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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Summarizing research accomplished on

MELTING BEHAVIOR AND PHASE RELATIONS IN THE LUNAR INTERIOR

Carried out under

NGR 22-007-175

during the period

1 May 1970 through 30 April 1973

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CONTENTS

Introduction

This report summarizes research carried out at Harvard University during the three-year period from 1 May 1970 through 30 April 1973 on "Melting Behavior and Phase Relations in the Lunar Interior." This research was supported by NASA grant NGR 22-007-175 and was carried out in conjunction with closely related research involving lunar samples as authorized under NASA grants NGR 22-007-199 and NGL 22-007-247.

This research consisted chiefly of phase equilibrium experiments at both high and low pressures on lunar samples and synthetic compositions, as well as related petrographic studies of lunar rock samples. The objectives were to trace the origins of rocks found on the lunar surface, to characterize the nature of the lunar interior and to locate and identify the sources of lunar magmas.

Most of the results have been published in full in the papers referenced here, so that only brief summaries are given in this report.

Personnel

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Summary of Research
Mare Basalts

The dark maria on the near side of the moon appear to be floored by the distinctive high-iron, low-alumina mare basalts sampled by the Apollo 11, 12, 15, 17 and Luna 16 missions. These rocks range in age from 3.2 to 3.8 x 10^9 years and show textures that unequivocally indicate a volcanic origin by crystallization from a silicate melt at or near the lunar surface. Some of these rocks give evidence for a history of crystal-liquid fractionation near the surface, and may owe their present chemical composition and petrological features largely to such processes. Others may represent nearly pristine samples of liquids produced by partial melting deep within the lunar interior. If the latter can be positively recognized, their high pressure melting behavior can be used to set limits on the mineralogy, chemical composition, and depth of the interior source region.

We have studied a mare basalt sample from Oceanus Procellarum (12002), two basalt samples from Hadley Rille (15555 and 15065), and a synthetic composition prepared to match one of the high-K intersertal ilmenite basalts of Mare Tranquilitatis (10072). None of these samples have chemical compositions corresponding to low pressure cotectic compositions. We have argued in references 6, 8, 12 and 14 that some of these rocks probably do represent partial melts from the lunar interior, and that, if so, the Moon at a depth of ~300 km must contain aluminous pigeonitic clinopyroxene, olivine, and/or ilmenite. The strong Eu anomalies discovered in the mare basalts by others strongly suggest that this source region is itself a mafic cummulate from an early wholesale melting of the Moon's outer several hundred kilometers.

Fra Mauro Basalts

Rocks sampled on the Apollo 14 mission consisted largely of a complex suite of breccias having a distinctive chemical composition. These breccias and the soil at the Fra Mauro site are characterized by relatively high levels of potassium, rare earth elements and phosphorus--hence the acronym "KREEP." This KREEP material had earlier been identified as a significant foreign component in the soil at the Apollo 12 mare site. Also present in the Apollo 14 sample were a very few specimens having the distinctive Fra Mauro chemistry, but with igneous textures implying crystallization from a melt at some stage in their history.

We have studied two of these igneous textured Fra Mauro rocks (14310 and 14072) and a soil sample (14259). Results have been published in references 7, 9, and 10 in which we use our phase equilibrium data combined with soil fragment abundance data collected by others to suggest a hypothesis for the origin of Fra Mauro rocks and soil and, by implication, KREEP-like materials found elsewhere on the moon. Briefly, partial melting of pre-existing rocks in the lunar crust consisting of olivine, plagioclase, and low-calcium pyroxene should yield a peritectic liquid with major element chemistry virtually identical to that of average Fra Mauro soil. If the degree of partial melting is sufficiently small or the trace element content of the source rocks sufficiently high, then the trace element content of Fra Mauro soil can also be roughly accounted for. The major element chemistry and melting behavior of Fra Mauro basaltic rocks contrasts markedly with that of mare basalts consistent with an origin in a source region of contrasting chemistry and mineralogy.

