Elemental Composition of the Martian Crust

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The composition of Mars’ crust records the planet’s integrated geologic history and provides clues to its differentiation. Spacecraft and meteorite data now provide a global view of the chemistry of the igneous crust that can be used to assess this history. Surface rocks on Mars are dominantly tholeiitic basalts formed by extensive partial melting and are not highly weathered. Siliceous or calc-alkaline rocks produced by melting and/or fractional crystallization of hydrated, recycled mantle sources, and silica-poor rocks produced by limited melting of alkali-rich mantle sources, are uncommon or absent. Spacecraft data suggest that martian meteorites are not representative of older, more voluminous crust and prompt questions about their use in defining diagnostic geochemical characteristics and in constraining mantle compositional models for Mars.

Over the past decade, instruments on orbiting spacecraft, landers, and rovers have measured the abundances of elements present in martian rocks and soils. Some analyses are incomplete, and the scales of analyzed areas range from centimeters to hundreds of kilometers in diameter, complicating comparisons. Martian meteorites [shergottite, nakhlite, and chassignite (SNC)] constitute another important source of geochemical data. Although the meteorites come from as-yet undetermined locations on Mars, laboratory analyses permit complete chemical characterizations that cannot be obtained by remote sensing techniques.

Based on these data, Mars has been viewed as a basalt-covered world (1). Although basalts are ubiquitous on rocky planets, the apparent lack of other rock compositions suggests that the geologic evolution of Mars has been distinct from Earth. Rocks at the Mars Pathfinder landing site previously identified as andesite (2) may be coated with alteration rinds, and martian spectral signatures formerly interpreted as andesitic (3) are now attributed to the effects of chemical weathering (4, 5). Only a few occurrences of evolved siliceous rocks have been discovered in global spectral surveys (6), supporting the view that magmatic differentiation has been very limited. Although much of the surface is covered by sediments, these materials largely retain the chemical compositions of their basaltic precursors.

Sufficient geochemical data now exist to better characterize the crust and the igneous processes that produced it. Here, we compare

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Fig. 1. (A) Total alkalis-silica diagram used for classification of volcanic rocks. Gusev RAT-ground and RAT-brushed compositions for the same rocks are connected by tie-lines. Analyses of Gusev rocks and soils, martian meteorites, and global GRS data (calculated on a volatile-free basis) indicate a crust dominated by basalts. TES-derived data and possibly the Mars Pathfinder rock composition may reflect alteration. Data sources in this and other figures are discussed in the text. (B) Calculated normative minerals in the martian crust. The three triangles correspond (from left to right) to alkaline basalts, olivine tholeites, and quartz tholeites. The critical plane of silica undersaturation separates alkaline basalts and olivine tholeites; fractionating liquids to the left of this plane form silica-deficient compositions, whereas those to the right evolve to silica-enriched compositions. Contours indicate the relative abundances of terrestrial basaltic rocks (37). Martian meteorites and Gusev rocks plot mostly in the fields of olivine tholeites and quartz tholeites; nepheline-normative rocks have not been encountered.

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SO2, the quantities of which were calculated oxide concentrations on a H2O-free and CO2-known chemistries. Finally, we calculated major clase, pyroxene, and olivine) and secondary (e.g., member set consisting of primary (e.g., plagio-
tially affecting the neutron flux in the upper 
~30 cm of the martian surface. We corrected 
the data for this effect (7) by a process that 
uses measured fluxes of γ-rays from H, Fe, Si, 
and Ca, and the fluxes calculated from a neu-
tron transport γ-ray production model. This ap-
proach produces reasonable values at equatorial 
latitudes but uncertain values at higher polar 
latitudes where H dominates elemental signa-
tures. Accordingly, we constrained our results 
using a mask based on H concentration, corre-
responding to roughly ±45° of latitude from the 
equator. The concentration of H does not affect 
K and Th data because their γ-rays result from 
radioactive decay. To compare igneous rock 
compositions, we further adjusted the data to a 
volatile-free basis by removing H2O, Cl, and 
SO2, the quantities of which were calculated 
from the S/Cl ratio of ~5 found at rover landing 
sites. We represent GRS element abundances as 
boxes defined by global averages and standard 
deviations (10).

