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MINERALOGIC AND PETROLOGIC STUDIES OF LUNAR SAMPLES AND METEORITES

Grant NSG 7596

Final Report

February 1, 1979 to August 31, 1980

Principal Investigator
Dr. John A. Wood

Prepared for

National Aeronautics and Space Administration
Johnson Spacecraft Center
Houston, Texas 77058

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Funding under Grant NSG 7596 has been used to support a long-term research effort primarily concerned with the conditions of formation of the moon, the differentiation of the lunar crust, and the character of the meteoritic parent planets. We carry out mineralogic and petrologic studies of lunar and meteoritic materials (using electron microprobe, scanning electron microscope, x-ray diffraction, and optical techniques) and computer modelling studies of the orbits of solar system bodies (primarily proto-lunar materials and asteroidal bodies) and the geochemical evolution of planetary materials.

This was a period of unusually high turnover among employees. Post-doctoral Research Associate Claude Herzberg left the group for a position at the LPI in July 1979, and has not been succeeded by another post-doc. Undergraduate student Michael Baker completed his undergraduate honors thesis and left the group in August 1979, to take a position at the LPI. Undergraduate student Philip Maloney joined the group in September 1978, and left in August 1980 to attend graduate school at the Department of Planetary Sciences at the University of Arizona. Undergraduate student Hartley Rogers joined the group in approximately September 1980. Graduate student Gayle Lux joined the group in June 1979, with a Master's degree from the University of New Mexico and Institute of Meteoritics. Lux unexpectedly postponed matriculation at Harvard University and left the group in September 1979. She will join us again in September 1980. Graduate student Ron Cohen joined the group in June 1980. In addition to these researchers, our instrument technician, James Bonomi, left the group in March 1980. We required some months to make a successful shift to instrument maintenance from other sources.

LUNAR RESEARCH

Research Associate Herzberg was engaged in a program of experimental and thermodynamic research on the pressure-temperature limits of stability of the mineral assemblages found in pristine, spinel-bearing lunar highland lithologies. Under Herzberg's supervision, Baker made detailed studies of mineral compositions in spinel-bearing clasts from samples 15455 and 72435. From criteria established by Herzberg, Baker demonstrated the likelihood that these minerals originated in the lower stratigraphic levels of the primordial lunar crust.

Herzberg also continued his efforts to evolve a thermochemical interpretation of experimental phase equilibria in silicate solid/liquid systems of planetary importance, for the purpose of modelling the early formation (as by the differentiation of magma oceans) of the crusts and mantles of Earth- and Moon-sized planets. An observation of significance was that the effect of pressure in increasing the density of silicate magmas in planetary interiors may be so profound as to call for a total re-evaluation of the processes of solid/liquid separation involved in the differentiation of large planetary objects.

Co-Investigator Ursula Marvin conducted a collaborative study with Paul H. Warren, examining the petrography and chemical composition of coarse-grained gabbro 61224,6. This is a pyroxene-plagioclase cumulate that is exceptionally low in plagioclase, high in augite, and enriched in Na and Fe for a highlands lithology. Warren's analysis of minor and trace elements show a very low siderophile content, which confirms that this is a pristine, plutonic rock. The sample bears a stronger resemblence to meteoritic eucrites than to other lunar gabbros.

As part of the Lunar Highlands Initiative, Marvin completed preliminary examinations, maps, and descriptions of Apollo 16 breccia 67015 and prepared a Guidebook that has been published and distributed by the Curator's Office in Houston. In May 1980 she was confirmed by LAPST as leader for a miniconsortium of investigators who have agreed to collaborate in the chemical analysis and age dating of selected clasts from this breccia. Members are L. Haskin (minor and trace element analysis), K. Marti (Sm/Nd dating), and C. Hohenberg (Ar/Ar dating). Six thin sections of clasts that Marvin separated from 67015 breccia fines have been received, and she has begun petrographic and microprobe examinations that should prove useful in selecting the most interesting material for study by the consortium.

