Headline Article

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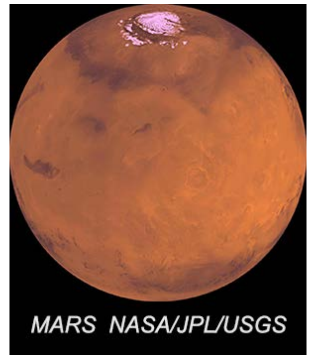
Explaining the Compositional Heterogeneities of the Martian Mantle by Late Accretion of Large Projectiles



--- Compositional variations in the Martian mantle may be caused by addition of a few large impactors after planet construction was mostly finished.

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Chemical and isotopic data from Martian meteorites show that the red planet's mantle is compositionally heterogeneous. These distinctive geochemical reservoirs in Mars might be the product of primary differentiation including core formation (possibly in a global magma ocean), subsequent magmatic activity (including interaction with the growing crust), or late addition of materials. Elements that concentrate strongly in metallic iron (called highly siderophile elements, or HSE) are particularly useful in tracking core formation and late additions. Basaltic Martian meteorites, which are derived from the Martian interior by partial melting, have platinum concentrations that average between 3 and 5 parts per billion (ppb), but vary from 0.071 ppb and 20 ppb, demonstrating the variability in the Martian interior. Simone Marchi (Southwest Research Institute [SwRI] Boulder), Richard Walker (University of Maryland), and Robin Canup (SwRI) have used the abundances of HSEs and dynamical modeling of late accretionary impacts to show that it is feasible to have added about 0.25% of the Martian mass by one to three impacts, assuming that the impactors were differentiated into metallic cores surrounded by silicate mantles. Impact modeling shows that the freshly added material would be deposited in patches inside Mars, explaining why the planet is not compositionally uniform. As a bonus, adding up the inventory of added hafnium and tungsten allowed Marchi and co-workers to use tungsten isotopic compositions to deduce that Mars might have formed over a span of 15 million years after the first solids in the Solar System, much longer than previous studies, 2 to 4 million years.

Reference:

- Marchi, S., Walker, R. J., and Canup, R. M. (2020) A Compositionally Heterogeneous Martian Mantle Due to Late Accretion, *Sciences Advances,* v. 6, eaay2338, doi: 10.1126/sciadv.aay2338. [**open access article**]

