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A CLOSER LOOK AT LUNAR VOLCANISM

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Abstract - Although the American Apollo and Soviet Luna missions concentrated on mare basalt samples, major questions remain about lunar volcanism. Lunar field work will be indispensible for resolving the scientific questions about ages, compositions, and eruption processes of lunar volcanism. From a utilitarian standpoint, a better knowledge of lunar volcanism will also yield profitable returns in lunar base construction (e.g., exploitation of rille or lava-tube structures) and in access to materials such as volatile elements, pure glass, or ilmenite for lunar industry.

INTRODUCTION

Volcanism is a fundamental planetary process. Lavas probably flowed across Mercury's lunar-like surface, erupted to build huge shield volcanoes on Mars, and even oozed across the surfaces of some asteroids. Glowing lavas still make their way to the surfaces of Earth, Jupiter's satellite Io, and probably Venus too. A major part of the Moon's landscape was formed by basaltic lava flows which now constitute the dark areas called maria.

But volcanism is much more than a surface process. Lavas originate inside a planet when rocks undergo partial melting. Consequently, lavas serve as probes of the mineralogy and chemical composition of otherwise inaccessible planetary interiors. Much of the research done on samples of lunar basalts has been geared to understanding the nature of their source regions in the Moon's mantle, the origin of these materials, and their vertical and lateral heterogeneity. Many of these mantle rocks crystallized from a gigantic magma system encompassing most of the Moon soon after it formed. Some lunar scientists have called this magma system the lunar "magma ocean" (Wood, 1975). Thus, understanding lunar basalts sheds light on the chemical composition of that "ocean." Basalts also contain information about a planet's thermal history. Did it form cold and heat up? Did it form hot and then cool? Did it heat up, cool, and then heat up again? Information about the Moon's origin and evolution is tied up in its thermal history, and lunar basalts contain much of the record. So, although covering only 17% of the Moon's surface and constituting a tiny 1% of its crustal volume (Head, 1976), mare basalts contain significant information about the Moon's history.

Basalts of the lunar maria contrast with the light-colored highlands areas that are so strikingly visible when one looks at the Moon. However, basalts of the lunar highlands have also been speculated upon and do occur but only a few small samples have been found within impact-generated breccias. It is important, however, to point out that the concept of "highland volcanism" may stretch the limits of our previous conceptions of what volcanism is.

The term "volcanism" implies eruption of a melt derived from solid material at depth. It has been suggested that some very old volcanic rocks on the Moon could be liquid remnants of the very large magma system ("magma ocean") that enveloped the Moon at some time prior to 4.4 billion years ago (Wood, 1975). This is one explanation for the occurrence of lunar magmatic compositions that are rich in the otherwise rare elements potassium, rare earths, and phosphorus (immortalized in the acronym "KREEP"). Such an origin, as a result of crustal cooling, is very different from volcanism caused by deep internal heating. There is also a possibility that some lavas could have been brought to the surface by impact excavation of crustal magma chambers (Schultz and Spudis, 1979). Although there is a slight semantic problem in calling such lavas "volcanic" it is intriguing to consider the chances of finding these rocks on the Moon, since comparable lavas have not been preserved on Earth.

Because of these conceptual problems with highland volcanism, the rest of this paper will deal solely with what we can hope to gain from a closer look at mare volcanism. We hasten to point out, however, that this restriction reflects our relative ignorance of lunar volcanism and the great deal that remains to be learned.

THE AGE AND EXTENT OF LUNAR VOLCANISM

Mare-flooding basalts that have been dated range from 3.8 to 3.1 billion years (b.y.) old. Clasts of mare basalts within breccias extend the time of such volcanism back to 4.2 b.y. (Taylor et al., 1983). Conversely, volcanic rocks younger than 3.1 b.y. have not been found among the lunar samples but photogeologic and remote sensing studies suggest that there are high-titanium basaltic lavas as young as 2.5 b.y. (Head, 1976) or younger (Boyce et al., 1974). The answers to several important questions concerning lunar history are tied to the resolution of how old, how young, and how much volcanism occurred.

