**MARS AS AN IGNEOUS SYSTEM: OUR CHANGING VIEW FROM ORBIT, GROUND, METEORITE.**
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**Introduction:** Mars has been volcanically active throughout its history, and volcanic landforms such as lava flows, shield volcanoes, volcanic cones, pyroclastic deposits, and dikes are ubiquitous on the Martian surface [1]. After the formation of primary mantle reservoirs, the evolution of Mars as an igneous system was primarily driven by mantle differentiation, with activity peaking during the early evolution, but likely stretching into the present in the Tharsis and Elysium provinces [2,3].

**Early Evolution:** Following accretion, Mars was likely covered by a magma ocean, which would also facilitate an early formation of the Martian core [4]. Freezing of the magma ocean would have resulted in an unstable density stratification and subsequent overturn due to gravitational instability, which is expected to have occurred on small spatial scales [5], and would have formed the primary mantle reservoirs. Isotopic anomalies in the SNC meteorites indicate that reservoir mixing was inefficient thereafter [4], but it should also be noted that fractional magma ocean crystallization does not seem to be required for these reservoirs to form [6].

Estimates of low elastic thicknesses during the Noachian period [7] derived from gravity and topography data indicate that mantle convection started early-on, and a thin and relatively hot lithosphere was established in the Noachian period. The igneous evolution was then driven by mantle cooling and lithospheric thickening. The early formation of isolated geochemical reservoirs by mantle overturn and an early onset of mantle convection are difficult to reconcile in geodynamic modeling, and self-consistent models accounting for all observations are still missing.

**Long-Term Evolution:** While volcanism was a nearly global process on early Mars, activity became focused in the Tharsis and Elysium provinces during the later evolution (Figure 1). Depths of the magma source regions and the degrees of partial melting have been constrainted from petrological modeling [8], and migration of the source regions from depths of 80 km in the Hesperian to 150 km during the Amazonian period have been reported. The compositions of the SNC meteorites can be modeled petrologically by assuming partial melting of a Wänke-Dreibus mantle composition [9], but different water contents in the respective source regions as well as crustal assimilation processes seem to be required to reproduce the full range of SNC compositions.

Degrees of partial melting derived from petrological modeling range from 5 to 15%, and magma storage at depth appears to have been of limited importance during the early evolution. Gamma ray spectroscopy data [10] and thermo-chemical evolution models [11] are consistent with a removal of about 50% of the incompatible species ($H_2O$, K, Th, U) to the crust, but the total amount of mantle differentiation remains uncertain because the average crustal thickness is merely constrained to within a factor of two.

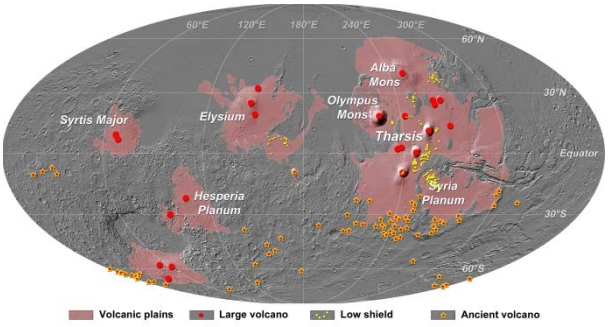


**Figure 1:** Volcanic landforms on Mars shown on a MOLA shaded relief digital elevation model. Figure modified after [7].

Another open question concerns the crystallization age of the shergottites, and different geochronometers yield discordand results. While most isotopic systems yield young crystallization ages (150-650 Myr [12]), the Pb isotopic system yields significantly older ages (4 Gyr [13]). Given that shergottites have formed at a depth of 80–100 km in the Martian mantle [14], it would be important to know if this depth corresponds to the Amazonian or Noachian periods. It should also be noted that old ages are easier to reconcile with thermo-chemical evolution models.

**Mantle water content:** The amount of water in the Martian mantle has been constrained from analysis of the SNC meteorites, estimates of the elastic lithosphere thickness, and estimates of tidal dissipation in the Martian interior. Evidence suggests that rheologically significant amounts of water of a few tens of ppm are present in the interior [7], but the total amount of water in the Martian mantle remains controversial.