Undergraduate student Rogers has undertaken to analyze approximately 100 glass particles from each of a number of soil samples taken at five stations of the Apollo 16 site. This study is in the spirit of the Apollo Soil Survey (ASS) of Reid and co-workers in the early days of the Flight Program. Preliminary results are compared in Figure 1 with compositional clusters identified by the original ASS. MKFM glasses appear to be less abundant in the Apollo 16 samples. The study's goals are (1) to further our knowledge of fundamental rock compositions of the moon, (2) possibly to shed light on the mode of formation of the soil glass droplets, and help us understand why they remember so faithfully the compositions of fundamental lunar rock types that are hard to find among the crystalline rock samples, and (3) to contribute to the decipherment of Apollo 16 site geology.

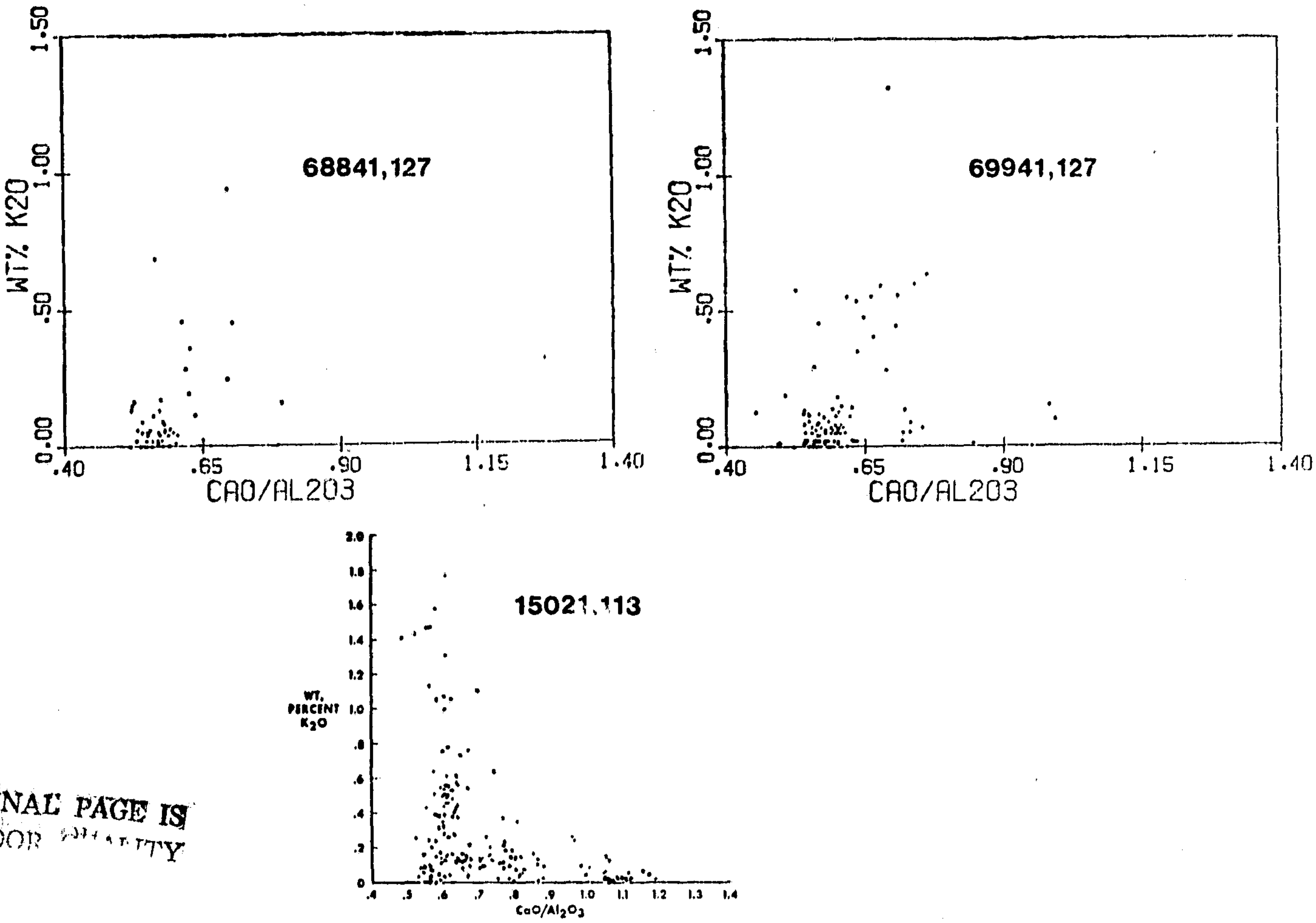

Figure 1. Glass compositions in two Apollo 16 soil samples (above) compared with compositions in 15021. The Apollo 16 soils are predictably richer in anorthositic glasses than the Apollo 15 soil, and are all but devoid of mare basalt glasses. MKFM glasses (~0.5% K_2O) are present in the Apollo 16 soils, but are less abundant than in 15021. Data for 15021 from Reid, et al. (1972).

