MINERALOGICAL STUDIES OF CRUSTAL ROCKS - ANORTHOSITES; NORITES; ARMALCOLITE AND ILMENITE. I. M. Steele, J. V. Smith, and A. J. Irving, HGS, University of Chicago, 60637

Our mineralogical studies on the above types of lunar samples are summarized below; complete manuscripts were submitted to American Mineralogist. Major conclusions are:

a) at least in part, the accessory phases (pyroxene, silica, ilmenite) in anorthosites result from exsolution of minor elements from plagioclase;
b) the parent liquid of anorthosites had an mg value of 0.7-0.8;
c) Apollo 17 soils from the Sculptured Hills contain a coarse-grained noritic component with enigmatic diopside bearing veins;
d) the morphology of the Sculptured Hills may in part be due to norite intrusions;
e) Zr-armalcolite and Cr-Zr-?armalcolite coexist with Mg-rich silicates in recrystallized Apollo 17 breccias in contrast to ilmenite which coexists with less Mg-rich silicates;
f) armalcolite is probably the stable Ti-oxide phase in the upper lunar mantle.

I. Anorthosites: Lunar anorthosites are characterized by high-Ca plagioclase with low contents of minor-elements (Fe,Mg,K) and by minor accessory minerals (pyroxene, silica and ilmenite) (e.g. 1,2). Textural and compositional data indicate solid-state equilibration. If the bulk pyroxene (usually augitic) is primary, experimental partition relations suggest mg $\sim$ 0.4 for the parent liquid (Fig. 1). On the basis of: a) pyroxene nucleation at twin boundaries (3); b) homogeneous compositions of pyroxenes both within and adjacent to plagioclase (1,2); c) chemical compositions of lunar plagioclase (4), we suggest that at least some, if not all, accessory phases have exsolved from plagioclase. The parental plagioclase had appreciable $Ca(Fe,Mg)Si_3O_8$ in solid solution similar to Fe-Ti-basalt plagioclase, but at low temperatures this component exsolved as augite and silica.

Based on the above mechanism, mg of the parental anorthositic liquid can be estimated from mg of the presumed parent plagioclase estimated from the composition of pyroxene inclusions but modified by the retained Mg and Fe in the plagioclase. Experimental data relating liquid-plagioclase Fe,Mg partitioning (Fig. 1) indicate that the liquid producing the anorthosites had mg $\sim$ 0.7 - 0.8. This value rather than the previously derived value of 0.4 is consistent with a primary differentiation of the Moon from a liquid giving rise to anorthosites, ultrabasics (mg $\sim$ 0.9)(Fig. 1) and the ANT suite. The characteristic low minor-element content of most if not all ANT plagioclase probably results from low-temperature equilibration.

II. Norites: Coarse-grained lunar rocks with igneous textures are rare; most have been severely altered by impact and thermal metamorphism. Apollo 17 1-2mm fines from Sta. 8 (Sculptured Hills) contain a minor coarse-grained noritic component with preserved primary igneous features. These grains consist of 1-2mm, single, unshocked orthopyroxene crystals (En 77-81,

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Fs 20-16: confirmed by X-rays) with enclosed or attached grains of plagioclase (An 92-95, Fe 0.15 wt.%, K 0.10 wt.%); grain boundaries suggest an igneous origin. Mesostasis areas rich in Ba,K,P and Si occur within some pyroxene grains. No silicate exsolution was observed (by optics or X-rays) in the pyroxene. Minor element data (Cr,Al,Ti) for the orthopyroxene are in the range for pyroxenes from both ANT and Fe-Ti-basalts.

Veins of diopside with minor chromite (Cr_2O_3 55.6 wt.%), iron, silica mineral and troilite occur within two pyroxene crystals. Exsolution is not responsible because the diopside is too Mg-rich and the veins are irregular. Fluid (liquid or vapor) intrusion, with possible fractional crystallization, produced these veins.

The association of the noritic fragments with Sculptured Hills' soil may be significant. The morphology of the Sculptured Hills is different from the surrounding massifs and no explanation has been proposed. We suggest that these hills and similar features may be coarse norite intrusions either not affected by impact or uplifted by major impacts. Better examples of this rock type may be found; an obvious candidate is 78235 - a coarse (1-5 mm) mafic-plagioclase rock sampled at Sta. 8.

