GEOLOGICAL PROBLEMS IN THE LOCATION OF A LUNAR BASE

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Abstract

Geological problems in base location are: 1) subsurface structure; 2) surface characteristics; and 3) natural resources.

1) Subsurface structure should favor base location in the maria.
2) Surface topography and microtopography should not appreciably affect base location. The key surface characteristic is the nature of the lunar dust. Evidence points to a sintered dust. Confirming experiments are suggested.
3) It is suggested that large concentrations of mineral deposits, composed largely of H2O, will be found beneath rilles, chain craters and domes at maria margins.

A base location is proposed in the highlands south of the Hyginus Rille near the crater Agrippa.

Introduction

Study of the moon is fascinating for a geologist, perhaps even more fascinating than study of the earth. The basic appeal lies largely in the many lunar geological problems which are almost, but not quite, solved. Each problem requires only a few more bits of information for solution, but those bits are invariably crucial, so that the geologist continually alternates between high expectation and bitter frustration.

There are, however, plans which must be made soon for exploration of the moon, which require definite answers and predictions from geologists, with or without full information. It is, therefore, an urgent requirement that the specific problems involved in planning lunar exploration be defined, that provisional solutions to these problems be supplied as working hypotheses, and that definite experimental programs be proposed for the final solution of the
This report is concerned specifically with the geological problems involved in the location of a lunar base. The problems involved in base location are divided into three groups: 1) Those concerned with subsurface structure; 2) those concerned with surface characteristics; and 3) those concerned with natural resources.

Subsurface Structure

The subsurface structure of the maria and highlands varies, of course, according to one's theory of origin of the major lunar surface features. At this time, two main theories of the origin of these features exist, the volcanic theory and the meteoritic theory. The writer does not subscribe to the volcanic theory, and those holding this theory are presently in a minority but, considering certain discrepancies in the meteoritic theory, it would appear the height of folly to totally ignore volcanic concepts in a serious discussion.

This being the case, subsurface structures which may have resulted from a volcanic evolution will be considered first. Modern proponents of this theory (1) generally hold that lunar craters are caldera structures, produced when molten material is blown from beneath the surface, emptying a lava reservoir and fracturing the overlying rock. The overlying rock collapses into the empty chamber to produce a depression surrounded by a ring of expelled debris. The common central peaks in the lunar craters are thought to be due to subsequent ordinary volcanism, and the maria are considered examples of more widespread internal melting.

Several predictions concerning subsurface structures may be made on the basis of the volcanic theory. It is apparent that the highlands should exhibit a complex of overlapping collapse structures containing layers of pyroclastic debris (largely ash), extrusive vesicular lavas, and intrusive dikes and sills, all overlaid in many cases by the lava flows and pyroclastics of the volcanic central peaks (Fig. 1). Considering the lower lunar gravity (1/6 earth normal), very large lava caverns are probable because of the greater possible unsupported roof span. Russell (2) has described lava caverns in the Snake River Plains of Idaho, formed when a rigid crust develops over a flowing lava stream and remains as the roof of a cavern when the flow of lava recedes. The Snake River caverns are as large as 70 ft in diameter and 400 ft long, indicating the tremendous possible size of lunar lava caverns. The collapse hazard of both lava caverns and vesicular lavas would make lunar
Fig. 1. Lunar subsurface structure under the volcanic theory. Large amounts of vesicular material and fault structures present a collapse hazard. (Slightly modified from Green, J., "Geophysics as Applied to Lunar Exploration," North American Report MD 59-277, 1960, p. 96.)
operations in the highlands extremely difficult.

According to the volcanic theory, the maria would exhibit much simpler structure than the highlands. One would expect a highly vesicular surface layer, grading downward into solid lava, and disturbed only by scattered wrinkle ridges, rills, domes and late craters.

