GEOPHYSICAL AND GEOCHEMICAL EVOLUTION OF THE LUNAR MAGMA OCEAN

Floyd Herbert, Michael J. Drake*, and Charles P. Sonett*, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721. *Also Department of Planetary Sciences

INTRODUCTION. Geochronological and geophysical constraints suggest that much of the outer region of the Moon was molten during the first 1-2x10^8 years of the Moon's existence. Considerations of the thermal evolution of this postulated magma ocean have led us to propose the production of a floating plagioclase-rich crust (Herbert *et al.*, 1977). Conduction across such a solid layer dominates the time scale for solidification of the magma ocean.

This proposed magma ocean evolution has important geochemical implications. Early-appearing plagioclase-rich "rockbergs" will generate a negative Eu anomaly in the associated magma. Olivine, orthopyroxene, and clinopyroxene must also have crystallized but, being denser than the melt, would sink and re-dissolve, locally modifying magma composition. If elements of magma with such modified REE patterns could be convected to the base of the magma ocean and participate in the formation of mare basalt source regions, geochemical models for mare basalt source regions may require extensive revision.

In this abstract we report on continuing model calculations of the thermal and geochemical evolution of the magma ocean, specifically addressing the question of the rate of convection in the magma ocean.

COOLING TIMES FOR MAGMA OCEANS. A simplified numerical thermal model of the magma ocean was constructed. Heat flow in the magma was treated by mixing length theory (Clayton, 1968) and heat flow in the thickening plagioclase crust by a two-point finite difference conduction model. The enthalpy of crystallization of the solidifying material was assumed to dominate the energy budget. For simplicity the ratio of plagioclase crystallization (at the top of the magma) to mafic mineral accumulation (at the base) was assumed to be constant. In practice the plagioclase to mafic mineral crystallization ratio must have increased with time. In this respect the calculated solidification times represent upper limits.

The cooling curves derived from this model are shown in Figure 1. If the assumptions of the model are correct, the inferred solidification time would limit the magma ocean depth at the time of permanent crust formation to the range 100-200 km. However, since the solidification times deduced from this model are upper limits, greater magma depths cannot be ruled out. More definitive answers await modeling of the magma chemistry.

CONVECTION VELOCITIES IN THE MAGMA. The loss of heat at the top of the magma by conduction through the thickening crust tends to steepen the thermal gradient in the interior of the magma until the convective heat flux is sufficient to prevent further steepening. Because of the low viscosity (10-100 poise), the great depth of the magma, and the low conductivity of the crust ($\sim$2 W/m/°C), the mixing length approximation is probably valid. The excess of the temperature gradient over the adiabatic gradient in units of the latter (the relative superadiabaticity) is plotted in Figure 2 for various magma and crustal thicknesses. The prevalence of low values indicates that the magma ocean could probably have never become substantially superadiabatic.

EVOLUTION OF LUNAR MAGMA OCEAN

Herbert et al.

The convective flow velocities calculated from the approximation described above and using the model of Figure 1 are plotted against time in Figure 3. Note the relative insensitivity of the convective flow to magma ocean depth compared to the strong dependence on crustal thickness. This sensitivity contrast is a general feature of the model and, we believe, of the actual magma ocean evolution.

RATES OF OVERTURN OF MAGMA OCEANS. Figure 3 also shows the variation of the rate of overturn of the magma ocean as its thickness decreases due to crystallization at top and base. This high rate of overturn will ensure that early-appearing rare earth abundance anomalies arising from the crystallization and separation of plagioclase and associated mafic phases will immediately affect REE concentrations in mafic minerals crystallizing at the base of the magma ocean from which mare basalts were subsequently derived.

WHOLE MOON MELTING. Modeling the melting of the whole moon is somewhat more complicated. The persistence of a plagioclase-rich crust at the top of the hot magma is expected because of plagioclase saturation effects in the magma, which raise the local plagioclase melting temperature (Herbert et al., 1977). However, any adiabat which lies above the solidus at the center of the Moon (i.e., any adiabat that describes a molten interior) will pass far above any reasonable plagioclase persistence temperature at the crustal base, because any reasonable solidus is much steeper than the adiabatic gradient (Walker et al., 1976; Ringwood, 1976). Thus, a moon with a fully molten interior would also have a liquid surface (or to the same end a constantly overturning quenched skin) (cf. Herbert et al., 1977) until a solid core of substantial size composed of mafic cumulus minerals developed. Our models shown in the figures do not reflect this phenomenon, which would markedly reduce the solidification times of very deep magma oceans.

