On the principle building blocks of Mars. C. Liebske[1] and A. Khan[2], [1]Institute of Geochemistry and Petrology, ETH Zürich, Sonneggstr. 5, 8092 Zürich, Switzerland (liebske@ethz.ch); [2]Institute of Geophysics, ETH Zürich, Sonneggstr. 5, 8092 Zürich, Switzerland (akhan@ethz.ch).

Introduction: The terrestrial planets are believed to have formed from primitive material sampling a broad region of the inner solar system. Several meteoritic mixing models attempting to reconcile isotopic characteristics of Mars and Earth have recently been proposed [1-5], but, because of the inherent non-uniqueness of these solutions, additional independent observations are required to resolve the question of the primary building blocks of the terrestrial planets. Here, we extend previous work [4,5] by seeking to reconcile geochemical signatures, geophysical properties, and redox characteristics of Mars [6].

Methods: We consider existing isotopic measurements of $\Delta'^{17}O$, $\varepsilon^{48}Ca$, $\varepsilon^{50}Ti$, $\varepsilon^{54}Cr$, $\varepsilon^{62}Ni$, and $\varepsilon^{84}Sr$ for primitive chondrites (CI, CM, CO, CV, H, L, LL, EH, and EL) and differentiated achondrites (APB and EPB) and mix these stochastically to reproduce the isotopic signatures of Mars. For both planets we observe ~10^5 unique mixing solutions out of 10^8 random meteoritic mixtures, which are categorized into distinct clusters of mixtures using principle component analysis. The large number of solutions implies that isotopic data alone are insufficient to resolve the building blocks of the terrestrial planets. To further discriminate between isotopically valid mixtures, each mixture is converted into a core and mantle component via mass balance. These compositions are subsequently converted to seismic P- and S-wave speeds and density using Gibbs free energy minimisation for the silicate mantle mineralogy (using the CFMASNa chemical model system) [7] and a parameterised equation-of-state approach for the core (assuming a binary mixture of liquid Fe-S) [8] from which bulk geophysical data in the form of mean density, mean moment of inertia, and elastic tidal response are computed and compared to observations.

Results: We ran two sets of model simulations using first mixtures of undifferentiated chondrites only, followed by mixtures that are extended to include the differentiated achondrites APB and EPB.

Chondritic mixtures: are found to reproduce isotopic matches with a “match rate” of ~0.1%. Figure 1a shows the results from principle components analysis (PCA) of 102050 unique solutions. The plot represents a bivariate histogram of the data projected onto first and second principle components, which together account for 85% of the total variance of the dataset. The inset in Figure 1a shows that typically 4--6 different meteorite groups contribute to the isotopic matches. The different clusters represent high abundances of mixtures for which the indicated meteoritic groups show relatively constant mass fractions, while others are highly variable. The bivariate histogram further allows mixing relations between the different clusters to be explored, for example, the near-horizontal trend among the clusters ``EL+LL" and ``EH+LL" can be interpreted as a continuous exchange between EL and EH, while LL remains almost constant. Similarly, along the vertical direction, substitution of different ordinary chondrite groups (H, L, LL) mixed with either EH or EL can be observed. The geophysical properties computed for each composition are shown in Figure 1b. The results indicate that none of the isotopically valid chondritic mixtures are capable of simultaneously “fitting" all geophysical properties. Since mean moment of inertia is sensitive to the mass distribution within the planet, this suggests that there are discrepancies in modelled core and mantle masses relative to Mars. The bulk Mars compositional model of [9] (diamond-shaped symbols in Fig 2b) also suffers this deficit but changes to core mass fraction and sulphur content can resolve this [10].