The lower lunar gravity would produce a greater thickness of vesicular material on the moon than would occur on the earth, and would also result in larger near-surface vesicles. Near zero atmospheric pressure cannot be called on, however, to produce even more extreme vesiculation, because the extensive degassing involved in the formation of craters and maria under the volcanic theory is thought to have produced a temporary, but thick, lunar atmosphere (3). Even assuming an atmospheric pressure equal to that of earth, however, the lower gravity could produce vesicles of significant size if terrestrial analogies are to be trusted. Such analogies, although always risky, appear to be the only method of obtaining some concept of vesicle size, even though it is a highly speculative concept. Shrock (4) reported that terrestrial vesicle pipes, caused by the coalescence and migration of bubbles in lava flows, range in diameter from 1/5 in. to 6 in., and may be as much as 6 ft long. It is apparent from field relations that the largest vesicle pipes are produced by steam generated in underlying wet ground or by overridden air, but these data are useful for a concept of maximum pipe size, which might well be achieved during a lunar degassing. Thus, the maximum expectable size of vesicle pipes under the lower lunar gravity would be 3 ft in diameter and 36 ft deep (six times the size of terrestrial vesicle pipes). The maximum depth of vesicular material would probably be on the order of 36 ft. Assuming a standard (Poisson) statistical distribution of vesicle sizes, the probable, as opposed to maximum, size of vesicles (pipes are generally rare) would be about 1-1/2 ft in diameter. The probable depth of vesicular material would be about 20 ft.

Lava caverns are also a possibility on the maria, although the simple circular maria are usually thought to be great lava pools rather than the product of lava flows. In this case, lava caverns are very unlikely, as the crust on a pool should rise and fall with the level of the lava beneath.

Thus, under the volcanic theory, the maria also appear to present a collapse hazard, but one which appears slightly less likely to be beyond the bounds of design compensation in lunar operations than that found in the highlands, due to a greater degree of regularity.
The second major theory of origin of the major lunar features holds that they are related directly or indirectly to high speed impact of meteorites or other external objects. The craters are thought to be the direct result of impact, although later volcanism, perhaps related to the impact, is generally called upon to produce the flat floors of some craters (5).

Under this theory, the highlands subsurface structure should consist of a highly fractured basement rock overlaid by discontinuous layers of rubble, rock flour and meteoritic material (Fig. 2). Except in the case of craters which have been subsequently filled with lava, this subsurface structure should exhibit very little collapse hazard, and would be very favorable for lunar operations from this point of view.

The subsurface structure of the maria under the meteoritic theory is very similar to that envisioned under the volcanic theory. As no general lunar degassing is called for, however, the lunar atmosphere is generally considered to be less dense, although some gas would necessarily be evolved from the molten maria. If we assume that melting of lunar material to form the maria produced the degassing of one half the volume of material degassed under the volcanic theory, then an atmospheric pressure one half that estimated under the volcanic theory is reasonable. Thus, if no other factors were involved, near surface cavities could double to reach a maximum of 6 ft in diameter, but the depth of the vesicular layer would increase by only about 12 percent due to the continued lithostatic pressure of the overlying material. A maximum depth for the vesicular layer would probably be about 40 ft. Again, the probable dimensions would be about one half the maximum figures.

It is apparent that the collapse hazard presented by the maria under the meteoritic theory make them less favorable than the stable highlands for the location of a lunar base from a subsurface structure point of view.

Having obtained concepts of lunar subsurface structure from theoretical considerations, it is important to inquire into any evidence which might be present on the moon to support these concepts.

