a soil-free composition (Pathfinder). Note that NWA 7034 may be a polymict breccia (78, 79). Larger filled colored circles labeled "Adirondack" through "Champagne" in the key denote specific Mars surface rocks analyzed by the MERs. (**B**) Comparison of the three JM analyses (Table 1) with lavas from Tenerife in the Canary Islands (25) and with terrestrial lavas that have been called mugearites, including some from Tenerife (25). Only Georoc (25) analyses with oxide sums between 97 and 102.5 wt % are plotted, and all have been normalized to 100 wt % on a volatile-free (including sulfur and chlorine) basis.

similar to those that have produced comparable terrestrial rocks. Although an infinite number of petrogenetic models could be constructed to account for a single rock composition such as JM, we emphasize again the strong compositional correspondence between JM and terrestrial mugearites (including JM's position close to the liquid line of descent of Tenerife magmas). This correspondence provides a plausible context for interpreting the composition of JM and is at least permissive that the petrogenetic processes responsible for the compositional trends observed in these terrestrial lavas could be applicable to the evolution of JM.

Evolved terrestrial alkaline rocks, including mugearites, are generally produced by extensive crystal fractionation of alkaline or transitional magmas. Whereas in some cases this fractionation appears to occur in the upper mantle, based on the presence of peridotite xenoliths in some mugearites and related rocks (*35*–*37*), it more commonly occurs in crustal magma chambers or at even shallower depths within a volcanic edifice [e.g., (*15*, *16*, *38*)]. With this in mind, we used MELTS software (*39*, *40*) to simulate fractional crystallization of a primitive Tenerife melt composition over a range of pressures (1 to 6000 bars), water concentrations (0 to 3 wt %), and oxygen fugacities [quartz-fayalite-magnetite (QFM) – 1 to QFM + 2].

A crucial constraint on the fractionation required to explain the trend of Tenerife magmas is the monotonic increase in the Al_2O_3 contents of the observed rocks with decreasing MgO content (at least down to 2 wt % MgO). As shown by MELTS calculations (Fig. 4), this monotonic change all the way down to 2 wt % MgO cannot be produced by fractionation from a dry primitive basanite at 1 bar: Under these conditions, plagioclase saturation is reached at ~7.8 wt % MgO, long before sufficient fractionation has occurred to produce residual liquids with MgO contents in the 2% range. As a result, residual liquids at 1 bar with MgO contents like those of JM (4 to 5 wt %) contain only 14 to 15 wt % Al_2O_3 (i.e., less than the ~15 to 19 wt % Al_2O_3 in JM and terrestrial mugearites) (fig. S5). To produce residual melts with monotonically increasing Al_2O_3 contents at these MgO contents, plagioclase crystallization must be suppressed. It is well known that elevated water contents and elevated total pressure individually or together can suppress plagioclase crystallization (*41*–*44*). MELTS calculations confirm this: Starting with the primitive basanite at 4 kbar dry, the MELTS calculations predict that plagioclase saturation is delayed relative to 1 bar crystallization, being reached only at liquid MgO contents of ~4.8 wt % (Fig. 4). In contrast, and as expected, clinopyroxene saturates earlier in the fractionation sequence relative to the calculated trend at 1 bar (Fig. 4). With the addition of 1 wt % H_2O to the parental basanite at 4 kbar, plagioclase crystallization is even further suppressed: Figure 4 shows that the model fractionation sequence reaches plagioclase saturation only at ~2 wt % MgO and that clinopyroxene appearance is also somewhat delayed relative to the 4-kbar anhydrous calculation. Note that the points along the model liquid lines of descent that mark the appearance of Fe-rich spinel are only slightly affected over the ranges in pressure and water content investigated here (Fig. 4 and fig. S11). These calculations were all done at an fO_2 fixed relative to the QFM buffer [i.e., at QFM + 1, an fO_2 consistent with estimates from Fe-Ti oxides in Tenerife volcanics (*38*)]; under more oxidizing or reducing conditions, Fe-rich spinel would appear earlier or later in the calculated liquid line of descent.

Although the 4-kbar dry simulation of the Tenerife parental basanite suppresses plagioclase crystallization sufficiently to account for the high Al_2O_3 contents of JM and of rocks from

