study, which will not be funded after this year, was a computer analysis of language use in British Parliamentary speeches and in German Reichstag speeches in the period before World War I, to test "a lateral pressure model for the path to war." The study has been ongoing since the early 1960's. However, the principal investigator, R. North, commented to SWOPSI of his work, "Most government people either could not or would not understand it."

Finally, the students uncovered an administrative decision, made in the wake of the Mansfield amendment, by which the scientists were relieved of giving their projects military-sounding titles, or writing about potential military applications. The report quotes Secretary of Defense Melvin R. Laird in congressional testimony as having said in March of 1970:

> I am going to recommend that we don't make the university scientists certify that any DOD-supported university research has a defense related outcome. . . . In their project report, in their request for a grant, I considered seriously requiring them to do that . . . [but] I hope we can avoid making it necessary for project applicants . . . to include a statement.

Why is DOD reluctant to require scientists to come forward and state military uses of their work? Laird explained that it might cause DOD to lose top scientific talent and research. In an interview, Edward Reilley, assistant director of Defense Research and Engineering, said it would "advertise" DOD's weaknesses. "we don't believe it's possible for any faculty member to be versed in DOD's needs." As for faculty who seek support from DOD telling their campus constituency that their work has no military uses, Reilley saw no need to "punish" those "few" by requiring a statement. Whether a "few" of the faculty at Stanford need their knuckles rapped, however, is a relatively minor matter. The main point is that DOD now exempts all scientists from grappling with the key moral issue of the uses to which their research results will be put.—DEBORAH SHAPLEY

RESEARCH NEWS

Lunar Research: No Agreement on Evolutionary Models

New and in some instances surprising results from experiments on Apollo 14 and 15 and on the U.S.S.R.'s Luna 16 were presented at the third lunar science conference a few weeks ago, and interpretations of the data provided additional perspective on the earlier findings from Apollo 11 and 12. In comparison with earlier conferences, a far more comprehensive picture of the moon but far fewer claims to understand how the moon evolved were evident. Independent evidence from several types of experiments indicates that the moon is now a relatively cold and inactive planetoid, but that it has had a complex thermal history. There is an apparent conflict between geochemical evidence that suggests an initially cold moon in which partial melting of its outer layers took place and magnetic evidence that seems to indicate an initially hot moon with a molten core during the early part of its history. Other observations were also puzzling to investigators, such as the indication that radioactive materials, at least on the moon's surface, are concentrated in one area, and evidence of an unexpectedly high heat flux from the moon's interior at the Apollo 15 site. Not so puzzling, but still unexpected, is seismic evidence that the moon has a layered crust some 65 kilometers in thickness.

The moon is thought to have originated about 4.6 billion years ago, at the time of formation of the earth, of meteorites, and presumably of the solar system itself. Although speculations that the moon fissioned from the earth or formed elsewhere and then was captured by the earth have not been ruled out, most lunar scientists believe that the moon was formed by the accretion of planetesimals orbiting the earth and of other space debris. Most of the moon's thermal and geophysical activity appears to have been confined to the first 1.5 billion years of its history. Within this period, two major phases of thermal evolution have been identified: (i) widespread melting that apparently occurred about the time of the moon's formation; and (ii) partial melting beginning perhaps as early as 4.1 billion years ago to form basalts enriched in potassium, rare earth elements, and phosphorus (KREEP basalts), and somewhat later, flooding of preexisting basins with lava to form the lunar maria between 3.1 and 3.7 billion years ago. Since the formation of the maria, however, the internal heat engine of the moon appears to have shut off, stopping further internal evolution and leaving the moon a slowly cooling and largely inactive body.

Geochemists and petrologists have now studied samples of lunar soil and rocks from five different locations on the moon (see Fig. 1). In addition to the detailed information available from the Apollo and Luna 16 samples, more systematic studies of the composition of the lunar surface were carried out from lunar orbit on Apollo 15. A team headed by I. Adler, of Goddard Space Flight Center in Maryland, used an x-ray spectrometer to determine concentrations of aluminum, silicon, and magnesium. Spectrometer measurements of the fluorescent x-rays produced by the interaction of solar x-rays with the moon's surface showed distinct patterns in the composition of the surface materials. The maria were found to have relatively low ratios of Al to Si, as do the samples of mare basalt returned from the surface; but the highlands of the moon showed high Al/Si ratios characteristic of plagioclase-rich materials. The concentration patterns correlated well, for the most part, with measurements of the amount of light reflected from the surface—the brighter, high albedo regions corresponding to the aluminum-rich highlands and the darker regions with the maria.

