FINAL TECHNICAL REPORT

TITLE OF GRANT Petrological studies on lunar rock samples

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PERIOD COVERED BY THE REPORT February 1, 1972 - September 1, 1974

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GRANT NUMBER NASA NGR 09-140-017

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(NASA-CR-141956) PETROLOGICAL STUDIES ON LUNAR ROCK SAMPLES Final Technical Report, 1 Feb. 1972 - 1 Sep. 1974 (Carnegie Institution of Washington) 14 p HC $3.25 CSCL 03B G3/91
N75-16443
Unclas 07710

SUMMARY OF STUDIES

Under the NASA Grant NGR 09-140-017, petrological studies have been carried out on the Apollo, 14, 15, 16 and 17 samples. The experimental studies have also been made on Allende carboaceous chondrite and model moon compositions. The following is a summary of those studies.

In the studies of the Apollo 14 samples, the melting experiments have been carried out on high-alumina basalt 14310 in the pressure range 5 to 30 kilobars. The liquidus phase determined under anhydrous conditions is plagioclase up to about 10 kb, spinel between 10 and 20 kb, and garnet above 20 kb. When plotted in the system olivine-anorthite-silica, the 14310 high-alumina basalt as well as other feldspathic basalts from the lunar highlands are separated from ultramafic compositions, including those of pyroxenite and peridotite, by a low-temperature trough. The high-alumina and feldspathic basalts, therefore, cannot be generated by direct partial melting of the lunar ultramafic mantle. They may have been generated by complete melting or by a large degree of partial melting of pre-existing plagioclase- or spinel-cumulate rocks which had probably been formed by a large-scale differentiation in the shallow parts of the lunar interior.

Melting experiments have also been made on a synthetic alkali-enriched 14310 composition, and it was found that the liquid of this alkali-enriched composition is close to the cotectic boundary of olivine, pyroxene and plagioclase at about 4 kb.

The results imply that if significant amounts of alkalis (~2.5 wt % Na_2O and about 1% K_2O) were lost before solidification of the high-alumina basalt, as suggested by Peckett and Brown (1971), the original magma could have been formed by direct partial melting of the lunar mantle at depths of about 70 km. The composition of olivine crystallized near the liquidus in the experiments at about 4 kb is Fo_{90}, indicating that the Fe/(Mg+Fe) ratio of the source rocks of the high-alumina basalts is about 0.1 which is not much different from that of the earth's upper mantle.

In the studies of the Apollo 15 samples, three crystalline rocks (15016, 15476 and 15545) have been analyzed with the electron microprobe, and the melting experiments have been made on rock 15016, one of the typical mare-type basalts with very few olivine phenocrysts.

Pigeonite porphyry 15476 contains large prismatic phenocrysts of pigeonite with rims of subcalcic augite, which have been studied in detail. The Al and Ti contents in both pigeonite and subcalcic augite increase as crystallization proceeds; however, the Al content in subcalcic augite drops drastically when plagioclase starts to crystallize. The Ti/Al ratio increases continuously with crystallization and exceeds 0.5 when the Fe/(Mg + Fe) of subcalcic augite is greater than 0.5. These relations are also found for subcalcic augite and pigeonite in rocks 15016 and 15545. These facts indicate that the oxygen fugacity decreases significantly during the crystallization of basalts 15016, 15476 and 15545. From the detailed study on pyroxenes in rock 15476, it is suggested that pigeonite started its crystallization beneath the lunar surface and grew relatively slowly from the basaltic melt. Subcalcic augite began to form by the reaction of pigeonite with the melt. Before the completion of the reaction, the magma was extruded on to the lunar surface, where it crystallized under very reducing conditions. Plagioclase crystallized rapidly and iron-rich pyroxenes crystallized metastably.

The melting experiments of basalt 15016 show that olivine (Fo_{70-72}) is on the liquidus or a near-liquidus phase up to about 11 kbar. The second phase to crystallize is chromian spinel, followed by pigeonitic clinopyroxene. From these experimental results, it is suggested that the source material of this basalt must have contained relatively iron-rich olivine, provided that the basalt was formed by melting in the lunar interior and its bulk composition was not significantly modified by the later crystallization process.

In the studies of the Apollo 16 samples, petrography, electron microprobe analysis and high-pressure melting experiments have been made on cataclastic anorthosite 60025, recrystallized breccia 60315, feldspathic basalt 68416 and fine-grained spinel troctolite 62295. The following conclusions have been obtained as a result of these studies.

