Lunar Science: Analyzing the Apollo Legacy

Man's knowledge of the moon has been dramatically transformed during the brief 3½ years between the first and last Apollo landing. One of the more remarkable aspects of this transformation is how rapidly data from surface experiments, orbital observations, and analyses of lunar samples has become available. In contrast to past voyages of discovery, where the detailed record often did not appear until 20 or more years later, coordination between the space agency and the burgeoning lunar science community has produced preliminary Apollo results almost before the dust from the departing lunar module has settled. A truly impressive array of reports, including early evidence from Apollo 17, was presented at last week's Fourth Lunar Science Conference in Houston, Texas. While it was clear that detailed study of the Apollo legacy has only begun (see page 1331), the meeting marked the end of the adventure itself and the first attempt at a summary of what has been gained.

Among the highlights of the Apollo 17 data was the confirmation by several investigators that the widely reported orange-colored soil found near Shorty crater was not rust but rather a red-tinted glassy substance with a composition similar to that of basalt (Fig. 1). Dating established that the glass beads were formed about 3.7 billion years ago, and while their origin remains obscure, with some proposing volcanic extrusion and others suggesting meteoritic impact processes, the notion that the soil might indicate a recent volcanic vent has been dispatched. A rock found by Apollo 16, however, did turn out to contain rust in considerable abundance. But it also was shown to contain zinc compounds and other volatile minerals uncommon on the moon, thus raising the question of whether the rust is due to indigenous water or, as many investigators believe, possibly came from a comet.

The Apollo 17 results and the more detailed analyses of data from earlier missions (including the Soviet Union's Luna 16 and Luna 20) reported at the Houston meeting are part of a virtual flood of empirical results pouring out of lunar laboratories. Emerging more slowly and still the subject of intense debate is a model of planetary evolution that can order and help explain the data. Many of the major constraints that such a model must meet are beginning to be clear, however, and the evidence is now overwhelming that the moon differs greatly from the earth in internal structure, in chemistry, and hence probably in the nature of its birth.

Before Apollo, virtually nothing was known of the interior of the moon except that its density was singularly less than that of any other terrestrial planet, and that it appeared (from its moment of inertia) to be a homogeneous body. The shape of the moon, as determined by laser altimeter data from Apollo 15 and Apollo 16, is such that the center of figure is displaced away from the earth by about 2.5 kilometers from the center of mass. But this discrepancy may be explained, according to W. M. Kaula of the University of California at Los Angeles, by the presence of the low mare on the near side of the moon and their absence on the far side. The mean altitude of the mare below the highlands is about 3.5 kilometers. If the crust is substantially thicker on the far side of the moon, as J. A. Wood of the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, and others have proposed, it may have inhibited generation or extrusion of the mare and hence explain why they occur only on the moon's near side. Revised measurements of the moon's moment of inertia do not allow a homogeneous internal structure, but, according to Kaula, do seem to indicate that gravitational isostasy prevails.

Few Quakes in a Quiet Moon

Evidence from the four seismometers that comprise the lunar seismic network indicates that moonquakes are rare and weak events compared to earthquakes. According to G. Latham of the University of Texas in Galveston, 43 active moonquake zones have been identified. Moonquakes in each zone occur at monthly intervals and show longer term variations that also correlate well with lunar tides.

A more puzzling finding concerns the spatial pattern of the moonquakes. Latham finds that the quakes occur at depths between 800 and 1100 kilometers, much deeper than any seismic activity on earth. Their focal centers seem to lie along two distinct belts that arc around the moon for about 1000 kilometers, one running roughly north to south and the other northeast to southwest. The pattern does not correlate with the rims of the lunar mare, as had been suggested earlier, but seismologists were at a loss to explain just what might give rise to the belts.

The depth of the moonquakes seems consistent with a model based on seismic data of the moon's interior structure. According to the model, the moon has a thick crust (for so small a body), a rigid mantle, and possibly a partially molten core. Measurements of the travel times of seismic signals generated when spent Saturn rocket stages are crashed into the moon had earlier shown the presence, at a depth of about 60 kilometers, of a sharp discontinuity in the velocity with which the signals propagated. The discontinuity is inferred to be the lower edge of the lunar crust. Data reported by M. N. Toksoz of M.I.T. from the last two Apollo missions and from the fortuitous impact of a large meteorite seem to confirm this view. The crust is thought to consist of two layers in the mare regions, of which the uppermost is inferred, by comparison with laboratory velocity measurements, to be basalt, and the second is thought to be rocks similar to the aluminous basalts and anorthositic gabbros found in the lunar highlands. Other investigators believe that the upper 20 kilometers of the lunar surface may be largely crushed and broken rock.