The oldest lunar volcanism may be difficult to define because of the widespread impact disruption of samples older than 3.9 b.y. Model isotopic ages derived from lunar basalts indicate that the source regions for magma production were established at 4.4 b.y.; the Moon may eventually provide volcanic rocks as old as this, or we may even find "pseudovolcanic" residual liquids that predate these source regions. It is encouraging that, even with our limited sampling of the Moon, we have obtained volcanic rocks that are almost as old as the process of planetary differentiation. There is a real possibility that more detailed sampling might provide a map of chemical compositions and times of eruption that will record the ancient separation of lunar crust and mantle. From the experience we have had so far, it appears that the best place to look is within soils and breccias where small volcanic clasts occur. The oldest breccias exposed deep within the walls of large basins should provide useful samples of these rocks.

The youngest lunar volcanism should be much easier to find, for these rocks will be the least impact-disrupted of lunar surface materials. Photogeologic and remote sensing studies have already pointed to volcanic flows in Mare Imbrium that may be as young as 2.5 b.y. (Schaber, 1973) or younger (Boyce et al., 1974). Spectral data indicate that these flows consist of high-titanium basalt (Pieters et al., 1974; Basaltic Volcanism Study Project, Chapter 8, 1981), an interesting observation when it is considered that high-titanium basalts are also among the older (3.6 - 3.8 b.y.) radiometrically dated samples from lunar mare. A closer look at the age-composition progression among mare basalt samples may reveal a complex lunar mantle history that goes far beyond single-event melting of differing mantle source regions. The history of lunar interior melting will also be an important parameter for determining lunar cooling history and the inventory of heat-producing radioactive elements in the lunar interior.

The volume of volcanic rocks on the Moon and the variation of eruption rates through time are important parameters for determining the coupled history of lunar heat transfer and mantle evolution. A recent speculative summary of lunar eruption rates over time (Basaltic Volcanism Study Project, Chapter 8, 1981) proposes two extreme scenarios: (1) very little volcanism prior to 3.9 b.y. or (2) abundant volcanism prior to 3.9 b.y. The total volume of volcanic rocks estimated for these two scenarios differ by a factor of about two; around 10^7 km^3 with minimal early volcanism and about 2×10^7 km^3 with abundant early volcanism. The difference in implications for lunar evolution, however, is greater because planetary evolution models that delay major heating of mantle sources for the basalts until about 4.0 b.y. ago must differ radically from models of high initial heat that peaked at the time that the mantle source regions formed (~4.4 b.y.) and decayed steadily thereafter. The resolution of this question lies in the discovery of how much old volcanic material underlies the highlands. Dark-haloed craters in the highlands have been pointed out as promising sites for such an investigation because they expose low-albedo basaltic materials that apparently underlie the high-albedo (non basaltic) highlands debris (Schultz and Spudis, 1979). The dark-haloed craters are excellent examples of a type of lunar deposit that has not yet been sampled, but where a closer look is vital to our understanding of the Moon.

COMPOSITIONAL RANGES OF LUNAR MARE BASALTS

The presently available samples of lunar basalts have been studied in great detail, though not yet exhaustively. Data from these samples show that mare basalts fall into three main categories, based on their content of TiO_2: high-Ti (8.5 to 13.0 wt.% TiO_2), low-Ti (2 to 5 wt.%), and very-low Ti (<1 wt.%). In addition, some low-Ti basalts are enriched in Al_2O_3 and are called aluminous mare basalts. However, data from remote sensing indicate that there are at least twenty different types of mare basalts. Moreover, as discussed below, our present collection of lunar basalts may not represent the full variety of lava types present at a given site. For reviews of mare basalt chemical and mineralogical compositions see Papike et al. (1976), chapter 1.2.9 in the Basaltic Volcanism Study Project (1981), and chapter six in S. R. Taylor (1982).

Sample analyses, geochemical calculations, and experiments at high temperatures and pressures suggest that most mare basalts formed by remelting of deep rocks (at 100 - 150 km) that had originally formed from the "magma ocean." We do not know, however, how much assimilation of surrounding rock and how much fractional crystallization took place as the basaltic magmas migrated to the lunar surface and then flowed across it. Both these processes affect conclusions about the nature and origin of the mantle source rocks.

In this section we outline what is needed for a better sampling of lunar basalts, both across the lunar globe and at any given locality, and for a better understanding of processes such as assimilation and fractional crystallization.