The region around the Imbrium basin (see Fig. 1), however, appears to have some unusual features. Observations of the gamma rays given off by radioactive materials showed much higher concentrations of uranium, thorium, and potassium in Mare Imbrium and in the neighboring lava flows of Oceanus Procellarum than elsewhere on the moon. The observations were made from lunar orbit, and the flight path of the Apollo 15 spacecraft allowed about 15 percent of the moon's surface to be mapped. The results of the experiment, conducted by a team headed by James Arnold, of the University of California at San Diego, indicate concentrations of about 10 parts per million of thorium in the Mare Imbrium soil, compared with 1 to ppm in the eastern part of the moon. The high concentrations of radioactive elements in the Imbrium region are similar to concentrations found in KREEP basalts, which were found in large quantities at the Apollo 14 landing site. This material has also been found, in smaller quantities, at all the landing sites, but why the Imbrium and Procellarum regions should be the overwhelming source of the radioactive elements on the moon's surface, as they appear to be, has been difficult for geochemists to explain.

Nonetheless the chemical evidence from the analysis of hundreds of returned samples and from the orbital experiments seem to indicate that the surface composition of the moon has three major components and that the surface materials are derived from three main rock types formed at different times and, possibly, at different places within the moon. The youngest rock types are the iron-rich mare basalts formed between 3.1 and 3.7 billion years ago. The older materials include the highly radioactive KREEP basalts and, characteristic of the highlands and possibly of the original lunar surface, the class of rocks (such as anorthositic gabbros) that are plagioclase-rich, high in aluminum, and low in iron and rare earth elements.

The processes that led to the chemical differentiation of the moon and hence to the existence of rocks with markedly different compositions are not completely understood. Nor is the thermal history of the moon, and hence the conditions under which the rocks formed, very well known, although experiments have convinced many petrologists that partial melting of the moon's interior has occurred. One model put forward by Paul Gast of the Manned Spacecraft Center in Houston and R. McConnell, of Earth Sciences Research, Inc., in Cambridge, Massachusetts, assumes that the moon was initially heterogeneous in its chemical composition, with layers of different materials having been formed as a result of the manner in which the moon accreted. The plagioclase-rich rocks were formed first, according to this model, from the molten outermost layer