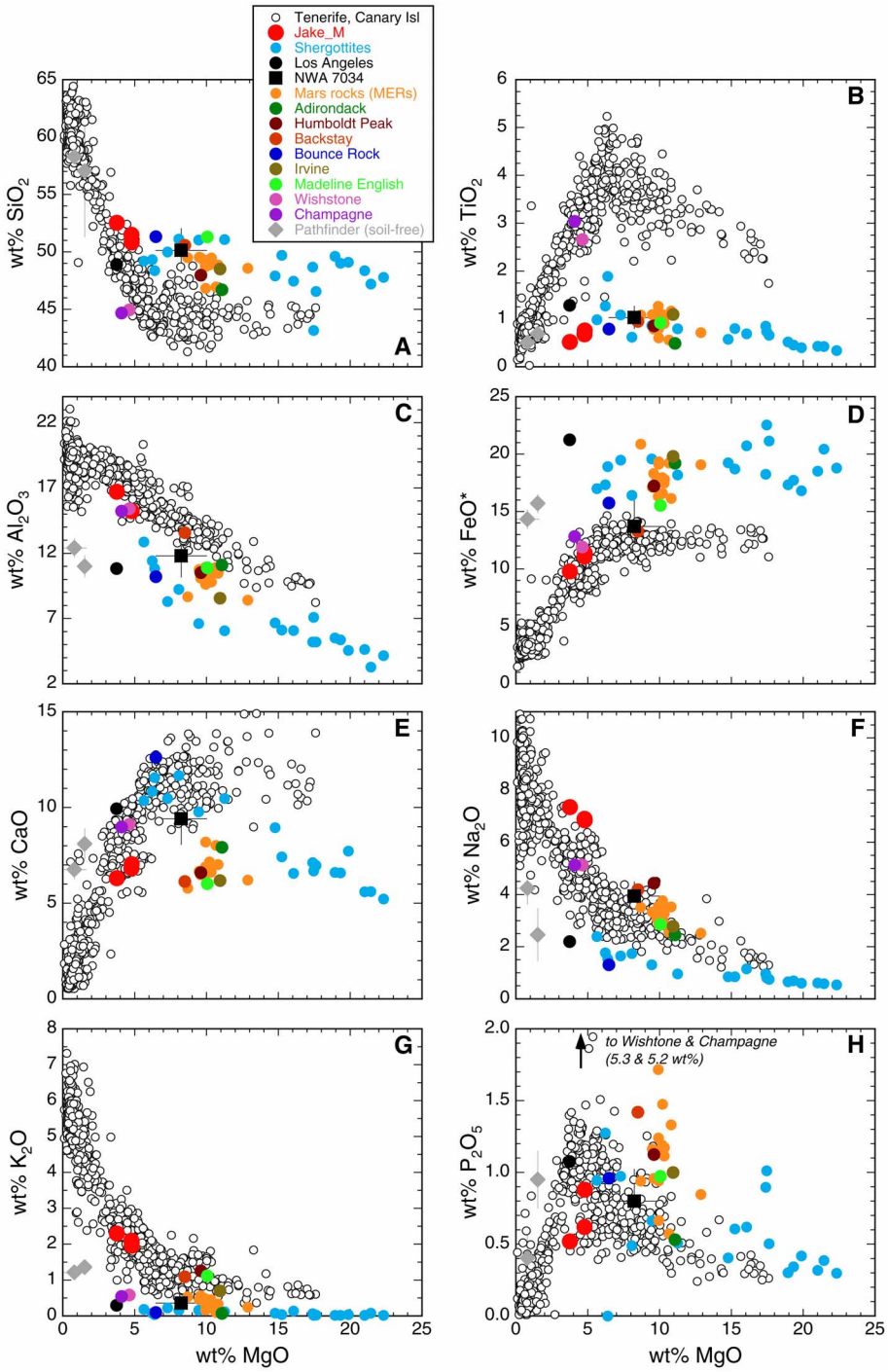

Fig. 3. Oxide-MgO variation diagrams (weight %) comparing Tenerife lavas, the three Jake_M compositions (Table 1), and various martian igneous rock compositions (see caption to Fig. 2 for references and filters applied to the Tenerife lava compositions). (A) SiO_2-MgO; **(B)** TiO_2-MgO; **(C)** Al_2O_3-MgO; **(D)** FeO*-MgO; where FeO* denotes all Fe as FeO; **(E)** CaO-MgO; **(F)** Na_2O-MgO; **(G)** K_2O-MgO; and **(H)** P_2O_5-MgO. Error bars are as in Fig. 2.

Tenerife with 4 to 5 wt % MgO, the simulated fractionation trend provides a poor fit to the more evolved lavas from Tenerife (Fig. 4), which would require even further suppression of plagioclase crystallization to account for their even higher Al_2O_3 contents. In contrast, the 4 kbar simulation with 1 wt % H_2O in the parent magma reproduces the observed trend in Al_2O_3 all the way down to ~2 wt % MgO (Fig. 4), reproduces reasonably well the trends of all of the other oxides (fig. S11), and matches the water contents measured in melt inclusions from Tenerife lavas with phonolitic compositions (*45*). The simulation at 4 kbar with 1 wt % H_2O in the parental basanite magma, which reaches the MgO content of JM after ~57% crystallization and with ~2.3 wt % H_2O in the JM-like residual melt, provides the best fit to the overall Tenerife trend (see fig. S12, which illustrates the degree to which the calculated liquid lines of descent reproduce the compositional trend of the lavas as pressure and initial water content vary). Similar calculations by Beier *et al*. (*46*) using lavas from Sete Cidades volcano, Sao Miguel (in the Azores) produced comparable results, requiring 0.5 wt % H_2O in the parent liquid and fractionation at 5 kbar to reproduce the overall observed liquid line of descent.