Sampling the full range of basalt types

Based on analyses of lunar samples, mare basalts seem to be quantized with respect to a number of chemical discriminants. Extremes of TiO_2 content have been recognized, but remote sensing data obtained by telescopic observations of the Moon and by gamma-ray and x-ray fluorescence experiments flown on the Apollo 15 and 16 command modules indicate that a full range of intermediate TiO_2 contents might be present among mare basalts. Moreover, a detailed analysis of spectral properties, summarized in chapter four of the Basaltic Volcanism Study Project (1981), suggest that the Apollo and Luna missions have sampled a mere one-third of the basalt types exposed on the earth-facing side of the Moon. A map of known, similar-to-known, and unknown basalt types based on this study is shown in Fig. 1. Figure 1 also summarizes some of the data from remote sensing using three of the critical signals used for this map: TiO_2 content, aluminum-to-silicon ratios, and K_2O content. An important feature shown in Fig. 1 is that the remote sensing data actually map the soils on top of the mare, and when we compare the soils with actual underlying basalt samples the match is not good. Clearly we have much to learn about lunar basalts. Consequently, future lunar expeditions must sample all types of mare basalts that remote sensing data suggest are present beneath the veil of soil. A major prerequisite for doing this sampling intelligently is a more thorough photographic and spectral coverage of the Moon. This coverage can be obtained from an unmanned polar-orbiting lunar mission such as those tentatively planned by the United States or by Japan.

Sampling problems at a given site

When working on Earth, geologists take great pains to collect samples from discernible rock units (e.g. from a single lava flow). No lunar basalt was collected in this manner. All were pieces of rock chipped loose by impacts and strewn about on the surface. As a result, we do not know how many individual lava flows were sampled at each landing site. We can guess from chemical and mineralogical data, but we have no definitive field data relating one basalt sample to another. Considering that the chemical variability among some suites of mare basalts is comparable to that observed in single terrestrial lava flows (Haskin et al., 1977), it appears that we have scarcely sampled the lunar maria at all.

Good sampling requires thorough field work. Samples must be taken from identifiable rock units. Such rocks are exposed in the walls of rilles and craters. Reaching them will be a technological (and possibly physiological) challenge. At this time, we have visited only two sites where the volcanic deposits were only slightly disturbed: (1) the edge of Hadley Rille where a basalt flow was exposed (Apollo 15 site, Fig. 1) and (2) an overturned section of pyroclastic rocks within a crater rim in the Valley of Taurus Littrow (Apollo 17 site, Fig. 1). Where such features are not exposed, samples can be obtained by drilling or by digging deep, wide trenches in the lunar surface. Sampling strategies are discussed in more detail by Korotev (1984).

Lateral variations in single flows

Mare basalt lavas were much more fluid than terrestrial basalts (Murase and McBirney, 1970) and so flowed easily across the Moon's surface. As they flowed, it is quite likely that they crystallized and their heavier crystals concentrated near the flow bottoms. How much crystallization took place before a given flow reached an area sampled by an Apollo or Luna mission is anyone's guess, but it seems probable that some did. It is also possible that as lavas flowed across the Moon they reacted with the underlying regolith, assimilating a variety of chemical components. As a result few if any of the basalts returned to us are unmodified by surface processes. None, therefore, is likely to be a "primary magma," one that retained its chemical integrity from its origin inside the Moon until its sampling billions of years later. This is especially true if crystallization and assimilation took place inside the Moon before the lavas erupted.

It is difficult to obtain field data about processes operating inside a planet, but we can test the extent to which lavas crystallized or reacted as they flowed on the surface. Mapped flows could be sampled where they emerged (vents) and at intervals to their distal ends. It is possible that deposits of heavy minerals, including potentially valuable ones like ilmenite ($FeTiO_3$), could be found by this type of exploration.

LUNAR VOLCANIC PROCESSES

Carefully documented stratigraphic studies of igneous rocks on the Moon will provide information on its thermal history and on the filling of the mare basins. To understand lunar volcanic processes, we must understand the mare basins where eruptive features are best preserved. It is important to find and study the following mare features and the processes that formed them:

(1) Dikes: determine dike locations, orientations, and ages to study the migration of dike systems as the basins filled.

(2) Products of explosive volcanism: determine the extent and means of deposition of pyroclastic deposits; find source vents for these deposits and determine their shape, location, number and size; find the lava flows that erupted contemporaneously with explosive activity.

(3) Lunar lava flows: by mapping and sampling, determine the eruption rates, sources, processes of thermal and volatile loss during flow over long distances, and mode of transport.

