# GRAIL Mission Constraints on the Thermal Structure and Evolution of the Moon

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**Introduction:** The GRAIL (Gravity Recovery and Interior Laboratory) mission has dramatically improved our knowledge of the Moon's gravity field [1-3]. This has enabled new insights into many aspects of the Moon, including lateral and vertical variability of the crust, deep mantle and core structure, volcanic history, and impact processes. We focus here on GRAIL constraints on the thermal structure and thermal evolution of the Moon.

**Radioactive Abundances:** Taylor and Wieczorek used measurements of crustal thickness from GRAIL gravity and Apollo seismology, along with aluminum concentrations in mare basalts, to show that the Moon and Earth have similar bulk $Al_2O_3$ abundances (±20%) [4, 5]. Because Al, Th, and U are all refractory elements, this implies that Th and U, which are the two main radioactive heat sources, are also present on the Moon in roughly terrestrial abundances. This is an improvement over the previous factor of ~2 uncertainty in Th and U abundances.

**Lunar Radius Change:** GRAIL observations demonstrate the existence of dense, quasi-linear structures that are hundreds of kilometers long. They have been interpreted as dike systems that formed in the pre-Nectarian to Nectarian, implying an expansion of the Moon's radius by 0.6-4.9 km during its early history [6]. The extensional stress required to produce this expansion helps to constrain the Moon's early thermal evolution, including the depth distribution of radioactivity in the lunar mantle [7].

**Volcanic History:** Much of the Moon's early (pre 3.8 Ga) volcanic history is obscured by superposed basin ejecta. Although cryptomare is, in places, visible in remote sensing observations, its thickness and volume have previously been poorly constrained. Because mare basalt and Mg suite rocks are denser than the feldspathic crust, GRAIL Bouguer gravity observations constrain the volume of cryptomagmatism to be between 1.8 and $4.8{\cdot}10^6$ $km^3$, which corresponds to 30-80% of the best-estimate volume of the visible mare [8]. GRAIL observations of the visible mare imply average basalt thicknesses of 0.7 to 1.5 km, locally reaching up to 7 km [9, 10]. These values overlap pre-GRAIL visible mare thickness estimates.

**Deep Mantle Melt Layer:** Apollo seismic observations have been interpreted as indicating the presence of a low velocity, partially molten mantle layer just above the core-mantle boundary [11], which if correct is an important constraint on the Moon's current thermal structure. GRAIL observations of the $k_2$ tidal Love number [12] permit a reduction in the Moon's rigidity at the bottom of the mantle but favor a rigidity similar to the bulk of the mantle [13]. The monthly tidal dissipation measured by lunar laser ranging and GRAIL [12] has been interpreted in terms of both a hot, melt-free mantle [14] and a partially molten lowermost mantle [15].

**Megaregolith Conductivity:** GRAIL observations require a high porosity highlands crust, ~25% near the surface and declining to zero at a depth of 20-30 km [16]. This will act as an insulating, low thermal conductivity layer, increasing the internal temperature. However, the specific effects on the interior thermal structure are not yet well quantified.

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