

IMPLICATIONS FOR LUNAR COMPOSITION FROM AN INVESTIGATION OF THE NAKAMURA SEISMIC VELOCITY MODEL; S.W. Mueller and R.J. Phillips; Dept. of Geological Sciences, Southern Methodist University, Dallas, TX 75275.

A recent revision of the lunar seismic velocity profiles by Nakamura [1] produced results that are quantitatively different from earlier models [2]. The Nakamura profiles were determined on the basis of the complete lunar seismic data set whereas earlier results were based on partial data sets. The most significant features of the new seismic profiles are large increases in P and S wave velocities at the boundary between the upper and middle mantle (500 km depth). Such increases have critical implications concerning the chemical evolution of the Moon and may require a reevaluation of our understanding of this evolution. Despite the fact that the errors associated with the Nakamura profiles are relatively large, his analysis is currently the best available and therefore it seems appropriate (after 3 years) that some interpretation is produced. The comments below refer to the estimated means of Nakamura's model; we are currently exploring the implications of the associated error envelopes (for the middle mantle, the portion of Nakamura's profiles that differ most significantly from previous work, the formal errors are  $\pm 4.8\%$  for P waves and  $\pm 3.4\%$  for S waves at the 1-sigma level).

The possibility that the velocity increases are solely due to a phase change involving spinel and garnet was investigated and tentatively ruled out because such a mineralogical transition would not be capable of producing seismic discontinuities of the magnitudes observed. This is due predominately to the fact that seismic velocities in the upper mantle limit the amount of Al-bearing phases potentially involved in such a transition. The data would seem to require a compositional change involving either an increase in the Mg content or an increase in the Al content below this depth. The latter alternative is favored, and modeled, in this work because it does not violate the assumption of a stably stratified Moon. This isn't necessarily true in the case of the first alternative: Mg-rich minerals are less dense than the relatively Mg-poor minerals at shallower depths. An increase in Al content at this depth would be expected if the putative lunar magma ocean was approximately 500 deep, as this element would have been removed from the region of melt via buoyant plagioclase. Thus, the very existence of a significant seismic velocity increase at depth might rule out the possibility of a once totally molten Moon. Additionally, removal of aluminum from the magma ocean would suggest that any seismic discontinuity associated with the garnet-spinel phase transition occurring at a depth less than 500 km would certainly be small compared to the seismic discontinuity associated with the compositional change at the 500 km depth.

In our study only the major oxides ( $\text{SiO}_2$ , MgO, FeO,  $\text{Al}_2\text{O}_3$ , and CaO) were considered in constructing the mineral assemblages that allowed the determination of seismic velocities and densities. After allowing for the substitution of Al into orthopyroxene, all the remaining Al was used to make garnet, spinel, or plagioclase (depending on the depth of the assemblage) and the Ca was used to make diopside. The amount of Ca was assumed to be chondritic with respect to Al. The remaining Mg, Fe, and Si was used to make olivine and orthopyroxene. The seismic velocities of the assemblages were calculated using simple mass weighted averages of the

component minerals. In this manner, combinations of Al content, Mg number, and "divalent cation number" (molar ratio of Mg + Fe to Si) resulting in the observed seismic velocities were identified. Assemblages were required to match both the P and S wave velocities; thus, both data sets were used as constraints and this allowed for a unique determination of both the Mg and divalent cation numbers for a given Al content. The range of the divalent cation number was restricted so that no undersaturated or oversaturated mineralogies occurred; with this restriction the range of  $\text{Al}_2\text{O}_3$  mass percentages for the region below 500 km depth extends from 4.9% ( $\text{Mg}\# = .90$ ) to 11.3% ( $\text{Mg}\# = .75$ ).

Seismic velocities in the upper lunar mantle are low enough to rule out such large amounts of magnesium or aluminum. Also, the variation in these velocities with depth in this region is too large to be the result of thermal effects alone, and therefore it is suggested that the upper mantle of the Moon is chemically stratified with more Mg at shallower depths (the precise variation of  $\text{Mg}\#$  as a function of radius depends on the specific Al content assumed for the upper mantle). Accounting for the Al deficit between the deep interior and the upper mantle by means of crustal plagioclase would succeed, at best, under highly restrictive circumstances (in general, the crust is simply too thick and/or the whole-Moon mass constraint would be violated). This would seem to suggest that the Moon may not have initially been in a homogeneous state. If this was indeed the case, differentiation in a global lunar magma ocean would only have promoted further chemical stratification. Relative Al-enrichment of the deep lunar interior obviously has profound implications concerning the origin of the Moon. The significance of these results will be established with the mapping of the seismic velocity model errors into the allowable spectrum of compositional models.

#### REFERENCES

- [1] Nakamura, Y., JGR, 88, 677, 1983.
- [2] Goins, N.R., A.M. Dainty, and M.N. Toksoz, JGR, 86, 5061, 1981.