The point of these simulations and their comparisons to JM and to the overall Tenerife liquid line of descent (Fig. 4 and fig. S11) is not whether a precise match can be achieved. As good as they are, MELTS calculations are no substitute for experiments in determining a fractionation path and its sensitivity to pressure, water content, other volatiles, and oxygen fugacity [e.g., the calculated best-fit liquid line of descent does not include amphibole and yet, amphibole is present in the more fractionated Tenerife lavas (*38*)]. Moreover, it is unreasonable to suppose that JM's bulk composition represents exactly a liquid composition or that the parent magma would be identical in all respects to one from Tenerife (as pointed out above, the Na_2O and TiO_2 contents of JM and the Tenerife trend do not match perfectly). The point of the comparison is simply that the overall trend of the Tenerife liquid line of descent is captured reasonably well only if plagioclase crystallization is suppressed relative to low-pressure, dry conditions and that several kilobars of pressure (corresponding to up to a few tens of kilometers depth within Mars) and water contents in the parent magma on the order of 1 wt % H_2O do this successfully. If the pressure were less than ~1 kbar, the fits worsen because, under these conditions, not enough water is able to dissolve in the melt to suppress plagioclase crystallization sufficiently to reproduce the monotonic enrichment with fractionation observed in Al_2O_3 among the most highly evolved rocks from Tenerife. Nevertheless, as stated above, the 4-kbar anhydrous trend provides a reasonable fit to the JM compositions, and thus we cannot say with any confidence that the fractionation of JM requires ~1 wt % H_2O in the parental magma. Although the model 1-bar fractionation trend at 4 to 5 wt % MgO is low in Al_2O_3 relative to JM, if we allowed for moderate plagioclase accumulation in JM or increased uncertainties in JM's stated composition, even fractionation under these conditions could not be ruled out. However, we can say with reasonable certainty that terrestrial magmas that are compositionally similar to JM require fractionation at both elevated pressure and water content. One way to resolve this for JM would be if more evolved alkaline lavas are discovered on Mars and whether these, like comparable terrestrial magmas, have even higher Al_2O_3 contents than JM. If so, this would strengthen the requirement for a moderate-pressure, hydrous liquid line of descent to explain JM because it would be difficult to match such elevated Al_2O_3 contents at low pressure or without dissolved water. Although they are not definitive, the pits on the surface of JM (Fig. 1) may be wind-eroded vesicles, which would be consistent with hydrous fractionation. Likewise, the inferred water content of JM (~2 wt %, if we accept the analogy with Tenerife magmas) is also consistent with previous efforts to constrain the petrogenesis of martian magmas, which have concluded that they contained up to several weight % dissolved H_2O (*47*–*49*). Measurements of water in amphiboles in Chassigny (*50*) also suggest that the mantle source region of Chassigny may have been relatively wet. In contrast, however, Filiberto and Treiman (*51*) have argued that magmas parental to the martian meteorites were chlorine-rich and water-poor; that is, <0.3 wt % H_2O. Although extensive work has been done on the partitioning of Cl between silicate melts and H_2O-rich fluids [e.g., (*52*, *53*)], it is not clear from available experimental data [e.g., (*54*)] whether Cl suppresses plagioclase crystallization to a similar degree as H_2O.

To explore whether any known martian igneous rocks could represent acceptable parent liquids for JM, we also performed MELTS calculations on Backstay, Humboldt Peak, and NWA 7034. In these cases, because there is no suite of lavas to constrain the liquid line of descent as in the case of the Tenerife calculations, we used MELTS simulations only to determine whether parent liquids corresponding to these known martian igneous rocks could fractionate to produce a residual liquid corresponding to JM and, if so, what conditions would be required. None of the martian rock compositions have high enough alkali contents to produce a close match to JM under any conditions (figs. S13 to S24). However, if we arbitrarily increased the alkali contents by amounts such that on fractionation the modeled alkali contents of the fractionated liquids matched those of JM at an MgO content of ~4 to 5 wt %, the alkali-enriched Backstay composition could produce a reasonable