Highland Rocks

The Apollo 15 and Apollo 16 missions sampled portions of the lunar terrae, confirming the widely held view that the lunar highlands consisted largely of plagioclase-rich rocks including anorthosites. The orbital x-ray and gamma experiments, the Surveyor VII and Luna 20 missions permit this limited direct sampling to be extrapolated with some confidence to other portions of the moon's highland surface.

Texturally, however, the highland rocks were found to be intensely brecciated and metamorphosed to varying degrees, thus their early igneous history, if any, has been obscured. The few samples that do show igneous textures may well be products of second generation, impact producted, melts.

We have made petrographic and microprobe studies of several Apollo 16 rocks (60025, 60315, 60335, 68415, 62295) including two with clear cut igneous textures (68415, 62295). Since the latter two must have been wholly or largely liquid at some time (regardless of the cause of the melting), we have carried out phase equilibrium studies on these two samples. We also studied a synthetic composition prepared to match early estimates of average lunar highland composition. The results of these studies are given in references 11 and 13 and an interpretive synthesis of this data combined with soil fragment abundance data collected by others on soils from the Apollo 16 and Luna 20 missions was given in reference 17. In addition to the peritectic melting giving rise to Fra Mauro-like liquid compositions, there exists, for spinel bearing rocks, another peritectic giving rise to liquids resembling those called "very high alumina basalts (VHA)" or "low-K Fra Mauro basalts" that appear to be significant components in highland soils.

We have come to share the now widely held view that early ($>4 \times 10^9$ years) widespread melting of (at least) the outer portion of the moon produced: 1) a plagioclase rich crust by accumulation of plagioclase and entrapped mafic material; and 2) a pyroxene, olivine rich sub-stratum by settling of mafic crystals and entrapment of late residual liquid enriched in (e.g.) iron and titanium. The former provides a source region for the production of high alumina, low iron, VHA and Fra Mauro-like basaltic liquids, while the latter provides a deep source for high iron, low alumina mare basalts.

Lunar Thermal History

At the Second Lunar Science Conference, there existed an obvious incompatibility between the low temperatures ($\lessdot 1000°C$) claimed for the lunar interior by students of electrical conductivity as derived from transient lunar surface magnetism, and the high temperatures predicted by all earlier studies of lunar thermal history. There appeared to be supporting evidence for both positions, and the "Hot Moon-Cold Moon" controversy became a staple of the popular press.

We undertook a new study of the lunar thermal history problem in an effort to resolve the apparent contradiction. The results of this study are given in references 2, 3, and 5. Three novel features characterized this study, two of which have been generally adopted in later, more complete, studies by others. First, new evidence on thermal conductivity variation with temperature was applied for the first time to the lunar problem; second, full account was taken of the distinctive lunar chemistry (unlike that of chondritic meteorites or terrestrial rocks); and third, lunar uranium content was treated as an adjustable parameter, and varied to match proposed versions of lunar internal temperatures.

It was shown that either the lunar uranium abundance was remarkably low, or that the temperature profiles based on electrical conductivities were grossly in error. More recently the Apollo 15 and Apollo 17 heat flow determinations, re-evaluation of the conductivity data, and new interpretations of seismic data, seem to have resolved the controversy on the side of the higher internal temperatures.

Experimental Techniques

Phase equilibrium studies on natural rock compositions entail special problems in addition to the familiar problems encountered in iron-free synthetic systems. The sample tends to react with the capsule material and/or the furnace atmosphere, thus altering the chemical composition of the charge. Furthermore, the crystallization behavior is strongly affected by the redox conditions established during the experiments. Neither we nor any other group of investigators has fully solved these problems. Our methods are discussed in detail in references 5, 8 and 10.

At high pressures there exists an additional problem of calibration since pressure cannot be directly monitored in a solid-medium apparatus. Reference 1 describes a cooperative study directed toward interlaboratory comparison of pressure calibration techniques, and references 15 and 16 place the earlier study and our present work on a more sound absolute basis.

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