That there is some difference between the structural characteristics of the maria and highlands is indicated by study of the ray craters. Continental ray craters show a strong dependence of the length of their rays on the diameter of the crater, but maria ray craters do not (6). Also, more ray craters are found on the maria than on the continents (ratio 3:1), whereas, considering relative areas, the ratio should be 1:3 (7).
Fig. 2. Creation of simplified lunar subsurface structure by meteoritic impact. A single crater with its associated debris is shown in A, and a second crater is created beside it in B. In C, two smaller craters (3 and 4) have penetrated the debris of the older craters, and in D two overlapping craters (5 and 6) have added to the complexity of the structure. A final large crater (7) has destroyed most of crater 4 in E. Actual lunar structure will be even more complex. Negative accretion would change the thicknesses of the layers, but not the essential structure.
The nature of this difference between the maria and continents is revealed in a study made by Gilvarry (8) of the depth-diameter ratios of craters formed on the maria and in the highlands. He finds that they fall on two different curves, the curve for maria craters falling in a region of less shear strength. This indicates to him that the rocks forming the maria are composed of less coherent sediments from ancient seas, while the highlands are composed of more coherent igneous rocks. Another, and perhaps more likely, explanation is that the maria are covered with vesicular lavas while the highlands are covered with compacted rubble.

The evidence brought forth above is strongly suggestive, but not proof, of the nature of the lunar subsurface structure. Future experiments must be planned fully to clarify this problem, but it can be tentatively concluded at this time that the subsurface structure of the lunar highlands should consist of a highly fractured basement rock overlaid by discontinuous layers of rubble, rock flour, and meteoritic material. The subsurface structure of the maria should consist of a highly vesicular surface layer grading downward into solid lava, and disturbed only by scattered wrinkle ridges, rills, domes, and late craters. The vesicles should reach a maximum size of 6 ft in diameter, and a maximum depth of 40 ft. Probable dimensions would be about one half the maximum figures.

Experimental verification of these conclusions will be accomplished by lunar probes. In the immediate future, the Ranger series of lunar probes may do much to help. Although accelerometers are to be aboard the semi-soft landing packages, they are, unfortunately, designed to record the deceleration of the protected instrument package, rather than the deceleration of the over-all structure. Considering, however, the difference in deceleration of the package for impact on solid rock, or even loose sand, as opposed to impact on forty feet of vesicular material, the accelerometer may give gross information on the characteristics of the near-surface structure. Further, the hard landing portions of the probes will act as artificial meteorites for which the velocity and mass are known. The brightness of flash (if any) produced upon impact would give semi-quantitative information on penetrability, as the partition of kinetic energy on impact into mechanical energy, heat, and light will depend on this parameter. Finally, and most important, the seismic experiment proposed by Press et al (9) should provide at least a rough indication of the structure in the vicinity of the probe.

Such measurements as can be made from the Ranger series are, however, point measurements. As these may be misleading, it is necessary to conduct surveys over large areas of the moon. For
this purpose, a lunar satellite would appear more practical than a surface vehicle, if proper instrumentation can be designed for it. In this connection, radio waves show promise of detecting underground structure from altitude. As reported by Green (10), Khmelevskoy and Frolov (11) have successfully used the "radio-comparative" method in determining the subsurface geology of the north Ural bauxite basin. This method uses low frequency radio waves (about 100 kc/sec) and involves measuring variations in intensity of the electromagnetic field of long-wave radio broadcasting stations. Further experiments using related techniques, referred to as "radar geology" techniques, are being conducted by the Waterways Experiment Station of the Army Engineers.

Other, more well-known, geophysical techniques might also be employed in a lunar satellite or hovering vehicle as detailed by Green (12). Of all of these, a gravimeter in a hovering vehicle would probably provide data most easily interpreted in terms of subsurface structure.

Failing all indirect techniques, it may be finally necessary to gain an idea of structure by simply increasing the number of point measurements, either by means of a rain of sensors from a satellite, or by means of tests by automatic roving vehicles.

**Surface Characteristics**

According to both major theories of crater origin, and according to obvious visible evidence, the highlands are more rugged than the maria in terms of gross topography. Although it is well-known that slopes are not as steep as they appear under low illumination with shadow exaggeration, the visual impression of ruggedness is so vivid that it appears wise to illustrate the actual relief (Figs. 3, 4, and 5). It should be emphasized that although the lunar surface is smoother than it appears, craters with diameters less than 50 km have mean inner slope angles of about 28°. The surface relief is, therefore, by no means negligible, because craters of this size comprise the vast majority.