(4) Physiographic features interpreted as volcanoes: determine if they are volcanoes; determine whether the variety of landforms, such as domes, shields (Fig. 2), cones, and fissure mounds imply a variety of magma types and eruption processes that we have not sampled.

(5) Products of eruption processes that we have not studied on Earth: rille formation is very important on the Moon (Fig. 3) but is still one of the great mysteries that challenge the volcanologist. Are the rilles due to high eruption rates and temperatures, 1/6 g, or lack of an atmosphere? Explosive eruptions into a vacuum have been modeled and we have representative samples of their products, but we have not explored the extent and nature of these pyroclastic deposits.

This list of problems is obviously not complete, for volcanism on the Moon is very different than that on Earth. Even on Earth we have found that generalizations about volcanoes are misleading. As we study more and more terrestrial volcanoes we find that each is different. The same might be said about the Moon's volcanoes as we move through the first phases of exploration.

CONCLUSIONS: A PROGRAM OF EXPLORATION

To address some of the problems described above, the following approach could be used (summarized in Table 1). The evolution of the mare basins could be studied by visiting maria of different ages and with different levels of lava fill. A series of landings and traverses within the rings of the Orientale basin (Fig. 2) would provide an opportunity to visit shield volcanoes and fissure vents that erupted only enough lava (and ash?) to fill the bottoms of ring depressions. Studies of vent areas will test ideas concerning cold traps that may have concentrated volcanic volatile phases as sublimates in and near the fissures. Subsidence of ponded lavas may also provide information on degassing of these ponds or on backflow of lavas into vents during waning stages of the eruptions.

Visiting progressively older mare basins for field studies will eventually provide the observations and samples necessary for reconstruction of the history of lunar mare volcanism. Older highlands volcanism will be considerably more difficult to study because of intense cratering of those surfaces; reconstruction of this activity may be limited to breccia sample studies.

Another major phase of exploration will be to visit volcanic vents. Distribution of pyroclastic rocks, associated sublimates, stratigraphy of those deposits, the relation of clastic rocks and lavas, and gravity surveys will provide information on the ages, compositions, and map relations of these vents and associated rocks, as well as on their eruption mechanisms and physical properties. Deposits near vent areas may also contain xenoliths of the Moon's mantle and crust. The search for lava tubes should begin near those vents identified by photogeologic mapping. Volcanic stratigraphy and the changes in basalt composition with time may be studied in rille walls, crater walls, and, if no outcrops are visible, by coring from the mare surface. Primary sites for these studies are along basin margins such as eastern Mare Serenitatis and Mare Imbrium and in what appear to be volcanic plateaus such as the Marius Hills and the Aristarchus Plateau.

As a final note, the possible utility of lunar mare basalt materials must not be slighted. Based upon samples from the Apollo 11 and 17 sites and on some good remote sensing studies, "dark mantle" deposits of the Moon's near side appear to be glasses of volcanic origin and may serve as unique resources for some manufacturing processes Sublimates on surfaces of these glass particles, the residue of gasses extruded during explosive volcanism, may provide the best source of volatiles on the Moon (Fig. 4). In addition to their value as a lunar resource, these deposits will provide basic information on lunar explosive volcanism. Much of what we know about this subject at present is based upon theoretical models that are untested. Furthermore, close study of these deposits may shed light on the sources of volatile elements within the Moon, which has implications for theories of lunar origin (Delano, 1982). Volatile elements associated with lunar pyroclastic glasses are indicative of the combined fruits of a closer look at lunar volcanism: both utility and science may be served.

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FIGURE CAPTIONS

Fig. 1 - Nearside map of the Moon based on remote sensing studies (Basaltic Volcanism Study Project, Chapter 4, 1981) showing areas of mare basalt that have been sampled or appear similar to samples in hand, contrasted with those areas that appear to be distinctive and unknown. The two perspective plots compare three compositional parameters measured by remote sensing (K_2O, TiO_2, and Al/Si compositions) used in generating the map. The perspective plots show that the map is based on the spectral reflectance properties of surface soils that mask and distort the true underlying basalt compositions, particularly in their K_2O and Al/Si compositions.