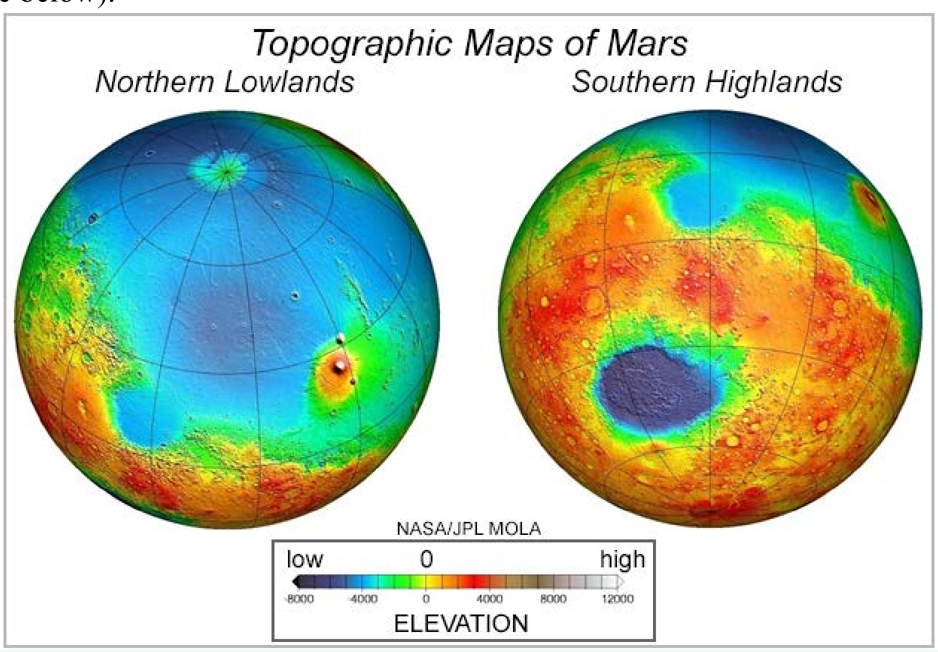
The Mixed and Mingled Martian Mantle

There are distinctive regions in the Martian **mantle**. They are identified by variations in element and **isotope** abundances in **Martian meteorites**. Basalt lava flows are particularly informative because their magmas formed by partial melting of the mantle, hence contain information about the composition of the regions of the mantle that melted. In other words, basalts are probes of planetary interiors. For example, the **shergottites** vary in several compositional aspects, including neodymium and strontium isotopic compositions, **rare earth element** abundances, and oxidation state. (See **PSRD** article: **The Multifarious Martian Mantle**. These elements are all **lithophile**, meaning that they concentrate in magma and rock forming minerals (olivine, pyroxene, feldspar, oxides). Simone Marchi and colleagues favor using **siderophile** elements. These elements concentrate in metallic iron (if present). A particular group called the highly siderophile elements (HSE) are especially informative about formation of metallic cores. Martian meteorites vary in their concentrations of HSEs. Which HSE can provide the most information? Laboratory analyses show that platinum in Earth's mantle is little **fractionated** between mantle rocks and the magmas formed by partial melting, which geochemists believe is likely to also be true for Mars. This means platinum is the most useful HSE to measure in a basalt when determining the mantle-source abundances of HSEs.

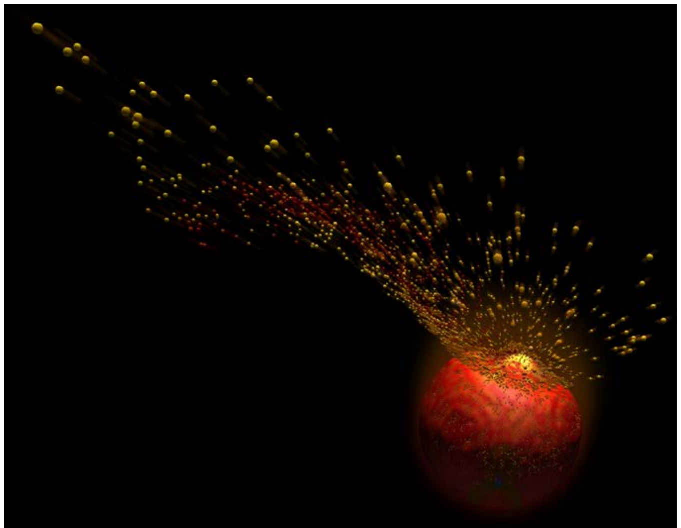
The average concentration of platinum in Martian meteorites is 3 to 5 ppb (parts per billion), but it ranges from 0.071 ppb in shergottite Dhofar 019 [Meteoritical **Database Link**] to 20 ppb in Y980459 [Meteoritical **Database Link**], a difference of about a factor of 280. The low end of the concentration range (0.071 ppb) probably represents regions from which metallic iron departed as it settled to the form the core. The concentration is low because almost all the platinum dissolved in the sinking metallic iron. The high end of the concentration range (20 ppb) is too high for the mantle rock to have equilibrated with metallic iron, leading Marchi and colleagues to suspect that platinum was added after core formation. If an impacting object was **differentiated** into metallic core and silicate mantle, it might not mix homogeneously with the Martian mantle and not all the core material will make it to the center of proto-Mars.

A Really Big Impact Basin on Mars

The Martian geologic record shows that at least one large impact happened after the planet had differentiated in core, mantle, and initial crust. Global topography of Mars obtained by NASA's Mars Orbiter Laser Altimeter (**MOLA**) shows that the northern lowland plains (also called the Borealis basin) are vaguely circular and much lower than the southern highlands (see below).