Both theories of crater origin predict that large amounts of rubble should be present on all of the highland surfaces, and on the maria surrounding late craters. Lahee (13) reports that coarse gravels consisting of angular fragments (breccias) have maximum angles of repose of about 35°, and an angle as high as 42° has been recorded. Should the coarse lunar crater debris assume such slopes, ignoring for the moment possible infilling by finer material, the surface roughness in terms of tens of feet (microtopography)
Fig. 3. Detail of Mare Imbrium, showing the mountain Piton and the craters Aristillus, Autolycus, and Archimedes C. (Pic du Midi Observatory photograph.)
Fig. 4. Topographic profiles across the craters Aristillus and Autolycus. (Rackham, T., "Studies in Lunar Topography V," University of Manchester Department of Astronomy, Technical Scientific Note 5, 1959.)
Fig. 5. Topographic profiles across the crater Archimedes C and across the mountain Piton. (Thomas Rackham, 1959.)
would make lunar operations extremely difficult. There are reasons, however, to believe that crater debris will not be a problem. Kopal (14) has suggested that lunar seismic waves caused by the impact of large meteorites or small planetesimals might have strong effects on surface structures. Certainly the debris of early craters would be shaken into low relief and a maximum density packing arrangement by the surface seismic waves of later craters. Only coarse debris surrounding the latest craters should present a surface roughness and landslip hazard. As a corollary to this, it is possible, as suggested by Gilvarry (15), that the apparent erosion of the older lunar craters is a result of their steady destruction by seismic waves. Certainly a large number of severe quakes would tend to reduce the height of the crater walls and produce infilling of crater floors with the wall debris. This might explain the rather severe scatter in plots of crater depth or rim height vs crater diameter.

Seismic effects on surface characteristics are not, however, confined to the meteoritic theory. The lunar degassing envisioned in caldera formation would also entail strong seismic action from internal structural readjustments. The degassing should also provide, however, for cementation of the debris, both by lava flows and by deposition of soluble salts by liquids and gases evolved from the interior, making its favorable adjustment in response to seismic waves less complete than under the meteoritic theory.

It appears from extrapolation of the meteoritic theory, therefore, that crater debris in the highlands, far from being a hazard, should present a favorable surface for lunar operations. Under the volcanic theory, the degree of favorable adjustment is doubtful and would probably be less than under the meteoritic theory. In the latter case, the adjustment should be as favorable as fragment size and size range will permit. The debris in particularly favorable areas not adjacent to any large craters might even be shaken down into a near equivalent of a compacted road bed.

Both theories of origin for lunar features agree that the maria are lava plains, and predict a similar microtopography for them. This microtopography should consist largely of burst vesicles, which should reach a maximum of about three ft in diameter and one or two ft in depth under the volcanic theory, and six ft in diameter and three or four ft in depth under the meteoritic theory. Probable vesicle size should be about one half this value.

Both theories also predict dust on the moon, although the volcanic theory holds that it should consist of volcanic ash as well as meteoritic and fragmented lunar crustal material. No matter how
the dust was produced, there are those who feel that it is very deep (16), and calculate its depth from the amount of material evidently removed from the older "eroded" craters. Gold believes that the average depth of dust on the moon is 1 km and that the maria are, in fact, composed of dust rather than lava. Whipple (17), on the other hand, shows that some of the material involved in high energy explosions will attain velocities greater than the velocity of escape from the moon, and that the amount of material so lost may possibly exceed the amount accreted. If the moon does actually suffer negative accretion, then the depth of the dust layer may remain at a constant, and probably low, level defined by the masses and velocities of the meteorite flux.

Two extremes are also predicted for the behavior of the dust. Gold (18) holds that electrostatic forces are likely to be significant for small particles, and may arise both from solar radiation and corpuscular streams. Migration of such charged particles could take place from higher ground to large, approximately flat regions. The top few feet would be effectively "in suspension" and would be extremely loose, lacking any bearing strength.

