

IGNEOUS MARS: CRUST AND MANTLE EVOLUTION AS SEEN BY ROVER GEOCHEMISTRY, MARTIAN METEORITES, AND REMOTE SENSING. M.E. Schmidt¹, C.D.K. Herd², T.J. McCoy³, H.Y. McSweeney⁴, A.D. Rogers⁵, and A.H. Treiman⁶. ¹Brock Univ. (St. Catharines, ON L2S 3A1 Canada, mschmidt2@brocku.ca), ²Univ. Alberta (Edmonton, AB T6G 2E3, Canada), ³Nat. Mus. Natural History, Smithsonian Inst. (Washington, DC 20560-0119), ⁴Univ. Tennessee Knoxville (Knoxville, TN, 37996-1410), ⁵SUNY Stony Brook (Stony Brook, NY 11794-2100), ⁶Lunar and Planetary Institute, USRA (Houston, TX 77058).

Introduction: Mars has a protracted igneous history and a crust largely composed of basaltic rocks and sediments. Diverse, igneous compositions revealed by remote sensing, meteorites, and landed missions indicate that ancient Mars differentiated and experienced varied igneous processes that generated heterogeneous distributions of volatile and incompatible elements. With time, planetary cooling thickened Mars' lithosphere and led to lower volume partial melts [1], while stabilizing convective upwelling beneath the Tharsis volcanic province [2].

Mars' Igneous Compositions: The array of Mars' known igneous compositions is presented in Figure 1. Tholeiitic to alkali basalt compositions are thought to form by varying degrees of partial melting of a nearly anhydrous mantle [3]. More evolved, higher SiO₂ magmas fractionated from those at varying depths [e.g., 4].

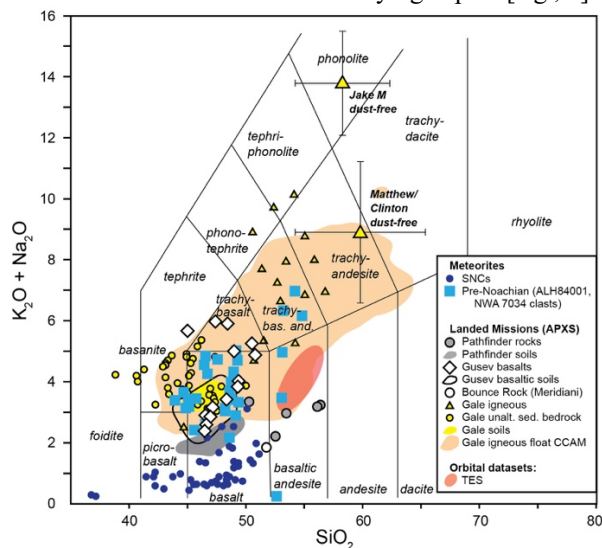


Fig 1. Total alkali vs. SiO₂ (TAS) diagram of Mars' igneous rocks [5-12]. Thermal Emission Spectrometer (TES) field density represents its highest point density [3].

Orbital datasets. Elemental and mineralogical information retrieved from gamma ray and infrared global data sets show that low-dust regions of Mars are basaltic [13, 14] with regional mineralogical variations on the order of ~10% of plagioclase, high-Ca pyroxene (HCP), low-Ca pyroxene (LCP), olivine and poorly crystalline/amorphous (likely secondary) phases [13]. Abundances of K and Th are higher than those in martian meteorites, although the abundance ratio is similar [15].

Meteorites. More than 120 meteorites are linked to Mars through trapped martian atmospheric gases and similar geochemical characteristics [e.g., 16]. Over 80% of the meteorites are alkali-poor basaltic igneous rocks that crystallized 165-600 Ma as flows or shallow intrusions (shergottites). Two others, NWA 7635 and NWA 8159, are ~2400-Ma, augite-rich basalts that are chemically distinct from the shergottites [17]. An additional 15% of the martian meteorites are clinopyroxene and olivine cumulates (nakhlites and chassignites), which were comagmatic at ~1300 Ma [e.g., 19]. Thus, nearly all of the meteorites are Amazonian-aged, alkali-poor mafic to ultramafic igneous rocks ('SNCs' of Fig. 1). The predominance of such rocks among martian meteorites likely reflects the fact that only impacts can deliver rocks from Mars to orbit, and only more competent, unaltered (=young) igneous rocks survive impact [e.g., 20]. Nevertheless, the bulk composition of Mars derived from their geochemistry [21] has been corroborated by remotely-sensed data [15] and is similar to that of the Earth, but enriched in volatiles, including alkalis.