Fig. 2 - Mare Veris, located at the base of the Rook Mountains scarp, eastern Mare Orientale. The rings of this large basin are only partly filled with lavas. Many of the basaltic volcanoes, the sources of these lava flows, are visible. In this Lunar Orbiter image, there are three lava shields (arrows); the topmost has a summit crater and the lower-right has a fissure vent crossing the shield.

Fig. 3 - Oblique photograph of Hadley Rille, eastern edge of Mare Imbrium. The rille (and the Apollo 15 landing site) lie at the base of the Apennine Mountains (bottom and right edge of the photograph). The rille begins at the cleft in lower left, traverses a lava-filled graben parallel to the Imbrium Basin, and becomes shallow, disappearing under mare lavas.

Fig. 4 - Constituents of lunar volcanic gas, based on Delano's (1982) synthesis of volatile elements correlated with lunar volcanic glasses. In abundance, sulfur predominates and has an abundance (about 0.2% in high-Ti basalts) that exceeds the sulfur abundance in most terrestrial basalts. Water and CO-CO_2 are notably deficient in lunar basalts.

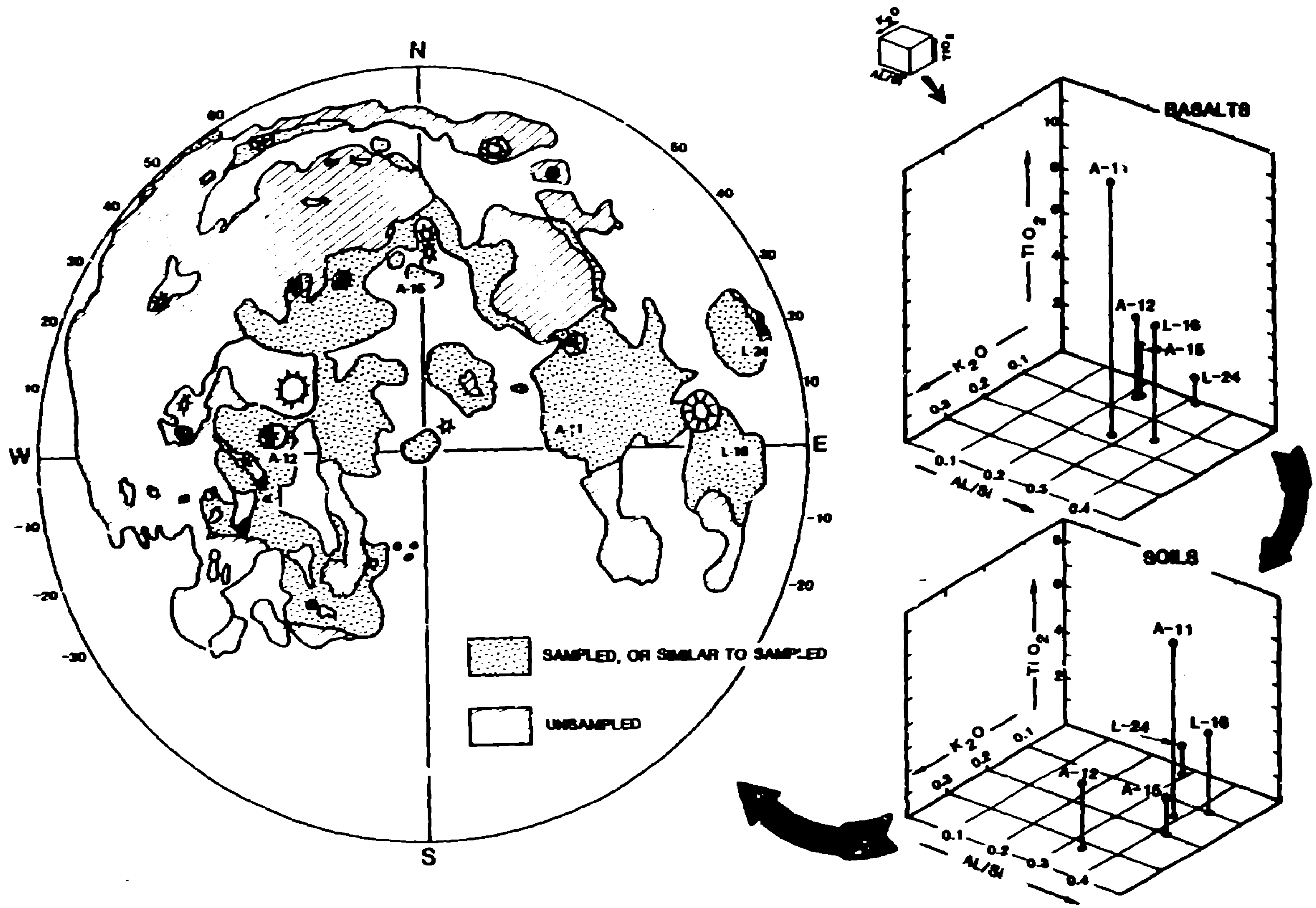
N
S
W
E
A-15
A-12
A-11
L-24
L-16
SAMPLED, OR SIMILAR TO SAMPLED
UNSAMPLED
BASALTS
SOILS
TiO_2
K_2O
AL/Si

