

PARTITIONING OF MG AND FE BETWEEN OLIVINE AND LIQUIDS OF LUNAR COMPOSITIONS: THE ROLES OF COMPOSITION, PRESSURE AND TI SPECIATION. John H. Jones, SN4, NASA Johnson Space Center, Houston, TX 77058.

Different authors have variously emphasized the roles of composition, temperature and pressure in the partitioning of Mg and Fe between olivine and basaltic liquids. Jones [1] used linear regressions of K_D^{Mg} and K_D^{Fe} to argue that olivine/liquid partitioning could be parameterized solely in terms of liquid composition. The implication of this analysis was that partition coefficients were relatively insensitive to changes in pressure -- as long as liquid composition did not change. The regressions of Jones [1] contained experiments on both low- and high-Ti lunar basalts and no influence of Ti on partitioning was observed. Alternatively, Grover et al. [2] emphasized the role of pressure in changes of K_D (olivine/liquid) and Longhi et al. [3] and Delano [4] have shown that high-Ti basalts have distinctly lower K_D 's than their low-Ti counterparts.

Clearly, different authors have chosen to emphasize different aspects of the physical chemistry of Fe-Mg partitioning. The conclusions of these authors are not of mere academic interest, but are important in deciding the bulk composition and origin of the Moon [5]. For example, if olivine/liquid K_D 's are ≤ 0.3 , it is possible for the Earth and the Moon to have the same Mg# [molar Mg/(Fe+Mg)] [6]. Conversely, if typical K_D values are > 0.34 , then to argue for a similarity between the Mg#'s of the Earth and Moon becomes difficult [5].

In an effort to better understand the relative roles of pressure and liquid composition on olivine/liquid partitioning, multivariate regressions have been performed on a set of 33 experimental olivine/liquid partitioning studies on lunar compositions. Of these experiments, 12 were conducted at high pressure (≥ 5 kbar) and 7 contain ≥ 8 wt.% TiO_2 . Experimental data were taken from Longhi et al. [3], Grover et al. [2] and Chen et al. [7]. Starting materials spanned a range of compositions and pressure ranged from 1 bar to 30 kbar. Some data from [2] and [7] were excluded. Any experiment of [2] that showed significant gain or loss of FeO was not used, although incorporation of these data does not significantly change the conclusions of this study. Similarly, because many of the experiments of [7] showed gains in FeO, only the longer-duration Apollo 14 VLT experiments were utilized; the shorter-duration Apollo 17 VLT experiments possess significantly lower K_D 's, even though the two bulk compositions are very similar, and are assumed to represent poorer approaches to equilibrium.

Method and Results. The regressions of Jones [1] imply that olivine/liquid K_D 's can be calculated if only the cation fractions of FeO and MgO in the silicate liquid are known. Consequently, K_D values of [3], [2] and [7] were regressed using X_{Mg} , X_{Fe} , X_{Ti} and P as independent variables, where X represents cation fraction in the liquid and P is pressure in kbar. The equation resulting from this multiple linear regression is:

$$K_D = 0.320 + 0.120 X_{Mg} + 0.106 X_{Fe} - 0.863 X_{Ti} - 0.00007 P$$

The correlation coefficient of the regression is 0.923 and the standard error is 0.013. The F-ratio of the regression indicates that the correlation is significant at the $>99.9\%$ ($>3\sigma$) level. The standard error corresponds to a relative error of $\sim 4\%$ and is probably comparable to the experimental error. Thus, while it is possible that the fit could be improved by consideration of other dependences, it is unclear that the results would be meaningful.

The results of the regression imply a moderate dependence of K_D on X_{Mg} and X_{Fe} , a strong dependence on X_{Ti} , and a negligible dependence on pressure. Thus, as liquids become more mafic (typically more olivine normative) K_D increases somewhat ($\sim 10 - 20\%$). As Ti is added to a melt, K_D decreases sharply; the difference in K_D between high-Ti basalts and VLT basalts can be as much as 30%. Again, no dependence on pressure was observed.

A model for the speciation of Ti in lunar basaltic liquids. If olivine compositions from experiments on high-Ti compositions are compared to those calculated using the method of Jones [1], MgD is found to agree acceptably, but the calculated K_D is typically 10-30% too high. Thus, Ti appears to reduce the FeO activity in the silicate liquid. The partitioning data are consistent with a melt model where Ti forms $FeTi_2O_5$ (ferropseudobrookite) complexes in the silicate liquid. To illustrate this conclusion, K_D 's calculated using the regressions of [1] were modified by assuming that the effective FeO activity could be approximated by $a_{Fe} \approx X_{Fe} - (X_{Ti}/2)$. If this model is correct, then measured K_D 's should be simple functions of K_D^* , where $K_D^* = K_{D(\text{calculated})} (X_{Fe} - X_{Ti}/2)/X_{Fe}$. Figure 1 shows the results of this model. A regression of $K_{D(\text{measured})}$ vs. K_D^* shows that the model acceptably accounts for the change in K_D with increasing Ti content of the silicate liquid. The correlation coefficient of the regression is 0.906 and the standard error is 0.014. Thus, the model predicts K_D essentially as well as the multivariate regression given above, and the simple stoichiometry of the model is appealing.

Conclusions. Firstly, the equations of Jones [1] seriously underestimate the influence of Ti on $^{Fe}D_{\text{olivine/liquid}}$. The original agreement of the high-Ti basalts with the Jones [1] model appears to have been fortuitous. Secondly, based on the data of [2] and [3], the conclusion of Grover et al. [2] that pressure influences olivine/liquid K_D appears unfounded. Why Grover et al. came to this conclusion is unclear. Presumably either the effects of (i) change in liquid composition with pressure (i.e., change in fraction crystallized) or (ii) gain or loss of FeO were interpreted only in terms of pressure increases. Thirdly, the original Jones regressions [1] may be applied to lunar compositions if modified using the regression in Figure 1. Finally, the K_D appropriate for modeling processes involving the lunar magma ocean appears to be $\sim 0.34 - 0.37$, which implies that the Moon is somewhat enriched in FeO over the Earth's upper mantle [5].

References. [1] Jones J.H. (1984) *Cont. Mineral. Petrol.* **88**, 126-132. [2] Grover J.E. et al. (1980) *Proc. Lunar Planet. Sci. Conf. 11th.*, 179-196. [3] Longhi J. et al. (1978) *Geochim. Cosmochim. Acta* **42**, 1545-1558. [4] Delano J.W. (1980) *Proc. Lunar Planet. Sci. Conf. 11th.*, 251-288. [5] Jones J.H. and Delano J.W. (1988) *Lunar and Planetary Science XIX*, this volume. [6] Warren P.H. (1986) In *Origin of the Moon*. pp. 279-310. [7] Chen H.-K. et al. (1982) *Proc. Lunar Planet. Sci. Conf. 13th.*, A171-A181.

