THE COMPOSITION AND EVOLUTION OF A GEOPHYSICALLY REASONABLE MOON PRODUCED BY A GIANT IMPACT. G. J. Consolmagno SJ[1], [1]Vatican Observatory (Specola Vaticana), V-00120, Vatican City State (gjc@specola.va).

Introduction: The magma ocean model for the early Moon's evolution has been one of the most important and influential hypotheses to come out of the Apollo program. Recognizing that the earliest stages of a terrestrial planet's evolution involve widespread melting, and attempting to understand what such a planetary-scale melting episode implies for geophysical and geochemical evolution, has been fundamental in our understanding not only of the Moon but of the major terrestrial planets and the HED parent body.

In the 1970s Cameron first suggested that the Moon formed as the result of a Mars-sized planesimal impacting onto the Earth. Since the 1980s this model has gained significant favor. It is consistent with our understanding of how planetesimals form, and we now know that a large number of such giant impacts did occur elsewhere in the solar system. It can explain the depletion of iron metal in the Moon, and might explain the identical oxygen isotope abundances between Earth and Moon rocks. It can explain the Moon's nearly circular but mildly inclined orbit. And, frankly, no other viable theory for the origin of the Moon exists.

However, as modeled by Cameron and by Canup et al. [1], the nature of the impact event has profound implications for both the physical origin of any magma ocean, and for the Moon's bulk composition.

Goechemical Consequences: Models indicate that the accretion of the Moon out of the debris of an impact occurs quite rapidly (in a matter of weeks) [1]. Both the energy of the initial impact and this rapid accretion should result in a Moon that in its entirety would be at least partially melted. A 100% partially melted Moon is in a very different state from a Moon with completely melted magma ocean over an unmelted core.

Furthermore, the models that succeed in reproducing the Moon's orbit all have the bulk of the material in the Moon being derived from the impactor, not the Earth. In order for this material to be depleted in iron and siderophiles, the impactor must itself have differentiated into a core and mantle before the impact occurred.

This means that the starting material of the Moon, derived from that mantle, was already chemically processed at least once before being melted again during or after lunar accretion. And if the Moon's material represents only the upper portions of the impactor, then it would be enriched in elements likely to be found in the crust, and depleted in the (presumably dunite-rich) mantle material, compared to cosmic abundances.

A simple mass balance here is instructive. Following the impact modellers, we can assume that Theia (the impactor) has a radius comparable to Mars, 3400 km. The volume of the Moon is only 13.5% of this volume. If the Moon were derived entirely from the upper layers of Theia, it would be sampling only material to a depth of 160 km. The thickness of the Martian crust is still a point of debate, but most models based on the Martian moment of inertia give a value on the order of 100 km. Thus, assuming Theia mimics Mars, the composition of the Moon could be almost as much as two thirds Mars crustal material, only one third dunite — a mixture rich in pyroxene and plagioclase.

The only sample we have of ancient Mars is the meteorite ALH 84001, an orthopyroxenite (normative 88% pyx, 6% ol, 4% plag, 2% chr [2]) so similar to the diogenites that it was in fact misclassified as a diogenite for nearly ten years. It is curious that though Mars and the HED parent body have produced orthopyroxenites, they are not common on the Moon (as pointed out by J. Delaney, personal communication). It is equally curious that no part of the Martian surface, nor any meteorite, appears to correspond to an anorthosite. If anorthosites are the natural result of plagioclase flotation in a magma ocean, and such magma oceans are a common phase in planetary evolution, then why do we only see anorthosites from the Moon?

Revised Assessment of the Seismic Data: One of the constraints on models for the evolution of the Moon is the structure revealed by the Apollo seismic experiment, which is usually reported as indicating a 60 km thick crust and a transition zone at 400 km. In fact, the data are far more ambiguous. Khan and Mosegaard [3] have reanalyzed the seismic wave travel time data set from the Apollo missions. By their analysis the lunar crust is 25% thinner, and the deep interior of the Moon more complex, than previously believed.

They have concluded that the Moon has a crustal thickness of 38.3 km. In the upper mantle (38 to ~570 km depth) they find S-wave velocities of 4.0 km/s (typical of augite, significantly lower than olivine), with a discontinuity in the upper mantle between 280-320 km depth, and further discontinuities for both P- and S- waves at 500-580 km depth.

