MEGAREGOLITH INSULATION AND THE DURATION OF COOLING TO ISOTOPIC CLOSURE WITHIN DIFFERENTIATED ASTEROIDS AND THE MOON

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Ages determined for extraterrestrial samples by the Sm-Nd and Rb-Sr techniques are commonly assumed to record igneous crystallization events. However, for coarse-grained igneous cumulate rocks from the Moon or from a large, thoroughly-brecciated asteroid, this assumption may not be reliable. The Moon and at least one asteroid (the parent body of the eucrite, diogenite and howardite meteorites) appear to have been largely molten at or about the time they formed. At about the same time, these bodies were heavily brecciated by meteoritic bombardment, which transformed their upper crusts into layers dominated by porous impact debris, i.e., megaregoliths. For a body >>100 km in radius, the timescale for global cooling is long in any case (due principally to the great quantity of specific heat that must be dissipated), and the insulating effect of a plaubibly thick megaregolith greatly prolongs the interval (I_c) of cooling between igneous crystallization and isotopic closure.

Many of the cumulate eucrites, i.e., eucrites with textures and other features indicative of origin in a slow-cooling environment deep in the parent crust [1], yield Nd-based ages (and Pb-based ages) lower than the typical age of noncumulate eucrites by roughly 100 Ma [2]. If all of these ages were set by igneous crystallization, the eucrite magmatism must have been driven by a remarkably long-lived heat source. The only age based on either Nd or Sr for a pristine lunar ferroan-anorthositic rock [3] is also roughly 100 Ma younger than several Sr-based ages for rocks of the lunar Mg-suite. Yet most models of lunar evolution invoke a primordial magmasphere, and the only plausible flotation crust from that magmasphere is the ferroan suite, not the Mg-suite, which thus should be at least slightly younger [4].

We have adapted our previous models [5,6] to model global cooling of the Moon and large (R = 40-250 km) asteroids, starting at or near the solidus. We calculate the isotopic closure temperature (T_c), which is the same for Nd and Sr systems, based on eqn. (18) of Sneeringer et al. [7], assuming a grain size (radius) of 2 mm. A key aspect of the findings of Sneeringer et al. [7] is that T_c is far from a constant for any given isotopic system. T_c shows a strong inverse correlation with cooling rate. Consequently, in the context of models of global cooling, where the cooling rate tends to be extraordinarily slow (especially in models involving megaregolith), T_c turns out to be remarkably low: e.g., 850 °C is a typical T_c for 20-30 km depths in our lunar models, and 900 °C is typical for mid-crustal depths in our asteroidal models.

We have tested models with a range of plausible assumptions regarding thickness of megaregolith, and in the case of asteroids also a non-negligible thickness of finely powdered regolith (sensu stricto). Assumed conductivities are, in W m^{-1} K^{-1}, 0.01 for (powdery) regolith, 0.2 for megaregolith, 1.5 increasing with depth to 3.0 for the nonmegaregolith, noncore portion of the Moon, 2.0 for the analogous portion of the model asteroid, and 60 for the core. The core radius is assumed to be 300 km in the lunar models, and 0.44 x R (the whole-body radius) in the asteroid models. All models assume that primordial melting redistributes U, Th and K [5,6]. For the Moon, a variety of evidence indicates that 2-3 km is the most likely average megaregolith thickness, although a thicker megaregolith might have existed for a short, early time [5]. The thickness of the megaregolith layer on an asteroid is harder to constrain. Many large asteroids probably evolve into gravitationally-bound rubble piles [e.g., 8]. The vast majority of noncumulate eucrites (29 out of 32, based on a quick survey) are brecciated. The textures of many eucrites indicate multiple brecciation events [9]. Howardites are obviously products of repeated brecciation. It seems likely that a major fraction of the eucrite-asteroid crust was megaregolith.

Results from some of our models are shown in the Figures. They indicate that for both the Moon and a relatively large asteroid, deep-crustal regions tend to remain above the Nd and Sr T_c for intervals that are significantly long, in comparison to the precision of modern Nd- and Sr-based age measurements, and in comparison to suggested chronologic scenarios of global differentiation. Cooling intervals of as

long as 100 Ma may be common among samples from both bodies. Application of our results to individual rocks is impractical without constraints on the depth of origin of the sample. However, Monte Carlo cratering models [10] can be used to estimate the statistical probability that any random lunar primordial rock has been excavated from a given depth to the surface. These probability(depth) results can be combined with our I_c(depth) results to calculate the probability that a random primordial rock currently at the surface of the Moon had a given I_c. Typical results, assuming that the "β" of [10] = 2, and bulk-Moon U = 20 ng/g, are 27.7% for $I_c \geq 20$ Ma, 24.5% for $I_c \geq 50$ Ma, and 22.6% for $I_c \geq 100$ Ma. Considering the geologic history of the Descartes region [11], these probabilities might be conservative for the case of the ferroan anorthosite dated by Carlson and Lugmair [3].