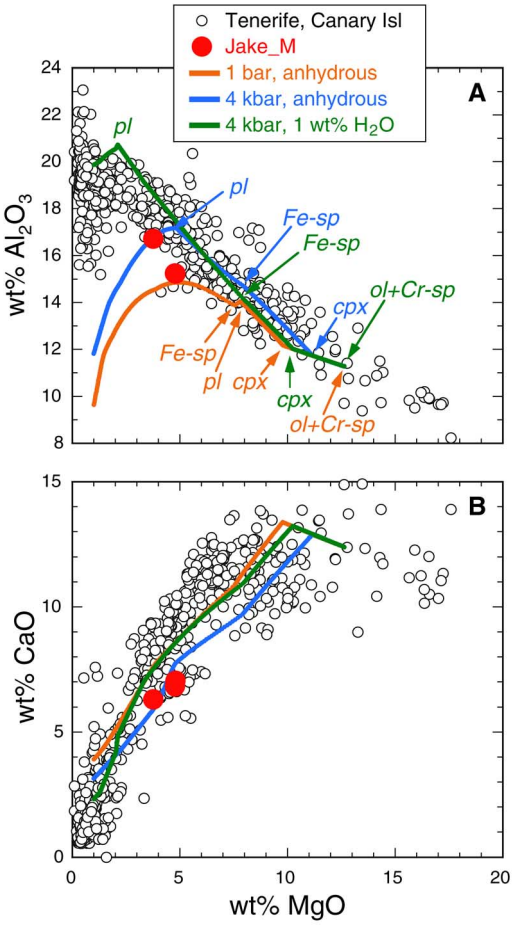

Fig. 4. Oxide-MgO variation diagrams (weight %) showing Tenerife lavas, the three Jake_M compositions, and three MELTS calculations. (**A**) Al_2O_3-MgO and (**B**) CaO-MgO; MELTS fractional crystallization calculations (colored curves) are described in the text (1 bar, anhydrous; 4 kbar, anhydrous; 4 kbar, 1 wt % water in the parental liquid composition; all three calculations were done at fo_2 = QFM + 1). Phase abbreviations: pl, plagioclase; Fe-sp, magnetite-rich spinel; cpx, clinopyroxene; ol, olivine; Cr-sp, chromite-rich spinel. Arrows point to the appearance of phases along the MELTS-modeled liquid lines of descent. Compositions of the Tenerife lavas are from (*25*) (see caption to Fig. 2); starting composition for the MELTS modeling is the average of Tenerife lavas with 12 to 13.5 wt % MgO and is reported in the supplementary materials, along with further details of the MELTS calculations.

approximation of JM after a few tens of percent crystal fractionation (although we note that the required arbitrary increases in alkalis are not trivial).

Origins of Alkaline Magmas on Mars

We have no constraints on conditions required on Mars to produce the parental alkaline or transitional liquids from which JM is presumed to have evolved by extensive crystal fractionation. On Earth, such parental magmas have been attributed to a variety of conditions and processes, including melting of lherzolite + CO_2 ± H_2O at elevated pressures [e.g., (*55*–*57*)], melting of metasomatized lithospheric mantle [e.g., (*58*–*60*)], and melting of pyroxenites and amphibolites [e.g., (*60*–*62*)]. Models for the origin of previously described alkaline and transitional martian magmas have called on melting of a more alkali-rich mantle source [relative to that of the shergottites (*63*)] and/or hydrous fractional crystallization of transitional magmas at pressures of a few kilobars (*64*).

Ratios of moderately volatile alkalis to refractory lithophile elements in martian rocks have been used to infer that the primitive martian mantle was richer in Na and K than the terrestrial mantle by as much as a factor of 2 [e.g., (*65*–*69*)]. On this basis alone, although few alkaline martian rocks have been documented thus far, it would not be surprising if alkaline magmas derived from relatively alkali-rich sources (either primitive martian mantle or mantle that has been metasomatized by low-degree melts of relatively primitive mantle) were more common on Mars than they are on Earth [on Earth, alkaline lavas are rare from a planetary perspective, representing an estimated <1 volume % of terrestrial igneous rocks; e.g., (*70*)]. Note that based on trace-element and radiogenic-isotope ratios, the average sources of most shergottite meteorites are inferred to have been depleted and, in some cases, highly depleted (i.e., melts have been extracted from these source regions before the melting events that produced the shergottites). This depletion of their sources could explain the low alkali (and alumina) contents that are characteristic of the shergottites. If the liquids extracted during these earlier depletion events were enriched in alkalis (i.e., because they formed as partial melts of relatively primitive martian mantle) and were emplaced into the crust and lithospheric mantle, they could have enriched and metasomatized portions of the martian mantle. Melting of such enriched sources might then have produced the magmas parental to alkaline rocks such as JM. The overall K-rich nature of rocks analyzed by the MSL mission thus far (*71*) could reflect the presence of such an enriched region in the mantle underlying Gale crater.