Chondritic and achondritic mixtures: Next, we simulate Mars by including differentiated objects (APB and EPB) in the chondrite mixtures. We obtain a “match rate” of ~0.2% with APB or EPB mass fractions of at least 1\%. The results from this simulation are shown in Figure 2. PCA indicates additional clusters, mostly characterised by 2--3 meteorite classes including APB or EPB, that are able to match Mars's isotopic composition. The predicted geophysical properties (Figure 2b) are, relative to purely chondritic mixtures (white circles), considerably extended in the geophysical data space toward larger mean moment of inertia values. This is a direct consequence of including differentiated objects, since these are assumed to be relatively oxidised and are therefore capable of compensating for the more reduced nature of the chondritic mixtures. This observation is also supported by bulk compositional parameters (not shown) such as Mg/Si ratio, Mg#, and core mass fraction for isotopic matches of chondrites-only and chondrites including APB and EPB. Compared to a mixture consisting of chondrites only, the compositional range in Mg#s for mixtures including APB and EPB is significantly extended to lower values and lower core mass fractions. Thus, an important conclusion to be drawn from these models is that building Mars requires a relatively oxidised object, such as the APB, in addition to chondritic material. We should note, however, that the bulk chemical compositions of APB and EPB are subject to uncertainty and, as a consequence, the solutions presented in Figure 2 are only valid for the explicit bulk APB and EPB compositions reported considered here. For these particular compositions, matches with <10% cC, ~30% EH, ~40% LL, and ~20% APB fulfill all isotopic and geophysical constraints.

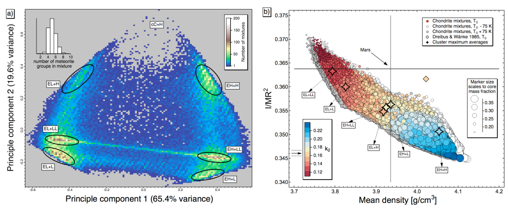

Figure 1. *a) Plot of principle components (PCA) of the first two principle components. PCA indicates several clusters of solutions (outlined in black) that are able to match the observed isotopic variation in Martian meteorites. The histogram in the inset shows the distribution in number of meteorite groups that contribute to matching solutions. b) Predicted Martian geophysical properties for each of the isotopic solutions (observed are indicated by horizontal and vertical lines and arrows, and widths show observational uncertainty).*

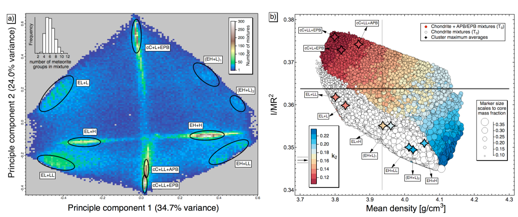

Figure 2. *Results for Mars as a mixture of chondrites and achondrites. a) Principal component analysis density plot shows additional clusters compared to the purely chondritic mixtures (cf. Figure 1a). b) The geophysical solution space is significantly extended relative to the chondrite-only case (compare with figure 1b) and mixtures that match all observations for Mars are identifiable).*

References: [1] K. Lodders and B. Fegley (1997), *Icarus, 126*, 373-394. [2] C. Sanloup, A. Jambon, P. Gillet (1999) *Physics of the Earth and Planetary Interiors 112*, 43-54. [3] R. Mohapatra and S. Murty (2003) *Meteoritics and Planetary Science 38*, 225-242. [4] T. Burbine and K. O'Brien (2004) *Meteoritics and Planetary Science 39*, 667-681. [5] C. Fitoussi, B. Bourdon, X. Wang (2016) *Earth and Planet. Sci. 434*, 151-160. [6] C. Liebske and A. Khan (2019*) Icarus, in revision.* [7] J. Connolly (2009) *Geochem. Geophys. Geosys. 10*,. [8] A. Rivoldini et al. (2011) *Icarus 213*, 451-472. [9] G. Dreibus and H. Wänke (1984) *Geochemistry and Cosmochemistry*, 3-11. [10] A. Khan et al. (2018) *J. Geophys. Res. 123*, doi:10.1002/2017JE005371