The overwhelming majority of the 3.8-3.9 Ga ages that support the "late cataclysm" hypothesis of lunar cratering history [12,13] are based on Ar or other labile elements. Our preliminary results for Ar modeling suggest that the scarcity of ages older than 3.9 Ga may simply reflect continued slow cooling within and beneath the megaregolith for all but a small proportion of present surface materials. In view of our current results, chronologies for the gross solidification of the Moon and the eucrite asteroid should allow for the possibility that *any single* age for a coarse-grained "plutonic" or cumulate-textured rock might be many tens of Ma younger than the igneous crystallization age.

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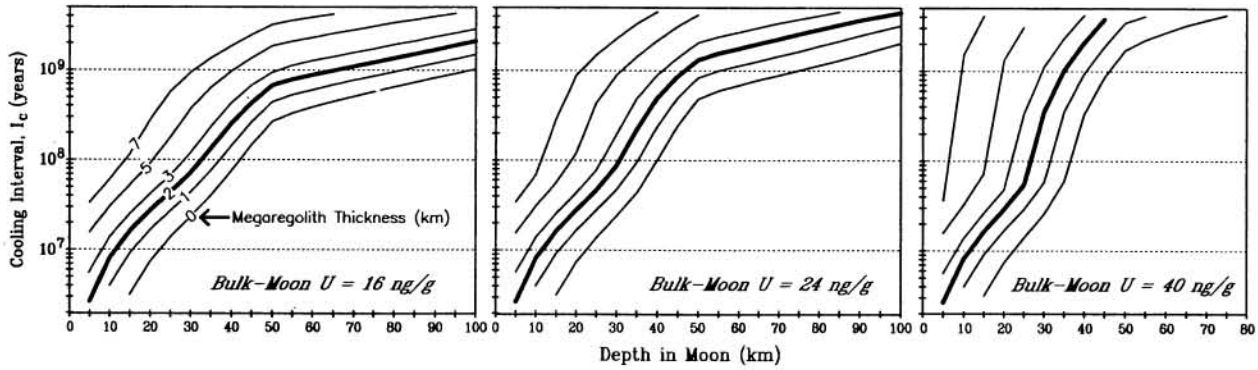

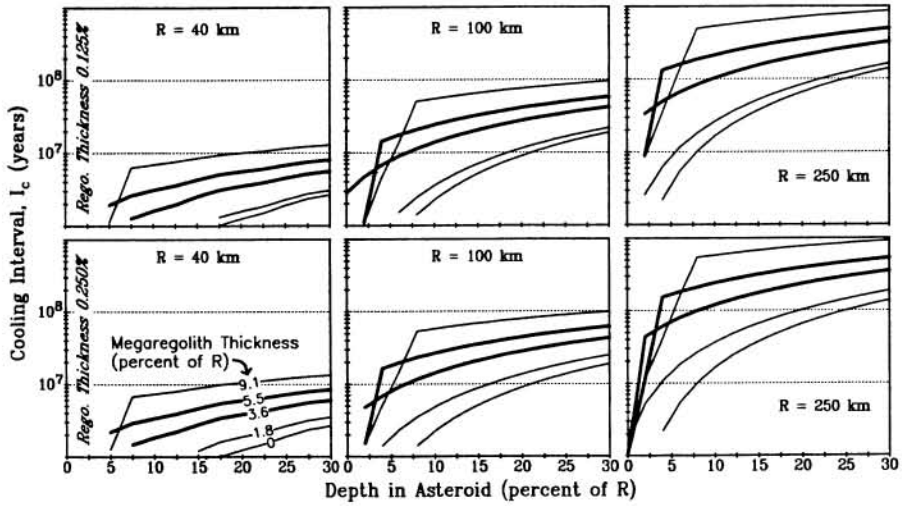

Figures: Results from thermal modeling for Nd and Sr I_c. The thick curves are for models with the most likely assumptions for megaregolith thickness. Note: the crust of a well-differentiated asteroid probably extends to an average depth of ~7% of *R* (and locally extends deeper).