Whipple (19), on the other hand, maintains that the influx of solar corpuscular radiation would produce sputtering which, assisted by the addition of a certain amount of heavier gases falling onto the lunar surface from the interplanetary medium and by gases vaporized from meteoritic impact, would cement together dust grains on the lunar surface (see also (20)). He also maintains that the lunar surface could not carry a strong electric charge because interplanetary space is relatively good conductor (10^3 electrons/cm^3 near the surface). Further, Roche (21) has found that outgassed surfaces in a vacuum show a strong tendency to adhere structurally to each other when jarred (vacuum welding), probably by virtue of the fact that there is no interstitial air to prevent the full exercise of Van der Waal's forces between surfaces.

Thus, it is expected from these theoretical considerations that the dust will be cemented into a low-density, semi-porous matrix, weak compared with normal sedimentary rocks on earth, but strong compared to a layer of earth dust and not subject to migration.

Having obtained very different predictions of microtopography, depth of dust and dust behavior from theoretical considerations, it is important to obtain evidence clarifying the role of these three variables. It is clear that lunar surface characteristics will change drastically with changes in these variables. Should the dust layer be deep, for example, it will submerge the most rugged microtopography. If the dust layer is shallow, it may or may not smooth out
the microtopography depending upon the ruggedness of the topography and whether or not the dust is capable of migration. Knowledge of these factors, and how they might vary from place to place on the moon, is obviously of extreme importance. It appears that a key factor in unravelling these interlocking variables is surface roughness on a scale of tens of feet.

The major line of evidence for surface roughness is provided by radar measurements. Not long ago it was agreed (22), (23), (24), (25) that the lack of limb reflections of radar pulses indicated that the lunar surface was very smooth on a 10 cm scale, most slope angles being less than 12°. More recent measurements (26), (27) have shown, however, that the apparent lack of limb reflections was due to the low sensitivity of previous receivers. Efforts to interpret this new data (28) indicate, more than anything else, how extremely complicated the situation has become. Radar evidence appears, therefore, promising for the future when it is better understood, but not reliable for the present.

Photometric studies provide a second line of evidence for surface roughness. Struve (29), reporting on the work of VanDiggelen and others, has shown that the lunar surface is probably heavily pitted. This agrees with the findings of Barabashov (30) and Sytinskaya (31), who maintain that the "microrelief" of the lunar surface is very great.

A line of evidence for the thickness of the surface dust layer is provided by thermal radiation measurements. Pettit (32) concluded that the insulating surface layer, which he believed to be pumice, was 2.6 cm thick. Jaeger and Harper (33) found that their infrared curves fit best for a surface layer 2 mm thick of dust over pumice or gravel. Gibson (34) following the work of Piddington and Minnett (35), found that thermal radiation at 0.86 cm wavelengths indicated an average dust thickness of 2 or 3 cm.

The fact that all of the above measurements agree within an order of magnitude is very encouraging, and appears to support Whipple's (36) hypothesis of negative accretion.

Thermal characteristics are also an indicator of dust behavior. Klein (37) has made some preliminary experiments and calculations which indicate that because thermal conductivity values on the lunar surface are so low, the dust can not be sintered by sputtering and vacuum welding, but must exist as a loose powder with minimum point contact of individual particles. If the dust is loose as Klein maintains, it appears to the writer that this can be only by virtue of the electrostatic charging mechanism advocated by Gold. Other mechanisms have been called upon to put the dust in suspension,
such as Gilvarry’s suggestion (38) that seismic waves were responsible, but none appear effective on a continuous basis.

It is possible to make deductions concerning the looseness of the lunar dust from observations of the characteristics of lunar features themselves. The lunar rays, for example, have retained their distribution and shapes for at least 300 years. No matter what the rays are composed of, any appreciable rate of dust migration should have long since covered, or at least altered, them. Thus, we can say that the dust probably does not migrate at an appreciable rate, but may nevertheless be charged and loose.