Cataclastic anorthosite 60025 probably formed by accumulation of calcic plagioclase, and small amounts of trapped interstitial liquid crystallized to plagioclase, augite, hypersthene and pigeonite. Subsolidus reequilibration prior to brecciation resulted in the breakdown of pigeonite to augite and hypersthene. Recrystallized breccia 60315 probably formed near the base of a large impact ejecta blanket. The presence of a small amount of interstitial melt is strongly suggested. Crystallization of orthopyroxene poikiloblasts concentrated in the melt, which crystallized with a well developed dolerite texture. The crystallization temperature is estimated to be about 1100° C. Fine-grained, intersertal, feldspathic basalt 68416 was most probably formed by rapid crystallization of a melt generated by melting of a plagioclase-cumulate rock. Fine-grained spinel troctolite 62295 was formed by rapid crystallization of a mafic magma with a high Mg/Fe ratio that may have been derived by partial melting of a plagioclase- and spinel- bearing peridotite under anhydrous conditions. The presence of xenocrystic calcic plagioclase (An_{98-94}) and chromian spinel suggests contamination by pre-existing anorthositic material.

The liquidus relations of spinel troctolite 62295 have been determined at pressures between 5 and 12.5 kbar and in the temperature range 1220° and 1375° C. Spinel is on the liquidus and is followed by olivine, plagiocalse and pyroxene with decreasing temperature at pressures lower than 7 kbar. From the experimental results, it is suggested that the temperature of the magma at eruption was between 1260° and 1230° C. However, if all phenocrystic plagioclase crystallized during the quenching on the lunar surface, the temperature of the magma could have been as high as

1310°C. The melt of rock 62295 after subtraction of xenocrystic spinel and plagioclase is close to the cotectic boundary of olivine and spinel and the four-phase boundary olivine+spinel+anorthite+liquid at pressures less than 7 kbar, suggesting that the magma of spinel troctolite composition could be formed by partial melting of plagioclase peridotite or an olivine gabbro with a low Ca-rich pyroxene. Complete melting of a pre-existing spinel troctolite by impact is another possible mechanism, although the presence of xenocrystic spinel and plagioclase may be more difficult to explain.

From the fact that the composition of many highland-type rocks including anorthosite, feldspathic basalt and anorthositic gabbro lie between anorthite and four-phase boundary olivine+spinel+anorthite+liquid, it is suggested that these highland-type rocks may have been formed by plagioclase accumulation (or floatation) in a magma close in composition to the four-phase boundary or 62295. The melting experiments have also been made on feldspathic basalt 68416. The results support the above suggestion, although basalt 68416 was probably remelted by impact after accumulation of plagioclase.

In the studies of the Apollo 17 samples, petrographic studies with detailed electron microprobe analysis have been carried out on mare-type basalts 70017 and 74275, partly crushed gabbro and anorthosite 77017, and breccia 73235.

The sequences of crystallization of principal minerals in two mare-type basalts are as follows: olivine, spinel → armalcolite

→ pyroxene, ilmenite → plagioclase (74275) and olivine, spinel → armalcolite → pyroxene → plagioclase → ilmenite (70017). Pyroxene is augite - subcalcic augite in 74275, and both pigeonite and augite-subcalcic augite in 70017. These differences may be explained by differences in their cooling histories; rock 74275 cooled much more rapidly than rock 70017. Titanaugites in 74275 contain approximately twice as much Ti as those in 70017. This is probably a result of higher Al activity in the 74275 melt brought about by supercooling with respect to plagioclase due to rapid cooling.

Rock 77017, a breccia consisting principally of gabbro and troctolitic anorthosite, is partly surrounded and invaded by dark brown mare basalt glass. In addition, the breccia contains small irregular veinlets of pale brown to colorless glass. The pale glass has a composition similar to that of the highland-type, high-alumina basalt (e.g., 14310). Because the liquidus temperature of the high-alumina basalt melt is considerably higher than that of mare-type basalts, the high-alumina basalt melt was not formed by heat from surrounding mare-basalt magma, but was formed by impact melting of 77017 gabbro. Such a melting process could be a source of lunar high-alumina basalts.

The experimental study of model moon compositions was made to understand the differentiation histories and the structure of the moon. The materials or compositions chosen for the study are (1) Ca- and Al-rich aggregates of the Allende carbonaceous chondrite, (2) the moon composition proposed by Krähenbuhl <u>et al</u>.

