# Crust and Mantle Evolution on the Terrestrial Planets: A Geophysical Perspective on Early Differentiation

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Each of the terrestrial planets has been differentiated into mantle, crust, and core, but evidence on the nature and duration of global differentiation differs greatly among solar system objects. The lunar crust differentiated within the first few hundred million years of solar system formation, most likely from a large-scale magma ocean produced in some manner by the process of lunar formation. The nature and history of any core are enigmatic, however, and the pronounced asphericity in crustal and mantle structure, temperature, and melt generation remains to be fully explained. For Mars, the topographic identification of numerous partially buried impact craters and basins in both hemispheres and the arguments for a very early core dynamo support isotopic evidence from Martian meteorites that global differentiation occurred within the first 100 My of solar system formation. Much of the Martian crust probably dates from that time, but the preservation of long-wavelength heterogeneity in crustal thickness requires rapid cooling of lower crustal material to temperatures below which ductile flow was significant on geological time scales. For Venus, early global differentiation was probable, but while the atmospheric $^{40}$Ar abundance constrains total outgassing, no geological or geophysical records of early history survived the most recent episodes of intense deformation preserved in tessera terrain and widespread volcanic resurfacing preserved in the plains. For Mercury, despite the fact that Earth-based telescopic observations from visible to mid-infrared wavelengths indicate a low-FeO surface, the bulk uncompressed density points to an Fe-rich core nearly two thirds of the planet by mass. Several possible mechanisms involving the evolution of the Sun, the solar nebula, or the last stages of planetary accretion in the inner solar system have been proposed to account for Mercury's high metal/silicate ratio. Distinguishing among these hypotheses, however, will require geochemical remote sensing of the uppermost crust from an orbiting spacecraft. While the terrestrial record of earliest global differentiation is lost, Earth is distinguishable from the other terrestrial planets by its ability to form comparatively thick, low-density continental crust and deep lithospheric roots that tend to stabilize that crust against disruption and recycling. Further, the rate of formation of new continent has been sufficiently modest to permit recycling of oceanic lithosphere to have continued essentially uninterrupted for billions of years. Planetary differences in volatile inventories and climates have played important roles.

# Constraining groundwater flow in fractured aquifers using environmental tracers

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Constraining groundwater flow system with environmental tracers can place powerful constraints on hydrophysical parameters. Portniaguine and Solomon (1998) utilized $^{3}$H/$^{3}$He ages and head measurements in a formal inverse model to place tight constraints on recharge (R) and hydraulic conductivity (K) in a granular aquifer. However, a sensitivity analysis showed that porosity, K, and R are correlated and a unique inverse solution requires an independent constraint on one of these parameters. In granular aquifers the porosity is generally known to better than a factor of 2 but in fractured flow systems it is generally uncertain by more than an order of magnitude. A multitracer approach has been used to overcome this limitation.

## Field Studies

In a fractured carbonate aquifer in southern Ontario, Canada, CFC data delineate the location of discrete recharge areas, whereas terrigenic $^{4}$He that diffuses into the aquifer from underlying shales provides a constraint on the total recharge flux. Vertical profiles of terrigenic $^{4}$He are sensitive to the amount of recharging waters that dilute the diffusive mass of terrigenic $^{4}$He. The K that permits this fluid flux is consistent with more than 1300 measurements on fractures (Novakowski et al., 2000).

In a mountain flow system in northern Utah, we have constrained flow parameters by measuring environmental tracers in a basin-fill aquifer that receives the majority of its recharge from the adjacent mountain block. $^{3}$H/$^{3}$He ages effectively constrain the minimum recharge flux. Noble gas thermometry delineates the location of R, and groundwater temperatures constrain the upper limit of R. Collectively, the tracers constrain the effective porosity and K of the mountain block.

These field investigations show the importance of using multiple tracers that individually are sensitive to specific hydrologic parameters.

## References

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