Measurements of the Thermal Emission Spec-
trometer (TES) onboard the Mars Global Survey-
or orbiter are sensitive to the chemistry and 
structure of silicates, (8). Complex mixtures can 
deconvolved into mineral abundances using a 
spectral library of known minerals (9). The major 
oxide concentrations can be estimated from TES 
data to within ±5 weight percent (wt %) using 
known mineral chemistries and deconvolved min-
eral abundances from thermal emission studies 
(10, 11). We modeled the spectra (12) over 233 
to 508 cm−1 and 825 to 1301 cm−1 using an end-
member set consisting of primary (e.g., plagio-
clace, pyroxene, and olivine) and secondary (e.g., 
phyllolosilicates, sulfates, and oxides) phases with 
known chemistries. Finally, we calculated major 
oxide concentrations on a H2O-free and CO2-
free basis. The data clouds in our graphs repre-
sent derived chemical compositions from global 
TES data binned at 4 pixels per degree.

In comparing GRS analyses and TES-
derived compositions, it is necessary to realize 
that γ-rays can penetrate to depths of 20 to 30 cm 
and thus analyze a much greater volume of 
material, relative to thermal emission spectra 
that sample only the outermost 10 to 100 μm. 
Thus, surface alteration processes may have a 
profound effect on geochemical classifications 
based on TES data.

Sediments potentially sample broad areas of 
the crust, although fractionation of heavy min-
erals is likely during their transport. X-Ray Flu-
orescence (XRF) instruments on the Viking landers 
obtained six soil analyses from two landing sites 
(13). Another five soils were analyzed by the 
Alpha-Proton-X-ray Spectrometer (APXS) on 
the Mars Pathfinder rover. APXS (14) on the 
Mars Exploration Rovers (MER), Spirit and Op-
portunity, analyzed nearly 100 soils at two dif-
ferent sites (15, 16). We plot Gusev crater soil 
compositions measured by Spirit, but Viking, 
Pathfinder, and Opportunity soils are illustrated 
by ovoids enclosing the data, to minimize com-
plexity in our diagrams.

Two different calibrations of five rock analy-
yses by the Mars Pathfinder APXS have been 
published (17, 18). The true compositions of the 
Pathfinder rocks are unknown, because the 
APXS analyzed only the outermost few micro-

Fig. 2. (A) Ca-Si/Mg-Si diagram used for classification of martian meteorites. The GRS-measured Ca/Si ratio and standard deviation is represented by a horizontal band. Global Mg/Si can be estimated from the intersection of that band with the regression line for shergottites or from the average Mg/Si value for Gusev rocks and soils (red arrows). (B) FeO*/MgO-silica diagram used for distinguishing dry tholeiitic (TH) and wet calc-alkaline (CA) rocks. All martian samples are tholeiitic. TES-derived compositions result from alteration. Arrows represent melting and fractionation trends in terrestrial magmas.
likely to be a major crustal component. However, one sample from Meridiani, Bounce Rock (22), has a chemical and mineralogical compositional similarity to martian meteorites (shergottites) and was included in our compilation. Unlike Meridiani, Spirit’s Gusev landing site spectrally resembles most of the martian surface, and thus its igneous rocks are more likely to represent other parts of the crust. Here, we focus especially on Gusev samples, estimated to have formed at ~3.7 billion years ago (23).

Martian meteorites (24) include three types of shergottites (basaltic, olivine-phyric, and lherzolitic), nakhlites, chassignites, and ALH84001—all igneous rocks. We focus on shergottites and nakhlites, because they are the most abundant and well characterized. Moreover, their petrographic characteristics are consistent with near-surface rocks. With the exception of ALH84001, the radiometric ages of all these meteorites indicate that they crystallized since ~1.4 billion years ago (25). Thus, they are considerably younger than Gusev rocks. The times of ejection of these meteorites from Mars, estimated from cosmogenic nuclide measurements (26), define four clusters with several outliers, each containing a single meteorite type and likely representing a distinct launch site. Although crystallization ages suggest that these meteorites constitute a chronologically biased sampling of the martian crust, they represent more sampling locations than those visited so far by landers and rovers. Bulk-rock geochemical data for shergottites and nakhlites from various sources were compiled by (27). Here, we consider major and minor elemental abundances that can be compared with remote sensing data.

Geochemical Classification of Crustal Rocks

The total alkalis-silica diagram (Fig. 1A) is commonly used for geochemical classification of volcanic rocks. Martian meteorites plot within the basalt field, as does compositionally similar Bounce Rock. Gusev rocks also are concentrated within the basalt field, but they have higher Na2O/K2O values. Their compositions are scattered (some are tephrites or picrobasalts), possibly resulting from fractional crystallization at varying depths (28). Gusev rocks are clearly more alkali-rich than other martian compositions. The Mars Pathfinder dust-free rock composition is andesitic, although this composition may reflect surficial silica enrichment during weathering.

