APOLLO 17 PETROLOGY AND EXPERIMENTAL DETERMINATION OF DIFFERENTIATION SEQUENCES IN MODEL MOON COMPOSITIONS, F. N. Hodges and I. Kushiro
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The differentiation of the lunar crust and formation of the plagioclase-rich highlands presents one of the most interesting problems in lunar petrology. One possible approach to this problem is the experimental determination of phase relations in compositions that for one reason or another appear to be reasonable moon compositions.

As a first step in the study of possible lunar compositions melting experiments have been carried out on Ca- and Al-rich aggregates from the Allende carbonaceous chondrite (1). It was found that over a wide pressure range spinel is the liquidus phase followed by aluminous clinopyroxene and plagioclase. Subsolidus phase assemblages are spinel and clinopyroxene $\pm$ plagioclase or melilite depending upon the pressure. Melts formed from Allende aggregates are very low in silica and iron and greatly enriched in calcium and aluminum, resembling no known lunar rock type. It was concluded that the Ca- and Al-rich aggregates from Allende represent an unlikely composition for the moon.

Two different model moon compositions, MC-1(2) and MC-2*(3) have subsequently been studied. Olivine and spinel crystallize from melt of MC-1 composition over a wide range of temperatures (1200-1400°C) and pressures (1 atm.-at least 20 kb), with clinopyroxene crystallizing near the solidus. At subsolidus temperatures olivine, clinopyroxene and chromite-rich spinel are the principal phases. Plagioclase was not detected in this composition. Melting experiments with the MC-2 composition indicate that below 9 kb olivine (Fo_{98-96}) is the liquidus phase followed by orthopyroxene, clinopyroxene and calcic plagioclase. Above 9 kb the order of crystallization with decreasing temperature is olivine, spinel, orthopyroxene and clinopyroxene.

The extreme difficulty of deriving a plagioclase-rich melt or cumulate from the MC-1 composition makes it an unlikely composition for the moon. Complete or nearly complete melting of the MC-2 composition, followed by fractionalcrystallization in the outer portion of the moon, could on the other hand produce the type of plagioclase rich melt necessary for formation of the lunar highlands. The production of a 60 km thick anorthosite layer from MC-2 would require the melting of at least the outer 200 km of the moon, which after differentiation would consist of dunite (olivine), harzburgite (olivine and orthopyroxene), pyroxene-rich gabbro and plagioclase-rich gabbro in order from bottom to top. This sequence is reasonable and we suggest that the MC-2 composition may be fairly near the bulk composition of the moon. On the basis of this model the undifferentiated portion of the moon (below 200 km) would consist of spinel lherzolite down to between 500 and 700 km and would consist of garnet lherzolite below that level. It is quite possible that a metallic phase (< 10%) exists within these deeper layers.

Basaltic crystalline rocks 70017 and 74275 are similar to Apollo 11 high-titanium basalts. 70017, a microgabbro with subophitic texture, probably represents the interior of a lava flow or sill. It consists principally of titanaugite (up to 3.6 wt % TiO_2), pigeonite, plagioclase (An_{88-71}) and ilmenite with minor olivine (Fo_{67-59}), armalcolite, spinel (Chr_{33} $ulvö_{57}$ $Sp{+}her_{10}$), cristabolite, tridymite, metallic iron (Ni<1 wt %), triolite and various late stage minerals in residual rhyolitic glass. Titanaugite and pigeonite occur principally in complex intergrowths, some with a distinct hour glass pattern. Titanium and aluminum content in pyroxenes (Al:Ti=2:1) decreases with decreasing calcium content. Lowest titanium and aluminum contents are found in euhedral pigeonite included within plagioclase. The iron-enrichment trend in pyroxenes, toward the ferrosilite corner of the pyroxene quadralateral, occurs only adjacent to residual glass and is much less extreme than the trend in Apollo 11 pyroxenes. Spinel occurs only within olivine, and armalcolite occurs only within pyroxene. The crystallization sequence is believed to be spinel, olivine, armalcolite, pyroxene, ilmenite (armalcolite reacts with liquid), plagioclase and residium.

Rock 74275, a fine-grained ilmenite basalt (TiO_2=12.5 wt %, microprobe analysis of fused glass), has a well developed variolitic groundmass of clinopyroxene, plagioclase, ilmenite, tridymite, metallic-iron (Ni<1 wt %) and troilite. Micro-phenocrysts are olivine (Fo_{80-71}), titanaugite (up to 6.5 wt % TiO_2) and armalcolite rimmed with ilmenite. Titanaugite also occurs as glomerocrysts intergrown with and replacing olivine. Spinel (Chr_{36-34} $ulvö_{52-48}$ $Sp{+}her_{16-14}$) occurs only within olivine. Titanaugites are strongly zoned with respect to titanium (Al:Ti=2:1) but show very little tendency toward iron enrichment. Plagioclase occurs as small blocky grains with hollow cores and as elongate anhedra intergrown with clinopyroxene. Armalcolite without ilmenite rims occurs as inclusions within pyroxene. The crystallization sequence for 74275 is very similar to that for 70017. Texture and chemistry of phases indicate that the magma that produced 74275 rapidly crystallized spinel, olivine, pyroxene, armalcolite and possibly small amounts of plagioclase and ilmenite during its rise to the surface. The fine-grained intergrowth of plagioclase, clinopyroxene and ilmenite in all probability formed upon extrusion onto the lunar surface.

