

LUNAR COMPOSITION AND STRUCTURE: I. A METHOD FOR CALCULATING MANTLE MINERALOGIES. J.H.Jones and L.L. Hood. Lunar and Planetary Laboratory, The University of Arizona, Tucson AZ 85721.

The origin and chemical composition of the Moon have proved to be very difficult problems which have thus far defied solution—at least insofar as no proposed solutions have yet met with universal acceptance by the planetary science community. In principle, lunar geophysical observations place constraints on many problems of interest to geochemists and petrologists. These problems include: (1) the bulk major element composition of the Moon; (2) the nature and scale of the differentiation event which produced the lunar magma ocean; and (3) the existence of a lunar core. The power of geophysical observations was recognized by Buck and Toksoz [1] in their integration of lunar density-moment of inertia data, lunar mantle seismic velocities, and lunar mantle mineralogy into a coherent model of lunar structure and composition. Two important results of the Buck and Toksoz study were (1) the determination of a bulk chemical composition which "satisfied all geophysical constraints" and (2) the inference of the existence of a lunar core.

Two possible problems with the Buck and Toksoz study are that (1) preliminary seismic velocities were used which did not incorporate all available data and (2) the solubility of Al in pyroxene was based on the experimental data of Akella [2], which have not been confirmed by subsequent investigations. Consequently, we have initiated a reinvestigation of the Moon's composition and structure, adopting the Buck and Toksoz technique but using (1) the most recent Nakamura et al. lunar mantle seismic velocities [3] and (2) more recent and better-evaluated experiments of alumina solubility in pyroxenes. We have not yet determined an optimal bulk lunar composition, but have, instead, evaluated four compositional models from the literature. In this abstract we describe in some detail our methods for computing normative mineralogies in the lunar interior. In two other abstracts in this volume [4,5], we compare model-derived seismic velocities to measured seismic velocities and evaluate the probability of the existence of a lunar core.

As inputs to our geophysical calculations we require knowledge of the chemical composition, temperature and pressure as a function of depth in the lunar interior. Given these parameters it is possible to calculate modal mineralogy, seismic velocity and density as functions of depth. Obviously, the uncertainties associated with even the bulk composition of the Moon are large and, if chemical composition varies with depth (as it surely must), the problem becomes even more complex. Our approach has been to adopt multiple models of (1) bulk composition, (2) thermal profile and (3) lunar differentiation. To this end we have investigated four models of bulk composition [6,7,8,9; Table 1], three models of the thermal state of the lunar interior [10,11,12], and four models of lunar differentiation. The compositional models cover a factor-of-two range in Al contents; the differentiation models are our own and represent simplified conceptions of what must have been a very complex igneous event; the thermal models include a simple conduction-dominated heat flow model [10] and a thermal profile which has been modified by solid state convection [11]. The differentiation models consist of: (1) complete homogeneity below the crust (crust + mantle = bulk composition); (2) differentiation of only the upper 500 km to produce a crust; (3) differentiation to some minimum depth  $d$  (to provide enough Al to produce a crust); and (4) differentiation to depth  $d$  with subsequent homogenization below 500 km. The total number of models investigated is  $4 \times 4 \times 3 = 48$ ; but, because some models turn out to be redundant, the number of distinct models is only 33. The validity of any model may be tested by comparing its predictions for the lunar interior to measured geophysical properties.

We are somewhat uncertain of the methods that others have used to evaluate the mineralogy of the lunar interior, and we therefore feel it appropriate to discuss in moderate detail our own methodology. We divide the lunar interior into three mineralogically distinct regions of plagioclase, spinel and garnet stability. The exact boundaries of these regions are not known with great certainty but, following other evaluations [13], we take the plagioclase-spinel and spinel-garnet transitions to occur at 200 km (~10 kbar) and 500 km (~23 kbar), respectively. It seems unlikely that the precise location of these boundaries will greatly affect our results.