They find a high velocity middle mantle, comprising the depth range from roughly 570 km to 1100 km, with S-wave velocities around 5.6-5.8 km/s; a transition to lower S-wave velocities of 5.0 km/s at a depth of 1100 km, which is taken to be the transition between the middle and lower mantle; a lower mantle, depth range 1100 km to about 1400 km with S-wave velocities of 5.2 km/s; and a central region where the S-wave velocity is 5.0 km/s. Thus only the lunar middle and lower mantle is comparable to Earth's mantle. Note by comparison that olivine typically has an S-wave velocity of around 5.0 ks/s, spinel around 5.7 km/s [4].

The difference in crustal thickness is significant. In terms of mass balance, a 60 km crust represents 10% of the Moon's volume, while a 38 km crust is only 6.4% of the volume. Compared to the canonical 500 km magma ocean, the difference is whether the crust makes up 15% or just 10% of the magma ocean.

The lack of a seismic velocity jump at this point is also significant; the seismic velocities of pyroxene can be nearly twice that of plagioclase [4], and the contrast with olivine is even stronger. It is hard to reconcile the seismic data with an anorthosite crust overlaying a mafic mantle.

The velocities in the crust and upper mantle (which makes up two-thirds of the Moon's volume) are also significant for being much lower than olivine. In fact, this had also been pointed out by Buck and Toksöz [5] more than twenty years ago in their original analysis of seismic velocities.

At that time, Consolmagno et al. [6] attempted to construct a simple model for mare basalt evolution from such a pyroxene-dominated source region, and found significant difficulties in matching REE abundances. On the other hand, such simple models fail to account for assimilation of trace elements during the transit of material from the deep source region through the lunar crust to the surface [7].

Discussion: The effect of the evolution of Theia on siderophile trace elements has been noted by Righter [8] and our first conclusion parallels his insight: the evolution of Theia before the giant impact inevitably changes both trace element and major element abundances of the Moon's starting composition. How exactly the lithophile abundances will change, however, can only be speculated, not rigorously modeled.

If the lunar material is predominantly derived from the upper layers of Theia, its starting composition may well be more enriched in pyroxene and plagioclase (i.e. higher Si/Mg and Al/Mg ratios) than original cosmic abundances might predict. Indeed, if the Moon is derived primarily from crustal Theia, its lithophile incompatibles could be enriched by as much as a factor of 10 compared to chondrites. Such a lunar composition may also be more compatible with the seismic velocities than more traditional models are.

On the other hand, one cannot rule out from the impact models alone the possibility (albeit less likely given the seismic velocities) that the initial lunar composition for some reason was instead depleted in Theia crustal material. In this case, the Moon would actually be depleted in incompatibles relative to cosmic abundances.

In either case, the Moon would have formed with a non-uniform REE abundances, including an initial Eu anomaly, positive or negative depending on the circumstances. In any event, the *least likely* scenario is that the Moon, representing only a small fraction of Theia's bulk mass, nonetheless somehow managed to capture material from Theia's crustal and mantle in exactly their initial proportions.

A Further Possibility: There is experimental evidence [9] that the pseudoeutectic composition, representing the first melt of a primordial basalt like that proposed for the eucrites, varies with the pressure and thus the size of the source planet. Eucrites are all roughly 40% plagioclase, while low-K Fra Mauro plagioclase proportion can range up to 65%, implying that they have seen a wider range of source region initial pressures [10].

If this trend holds for Theia, perhaps its initial crustal material, and hence the initial lunar composition, was even more rich in plagioclase than a lunar-sized body's crust would be.

Recall that melting a source region with cosmic proportions of plagioclase and pyroxene will exhaust the plagioclase first, so that further melting produces orthpyroxenites like the diogenites (and ALH 84001). However, what if at least some portion of the Moon were derived from Theia "eucrites" more plagioclase-rich than the lunar pseudoeutectic? When remelted, the production of more pyroxene-rich basalts under lunar pressures would exhaust pyroxene in such a source region first. Further melting would result in the production of anorthosites instead of orthopyroxenites.

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