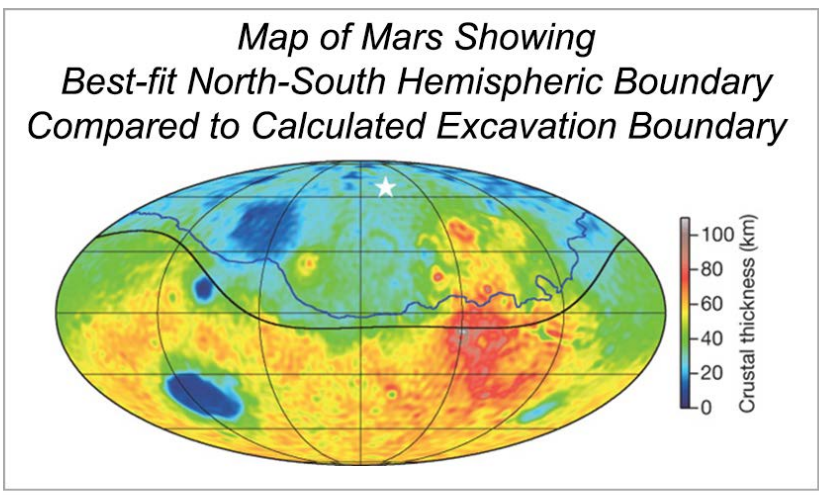


These topographic maps were made with data obtained by NASA's Mars Orbiter Laser Altimeter (nicknamed MOLA) and color-coded for elevation; see elevation scale. The maximum difference in elevation between the northern lowlands and southern highlands is about 7 kilometers. Click **image** for more information.



Computer-simulation illustration of a large impact forming the northern plains of Mars.
From M. Marinova, O. Aharonson, and E. Asphaug.

Impact modeling in 2008 by Margarita Marinova (Caltech, now at Space X), Oded Aharonson, and Erik Asphaug shows that a large impactor can dig a massive hole of the right size. They performed physics-based impact simulations under various conditions (impact angle, velocity, impactor size) and compared the crater produced to the actual topography of the Martian northern lowlands. They obtained a best fit to the topography for the case of an impactor 2230 kilometers in diameter hitting Mars at 6 kilometers/hour at an angle of 45^{o} (see below). This shows that Mars was affected by at least one large impactor near the end of its accretion.



(Marinova, M. M. *et al.*, 2008, *Nature*, doi: 10.1038/nature07070.)

Crustal thickness map of Mars was derived from gravity and topographic data. The black line is the best fit northern-southern dichotomy boundary, from a paper by Jeff Andrews-Hanna and colleagues. The blue line is the calculated excavation boundary from impact modeling by Marinova and colleagues of an impactor 2230 kilometers in diameter traveling 6 kilometers/second and hitting the Martian surface at a 45-degree angle. Impact point is shown by the star at 66^{o}N, 206^{o}E. Note the reasonable agreement between the topographic boundary and the simulated boundary. Not perfect, but reasonable considering the geologic processing (volcanism, faulting, and erosion) that have occurred since the postulated impact.