Below the crust, seismic velocities are higher and relatively constant to depths of about 1000 kilometers, indicating the presence of more rigid material with constant elastic properties. Seismic shear waves from events on the far side of the moon seem to be damped out when they pass through the deep interior, an indication, according to Latham, that below 1000 kilometers the moon contains a partially molten core. If this model is correct, and if the core material is silicate rock, temperatures of about 1500°C would be required. The model makes plausible the explanation that moonquakes occur and that tidal energy is released primarily in a zone between the rigid lower mantle and the less-rigid core material.

Heat flow measurements at the Apollo 17 site, reported by M. G. Langseth of Lamont-Doherty Geological Observatory, bear out the surprisingly high values reported on Apollo 15. The installation of the experiment on the lunar surface, which according to Langseth's description was "as difficult as plowing a straight furrow in New Hampshire," went off without a hitch. But the reported flux, about 2.8 microwatts per square centimeter, seems to indicate that there is more radioactive material and hence a hotter moon than had been expected. The heat flow corresponds to a lunar abundance of uranium between 0.05 and 0.075 parts per million. Langseth raised the possibility of regional bias in the heat flow measurements, since the two data points were both obtained on the margins of large mare basins and also suggested that corrections for the topographic effect of the narrow valley at Taurus-Littrow might lower the Apollo 17 result slightly. Nonetheless the heat flow measurements exceed those predicted by many geochemical models based on a chondritic composition and appear to put a strong constraint on calculations of the moon's thermal history.

The history appears to have been a complicated one, including such events as volcanic flooding of the mare basins between 3.1 and 3.9 billion years ago. Toksoz and his colleagues have computed models of the moon's thermal history that provide for the mare volcanism and also meet the high values for heat flow. The resulting theoretical picture requires complete melting of the outer few hundred kilometers of the moon at the time of formation, then gradual cooling of the exterior while the interior heats up because of radioactive decay. The heating progresses downward, possibly melting each deeper zone of the moon in turn. At present, the model predicts a warm lunar interior with partial melting below about 800 kilometers, consistent with the deep seismic evidence.

The major objection to a moon with an initially cold core has come from investigators concerned with magnetic phenomena. The remanent magnetic field of the moon varies from one location to another, but it seems inescapable that the mare lava flows crystallized in a magnetic field with a strength of a few thousand gammas, much stronger than the present one. Speculation has centered on a self-generated field, excited by convection in a molten iron core that later cooled, turning off the field. This explanation, however, would require an initially hot moon and thus runs contrary to the prevailing consensus.

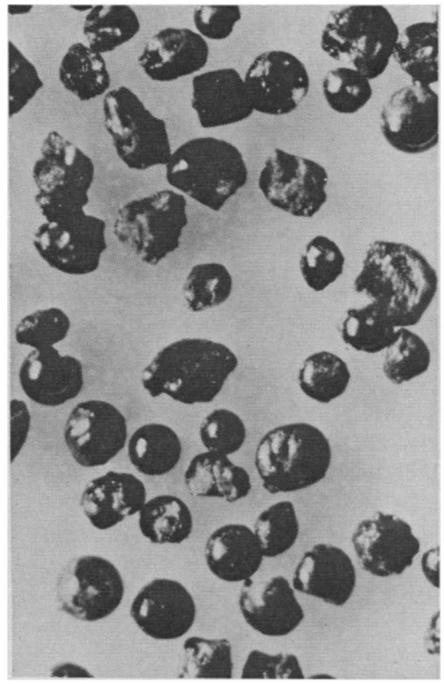

Fig. 1. Photomicrograph of glass spheres and fragments from the orange-colored soil found by the Apollo 17 astronauts. The samples shown here are in the 150- to 250-micrometer range. [Source: National Aeronautics and Space Administration]