The only martian meteorites older than the Amazonian are the ALH84001 orthopyroxene cumulate (4100 Ma; [22]), and some clasts and mineral grains in the NWA 7034 (and pairs) regolith breccia [23]; its zircons are as old as 4400 Ma, although the breccia was annealed at ~1500 Ma [23].

Landed missions. Alpha Particle X-Ray Spectrometers (APXS [24]) have been flown on four Mars rover missions, which allows direct comparisons of their analyses. Most soils analyzed by landed missions since Viking are basaltic [25, 26]. A few soils analyzed in Gusev crater are sulfatic or silicic [27]. The Pathfinder mission in Chryse Planitia analyzed basaltic to andesitic rocks, but these may be weathered basalt [5].

The Mars Exploration Rover (MER) Spirit examined relatively unaltered basalts in Gusev crater, including subalkaline to alkaline olivine and pyroxene-bearing lithologies of likely Hesperian age [28]. The MER Opportunity in Meridiani Planum identified a shergottite-like, pyroxene-rich exotic called BounceRock [12].

The Mars Science Laboratory (MSL) Curiosity rover in Gale crater has mainly encountered sedimentary rocks, which include conglomerates with feldspar-rich igneous clasts, and also igneous float rocks [29]. The Jake M class rocks were classified as mugearites [5], but corrected, dust-free compositions are phonolitic

to trachyandesitic-trachydacitic (higher silica and alkalis) [12]. Some relatively unaltered basaltic sediments (Bathurst Inlet class) [30], and components in other sediments [31] have K_2O up to 3.7 wt%, and are thought to imply alkaline igneous source rocks [31].

Pre-Noachian Mars: There is general consensus that Mars had a magma ocean early in its history [e.g., 32], an inference based principally on the short- and long-lived radiogenic isotopic characteristics of the shergottites [e.g., 33]. Though young, the shergottites preserve evidence of geochemically distinct mantle sources that formed as early as 25 Ma after accretion; these distinct sources are consistent with magma ocean crystallization. The crust and the primordial atmosphere may have formed in the following 15 Ma [34]. Enriched and depleted mantle sources are generally oxidized and reduced, respectively [e.g., 35]. Estimated fO_2 variations among the Gusev basalts are consistent with those observed in the shergottites [36].

The NWA 7034 regolith breccia provides our only view of lithologic diversity of Mars' ancient crust. It includes clasts of basalt, basaltic andesite, trachyandesite, and an Fe-Ti-P rich lithology [9, 23]; a 4400 Ma zircon sits in an alkali-rich basaltic clast, confirming the presence of alkali volcanism on early Mars [23]. The petrogenesis of the NWA 7034 breccia is dominated by relatively water-poor, impact-generated episodic lithification and provides novel insights into processes that dominated the southern highland crust [23].

Evolving Interior: Relative to Noachian surfaces, Hesperian volcanic provinces in the highlands exhibit a lower abundance ratio LCP:(LCP+HCP) [13], consistent with lower degrees of partial melting, caused by a cooling mantle and thickening lithosphere [37]. Hesperian highland volcanic terrains have relatively low K (and Th to a lesser extent) relative to Noachian crust; together, these observations suggest that the Noachian crust was built by a more complex set of processes than acted in the Hesperian, including varying degrees of partial melting and magmatic differentiation [13]. Moving forward in time, Amazonian volcanic provinces are geochemically distinct from Hesperian highland volcanic terrains, with lower SiO_2 and higher Th, both of which are consistent with continued mantle cooling, thickening crust and smaller melt fractions [1].

A thicker lithosphere insulates the Mars interior and slows cooling, meanwhile preserving ancient heterogeneities [2], including LREE-depleted, LREE-enriched, and alkali metasomatized domains later sampled by basaltic magmas, as evidenced by shergottite, nakhlite parent magma, Gusev basalt, and Gale igneous compositions [e.g., 31, 33, 38, 39].

Feldspar-Rich Crustal Rocks: Rare areas of feldspar-rich crust have been detected from orbit [40] and

the presence of feldspar-rich lithologies in Gale crater has been interpreted as evidence of ancient silicic crust [41]. Feldspar-rich lithologies may instead be anorthositic [42] or fractionally crystallized basaltic magmas [43]. The evolved Jake M composition also likely fractionally crystallized at depth [4, 12]. Thus there is no need to invoke repeated assimilation and fractional crystallization as is essential for continental crust formation.

Conclusions: The desire to return samples from Mars originates from Apollo, which demonstrated the immense value of samples collected within context. Well-characterized igneous materials from a not yet sampled period of Mars history (Noachian or Hesperian) would yield insights to the mantle state and composition at that time, and contribute to our understanding of the long-term petrological and geochemical evolution of the planet.

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Acknowledgements: Schmidt is funded by a CSA MSL PS grant. LPI is run by USRA under a CA with NASA.