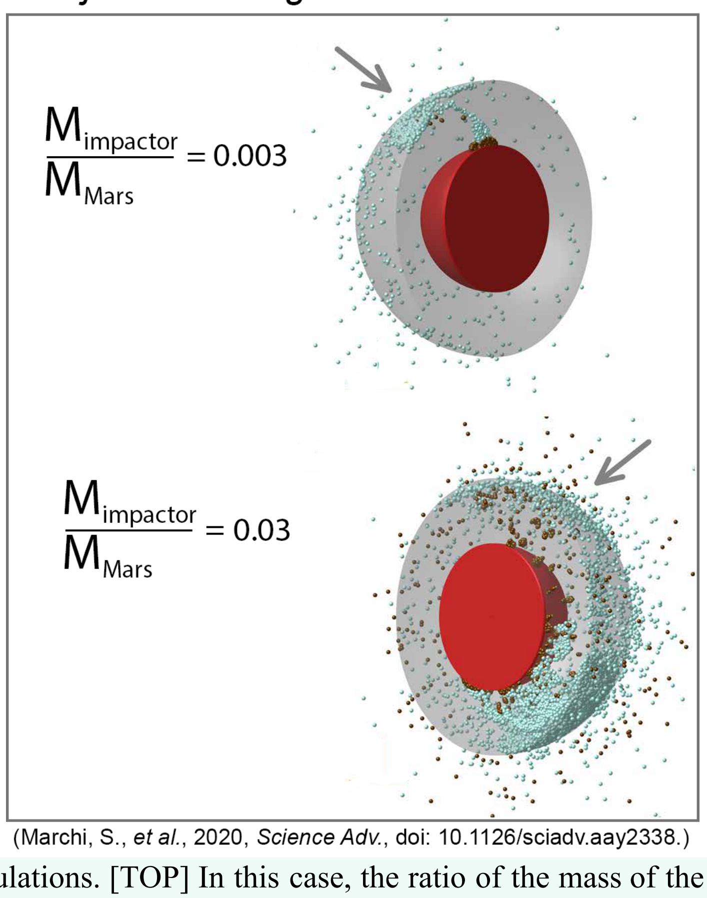
Modeling the Mixing and Mingling

The agreement between topography and impact modeling is consistent with the northern lowlands/southern highlands dichotomy having been formed by a large impact early in the history of Mars. This impact or others whose scars are no longer visible might have added siderophile elements to the Martian mantle. A central unknown, however, is how the impact mass was distributed inside Mars. Was it mixed uniformly throughout the Martian mantle? Or heterogeneously?

To figure this out, Simone Marchi and colleagues modeled the fates of large impactors using smoothed-particle hydrodynamics (SPH). This is an established computational method for simulating how solids and fluids are affected by forces such as gravity and **shock waves**. The computations used about a million particles. Simulations were done for two different projectile masses: 0.003 and 0.03 times the mass of Mars, assorted impact angles (0, 30, 45, 60 degrees), and different impact velocities ranging from 1.5, 2, and 2.5 times the escape velocity of Mars plus the impactor. These masses and velocities comprise those calculated for formation of the Borealis basin (the northern lowlands). The projectiles are **chondritic** in composition (important for the chemical tests described below) but each differentiated into a core and mantle. The computer program keeps track of core and mantle components added to Mars from the impactor.

The results indicate that projectile debris are not distributed uniformly (see graphic below). Although most of the impactor's core ends up in the core of Mars, about 20% (on average in the simulations) is deposited into the Martian mantle. One impactor the size of the one that might have formed the Borealis basin could have deposited all the highly siderophile elements in the Martian mantle, as recorded by Martian meteorites. Three smaller impactors would also do the trick.

Impact Simulation Results of Projectile Mixing in the Martian Mantle



(Marchi, S., *et al.*, 2020, *Science Adv.*, doi: 10.1126/sciadv.aay2338.)

Final products of two simulations. [TOP] In this case, the ratio of the mass of the impactor ($M_{impactor}$) to the mass of Mars plus the impactor (M_{Mars}) is 0.003. [BOTTOM] In this case, the mass ratio is 0.03. Mars core is shown in red and its mantle in gray. Projectile core particles are shown as brown spheres; projectile mantle particles are shown in light green. The arrows indicate locations where mantle particles (0.003 case) or core particles (0.03 case) are concentrated. The important point is that neither core nor mantle particles are uniformly distributed. (Particles detached from Mars are in orbit; some will reaccrete, others will be lost.) Click **image** for more information from SwRI.