References and Notes

1. J. P. Grotzinger *et al.*, Mars Science Laboratory: First 100 sols of geologic and geochemical exploration from Bradbury Landing to Glenelg. *Lunar Planet. Sci. Conf. 44*, abstract 1259 (2013).
2. R. Gellert *et al.*, Initial MSL APXS activities and observations at Gale Crater, Mars. *Lunar Planet. Sci. Conf. 44*, abstract 1432 (2013).
3. A. Cousin *et al.*, ChemCam analysis of Jake Matijevic, Gale Crater. *Lunar Planet. Sci. Conf. 44*, abstract 1409 (2013).
4. M. E. Minitti *et al.*, Mars Hand Lens Imager (MAHLI) observations of rocks at Curiosity's field site. *Lunar Planet. Sci. Conf. 44*, abstract 2186 (2013).
5. W. Cross, J. P. Iddings, L. V. Pirsson, H. S. Washington, *Quantitative Classification of Igneous Rocks* (Univ. of Chicago Press, Chicago, 1903).
6. M. Wadhwa, Redox conditions on small bodies, the Moon and Mars. *Rev. Mineral. Geochem.* **68**, 493–510 (2008). doi: 10.2138/rmg.2008.68.17
7. J. Tuff, J. Wade, B. J. Wood, Volcanism on Mars controlled by early oxidation of the upper mantle. *Nature* **498**, 342–345 (2013). doi: 10.1038/nature12225; pmid: 23783628
8. J. M. Rhodes, Geochemical stratigraphy of lava flows sampled by the Hawaiian Scientific Drilling Project. *J. Geophys. Res.* **101**, 11729–11746 (1996). doi: 10.1029/95JB03704
9. C. Meyer, The Martian Meteorite Compendium (2012); http://curator.jsc.nasa.gov/antmet/mmc/index.cfm.
10. R. Gellert *et al.*, Alpha Particle X-ray Spectrometer (APXS): Results from Gusev crater and calibration report. *J. Geophys. Res.* **111**, E02S05 (2006). doi: 10.1029/2005JE002555
11. H. Wänke, J. Brückner, G. Dreibus, R. Rieder, I. Ryabchikov, Chemical composition of rocks and soils at the Pathfinder site. *Space Sci. Rev.* **96**, 317–330 (2001). doi: 10.1023/A:1011961725645
12. C. N. Foley, T. E. Economou, R. N. Clayton, W. Dietrich, Calibration of the Mars Pathfinder Alpha Proton X-ray Spectrometer. *J. Geophys. Res.* **108**, 8095 (2003). doi: 10.1029/2002JE002018
13. A. Harker, *The Tertiary Igneous Rocks of Skye. Memoirs of the Geological Survey of the United Kingdom* (James Hedderwick and Sons, Glasgow, 1904).
14. I. D. Muir, C. E. Tilley, Mugearites and their place in alkali igneous rock series. *J. Geol.* **69**, 186–203 (1961).
15. I. S. E. Carmichael, F. J. Turner, J. Verhoogen, *Igneous Petrology* (McGraw-Hill, New York, 1974).
16. M. Wilson, *Igneous Petrogenesis* (Unwin Hyman, London, 1989).
17. R. V. Morris *et al.*, Iron mineralogy and aqueous alteration from Husband Hill through Home Plate at Gusev crater, Mars: Results from the Mössbauer instrument on the Spirit Mars Exploration Rover. *J. Geophys. Res.* **113**, E12S42 (2008). doi: 10.1029/2008JE003201
18. V. Sautter, A. Jambon, O. Boudouma, Cl-amphibole in the nakhlite MIL 03346: Evidence for sediment contamination in a martian meteorite. *Earth Planet. Sci. Lett.* **252**, 45–55 (2006). doi: 10.1016/j.epsl.2006.09.024
19. J. M. D. Day, L. A. Taylor, C. Floss, H. Y. McSween Jr., Petrology and chemistry of ML 03346 and its significance in understanding the petrogenesis of nakhlites on Mars. *Meteorit. Planet. Sci.* **41**, 581–606 (2006). doi: 10.1111/j.1945-5100.2006.tb00484.x
20. A. H. Treiman, The parent magma of the Nakhla (SNC) meteorite, inferred from magmatic inclusions. *Geochim. Cosmochim. Acta* **57**, 4753–4767 (1993). doi: 10.1016/0016-7037(93)90198-6
21. H. Y. McSween Jr., G. J. Taylor, M. B. Wyatt, Elemental composition of the martian crust. *Science* **324**, 736–739 (2009). doi: 10.1126/science.1165871; pmid: 19423810
22. A. S. Yen *et al.*, Nickel on Mars: Constraints on meteoritic material at the surface. *J. Geophys. Res.* **111**, E12S11 (2006). doi: 10.1029/2006JE002797
23. T. N. Irvine, W. R. A. Baragar, A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* **8**, 523–548 (1971). doi: 10.1139/e71-055
24. T. Usui, H. Y. McSween Jr., B. C. Clark III, Petrogenesis of high-phosphorus Wishstone Class rocks in Gusev crater, Mars. *J. Geophys. Res.* **113**, E12S44 (2008). doi: 10.1029/2008JE003225
25. Georoc database; http://georoc.mpch-mainz.gwdg.de/georoc/.