A second hypothesis, proposed by S. K. Runcorn of the University of Newcastle-upon-Tyne and H. C. Urey of the University of California at San Diego, is that the moon became magnetized early in its history. In the form advanced at the Houston meeting by D. W. Strangeway of the National Aeronautics and Space Administration's (NASA) renamed Johnson Space Center (JSC), this model is based on the assumption that the moon's interior was initially below 780°C, the curie point of iron, and was briefly exposed to an external magnetic field as high as 20 gauss. As the magnetized moon evolved, the iron-bearing rocks near the moon's surface cooled and acquired some residual magnetism from the internal field. Later the moon's interior heated up, destroying the moon's original magnetic field, but leaving the remanent magnetism at the surface. This model agrees much more closely with the other evidence for the moon's thermal history, but the source of the magnetizing field—whether an interplanetary field of some kind or, as H. Alfvén of the University of California at San Diego has suggested, an amplified geomagnetic field—is still a matter of speculation.

The chemistry of the moon was also an enigma prior to Apollo. Data from the diverse and often complex surface materials returned from the moon have demonstrated that compared to the earth the moon is enriched in refractory elements and depleted in volatile elements. Although there is general agreement that the mare basaltic rocks were produced by internal melting, the composition and origin of the lunar highlands is more complicated. Both the samples and orbital geochemistry experiments indicate that the three most common rocks on the lunar surface are iron-rich mare basalts, plagioclase or aluminum-rich anorthosites (more than 25 percent Al_2O_3), and uranium- and thorium-rich basalts that are also enriched in potassium, rare earth elements, and phosphorus (KREEP basalts, with 15 to 20 percent Al_2O_3). A fourth major rock type proposed by P. W. Gast of JSC is a class of very high aluminum (VHA) materials (20 to 25 percent Al_2O_3) that may represent basalts (Fig. 2). In addition to their bulk composition, the pattern of rare earths varies greatly from one rock type to another—a characteristic depletion of europium in the KREEP and VHA basalts, for example, as compared to mare basalts. Unambiguous explanations for the chemical and mineralogical properties of most of these rocks are not yet available. The distribution of these rocks on the lunar surface—in particular the concentration of KREEP basalts around Mare Imbrium—is also very baffling.

Despite the petrological puzzles of the major rock types and the variety of minor rock types found on the moon, the preponderance of evidence is that the outer parts of the moon were formed by igneous processes and then modified by the effects of massive bombardment with meteorites. Major collisions such as those that resulted in the mare craters are thought to have had ample kinetic energy to melt large quantities of surface rock. According to Gast, the combined thermal and mechanical effects of the moon's collisional history have largely obliterated the structural and textural characteristics of the ancient lunar rocks. From their chemistry, however, he believes that early melting of the outer surface of the moon led to the formation of an anorthositic crust and that all subsequent magmatic activity was the result of internal melting caused by radioactive heating—a model that accords well with the physical evidence. A consequence of the model, however, is that the moon was chemically zoned in its original state—rich in calcium and aluminum in its outer layer and richer in iron in deeper layers. Because of the implications for the process by which the moon was formed, not everyone agrees with the concept of an initially heterogeneous, largely cold moon.

There is also disagreement about the processes that led to formation of highland rocks. The evidence from Apollo 16 seems to indicate that the Cayley formation, earlier thought to be an example of highlands volcanism, is a breccia deposit—rocks composed of previously crystallized fragments that have been shocked and transformed by meteorite impacts. The lesson, according to N. Hinners of NASA, is that impact processes are capable of yielding materials whose surface morphology looks like that of volcanic terrains. As a result, new emphasis is being given to the study of breccias, whose complex history makes their ages and origins difficult to unravel, and to the chemistry of impact processes.

The bombardment of the lunar surface by projectiles as large as tens of kilometers in diameter has also apparently had the effect of resetting the isotopic clocks used to determine the absolute age of rocks in most of the samples brought back so far. Thus the chronology of lunar events, particularly the filling of the mare basins, is reasonably well determined up to about 4.0 billion years ago, but is unknown between that date and the formation of the moon perhaps 600 million years earlier. Dates obtained by the group headed by G. J. Wasserburg of the California Institute of Technology for highland rocks from several different locations on the moon (including data from Luna 20) all seem to indicate that the rocks have been formed or have undergone metamorphic changes around 3.95 billion years ago. Because his dates cluster so narrowly around 3.9 to 4.0 billion years, Wasserburg proposes that the moon underwent a major cataclysm at this time. An alternative hypothesis is that the number of impacts was so high as to steadily reset the isotopic clocks throughout the moon's early history. The impact which formed the huge Imbrium basin is thought to have occurred about 4.0 billion years ago and may have been enough of a super-impact to scatter a blanket of debris over much of the moon, or the cataclysm may have been a series of events which terminated very abruptly about 3.9 billion years ago. In either case the collisions must have been, as Wasserburg put it, "one hell of a good show."