The nature of the different mineralogical regions is thus mainly a function of the mineralogical state of Al and its solubility in silicates which do not require Al in their crystal lattice. In the plagioclase stability field, where neither pressure nor temperature is high, we neglect the solubility of Al in any species other than plagioclase. In the spinel and garnet fields, we must take the solubility of Al in ortho- and clinopyroxene into account. Previous estimates of Al concentrations in pyroxenes in the lunar mantle have used the experimental work of Akella [2] as a guide. More recent work by Gasparik and Newton (spinel field) [14] and Perkins et al. (garnet field) [15] seem to indicate that the solubilities of alumina in pyroxenes reported by Akella are likely to be too high. The good agreement between the high pressure experimental results of Gasparik and Newton and Perkins et al. with data from

experimental calorimetry argues that the Chicago group data [14, 15] should be preferred over others. A drawback is that the Gasparik and Newton [14] and Perkins et al. [15] experiments were performed in the MAS system and do not contain Fe and no correction for Fe on the solubility of Al in pyroxene has been made. Addition of Fe should, however, further lower the solubility of Al in pyroxene and widen the gap between the Chicago group and Akella data sets. For our purposes here, we have used the simplified regression of Gasparik and Newton [14] to determine the solubility of Al in orthopyroxene in the spinel field and have used our own regressions on the data of Perkins et al. [15] to determine the solubility of Al in enstatite in the garnet field. The spinel field regression is probably valid for Fe-bearing systems as long as the Fe concentration is not high [14]. We have used comparisons of the experiments of Perkins and Newton [16] and Perkins et al. [15] to make a small correction to the garnet field alumina solubilities--i.e., alumina (opx-CMAS)  $\approx$  0.7 alumina (enstatite). We have also used the data of Perkins and Newton [16] to estimate the solubility of Al in clinopyroxene; we define alumina (diopside)  $\approx$  0.7 alumina (orthopyroxene). Al contents of pyroxenes in a given mineralogical region are not fixed, but are allowed to continuously vary with temperature (spinel field) or pressure and temperature (garnet field). In some cases garnet or spinel may not exist in some "subregions" of a particular (compositional, thermal, differentiation) model, because all the Al has been taken up by the pyroxenes. We assume in our model that Fe and Mg do not fractionate between olivine and orthopyroxene. We do, however, allow for changes in Fe/Mg ratios between olivine and either spinel or garnet. To this end we have utilized the (Fe/Mg) exchange regressions of O'Neill and Wood [17] and Fujii [18] for garnet-olivine and spinel-olivine, respectively. Thus, our method allows for mineralogical variation within a given stability field.

Using this approach, volume fractions of olivine, orthopyroxene, diopside,  $\pm$  (jadeite, Ca-tschermakite, Mg-tschermakite, plagioclase, spinel and garnet) are calculated at every 8-10 km depth increment from the base of the crust (which is taken to be 70 km) to the center of the Moon. The total number of mineralogical increments is 200. Since seismic velocities are not known for the tschermakitic components, Ca-tschermakite and Mg-tschermakite are summed with diopside and orthopyroxene, respectively, for seismic velocity calculations. Volume fractions are corrected for compressibility and thermal expansion using the method of [19].

In summary, our model allows for continuous mineralogical change as a function of temperature and pressure throughout the lunar mantle. The model takes into account the change in Al species from plagioclase to spinel to garnet and allows for variation both in the solubility of Al in pyroxene and in the partitioning of Fe and Mg between olivine and other (Mg, Fe) reservoirs with pressure and temperature. Because no correction has been made for Fe in the garnet stability field, it is possible that our calculated garnet contents (and, consequently, our calculated garnet field seismic velocities) will be slightly low. However, comparison of calculated Al contents of spinel field- and garnet field-pyroxenes at the spinel-garnet boundary suggests that any problems with alumina solubility in pyroxenes in the garnet field are minor.

Table 1

OXIDE	COMPOSITIONAL MODELS			
	(1)	(2)	(3)	(4)
SiO <sub>2</sub>	43.3	44.4	45.6	41.3
Al <sub>2</sub> O <sub>3</sub>	7.58	6.14	4.59	3.50
FeO	13.0	10.9	13.0	16.3
MgO	29.1	32.7	32.3	33.6
CaO	6.13	4.6	3.79	2.80

(1) Morgan et al.; model 4b [6]. (2) Taylor [7]. (3) Wanke et al. [8]. (4) Delano [9].

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