Geochemical analysis of the SNC meteorites indicated that the water content of the shergottite parent magma was relatively small, corresponding to a mantle bulk water content of only 5 to 15 ppm [15]. However,

it has also been argued that magmatic degassing could be responsible for these (artificially) low values. Accounting for degassing, bulk mantle water contents of 55 to 220 ppm $H_2O$ have been derived (e.g., [16]), values similar to that of the Earth's mantle. As already a few tens of ppm of $H_2O$ significantly influence the visicosity of mantle rocks, this implies that rheologically significant amounts of water can be assumed to be present in the Martian interior. However, to significantly influence the mantle solidus, at least a hundred ppm $H_2O$ would be necessary. Whether water is present in these quantities in the Martian mantle must be considered an open issue and is still under debate.

**Martian Igneous Petrology**: Remote sensing data, geochemical analysis of the SNC metoerites, as well as in situ measurements by landed missions agree that igneous rocks on Mars are predominantly basaltic in composition (Figure 2). Gamma ray data indicate a trend towards a more Si-poor composition of younger volcanics [8], and $SiO_2$ content appears to have decreased from 45 to 48 wt% during the Hesperian to 42 to 45 wt% in the Amazonian period.

In addition to the trend in $SiO_2$ content, younger volcanics appear to have a lower content of low calcium pyroxenes, with LCP/(LCP+HCP) = 0.2 to 0.3 for Hesperian and LCP/(LCP+HCP) = 0.5 for Noachian volcanism [17,18]. This decrease has been interpreted in terms of mantle cooling [19].

Analysis of the SNC meteorites and remote sensing data are consistent with the crystallization of Martian igneous rocks from primary mantle melts, and magma storage at depth appears to have been of limited importance [20]. However, evidence for magmatic differentiation is found in the Nili Patera caldera of Syrtis Major, where measurements in the thermal infrared indicate a dacite composition of lave flows [21]. Even more extreme magmatic differentiation products rich in quartz have been reported in other areas of the Syrtis Major region [22], and although these examples appear to be isolated, they nevertheless indicate that magmatic differentiation has occurred on Mars.

**Conclusions:** Although the general evolution of Mars as an igneous system is relatively well understood, some important issues remain to be resolved: First of all, a coherent geodynamical model of the earliest evolution including magma ocean formation, overturn, formation of geochemical reservoirs, and the onset of mantle convection is missing. Second, the total amount of mantle processing is still unknown to within a factor of two due to the poorly constrained crustal thickness. Furthermore, the bulk mantle water content of the Marian mantle remains to be determined, as this directly influences mantle dynamics and the mantle solidus. Finally, the debate concerning the crystallization age of the shergottites needs to be resolved, because it would be important to determine if the source region depth determined for the parent magmas corresponds to modern or ancient Mars.

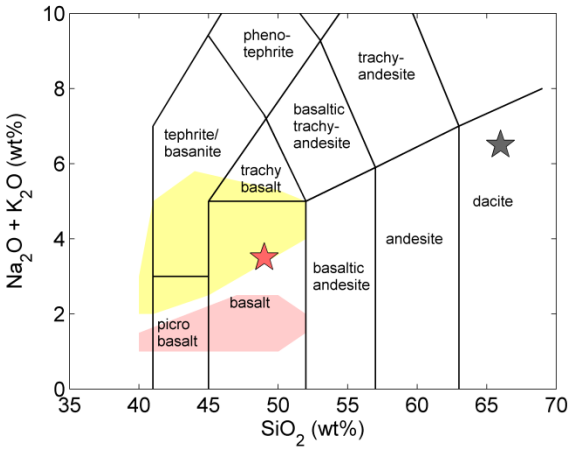


**Figure 2:** Total alkali vs. silica (TAS) diagram modified after [7]. Range of in-situ determined compositions are marked in yellow, SNC compositions are marked pink. The composition of the average Martian crust is given by the red star, the average composition of Earth's upper continental crust is shown by the gray star.

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