Tracking Siderophile Elements

The dynamical simulations seem to explain the apparent heterogeneous distribution of HSEs within the Martian mantle, as recorded by Martian meteorites. Tungsten (a moderately siderophile element) isotopic compositions give clues to the time of core formation. Tungsten-182 (^{182}W) forms by the decay of radioactive hafnium-182 (^{182}Hf), which has a **half-life** of only 8.9 million years. The short half-life is useful in determining the timing of events in the history of the solar system, such as formation of planetary cores. (Elements with short half-lives were produced by **supernovae**, the powerful explosions of spent stars.) For example, tungsten dissolves readily in metallic iron but hafnium does not, leading to low tungsten concentrations in the mantle without affecting the hafnium concentration. This geochemical behavior makes it possible to use the abundances of ^{182}W relative to the stable (nonradioactive) ^{184}W isotope in rocks formed by melting of the silicate mantle as an indicator of the timing of core formation because decay of ^{182}Hf produces ^{182}W, thereby increasing the $^{182}W/^{184}W$ ratio. There are, of course, some complications, such as the fact that concentrations of Hf and W in rocky material can be affected by melting and crystallization. (For a discussion of the Hf-W isotopic system see **PSRD** article: **Hafnium, Tungsten, and the Differentiation of the Moon and Mars**.

Simone Marchi and colleagues used the results of the impact simulations to model variations in tungsten isotopic composition and the addition of HSEs to Mars after its core had formed. The tungsten isotopic variations are expressed as the measured $^{182}W/^{184}W$ ratio compared to the bulk silicate Earth and expressed in parts per ten thousand and nicknamed $\varepsilon^{182}W$. Specifically, $\varepsilon^{182}W = 10{,}000 \times [(^{182}W/^{184}W)/(^{182}W/^{184}W)_{BSE} - 1]$. Important assumptions go into the calculations, including the time of core formation in Mars and in the impactors, the number of impactors (1–4), the HSE concentrations and $\varepsilon^{182}W$ of the cores and mantles of the impactors and pre-final-accretion Martian mantle, and all the impact parameters such as impact and velocity. To follow all this, the investigators divided the Martian mantle into cone-shaped domains all of which had the same volume and used the results of 400 simulations (randomly varying in impact angle, velocity, etc) to track the addition of HSEs and the resulting $\varepsilon^{182}W$ value. The results (in simplified form) are shown in the table below.

	Platinum (ppb)	**$\varepsilon^{182}W$**
Simulations	1 to 20	+0.60 to +6.00
Martian Meteorites	0.071 to 20	+0.09 to +3.35

The simulated platinum concentrations and $\varepsilon^{182}W$ are in reasonable agreement to conclude that addition to Mars of late accreting, differentiated bodies is feasible. The simulations reproduce both the compositional ranges and the variations observed from analyses of Martian meteorites. Careful tracking of the tungsten isotopic composition also indicates that these final accretionary events in the construction of Mars could have taken place up to 15 million years after formation of the first solids (calcium-aluminum rich inclusions, **CAIs**) in the **solar nebula**. This contrasts with previous estimates based on tungsten isotopes that put the age of Mars formation at 2–4 million years after CAIs.

Additional Resources

Links open in a new window.

- Andrews-Hanna, J. C., Zuber, M. T., and Banerdt, W. B. (2008) The Borealis Basin and the Origin of the Martian Crustal Dichotomy, *Nature,* v. 453, p. 1212-1215, doi: 10.1038/nature07011. [**article**]
- Marchi, S., Walker, R. J., and Canup, R. M. (2020) A Compositionally Heterogeneous Martian Mantle Due to Late Accretion, *Sciences Advances,* v. 6, eaay2338, doi: 10.1126/sciadv.aay2338. [**open access article**]
- Marinova, M. M., Aharonson, O., and Asphaug, E. (2008) Mega-impact Formation of the Mars Hemispheric Dichotomy, *Nature,* v. 453, p. 1216-1219, doi: 10.1038/nature07070. [**article**]
- Taylor, G. J. (Nov. 2003) Hafnium, Tungsten, and the Differentiation of the Moon and Mars, *Planetary Science Research Discoveries,* **www.psrd.hawaii.edu/Nov03/Hf-W.html**.
- Taylor, G. J. (June. 2004) The Multifarious Martian Mantle, *Planetary Science Research Discoveries,* **www.psrd.hawaii.edu/June04/martianMantle.html**.

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