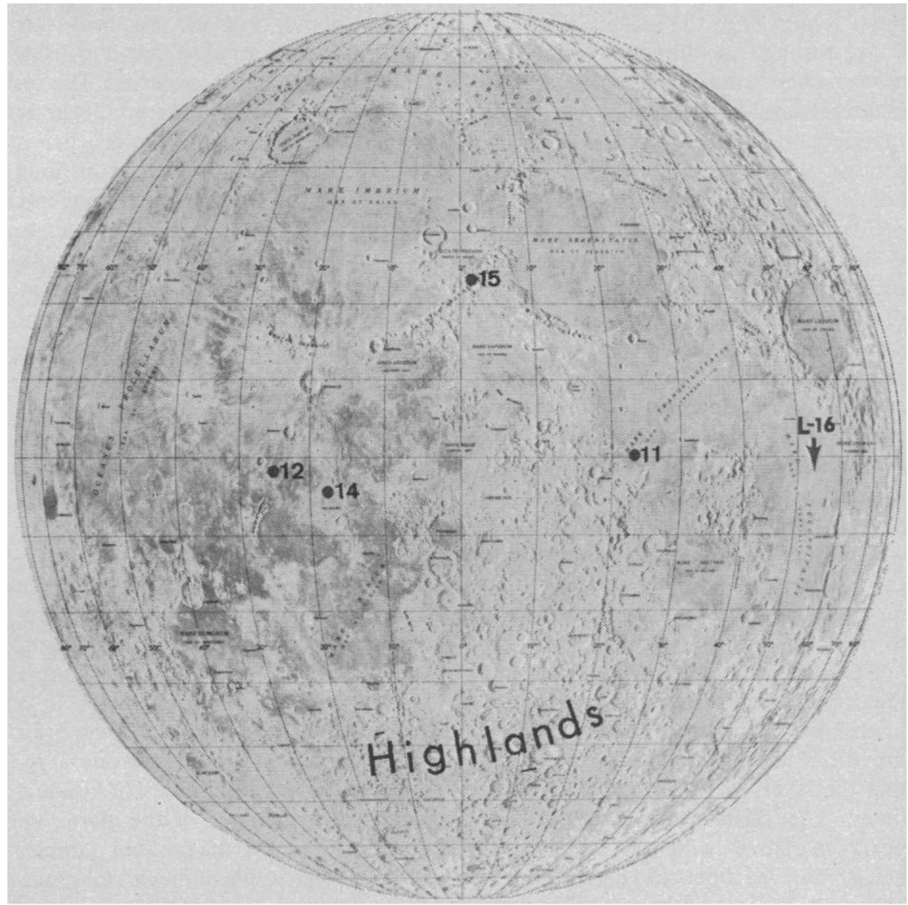

Fig. 1. Near side of the moon indicating the highlands, major maria, and landing sites for Apollo 11, 12, 14, 15, and for Luna 16. [National Aeronautics and Space Administration]

of the moon and the remnant of this material—since much of this original rock has presumably been shattered and fragmented by the meteoroid impact—constitutes most of the moon's highlands. Then, Gast believes, partial melting of the moon's solid interior continued at greater and greater depths, producing at first the KREEP basalts, which may have been brought to the surface following the impact of the projectile that created the Imbrium crater about 4.0 billion years ago. Still later, and in a deeper, iron-rich layer, the basalts characteristic of the moon's maria were formed, according to this model.

Other models of the moon's thermal history have been proposed, and there is disagreement about some of the interpretations of the petrological data. But most of the geochemical evidence seems to support the idea that the moon's constituents evolved through a series of partial melting incidents and that the moon's interior was never completely molten. The geophysical evidence, however, is more contradictory.

Some indirect information about the structure and properties of the lunar interior comes from seismic experiments on the lunar surface. Three seismometers are now in operation, allowing the location of moonquakes to be determined. Naturally occurring quakes on the moon are weak and relatively infrequent, however, and the rate of seismic energy release is about 1 million times less than that on Earth; the low rate implies, for example, that internal convective motions are not occurring. Moonquakes appear to be released periodically by tidal stresses, according to Gary Latham, of Lamont-Doherty Geological Observatory in New York and others; 80 percent of the energy release has occurred at one location, approximately 800 km deep, during the period studied. The seismic evidence thus indicates that the interior at these depths is rigid enough to support considerable stress and that the outer shell of the moon is relatively cold and rigid compared to the earth.

In addition to naturally occurring seismic events, six artificial events caused by the impact of spent Saturn rocket stages and lunar modules on the moon have been analyzed by a team headed by Nafi Toksoz, of the Massachusetts Institute of Technology. The times required for the seismic signals to travel through the upper layers of the moon, when combined with laboratory measurements of seismic velocities in lunar rocks, indicate that the moon has a crust about 65 km thick with sharp boundaries, at least in the Fra Mauro region. The upper 1 to 2 km appear to be composed of broken rocks and rock fragments. Below this, to a depth of about 25 km, the sound velocity appears to be similar to that in mare basalts. A second, deeper layer of the crust extending down to 65 km appears to be of different composition, with higher seismic velocities similar to those measured in plagioclase-rich materials. Seismic velocities below the crust, in what would correspond to the mantle of the moon, are still higher and seemingly do not correspond, according to Toksoz, to common rocks.

The existence of a layered crust and the apparent differences in composition in the two layers are evidence that the moon has undergone differentiation and that the layers were formed at different times. The seismic evidence thus appears to agree with the hypotheses, based on geochemical data, that a moonwide crust was formed from early melting of an aluminum-rich material and that this original crust was partially covered by the outpouring of lavas which formed the maria.