Gusev soils plot in the basalt field, superimposed on compositions of the local basaltic rocks. Meridiani soils are basaltic, with slightly lower alkalis than Gusev soils. Pathfinder soils have lower silica and alkalis and are distinct from the composition of the local rocks. Viking soils are not plotted because Na was not analyzed.

The globally averaged GRS-measured silica abundance (Fig. 1A) corresponds to basalt, and the standard deviation indicates that few analyses lie outside the basalt range. The GRS analysis of ejection of these meteorites from Mars, estimated from cosmogenic nuclide measurements, suggests that these meteorites are from Earth rocks. Gusev and GRS data do not show the Al depletion seen in martian soils. Pathfinder soils from the Gusev landing site spectrally resemble most of the martian surface, and thus their igneous rocks are more likely to represent other parts of the crust. Here, we focus especially on Gusev samples, estimated to have formed at ~3.7 billion years ago (23).

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Mars Geochemical Discriminants

Several distinctive geochemical characteristics of martian meteorites are commonly assumed to be fingerprints of Mars, although it has been noted that some unusual terrestrial rocks (ferropicroites) share their compositions (33). Martian meteorites are depleted in Al relative to terrestrial rocks and, in fact, ancient Gusev rocks are not as depleted in Al as are the younger meteorites. The GRS global average data also support the higher Al/Si ratios for Gusev rocks. This brings into question the validity of Al depletion as a geochemical discriminant for all Mars samples. The Gusev RAT-ground rock compositions have consistently higher Mg/Si ratios than RAT-brushed compositions (inset in Fig. 3). This difference can be explained by preferential leaching of olivine in alteration rinds during acidic weathering (35).

The Fe/Mn ratio is another geochemical characteristic thought to be diagnostic for Mars. Fe/Mn ratios of pyroxene and olivine in martian meteorites are distinct from those of lunar and terrestrial minerals (36), and the average bulk Fe/Mn in meteorites was used to constrain the martian mantle composition (31). The Fe/Mn weight ratio in the martian mantle, based on martian meteorites, is ~41, lower than that of Earth’s mantle (~62). However, Fe/Mn ratios for Gusev rocks and soils are significantly different (Fig. 4A). It is unclear which ratio provides a more accurate assessment of the martian mantle composition.

Ni/Mg ratios are distinctive for martian meteorites (Fig. 4B) and have been used to estimate a Ni abundance for Mars that is considerably lower than for Earth (31). However, RAT-ground Gusev basalts plot along the terrestrial trend, clearly distinct from the meteorites (Fig. 4B). RAT-brushed rocks and soils generally fall to the Mg-poor side of this trend. This diagram suggests that Ni/Mg may not be a valid discriminant for Earth and Mars rocks. The global Mg abundance estimated for GRS data is shown by a vertical bar, but Ni data are unavailable.

Conclusions

A critical review of element abundance data for Mars from available sources supports the conclusion that the crust is basaltic, with very limited siliceous rocks and no rocks critically undersaturated in silica. The basalts are tholeiites, and a previous hypothesis that older crustal rocks are depleted in Al relative to terrestrial rocks may not be a valid discriminant for Earth and Mars rocks. The global Mg abundance estimated for GRS data is shown by a vertical bar, but Ni data are unavailable.

References and Notes

12. TES spectra are limited from the mapping orbit data set up to 5317 and are constrained by surface temperatures >250 K, lambert albedo <0.35, dust extinction of ~0.18 (1075 cm^-1 opacity of ~0.3), water ice extinctions of ~0.1 (800 cm^-1 opacity of ~0.15), and emission angles <30°.
14. The APXS on Mars Pathfinder was an Alpha Proton X-ray Spectrometer; the same abbreviation on MER stands for Alpha Particle X-ray Spectrometer.
38. This work was partly supported by NASA Cosmochemistry grant NNG06GG36G to H.Y.M.

Fig. 4. (A) Mn-Fe diagram suggests that the commonly accepted Fe/Mn ratio for the martian mantle, based on martian meteorites, may not apply to all mantle sources, such as that for Gusev rocks. (B) Ni-Mg diagram thought to distinguish Mars and Earth samples. Gusev rocks and soils plot along a trend defined by terrestrial basalts rather than martian meteorites.