26. H. Y. McSween Jr., What have we learned about Mars from SNC meteorites. *Meteoritics* **29**, 757–779 (1994). doi: 10.1111/j.1945-5100.1994.tb01092.x
27. A. Ruzicka, G. A. Snyder, L. A. Taylor, Comparative geochemistry of basalts from the Moon, Earth, HED asteroid, and Mars: Implications for the origin of the Moon. *Geochim. Cosmochim. Acta* **65**, 979–997 (2001). doi: 10.1016/S0016-7037(00)00599-8
28. J. Filiberto, Similarities between the shergottites and terrestrial ferropicrites. *Icarus* **197**, 52–59 (2008). doi: 10.1016/j.icarus.2008.04.016
29. E. Stolper, H. Y. McSween Jr., J. F. Hays, A petrogenetic model of the relationships among achondritic meteorites. *Geochim. Cosmochim. Acta* **43**, 589–602 (1979). doi: 10.1016/0016-7037(79)90167-4
30. H. Wänke, G. Dreibus, Chemical composition and accretion history of terrestrial planets. *Philos. Trans. R. Soc. London Ser. A* **325**, 545–557 (1988). doi: 10.1098/rsta.1988.0067
31. J. Karner, J. J. Papike, C. K. Shearer, Olivine from planetary basalts: Chemical signatures that indicate planetary parentage and those that record igneous setting and process. *Am. Mineral.* **88**, 806–816 (2003).
32. J. Karner, J. J. Papike, C. K. Shearer, Comparative planetary mineralogy: Pyroxene major- and minor-element chemistry and partitioning of vanadium between pyroxene and melt in planetary basalts. *Am. Mineral.* **91**, 1574–1582 (2006). doi: 10.2138/am.2006.2103
33. A. Lacroix, Les lavas à haüyne d'Auvergne et leurs enclaves homoeogènes. *Comptes Rendus* **CLXIV**, 581–587 (1917).
34. J. Andújar, F. Costa, J. Martí, J. A. Wolff, M. R. Carroll, Experimental constraints on pre-eruptive conditions of phonolitic magma from caldera-forming El Abrigo eruption, Tenerife (Canary Islands). *Chem. Geol.* **257**, 173–191 (2008). doi: 10.1016/j.chemgeo.2008.08.012
35. J. F. G. Wilkinson, R. A. Binns, Hawaiite of high pressure origin from northeastern New South Wales. *Nature* **222**, 553–555 (1969). doi: 10.1038/222553a0
36. A. J. Stolz, Garnet websterites and associated ultramamfic inclusions from a nepheline mugearite in the Walcha area, New South Wales, Australia. *Mineral. Mag.* **48**, 167–179 (1984). doi: 10.1180/minmag.1984.048.347.02
37. D. H. Green, A. D. Edgar, P. Beasley, E. Kiss, N. G. Ware, Upper mantle source for some hawaiites, mugearites and benmoreites. *Contrib. Mineral. Petrol.* **48**, 33–43 (1974). doi: 10.1007/BF00399108
38. G. J. Ablay, M. R. Carroll, M. R. Palmer, J. Martí, R. S. J. Sparks, Basanite-phonolite lineages of the Teide-Pico volcanic complex, Tenerife, Canaray Islands. *J. Petrol.* **39**, 905–936 (1998). doi: 10.1093/petroj/39.5.905
39. P. M. Smith, P. D. Asimow, Adiabat_1ph: A new public front-end to the MELTS, pMELTS, and pHMELTS models. *Geochem. Geophys. Geosyst.* **6**, Q02004 (2005). doi: 10.1029/2004GC000816
40. M. S. Ghiorso, R. O. Sack, Chemical mass transfer in magmatic processes. IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria. *Contrib. Mineral. Petrol.* **119**, 197–212 (1995). doi: 10.1007/BF00307281
41. H. S. Yoder, C. E. Tilley, Origin of basaltic magmas: An experimental study of natural and synthetic rock systems. *J. Petrol.* **3**, 342–532 (1962). doi: 10.1093/petrology/3.3.342
42. D. C. Presnall *et al.*, Liquidus phase relations on the join diopside-forsterite-anorthite from 1-atm to 20 kbar: Their bearing on the generation and crystallization of basaltic magma. *Contrib. Mineral. Petrol.* **66**, 203–220 (1978). doi: 10.1007/BF00372159
43. D. H. Eggler, Water-saturated and undersaturated melting relations in a Paricutin andesite and an estimate of water content in the natural magma. *Contrib. Mineral. Petrol.* **34**, 261–271 (1972). doi: 10.1007/BF00373757
44. P. J. Wyllie, Magmas and volatile components. *Am. Mineral.* **64**, 469–500 (1979).
45. G. J. Ablay, G. G. J. Ernst, J. Marti, R. S. J. Sparks, The ~2ka subplinian eruption of Montana Blanca, Tenerife. *Bull. Volcanol.* **57**, 337–355 (1995).
46. C. Beier, K. M. Haase, T. H. Hansteen, Magma evolution of the Sete Cidades volcano, São Miguel, Azores. *J. Petrol.* **47**, 1375–1411 (2006). doi: 10.1093/petrology/egl014

