

**THE THERMOCHEMICAL HISTORY OF THE MOON: CONSTRAINTS AND MAJOR QUESTIONS.** M. E. Pritchard and D. J. Stevenson, *Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena CA 91125, USA, (matt@gps.caltech.edu).*

**INTRODUCTION:** Modeling the thermal evolution of the Moon is important for understanding many large-scale processes, from generating melt to determining the thickness of the lithosphere. Many thermal histories are allowed because of our ignorance of the initial lunar thermal state, and the composition and rheological properties of the lunar interior, but most of these models are overly simplistic -- specifically purely thermal conductive and convective histories. Purely conductive models are unacceptable because they produce melting, and the advection of (latent) heat by melt migration becomes important. Melting in the Moon likely affects a large fraction of volume (unlike on the Earth) because the low gravity on the Moon means that the solidus and liquidus change slowly with depth -- the pressure range over 150 km of the upper mantle of Earth is equal to the total pressure range in the Moon (40 kbar). Melt migration under these conditions is imperfectly understood, so even conductive models that include melting [1-4] crudely parameterize processes that are in reality far more complex. Purely thermal convection models [5,6] (or convective models that exclude melt migration [7,8]) are unacceptable because: of complexities of melting mentioned above, chemical buoyancy could be as important as thermal buoyancy, and its not even clear that convection ever occurred in the Moon. Recent work has emphasized that coupled thermal and chemical models must be used [9,10,4] (hence the title of this contribution). Here we review the observations that should be used to constrain thermal histories and themes to be explored in future work.

**OBSERVATIONAL CONSTRAINTS:** Thermal models must agree with observations which we list in order of importance.

*Global asymmetries.* The distribution of mare basalts, KREEP, and in crustal thickness [11] are not uniform. Any thermal history model should try to explain the distribution of mare basalts and KREEP, but the crustal dichotomy is not understood and might or might not be fundamentally important for most of lunar history. To understand the origin of these non-uniformities, their dominant lengthscale needs to be characterized -- *e.g.* should we pay more attention to the hemispheric differences in mare basalt distribution and crustal thickness or to the fact that KREEP and mare basalts appear confined to the Procellarum region [12]? More generally, we would like to understand whether the variations of crust, KREEP and mare are genetically related to each other and over what time period they formed. An important recent contribution is that the *Clementine* mission revealed that there was very thin crust in the South Pole Aiken basin but little basalt there, so the distribution of mare can't be simply related to crustal thickness [13].

*Volcanic record.* The age and chemical composition of igneous rocks sampled from the Moon provides critical tests for any thermal history. However, the volcanic record might

not accurately reflect the history and composition of melting on the Moon both because of biases in the sample collection and because the ratio of melt generated to melt extruded on the surface is likely to be very large. The primary record of volcanism is the mare basalts, which began several hundred million years after lunar formation ( $\sim 3.9$  Ga -- maybe earlier) and lasted until perhaps 2 Ga (maybe later in some places). A major requirement for thermal models is to explain the duration of volcanism. The delay between formation and the onset of volcanism may or may not be real if earlier basalts are hidden cryptomare. The time delay for basalt genesis could be  $\rho C_p \Delta T / Q$ , where  $\Delta T$  is the temperature rise needed to reach solidus at depth,  $Q$  is the radiogenic heating rate, and  $\rho$  and  $C_p$  are respectively the density and specific heat of the lunar interior. Multiple models [8,14,15] will give time delays of order  $10^9$  years, so this observation is not very diagnostic.

The mare basalts provide an indication of mixing within the lunar interior. There is evidence for vertical mixing within the cumulate pile following crystallization of the magma ocean [16 and references therein], and this has implications for the initial distribution of radioactive elements, compositional stratification, and early pressure-release melting. In addition, isotopic studies indicate heterogeneity in the mare basalt source region [*e.g.* 17,18,19] and an ancient age for these regions, which would seem to rule out vigorous convection at these depths early in lunar history [20].

*Lunar origin and the magma ocean.* For any thermal history it is important to know the initial condition. Current models of rapid accretion of the Moon following a giant impact of a projectile with the Earth imply a hot initial Moon [21 and references therein]. This is consistent with several other lines of evidence that indicate that the outer several hundred km of the Moon were part of a magma ocean [22]. Debate continues on the thickness of the magma ocean and whether the Moon was initially completely molten. Nearly all thermal models start with a temperature profile appropriate for times immediately following crystallization of the magma ocean -- temperatures at the solidus in the outer 300-800 km, but with (justified) considerable variation at smaller radii.