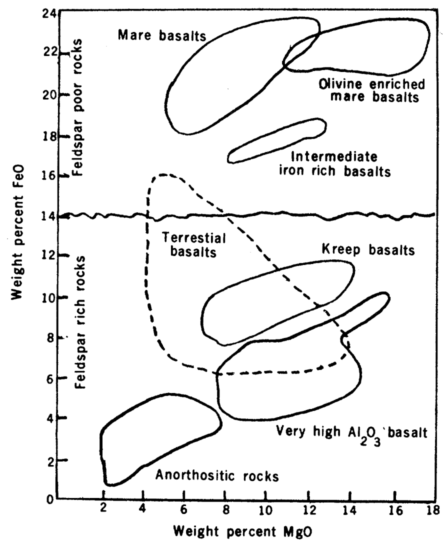

Fig. 2. Iron oxide, magnesium oxide, and aluminum oxide content of different lunar rock types. [Source: Paul Gast, Johnson Space Center, Houston, Texas]

Not everyone agrees with the Wasserberg hypothesis, and there was controversy at the Houston meeting over dates of about 4.2 billion years reported for some breccia fragments from Apollo 16 by L. Husain and his colleagues at the State University of New York at Stony Brook. If these earlier dates are confirmed, the rocks would antedate the hypothesized cataclysm. Other investigators such as C. Meyer, Jr., of JSC believe that the Imbrium impact may have occurred much earlier than 4.0 billion years ago. Meyer put forward the hypothesis that the distribution of KREEP basalts on the lunar surface may be explainable as an ejecta pattern of material formed in the Imbrium basin and scattered by later impacts, if the Imbrium impact itself occurred about 4.4 billion years ago. But the cataclysm hypothesis clearly seemed to be the favorite of most investigators.

Wasserburg also believes that no significant amount of volcanism occurred on the lunar surface after 3.1 billion years ago, when the youngest mare are believed to have been formed. This view, held by many sample analysts, contrasts with the view of those investigators who study the orbital lunar photographs and who have attempted to apply the traditional methods of field geology to the moon. The debate centers around dark deposits on the lunar surface that seem to form a mantle over or cover large areas of the preexisting topography. According to F. El-Baz of the Smithsonian Institution in Washington, D.C., these deposits are probably volcanic and as recent as 2.5 billion years ago. But if this material was sampled at the Apollo 17 site, it has not yet turned up among the soils that have been dated, and many lunar scientists are consequently inclined to be skeptical of photogeological interpretations.

One of the more interesting models of lunar evolution presented at the Houston conference was that described by D. L. Anderson of Caltech. He proposes that, as the earth and moon from the solar nebula, the larger and earlier-formed body grew at a more rapid rate and trapped more of the late condensing, volatile elements. Hence the refractory-rich composition of the moon is a consequence of its delayed condensation and of its subsequent competition with the earth, in this model. The high temperatures at which most of the moon would have condensed and the high concentration of radioactive elements might lead to early and extensive geochemical differentiation. Among the consequences of the model is that the deep interior of the moon is virtually barren of iron. The model is thus consistent with those explanations for the moon's remanent magnetism that do not require a molten iron core. However, D. H. Green of the Australian National University in Canberra finds that Anderson's model implies a lunar interior more dense than it is thought to be.

Understanding of how the moon was formed is still evolving, and at a rapid pace. Renewed emphasis on the study of brecciated rocks as the key to the surface history may help to clear up a number of unresolved puzzles such as why the soils on the lunar surface appear to be so much older than the rocks from which they presumably came. Where the meteorites or moonlets that caused the lunar cataclysm came from is also unknown. The answers to these and other outstanding questions may with luck yet be found among the nearly 400 kilograms of lunar samples that, in the view of lunar scientists, amount to a treasure house of incalculable scientific worth. What they hope to gain from the Apollo legacy is not only insight into the origins of the moon, but of the earth and the solar systems as well.

—Allen L. Hammond