(1973) and the revised moon composition by Ganapathy and Anders (1974a). The results of melting experiments on the Ca- and Al-rich aggregates indicate that spinel and aluminous clinopyroxene coexist with silica-poor, Ca-rich melt over a wide pressure and temperature range. At subsolidus temperatures, spinel and clinopyroxene crystallize with or without gehlenite-rich melilite and anorthite. If the moon consists of this material, the moon must contain a significant amount of melilite at shallow depths (< 300 km), and spinel and clinopyroxene in the deeper parts. Such a lunar interior would produce highly silica-undersaturated, Ca-rich magmas, the compositions of which are unlike any known lunar rocks. In addition, such a lunar interior cannot produce mare-type basalts. Thus, the Ca- and Al-rich aggregates of the Allende chondrite or chemically similar materials cannot be the dominant components of the moon.

The model moon composition (2) has been examined using the 3:2 mixture of the Allende bulk sample and its Ca- and Al-rich aggregates. The results of melting experiments indicate that olivine, spinel and Ca-rich clinopyroxene crystallize with decreasing temperature at pressures between 1 atm and 5 kbar. No plagioclase crystallizes even very near the solidus. From these results it is apparent that this material containing only a few wt. % normative plagioclase cannot yield the 65 km-thick anorthositic crust, even if the entire moon was melted and differentiated.

The model moon composition (3) crystallizes olivine, orthopyroxene, clinopyroxene and plagioclase with decreasing temperature at pressures between 1 atm and about 8 kbar. If the outer layer of the moon was completely or largely molten in the final stage of accretion of the moon and was followed by fractional crystallization of the molten layer, the following layered structure would be formed; dunite (olivine), harzburgite (olivine+orthopyroxene), lherzolite (olivine+orthopyroxene+clinopyroxene±plagioclase), pyroxene-rich gabbro with ilmenite, and plagioclase-rich gabbro in acending order. This layered structure is essentially the same as those originally proposed by Wood et al. (1970) and Anderson et al. (1970) and appears to be consistent with the petrological evidence. It is concluded that the model moon composition (3) or similar to it is a reasonable bulk composition for the moon. There are some problems, however; for example, an important rock type, spinel troctolite cannot be formed in the crystallization sequence. This difficulty could be removed, if plagioclase began to crystallize before pyroxene. If the model moon composition (3) contains more Al_2O_3, plagioclase would begin to crystallize before pyroxene. The revised model moon composition containing 3 wt. % more Al_2O_3 (Ganaphathy and Anders, 1974b) may explain more fully the petrological evidence.

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INVENTORY OF RESIDUAL EQUIPMENT (COST OVER $1,000):

N O N E

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INVENTORY OF RESIDUAL EQUIPMENT AND PROPERTY FURNISHED BY THE GOVERNMENT:

N O N E

STATEMENT ON LUNAR SAMPLE RETURN

The following lunar samples were received by the Principal Investigator under the Grant NGR 09-140-017, and all have been returned to the Lunar Sample Curator with the sample histories. The dates of receipt of these samples by the Curator are shown.

Sample number	Type of sample*	Date of recipt by the Curator
14321,102		1-10-72
14321,22	PM	3-23-72
14162,29		3-23-72
14053,6	PM	3-23-72
14310,22	PM	3-23-72
14310,139		3-23-72
15476,32	PTS	8-3-73
15476,13		9-11-74
15016,11	PM	11-15-72
15016,143	PTS	1-29-73
15016,51		1-29-73
15545,2	PTS	1-29-73
15545,26		1-29-73
68416,21		8-3-73
68416,78	PM	8-3-73
62295,49		8-3-73
62295,68	PM	8-3-73
60335,41		8-3-73
60315,84		8-3-73
60315,62	PM	8-3-73
60025,132	PM	8-3-73
60025,91		8-3-73
60335,69	PM	7-24-74

*PM, probe mount; PTS, polished thin section; others are either rock chip or homogenized powder of rock

70017,110	PM	7-24-74
70017,124	PM	7-24-74
70017,58		9-11-74
73235,65	PM	7-24-74
73235,69	PM	7-24-74
74275,84	PM	7-24-74
74275,86	PM	7-24-74
74275,79		9-11-74
77035,73	PM	7-24-74
77035,69	PM	7-24-74
77017,5		9-11-74
77017,13		9-11-74
77017,71	PTS	9-11-74
77017,85	PM	9-11-74
79215,54	PTS	9-11-74
79215,71	PM	9-11-74
78155,104	PTS	7-24-74