Improved measurements of the moon's gravitational field obtained by radio tracking of the Apollo 15 spacecraft also suggest that a rigid crust was present at the time the maria were formed. Simulations with theoretical models of the mascons (or gravity anomalies that are located near some of the smaller maria) by a group headed by W. Sjogren of the Jet Propulsion Laboratory in Pasadena indicates that the anomalies are due to a surface disk of material that is denser than the surrounding crust—rather than to a buried spherical mass. One interpretation of the finding is that the mascons were formed as the mare lavas cooled, contracted, and became more dense, but did not settle (in the smaller maria) because of the strength of the underlying original crust.

Other observations do not fit in with the geochemical hypotheses as nicely, however. Measurements of the temperature gradient and the thermal conductivity in soil at the Apollo 15 site by M. Langseth, of the Lamont-Doherty Geological Observatory, and his colleagues indicate a heat flux from the moon of 3.3 microwatts per square centimeter (about half of the heat flux from the earth), a value that is considerably higher than was expected. The result is also higher than that predicted by thermal calculations based on geochemical models of the moon's interior, and, if sustained by further measurements on Apollo 16 and 17, it might lead to a revision in esttimates of the amount of radioactive materials (whose decay is thought to be the heat source) present within the moon.

A Magnetic Field for the Moon?

Even more disturbing to many geochemists is evidence that the moon had a magnetic field, and hence presumably a molten iron core, throughout most of its first 1.5 billion years. Residual magnetism has been found in many of the lunar rock samples. In an experiment conducted by Paul Coleman and his colleagues at the University of California in Los Angeles, a magnetometer in a small satellite launched into lunar orbit by the Apollo 15 crew has now recorded measurable amounts of residual magnetism over much of the moon, an indication that the magnetized samples are not isolated phenomena. Coleman believes that the residual field is due to a magnetized crust, which would imply that the moon was immersed in strong magnetic field at the time that the crust was formed.

Neither the magnetic field associated with the solar nebula nor the dipole magnetic field of the earth, according to S. Runcorn of the University of Newcastle-upon-Tyne in England, could have magnetized the moon's crust because of the orientation of the field in the solar wind and the length of period during which the moon would have had to be very close to the earth. Hence, Runcorn concludes, no external field could have produced the residual magnetism, and the moon must have had an internal field from its early moments until some time later than 3.1 billion years ago (when the youngest mare samples were formed—thus the last date for which evidence of rocks formed in a magnetic field is available). As far as is known, planetary magnetic fields are generated by dynamos resulting from convection in a molten iron core. If the moon has a small iron core (an iron core larger than about 0.2 lunar radii is ruled out by the moon's known mass and amount of inertia) and the core was at one time molten, the temperature, at least in the moon's core, must have been much higher than projected in geochemical models of the moon's thermal history. Runcorn believes that the moon's deep interior was initially quite hot and that the convective process—which is a more effective means of transporting heat than the conduction that would occur in a solid core—cooled the moon rapidly to the point where convection could no longer take place, thus turning off the magnetic field.

The magnetic evidence therefore leads to a picture of the moon's evolution that conflicts with models based on geochemical considerations. It is still not known, for example, whether if the moon's core were molten during the early part of the moon's history, the outer layers could have remained cool enough so that only partial melting took place.

Other significant questions, in addition to the debate about whether the moon's interior was initially hot or cold, are also receiving new attention. More details of the lunar chronology, such as the date of formation of the Imbrium basin about 4.0 billion years ago and of the Copernicus crater only 900 million years ago, have been determined. It also appears that, because of the initially high rate of meteoroid impacts on the moon, very little if any of the original crustal rocks have survived—all the rocks examined so far seem to have been formed or recrystallized between 4.0 and 3.1 billion years ago. But some of the Apollo 14 samples have been found to contain xenon, presumably from the decay of plutonium-244—a short-lived isotope—evidence that some very old rocks must exist. The chemistry of the lunar samples is also proving to be far from easy—the possibility that volatile elements have migrated on the lunar surface, for example, is complicating the analysis of trace constituents.

Despite these complications, the scientific understanding of the moon is much further advanced than was the case even a year ago. The systematic coverage of the moon's surface provided by the orbital experiments on Apollo 15, in combination with the lunar samples, laboratory work, and the experiments on the lunar surface have provided new data to replace what sometimes proved to be unfounded speculations. Far from being a cold and inactive body that has passively recorded the history of the solar system, the moon turns out to have had a complex history of its own, a history that, like the earth's, is still to be finally told.

—ALLEN L. HAMMOND