D'S FOR Cr, Mn, & Ti AS TESTS OF IGNEOUS VS. SUBSOLIDUS EQUILIBRATION OF MAFIC MINERALS IN LUNAR ROCKS; Wm. C. Phinney, NASA Johnson Space Center, Houston, TX 77058

There is abundant evidence to indicate that the lunar crust underwent a prolonged period, perhaps 100's of millions of years, at high temperatures in the range of several hundred to 1000°C [e.g. 1, 2]. Under such conditions, it is clear that re-equilibration of some components and phases will occur. Without more detailed knowledge of the behavior of various components in the phases of lunar crustal rocks, it is not clear which components and phases were substantially modified during this high temperature event. Phinney [3, 4] provided evidence that Fe, Mg, Co, and Ni in plagioclases of lunar anorthosites were significantly depleted during this period while the REE's, and perhaps Ba, Sr, Ti, and Hf, remained essentially unchanged. Such evidence suggests that other minerals and rocks from the early lunar crust should be examined to further evaluate the redistribution of components during metamorphism.

If rocks from the early lunar crust are to be used for interpreting either the petrochemical evolution of the melt(s) or the crystallization ages of the rocks that produced the crust, then one must assume that the compositions of the minerals reflect their compositions at the time of crystallization from their respective melts. If such is the case for some components but not for others, then it is important to delineate which components can and cannot be used for this purpose. One means of testing the reliability of the components is to evaluate the consistency of partition coefficients in comparisons of coexisting phases in appropriate lunar samples. If ratios of elements between phases compare favorably with the ratios expected from both experimental petrology and non-metamorphosed natural assemblages, then these elements may reflect their initial igneous concentrations.

In an attempt to make such comparisons, a review of the lunar literature indicates that very few elements have been analysed in the detailed manner necessary for such an evaluation. For the common mafic minerals, olivine and pyroxene, only Cr, Ti, Mn, and Al are commonly analyzed (in addition to the standard major elements of Si, Fe, Mg and Ca). Furthermore, it is not always possible to determine whether the reported analyses are of minerals that coexisted at the same stage of fractional crystallization. Compilations of analyses were made for the ferroan anorthosites, the Mg-suite, and mare basalts, each set of analyses being evaluated as to whether the mineral pairs were coexisting igneous phases. The most immediately obvious feature in a first observation of the compiled data is the anomalously low content of Cr in olivines of the anorthosites when compared to olivines in any of the other rock types. To evaluate the cause of this anomaly, the ratios of Cr, Mn and Ti were calculated for Lo-Ca Px/Oliv, Aug/Oliv, and Aug/Lo-Ca Px. If igneous chemistries are preserved, such ratios should be identical to the ratios of the partition coefficients between the mineral phases and melt. These partition coefficients are reasonably well known and in good agreement from both experimental petrology and non-metamorphosed natural assemblages [5, 6].

The results for Cr are shown in Figs. 1 and 2. It is immediately obvious that the ratios in anorthosites are one to two orders of magnitude greater than are found in mare basalts, which agree very well with the expected ratios from experiments and non-metamorphosed natural pairs. Even the troctolites and norites appear to have ratios that are several times higher than mare basalts or expected values. The ratios for mare basalts do not vary significantly with Fo content of the olivine. Thus, the greater degree of fractionation exhibited by the mafics in the anorthosites cannot be accepted as an explanation for the extremely high ratios. Furthermore, the Cr content of the pyroxenes in the mare basalts covers a very wide range, the lower part of which is in the same range as the Cr in pyroxenes of anorthosites and troctolites. Thus, a large difference in the concentration of Cr in the melts can not explain the apparent variation in D. In fact, when nearly pure fayalite olivines in mare basalts have very low Cr contents, so also do the associated Fe-rich pyroxenes, and the ratios remain in the range of 1 to 3. Although Cr with its multiple valencies may have partition coefficients that vary with fO2, that can not explain the differences in the ratios. Experiments show almost no variation of D(Cr) in the range of lunar fO2 [7] and mare basalts should not have formed in an fO2 that differs appreciably from the other lunar crustal rocks. Consequently, the Cr content of olivines in anorthosites, and probably troctolites and norites, do not reflect igneous processes. In contrast, the Mn ratios of anorthosites and other crustal rocks are very consistent with both mare basalts and expected values (Fig. 3). There is only a 20-30% difference
exhibited by the entire suite of samples. Thus, the Mn D-values reflect igneous values unless the Mn has been changed uniformly in all phases, which seems unlikely in view of the significantly different diffusion rates in olivines and pyroxenes. Ti shows large departures from expected values in D's that involve olivine (Fig. 4). The huge range in Ti content of lunar melts and the presence of multiple Ti-oxide phases in lunar rocks may account for these departures. A more detailed evaluation of the cause of the variations in D for Ti is needed.

It is not clear what mechanism has redistributed the Cr. There may have been a subsolidus re-equilibration between olivine and pyroxene that would require olivine to lose Cr and pyroxene to gain it as the temperature decreases. In some thin sections there is no pyroxene present with the olivine and vice versa. Thus, if such a re-equilibration occurred, it required diffusion over distances of several millimeters. Or, perhaps some oxide or sulfide phases grew during the subsolidus re-equilibration and drew upon the olivine for Cr. Further assessment of the behavior of other components during this process should help delineate the mechanism as well as discriminate which components can be used to interpret the petrochemical evolution of the melt(s) and the crystallization ages of the rocks that produced the lunar crust.