Principal Investigator John Wood has resumed consideration of the problem of the origin of Earth's moon by a "disruptive capture" mechanism by which planetesimals that approached the growing earth and passed through its Roche zone without actually impacting would be tidally disrupted; in some cases (depending upon approach velocity and distance of the nearest approach), debris from the portion of the planetesimal that passed nearest the protoearth would be slowed to a velocity less than that necessary to escape from the protoearth. These planetesimals would be captured into a swarm of material in geocentric orbit and would eventually accrete to form a moon (Wood and Mitler, 1974). The model was attractive originally because some degree of disruptive capture of approaching planetesimals undoubtedly occurred if the earth formed by accretion; additionally, if the planetesimals had undergone some internal differentiation prior to disruption, the capture mechanism outlined would have operated selectively, retaining crustal and mantle materials from the disrupted planetesimals and flinging core material back into heliocentric orbit. This would rationalize the metal-poor composition of the moon. Difficulties of the model are: debris would have been captured from retro- as well as prograde approaches, and collisions between these two populations might have caused virtually all such material to be decelerated so that it fell to Earth; and relic Fe-rich materials from planetary interiors would have remained at large in the solar system to contaminate an Fe-poor moon if it did form. These problems led Wood to temporarily abandon the model. Recently the problem of prograde and retrograde collisions has seem less serious, since accretionary processes apparently caused most of the planets to take up the same sense of rotation as the orbits of the objects they accreted from. While the reason for this is not clear, it seems likely that the same mechanism or effect would have caused material captured by disruption in the Roche zone to also have a net positive angular momentum. It remains to be seen how strong such an effect would have been, and whether it would have left enough material in prograde orbit to form a moon. The problem of available "free" Fe also appears less serious, since rejected Fe-rich planetesimal material, having already been disrupted in Earth's Roche zone, would no longer be eligible for capture via disruption during subsequent passes. It would affect the moon only by direct capture, and Earth's much larger capture cross-section would have caused Earth to absorb much of this unwanted component.

The model, with these refinements, is subject to testing via computer simulation. Wood has written a program in which planetesimals in (appropriately weighted) random orbits and with random dimensions are fired at a growing Earth in two-dimensional space. The three-body system sun-Earth-planetesimal is considered. The planetesimals may accrete to Earth, they may pass through the Roche zone on either side, or they may miss on either side. The disposition of tidally disrupted planetesimal material is assessed. The masses, angular momenta, and compositions (assuming differentiated planetesimals) of Earth and pre-lunar swarm are followed as Earth grows from 1% to 100% of its present mass.

METEORITIC RESEARCH

Wood completed computer modelling studies of the thermal evolution of hypothetical parent meteorite bodies in which continued accretion of thermally insulating particulate matter, heat generation by ^{26}Al decay, melting or sintering of the particulate matter into conductive rock, and establishment of the properties of the meteorites were assumed to have occurred concurrently.

Though this combination of interactive processes is difficult to model, it is believed to better approximate conditions in the early solar system than does the simpler massive-rock parent meteorite planet model treated by previous thermal evolution studies. Wood found that under some circumstances the substance of a parent object at first cools rapidly (which seems to be required by the very old radiometric ages of most meteorites), then cools much more slowly through the lower ranges of temperature (as the relatively slow metallographic cooling rates of meteorites appear to require). Continued accretion of insulating particulate matter, after temperatures have fallen too low to sinter the dust into conductive rock, causes the decrease in cooling rate according to this model.

As a corollary to the research outlined above, Wood reviewed the studies of metallographic cooling rates done to date for five classes of meteorites (irons, stony-irons, and H-, L-, and LL-group chondrites), and made a formal comparison of cooling rates with radiometric ages. He noted a discrepancy, in the sense that metallographic cooling rates appear to be too slow by a factor of $\sim$6 to be consistent with established radiometric ages and a simple cooling model. Reconciliation of the two bodies of data appears to require that a more complex (and presumably more realistic) cooling model be employed.