III. Armalcolite and Ilmenite: Meta-breccias from all Apollo 17 stations contain minor Ti-oxide phases with textures suggesting late growth relative to the matrix silicates. Microprobe data for silicates show a narrow range of variation for any one fragment and thus a bulk mg value can be assigned to each fragment. The term Cr-Zr-"armalcolite" is used purely for convenience, but we think that it may not be a member of the pseudo-brookite family. Microprobe data for coexisting oxides show: a) armalcolite (Zr- or Cr-Zr) occurs with olivine if mg $> \sim 0.75$ (Fig. 2); b) ilmenite occurs with olivines of lower mg (Fig. 2); c) at mg ≈ 0.75 both ilmenite and armalcolite coexist suggesting a reaction (5) at this mg value; d) the distribution coefficient ($K_D = (Mg/Fe)_{oxide}/(Mg/Fe)_{olivine}$) for Zr-armalcolite ($K_D \approx 0.29$) is distinctly different from that of Cr-Zr-armalcolite ($K_D \approx 0.12$) (Fig.2), which is additional evidence for a structural difference as previously proposed (6).

Ilmenite shows high MgO contents, consistent with the high mg value (~ 0.7) of the breccia. K_D for ilmenite/olivine is 0.125 (Fig. 2) for Apollo 17 breccia indicating temperatures of about 900°C for equilibration. Relative temperatures for breccia equilibration could be estimated for MgO contents of ilmenite or recrystallized breccia by comparison. CaO contents differ between Fe-Ti-basalt ilmenite (CaO $<$ 0.10) and breccia ilmenite (CaO $>$ 0.10 wt.%).

The apparent stability of armalcolite with Mg-rich silicates suggests that it is the stable oxide phase in the Moon's mantle if the latter consists of Mg-rich mafics. The early crystallization of armalcolite may have been an efficient means of concentrating Ti in the lunar mantle during an early lunar differentiation.

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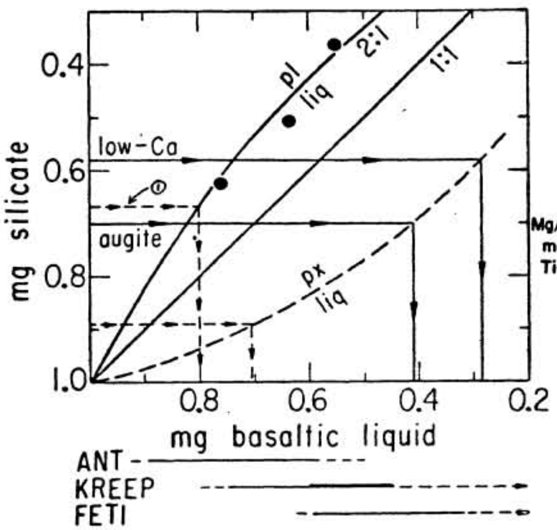

Fig. 1

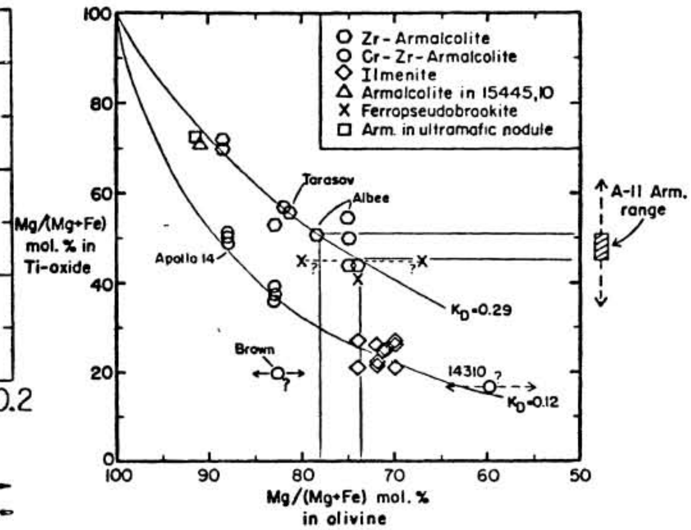

Fig. 2

Fig. 1. Relation of mg for coexisting basaltic liquid and plagioclase or pyroxene. The dashed curve is the approximate mean of experimental data, and the data below the diagram summarize the ranges of mg for three types of lunar rocks. The dots show coexisting plagioclase and liquid from synthetic charges of 14310 basalt. Solid lines with arrows show mg of liquid (~0.4) in equilibrium with pyroxenes found in anorthosites. Dashed line labeled ① shows mg of coexisting liquid (~0.8) with plagioclase having mg equal to present mafics. Mafics crystallizing from any basaltic liquid can also be determined from this diagram.

Fig. 2. Plot of Mg/(Mg+Fe) in armalcolite types and ilmenite vs. Mg/(Mg+Fe) in coexisting olivine. Labeled points are from the literature. Different distribution coefficients are indicated for the two armalcolite types. Solid lines parallel to axes show olivine compositions which would be in equilibrium with Apollo 11 armalcolites.