*Surface geology.* The lack of global scale thrust or extensional faults on the Moon have been used to constrain the net lunar radius change since the end of the heavy bombardment (3.5 Ga) to be  $\pm 1$  km [2]. On a one plate planet, net radius change is related to the interior temperature evolution and this has led some modelers to place strong constraints on lunar thermal history [2]. However, recent work indicates that relating radius change to thermal evolution might be more complicated and allow more thermal histories (particularly hot ones) to be consistent with the geologic evidence [21,23].

*Current temperature profile.* Seismic and electromagnetic observations suggest that the lunar interior is mostly subsolidus, with potentially higher temperatures below  $\sim$

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1000 km [see review in 24]. However the large error bars and non-uniqueness of this data make this a poor constraint.

*Gravity field and stress state.* The lunar lithosphere has supported mascons from  $\sim 3$  Ga, and this constrains shallow temperatures in the Moon [e.g. 1]. An understanding of the low degree spherical harmonics in the lunar gravity field might reveal the stress state and rheological properties of the lunar interior [29], but further work is needed.

*Heat flow.* Two measurements of surface heat flow were made during *Apollo*, but it is unclear how representative they are of global heat flow and how to extrapolate them to global estimates of radioactive elements [see review in 24]. Because these measurements lie near or within the radioactively enriched Procellarum KREEP Terrain, makes global extrapolations even more suspect.

*Magnetism.* Several lines of evidence support the possibility of a small, Fe-rich, conducting and liquid lunar core [e.g. 25,26]. Maintaining a liquid core for the duration of lunar history provides a weak constraint on interior temperatures since the eutectic temperature of an Fe-S core under lunar conditions is very low (1250 K). Lunar remnant magnetism may require an internally generated dynamo [27], but this interpretation is suspect because of the incredibly high field (and concomitant vigor of convection from cooling of the interior) that is needed due to the small size of the lunar core. Alternative mechanisms for mechanical stirring of the core may exist -- such as energy dissipation at the core-mantle interface [28].

**MAJOR THEMES:** Instead of trying to summarize particular thermal models, we list below some of the major results that should be considered in future work.

*Importance of Chemistry.* Lunar differentiation is important for thermal modelers because it concentrated radioactive elements near the surface in general, and the Procellarum KREEP Terrain in particular. The details of how KREEP was concentrated still need to be worked out, but Wieczorek and Phillips have shown that the existence of this region has implications for the heat source and location of mare volcanism [30]. Another effect of differentiation, particularly the crystallization of the magma ocean, appears to establish a gravitationally unstable compositional gradient in the upper lunar mantle that results in overturn of the cumulate pile (e.g. [9,16]). Parmentier and collaborators argue that this overturn might reach all the way to the core, where the radioactively enriched ilmenite cumulates would heat up and later rise as a plume with a spherical harmonic degree 1 that would cause melting in the mare source region, and the hemispheric asymmetry in mare basalts [15,31]. In addition, thermal and chemical buoyancy might be equivalent in magnitude within the Moon [9,10] such that, among other effects, compositional gradients might inhibit or weaken thermal convection [10,4].

*Importance of Initial Condition.* The studies just mentioned indicate that thermal models of the Moon need to include more than just the physics of heat transport. In particular, they need to include the initial distribution of chemical elements to trace the coupled thermochemical evolution of the lunar interior. Unlike the upper sub-oceanic mantle on the Earth which has largely lost any memory of its initial

state because of vigorous convection since it formed, the lunar mantle appears to be less well mixed [20] and a better record of ancient events -- perhaps because convection was weak or non-existent and occurred over a much briefer period. Thermochemical models are contrary to standard thermal models that employ parameterized convection, where the planet quickly loses memory of its (unknown) initial thermal state. Unfortunately, there is uncertainty about the exact initial thermal and chemical conditions within the Moon. In particular, we would like to know what portion of the Moon was initially molten or unmelted, what initial inventory of radioactive elements, and whether we can constrain the possible lateral variations in the crystallization of the magma ocean.

*Importance of Melting.* Melting in the Moon occurs over a much larger volume than melting in the Earth, and is poorly understood. Previous models have skirted the complexities of the issue by ignoring melt migration and instantaneously transporting the melt and heat to the near surface. A potential method for testing future thermal models that include more realistic melt migration will be to match the chemistry of the samples. Yet, there are several difficulties in using the chemistry: 1) there is debate over the composition and depth of the mare source, 2) even if the composition is known, its signature may be confused if melting occurs over a large depth range, which is likely under the low pressure conditions within the Moon, 3) the physics of melt migration (and possible chemical interactions along the way) are poorly understood on the Moon, and 4) our chemical record may not completely reflect melting on the Moon because very little of the melt generated likely reached the surface. Another area that requires future work is understanding the heat source for melting of the ancient Mg and alkali suites (beginning about 4.4 Ga).

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