Fig. 1

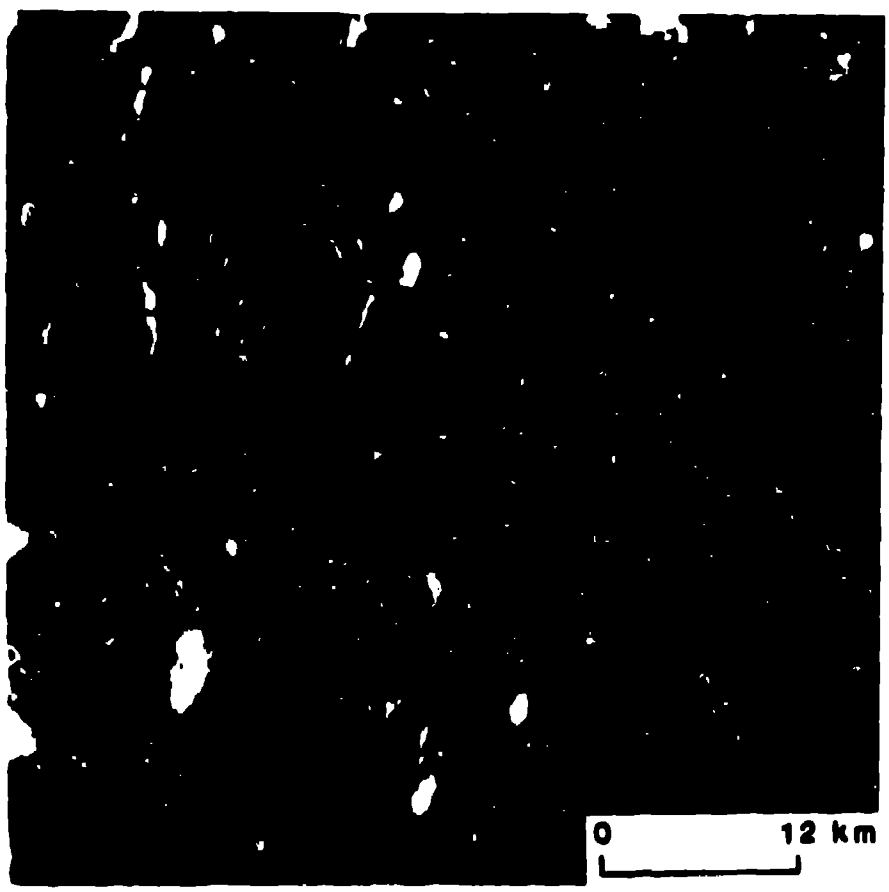

Fig. 2

Fig. 3

CONSTITUENTS OF LUNAR VOLCANIC GAS

(From Delano, 1982)