Wood has advocated an unorthodox source for the ordinary chondrite parent bodies: by this concept, these bodies were asteroidal and stony in character, but spent most of the age of the solar system in the Oort cloud of comet nuclei rather than in the asteroid belt. The two major questions to be resolved are (1) what are the relative proportions of icy planetesimals from the outer solar system and rocky planetesimals from the inner solar system that would have been ejected in early times to form the Oort cloud; and (2) what proportion of objects re-entering the planetary system in comet-like orbits that could evolve into Apollo/Amor asteroid orbits (the apparent immediate source of ordinary chondrites), as opposed to being ejected from the solar system again by Jupiter's gravitational perturbations. Initially Wood applied Arnold's (1964) Monte Carlo routine for following the orbital evolution of small objects in the solar system, but determined that this procedure cannot handle Jovian perturbations realistically. Specifically, if only encounters within 10 capture radii of Jupiter are considered, as is traditional with the Monte Carlo routine, a very large class of middle-sized perturbations of objects in cometary orbits is ignored. If the radius within which encounters are treated is expanded to include these, the traditional assumption that solar gravity can be neglected during the encounters becomes unrealistic. Wood is now engaged in completing a computational routine that treats very close interactions between orbiting objects, along the lines of Everhart (1972).

Graduate students Kornacki and Cohen have conducted detailed systematic studies of the C3(V) meteorites Allende and Mokoia as a source of information about events in the solar nebula.

To judge from the relative crystallinity of their matrixes, Mokoia has not experienced the same degree of post-accretional metamorphism as Allende. In addition, Mokoia contains more abundant inclusions and chondrules than most C2 chondrites. It should therefore, be a rich source of information about the physical and chemical state of the medium in which the components of these objects formed.

Rather than following the traditional plan of attack, which is to locate large coarse-grained inclusions on broken surfaces and study them, Kornacki and Cohen have made comprehensive studies of approximately 20 thin sections of Allende and Mokoia, chosen from random samples of the materials. They find that coarse-grained Ca,Al-rich inclusions (CAI's) are more rare than one would gather from their coverage in the literature. The great majority of objects that have "inclusion" morphologies are fine- to medium-grained aggregates. Of 154 such objects studied in Allende sections by microprobe, SEM, and optical microscope, 55% were found to be olivine-rich, 25% Ca,Al-rich, and 20% of intermediate composition. Only one coarse-grained CAI was found in the same thin sections. Currently a major objective is to establish the modal proportions of different types of materials that are actually present in Allende. The literature is not helpful on this point. The chondrule/inclusion population of Mokoia will be compared. By contrast to Allende, Mokoia has been found to contain less than 5% Ca,Al-rich objects by volume.

The mineralogy of the fine/medium-grained inclusions in Allende, especially their content of hedenbergite, fassaite, and Fe-spinel, is not predicted by the condensation sequence. The mineralogy predicted for material cooled sufficiently to contain this much Fe^{2+} would be olivine, orthopyroxene, and plagioclase (the ordinary chondrite assemblage). Kornacki and Cohen have noted that in the system $CaO-SiO_2-MgO-FeO-Al_2O_3$ with the phases ol(fo,fa), sp(Mg-sp,Fe,sp), an, mel(geh, ak), cpx(di,hed,fass), one independent reaction is

$$ak + geh + 4fo_{50} + 3an \rightleftarrows 3di + 3hed + fass + 2Mg\text{-}sp + Fe\text{-}sp$$

Here the assemblage on the left consists of minerals abundant in the matrix and coarse CAI's of C3(V) chondrites; the assemblage on the right approximates that of fine/medium-grained CAI's. An interesting aspect of this reaction is that at equilibrium it proceeds to the right only at high pressures. There are, in fact, other suggestions of mineralization at pressure in the CAI's, such as the grossular component in garnet and the jadeite component in pyroxenes, which have received little or no attention in the literature. Kornacki is now exploring the possibility that the mineralogy of fine/medium-grained inclusions is not due primarily to condensation from the nebula (even from regions of non-solar composition), or to back reaction of high-temperature condensates with cooler nebular gas, but rather to high-energy events (possibly involving transient high pressures?) that thermally processed and to varying degrees distilled the less refractory elements from material that was already condensed. Work is underway to define the P,T conditions that appear to be required.