Rock 77017 is a partly crushed block of gabbro and anorthosite that has been invaded by liquid of mare basalt type. It was collected near the large boulder at site 7 and may have a similar origin. Uncrushed areas are of two types; poikilitic gabbro consisting of euhedral plagioclase (An_{97-94}) and rounded olivine (Fo_{62-64}) enclosed in large plates of pyroxene and troctolitic anorthosite consisting of plagioclase (An_{97-94}), subhedral olivine (Fo_{62-60}) and poikilitic ilmenite. Pyroxenes were probably originally augite and pigeonite; both are now exsolved on a scale too fine for accurate microprobe analysis. This sample quite likely is derived from a layered gabbro complex of highland affinities.

One thin-section (77017,71) consists of a rounded gabbro fragment surrounded by dark brown mare basalt glass (TiO_2=6.3 wt %). The interior of the clast contains patches of pale brown to colorless glass that has the composition of high-alumina basalt (TiO_2 1.8, Al_2O_3 23.4, FeO 7.4, MgO 7.1, CaO 14.1 wt %). Where the two types of glass are in contact there

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is a relatively sharp break in composition with a plateau of intermediate composition. We believe that this is a result of mixing of the two melts, indicating that the high-alumina basalt melt is not simply a product of contamination of mare basalt by the highland type gabbro. The high-alumina basalt melt is probably a result of partial melting of 77017 gabbro brought about by heat from the surrounding mare basalt. Large scale partial melting of rocks similar to 77017 could be an important source of high-alumina basalts.

A clast of mare-type ilmenite basalt included within the mare basalt glass in 77017, 71 shows an extreme iron-enrichment trend in its titan-augites very similar to that observed in Apollo 11 samples (Al:Ti=2:1).

Rock 73235 is a complex breccia with a very fine-grained, slightly metamorphosed, dark brown matrix. Monomineralic clasts consist of plagioclase (with a wide range of shock features), olivine (Fo_{89-79}), zoned pigeonite-subcalcic augite ($Ca_{10}Mg_{60}Fe_{30}$-$Ca_{26}Mg_{44}Fe_{30}$), augite (near $Ca_{45}Mg_{36}Fe_{19}$) containing very thin exsolution lamallae of orthopyroxene, augite ($Ca_{43}Mg_{32}Fe_{25}$) with 10-15 μm lamallae of orthopyroxene ($Ca_{4.5}Mg_{45.5}Fe_{50}$), chrome-rich spinel ($Chr_{68-58}Sp{+}her_{39-30}$ $ulv\ddot{o}_{6-1}$), dark red spinel ($Chr_{31-10}Sp{+}her_{89-67}$ $ulv\ddot{o}_{2-1}$), pink spinel ($Chr_{5-4}Sp{+}her_{95-96}$) and baddeleyite. Lithic clasts are relatively unshocked and consist predominately of a suite of gabbroic to anorthositic rocks containing plagioclase (An_{97-94}), olivine (Fo_{79-73}), orthopyroxene ($Ca_4Mg_{73}Fe_{23}$-$Ca_4Mg_{77}Fe_{19}$) and minor clinopyroxene ($Ca_{31}Mg_{48}Fe_{21}$). In one clast clinopyroxene occurs in a symplectite-like intergrowth with chrome-rich spinel, possibly representing residual liquid rather than solid state reequilibration. One small clast consists entirely of an intergrowth of chrome-rich spinel and orthopyroxene, and one small clast of fine-grained spinel troctolite (An_{90-88}, Fo_{86-82}, $Chr_{5-4}Sp{+}her_{95-96}$) was observed. Clasts of mare basalt were not observed in the two thin-sections examined (73235,65 and 69). All material observed in these two sections is of highland derivation, greatly resembling material returned by the Apollo 16 mission.

*MC-1 = SiO_2 35.88 Al_2O_3 12.81 TiO_2 0.630 FeO 12.73 MnO 0.235 MgO 20.93
CaO 10.59 Na_2O 0.583 K_2O 0.0335 Cr_2O_3 0.390 P_2O_5 0.245 Cl 0.073
FeS 2.80 Fe 1.31 Ni 0.69(2)

MC-2 = SiO_2 42.28 Al_2O_3 8.226 TiO_2 0.4210 FeO 3.195 MnO 0.039 MgO 30.08
CaO 7.676 Na_2O 0.1092 K_2O 0.0116 Cl 0.1336 FeS 2.78 Fe 4.26(3)

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