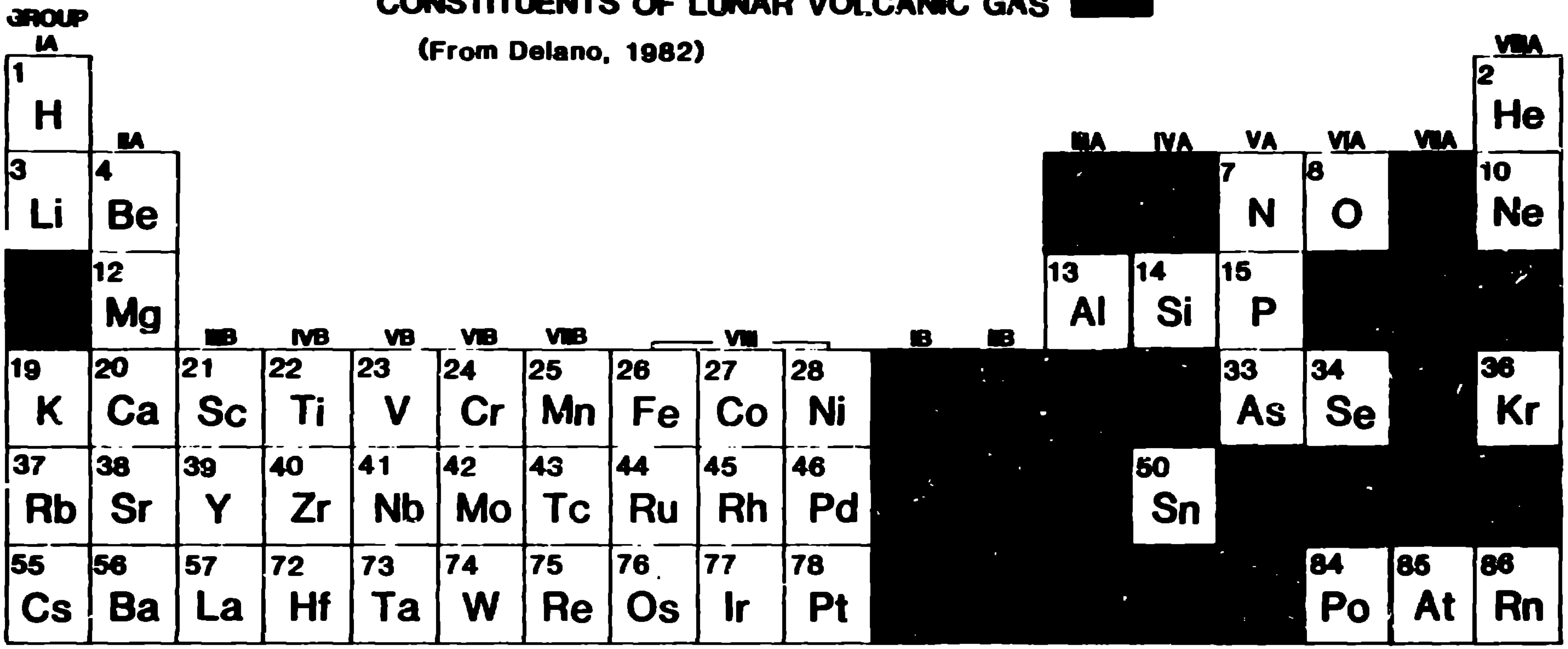

Fig. 4

Table 1: A Closer Look at Volcanological Processes on the Earth's Moon -- Summary

Processes to be Studied	Scientific Significance	Pragmatic Significance	Exploration
Filling of the maria. Eruption rates and basin structure.	a. History of lunar volcanism. b. Vent locations and relation to basin structure. c. Variations in eruption processes in stages of mare filling and lava flowback. d. Deformation of mare surfaces during filling.	a. Search for volatiles associated with vents. b. Lava tubes and rilles for structures that must be buried.	a. Visit mare basins of different ages, levels of fill, and with a variety of volcanic landforms. At each location: determine the volcanic stratigraphy in crater and rille walls or by coring. Following field studies, obtain a complete complement of laboratory studies such as age dates. petrology, chemistry. b. Begin exploration with the rings of Mare Orientale (Fig. 2).
Explosive volcanic activity.	a. Evolution of lunar magmas through time with regard to volatile phases. b. Size, shape, and extent of vents responsible for mare volcanism. c. Relations of lava flows and pyroclastic deposits. d. Dark mantle deposits - a few vents with widespread deposits or many vents with small deposits?	a. Locate concentrations of volatiles (sublimates in vent "cold-traps."). b. Major deposits of fine-grained glass for lunar resource development.	a. Visit vent areas identified. b. Map the extent and stratigraphic variations of the dark mantle deposits. Look for exposures in rilles and crater walls. c. Visit the variety of volcanic landforms seen on satellite photos of the Aristarchus Plateau and Marius Hills. d. Gravity and active seismic surveys of suspected vents.
Magma migration within the Moon	a. Rise of lunar magmas--dike formation. b. Search for mantle and crustal xenoliths.		a. Visit dike and vent localities.