IMPLICATIONS FOR GEOCHEMISTRY. As noted above and by Herbert et al. (1977), the early fractionation of plagioclase to form "rockbergs" will result in magmas beneath the crust with compositions and trace element characteristics which differ from those of the bulk, unfractionated magma. We have shown that such fractionated magmas will be convected to the base of the magma ocean on timescales which are rapid relative to the inferred ($\approx 2 \times 10^8$ year) solidification period. Thus, we expect that fractionated magma would have participated in the formation of mare basalt cumulate source regions at the base of the magma ocean. Examples of REE patterns in such magmas are schematically illustrated in Figure 4. Thus, one should not expect mare basalt source regions to have sampled magma with an essentially chondritic relative REE abundance pattern. Until the processes by which the magma ocean evolved have been better understood, great caution should be exercised when utilizing mare basalt liquids as probes of the geochemistry of the primitive Moon.

This work was supported by NASA grants NGR 03-002-388, NGC 7020, and NGR 03-002-370.

REFERENCES

Clayton, D.D. (1968) Principles of stellar evolution and nucleosynthesis, McGraw-Hill, 612 pages.

Herbert, F., Drake, M.J., Sonett, C.P. and Wiskerchen, M.J. (1977) Proc. Lunar Sci. Conf. 8th, 573-582.

EVOLUTION OF LUNAR MAGMA OCEAN

Herbert et al.

Ringwood, A.E. (1976) Icarus, 28, 325-349.
Walker, D., Longhi, J., and Hays, J.F. (1975) Proc. Lunar Sci. Conf. 6th, 1103-1120.

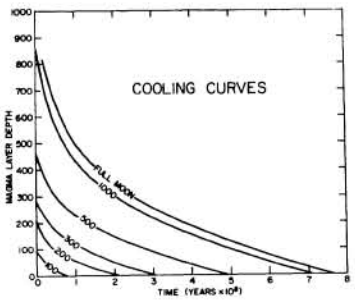

Figure 1. Magma layer thickness as a function of time for various initial magma depths.

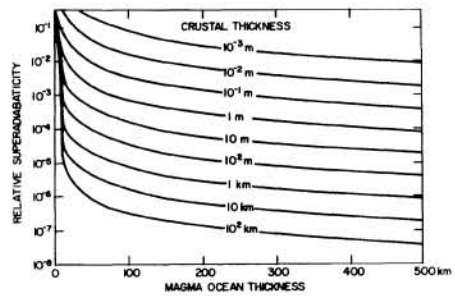

Figure 2. Relative superadiabaticity in the magma layer calculated from mixing length theory for various magma layer and crustal thicknesses.

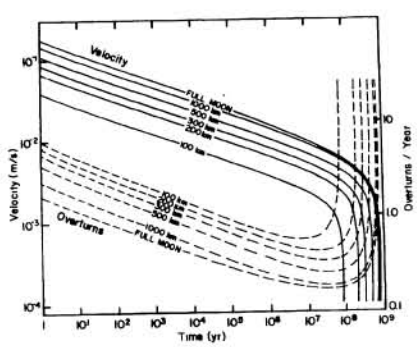

Figure 3. Convective velocities and the corresponding overturn rates calculated from mixing length theory as a function of time using the model described in the text.

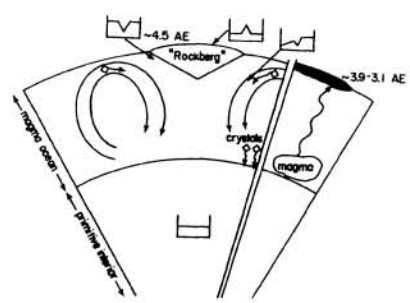

Figure 4. Schematic illustration of the variety in fractionated REE abundance patterns in the early magma ocean.