47. J. C. Dann, A. H. Holzheid, T. L. Grove, H. Y. McSween Jr., Phase equilibria of the Shergotty meteorite: Constraints on pre-eruptive water contents of martian magmas and fractional crystallization under hydrous conditions. *Meteorit. Planet. Sci.* **36**, 793–806 (2001). doi: 10.1111/j.1945-5100.2001.tb01917.x
48. H. Nekvasil, J. Filiberto, F. M. McCubbin, D. H. Lindsley, Alkalic parental magmas for chassignites? *Meteorit. Planet. Sci.* **42**, 979–992 (2007). doi: 10.1111/j.1945-5100.2007.tb01145.x
49. M. C. Johnson, M. J. Rutherford, P. C. Hess, Chassigny petrogenesis: Melt compositions, intersive parameters, and water contents of martian (?) magmas. *Geochim. Cosmochim. Acta* **55**, 349–366 (1991). doi: 10.1016/0016-7037(91)90423-3
50. F. M. McCubbin *et al.*, Hydrous magmatism on Mars: A source of water for the surface and subsurface during the Amazonian. *Earth Planet. Sci. Lett.* **292**, 132–138 (2010). doi: 10.1016/j.epsl.2010.01.028
51. J. Filiberto, A. H. Treiman, Martian magmas contained abundant chlorine, but little water. *Geology* **37**, 1087–1090 (2009). doi: 10.1130/G30488A.1
52. D. R. Baker, M. Alletti, Fluid saturation and volatile partitioning between melts and hydrous fluids in crustal magmatic systems: The contribution of experimental measurements and solubility models. *Earth Sci. Rev.* **114**, 298–324 (2012). doi: 10.1016/j.earscirev.2012.06.005
53. M. R. Carroll, J. D. Webster, Solubilities of sulfur, noble gases, nitrogen, chlorine, and fluorine in magmas. *Rev. Mineral.* **30**, 231–279 (1994).
54. P. J. Wyllie, O. F. Tuttle, Experimental investigations of silicate systems containing two volatile components. Part III. The effects of SO_3, P_2O_5, HCl, and Li_2O, in addition to H_2O, on the melting temperatures of albite and granite. *Am. J. Sci.* **262**, 930–939 (1964). doi: 10.2475/ajs.262.7.930
55. A. D. Edgar, in *Alkaline Igneous Rocks*, J. G. Fitton, B. G. J. Upton, Eds. (Geological Society of London, London, 1987), pp. 29–52.
56. D. H. Green, T. J. Falloon, W. R. Taylor, in *Magmatic Processes: Physiochemical Principles*, B. O. Mysen, Ed. (The Geochemical Society, University Park, PA, 1987), pp. 139–154.
57. R. Dasgupta, M. M. Hirschmann, N. D. Smith, Partial melting experiments of peridotite + CO_2 at 3 GPa and genesis of alkalic ocean island basalts. *J. Petrol.* **48**, 2093–2124 (2007). doi: 10.1093/petrology/egm053
58. F. E. Lloyd, D. K. Bailey, Light element metasomatism of the continental mantle: The evidence and the consequences. *Phys. Chem. Earth* **9**, 389–416 (1975). doi: 10.1016/0079-1946(75)90030-0
59. M. Menzies, V. Rama Murthy, Mantle metasomatism as a precursor to the genesis of alkaline magmas—Isotopic evidence. *Am. J. Sci.* **280-A**, 622–638 (1980).
60. S. Pilet, M. B. Baker, E. M. Stolper, Metasomatized lithosphere and the origin of alkaline lavas. *Science* **320**, 916–919 (2008). doi: 10.1126/science.1156563; pmid: 18487189
61. S. Keshav, G. H. Gudfinnsson, G. Sen, Y. W. Fei, High-pressure melting experiments on garnet clinopyroxenite and the alkalic to tholeiitic transition in ocean-island basalts. *Earth Planet. Sci. Lett.* **223**, 365–379 (2004). doi: 10.1016/j.epsl.2004.04.029
62. T. Kogiso, M. M. Hirschmann, D. J. Frost, High-pressure partial melting of garnet pyroxenite: Possible mafic lithologies in the source of ocean island basalts. *Earth Planet. Sci. Lett.* **216**, 603–617 (2003). doi: 10.1016/S0012-821X(03)00538-7
63. M. E. Schmidt, T. J. McCoy, The evolution of a heterogeneous Martian mantle: Clues from K, P, Ti, Cr, and Ni variations in Gusev basalts and shergottite meteorites. *Earth Planet. Sci. Lett.* **296**, 67–77 (2010). doi: 10.1016/j.epsl.2010.04.046