Wood is developing a model in which the most refractory elements condense in pre-solar system stellar and supernova envelopes, into grains that are systematically coarser than other interstellar dust, and are thus readily fractionated from other mineral components in the solar nebula. In this model, heating of dispersed dust, and aggregation in the nebula, would produce Group III CAI's in the regions where refractory-rich grains were present, and Group II (Er-, Lu-poor) CAI's where they were absent.

Undergraduate student Maloney carried out an experimental investigation of the hydrothermal alteration of amorphous material, under the guidance of Herzberg. The thesis under test was that the accretion of amorphous interstellar dust into planetesimals, followed by warming and hydrothermal reactions within the planetesimals, best accounts for the properties of the C1 chondrites. He subjected a gel (an amorphous laboratory product, representing interstellar grains) of bulk C1 chondrite major element composition (approximate solar non-volatile abundances) to conditions of elevated temperature and P_{H_2O} in an attempt to reproduce hydrothermally some of the mineralogies and morphologies observed in such carbonaceous chondrites as Orgueil. Experiments were carried out at temperatures of 200°, 300°, and 400°C. While petrological characteristics of Cl chondrites suggest that they have not been heated to temperatures above 300°C, the 400°C temperature acknowledged the possible need to compensate for the unavoidably short time scale of laboratory experiments. SEM studies of run products revealed a number of morphological similarities between the experimentally produced materials and Orgueil. Most significantly, the presence of both spheroidal and plate-like particles of magnetite was observed in both natural and experimental materials.

Marvin and laboratory technician Karen Motylewski studied white evaporite deposits occuring on 7 stony meteorite specimens collected that the Allan Hills site during the 1977-78 Antarctic field season. The hosts for the deposits are all different: a C3, H3, H4, H5, L3, and L6 chondrite and a ureilite. Five of these stones were originally classifed as unweathered, with only inconspicuous traces of oxides around metal grains and in cracks; one was severely weathered and stained, and one was intermediate. X-ray diffraction and SEM determinations show that the salts are chiefly hydrous Mg-carbonates and Mg-sulfates. The source of the C,S, and Mg components is yet to be determined; there is undoubtedly a component of leaching from the meteoritic minerals, but some Mg and S may derive from airborne pollutants. Although two of the stones are carbon-bearing, they are coated with completely different salts. The carbonates are most likely to derive from atmospheric CO_2, which dissolves in snow melt-water and percolates through meteorites during hours of high sun angle in the

Antarctic summer. In order to determine the sources of carbon and the temperatures of formation of the salt deposits, Marvin has arranged for isotopic measurements of C, O, and D to be made by Irving Freidman of the U.S.G.S. Progress reports on this work were presented at the Lunar and Planetary Science Conference in March 1980 and at the International Geological Congress in July 1980. A short article has been submitted to the Antarctic Journal of the U.S. We hope additional study will provide insight into the special conditions that affect a few of the meteorites exposed on the Antarctic icecap, and into the alteration processes that occur in meteorites on the earth.

MISCELLANEOUS

Since 1977 Wood has served as Leader of Team 4 of the Basaltic Volcanism Study Project of the Lunar and Planetary Science Institute. The manuscript representing this collaboration will appear as Chapter 4, Geophysical and Cosmochemical Constraints on Properties of the Mantles of the Terrestrial Planets, in a volume by Pergamon Press, in press.

Marvin began serving a term as an at-large member of the Board of Directors of the Universities Space Research Association (USRA). She also served on an ad hoc committee established by LAPST to consult on and recommend a system of nomenclature for lunar highlands rocks. The committee has a detailed manuscript on the subject in press. Marvin continues her membership in the NSF-sponsored Antarctic Meteorite Working Group. At the request of LAPST, Marvin wrote a booklet presenting the value of research on extraterrestrial samples to a general audience, particularly pre-college students and teachers. LAPST has reviewed the manuscript and is looking into NASA publication.

Marvin completed work as co-editor (with Brian Mason) of a Catalogue of Antarctic Meteorites.

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