64. H. Y. McSween Jr. *et al.*, Alkaline volcanic rocks from the Columbia Hills, Gusev crater, Mars. *J. Geophys. Res.* **111**, E09S91 (2006). doi: 10.1029/2006JE002698
65. G. Dreibus, H. Wänke, Volatiles on Earth and Mars: A comparison. *Icarus* **71**, 225–240 (1987). doi: 10.1016/0019-1035(87)90148-5
66. G. J. Taylor *et al.*, Bulk composition and early differentiation of Mars. *J. Geophys. Res.* **111**, E03S10 (2006).
67. K. Lodders, B. Fegley Jr., An oxygen isotope model for the composition of Mars. *Icarus* **126**, 373–394 (1997). doi: 10.1006/icar.1996.5653
68. S. M. McLennan, Large-ion lithophile element fractionation during the early differentiation of Mars and the composition of the Martian primitive mantle. *Meteorit. Planet. Sci.* **38**, 895–904 (2003). doi: 10.1111/j.1945-5100.2003.tb00286.x
69. A. H. Treiman, Chemical compositions of martian basalts (shergottites): Some inferences on basalt formation, mantle metasomatism, and differentiation in Mars. *Meteorit. Planet. Sci.* **38**, 1849–1864 (2003). doi: 10.1111/j.1945-5100.2003.tb00019.x
70. J. D. Winter, *An Introduction to Igneous and Metamorphic Petrology* (Prentice Hall, Upper Saddle River, NJ, 2010).
71. M. E. Schmidt *et al.*, APXS of first rocks encountered by Curiosity in Gale Crater: Geochemical diversity and volatile element (K and Zn) enrichment. *Lunar Planet. Sci. Conf. 44*, abstract 1278 (2013).
72. R. W. Le Maitre, Ed., *Igneous Rocks: A Classification and Glossary of Terms* (Cambridge Univ. Press, Cambridge, ed. 2, 2002).
73. H. C. Aoudjehane *et al.*, Tissint martian meteorite: A fresh look at the interior, surface, and atmosphere of Mars. *Science* **338**, 785–788 (2012). doi: 10.1126/science.1224514; pmid: 23065902
74. C. B. Agee *et al.*, Unique meteorite from early Amazonian Mars: Water-rich basaltic breccia Northwest Africa 7034. *Science* **339**, 780–785 (2013). doi: 10.1126/science.1228858; pmid: 23287721
75. D. W. Ming *et al.*, Geochemical properties of rocks and soils in Gusev crater, Mars: Results of the Alpha Particle X-ray Spectrometer from Cumberland Ridge to Home Plate. *J. Geophys. Res.* **113**, E12S39 (2008). doi: 10.1029/2008JE003195
76. R. Rieder *et al.*, Chemistry of rocks and soils at Meridiani Planum from the Alpha Particle X-ray Spectrometer. *Science* **306**, 1746–1749 (2004). doi: 10.1126/science.1104358; pmid: 15576611
77. S. W. Squyres *et al.*, Pyroclastic activity at Home Plate in Gusev crater, Mars. *Science* **316**, 738–742 (2007). doi: 10.1126/science.1139045; pmid: 17478719
78. R. H. Hewins *et al.*, Northwest Africa 7533, an impact breccia from Mars. *Lunar Planet. Sci. Conf. 44*, abstract 2385 (2013).
79. M. Humayun, B. Zanda, R. H. Hewins, C. Göpel, Composition of Northwest Africa 7533: Implications for the origin of martian soils and crust. *Lunar Planet. Sci. Conf. 44*, abstract 1429 (2013).
80. A. K. Matzen, M. B. Baker, J. R. Beckett, E. M. Stolper, Fe-Mg partitioning between olivine and high-magnesian melts and the nature of Hawaiian parental liquids. *J. Petrol.* **52**, 1243–1263 (2011). doi: 10.1093/petrology/egq089
81. J. Filiberto, R. Dasgupta, Fe^{+2}-Mg partitioning between olivine and basaltic melts: Applications to genesis of olivine-phyric Shergottites and conditions of melting in the Martian interior. *Earth Planet. Sci. Lett.* **304**, 527–537 (2011). doi: 10.1016/j.epsl.2011.02.029

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Supplementary Materials

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Materials and Methods
Supplementary Text
Figs. S1 to S24
MSL Science Team Author List
References (*82–98*)

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