If, as is generally believed, the lunar rays are composed of finely divided material (rock flour), then the variation of ray brightness with phase angle is a second line of evidence indicating that the dust is sintered. As reported by Bobrovnikoff (39), the curves of variation of brightness have sharper peaks near the time of full moon for rays than the curves for neighboring regions. If solar radiation does produce an electrostatically charged dust, then the number of dust particles "in suspension" above the lunar surface should reach a maximum at a phase angle of 90°. The self-shadowing effect of such particles would then act as a brightness inhibitor, tending to produce a smooth curve rather than a sharply peaked one.

Such deductions from the observed characteristics of lunar features are strongly suggestive of a sintered lunar dust layer, but are, unfortunately, based upon assumptions of the nature of the lunar features observed - i.e. assumptions that the rays are not self-replenishing in the first case, and that rays are composed of finely divided material in the second. It appears at this time, nevertheless, that the micro-relief is great, that the dust layer is thin, and that the dust is not loose and does not migrate.

In order to prove conclusively that the lunar dust is either sintered or loose, a characteristic of the dust itself that is directly related to the property of "looseness" must be measured. Thermal conductivity appears to be such a characteristic because it will vary as the number of point contacts between dust particles vary, and the number of point contacts between particles defines the looseness of the dust.

Thus, should the dust bear an electrostatic charge, the strength of this charge will vary with the intensity of solar radiation and corpuscular streams. As the strength of the charge varies, the thermal conductivity of the dust will also vary as the number of point contacts between individual grains increases or diminishes.

Should all efforts to determine lunar surface characteristics
from earth fail, the lunar probe penetrometer and seismic experiments mentioned in the previous section should finally resolve many of these questions. It appears, however, that it should be possible to determine many of the lunar surface characteristics without resorting to such expensive methods.

**Natural Resources**

On earth, natural resources often dictate the location of a town or city with no regard to favorable or unfavorable subsurface structure and surface characteristics. It would appear that appropriate natural resources could play an even more important part in the location of a lunar base.

Limited amounts of useful materials may be present on the lunar surface. Vestine (40), Green (41), and Watson et al (42) have calculated that such a useful material as water has a vapor pressure sufficiently low at -150°C to remain for millions of years in the solid phase at zero pressure. Such pressure-temperature conditions may reasonably be assumed at the bottom of such craters as Newton, which are in perpetual shadow, and in shadowed portions of cracks and various other types of surface cavities. These deposits should contain gases leaked from the interior as well as remnants of the former lunar atmosphere produced during the general lunar degassing and/or maria formation. It is doubtful, however, whether mineral deposits of this sort would control base location. Though relatively common, they would be small, scattered and more or less random in their location. Thus, mining such deposits would not be very economical, and they would probably correspond in usefulness to pegmatite deposits on earth.

To be truly useful and effective in controlling base location, mineral deposits must be large, centralized, and predictable in their location. It is the main purpose of this section to predict the location of such deposits.

Both major theories of maria origin hold that they are composed of lava. Some disagreement remains, however, upon the internal structure of maria in general, and of some maria in particular. Even so, a reasonable hypothesis, after Baldwin (43), is that the circular maria are not made up of many thin layers or sheets of lava, but originated as giant lava pools. Overflow of these pools produced the irregular maria and, as a result, these maria may be made up of lava sheets.

If an idealized lava pool is followed through its cooling cycle (Fig. 6), the following phases might be expected to occur.
Fig. 6. Phases in the creation of volatile concentrations at maria margins. Mare several hundred kilometers in diameter. Vertical scale greatly exaggerated.
Phase 1
The lava pool is created by whatever means, and over it forms a highly vesicular crust.

Phase 2
The vesicular crust acts as a slowly thickening insulating blanket, sealing off the pool from the surface. Thus, the rate of cooling drops sharply and crystallization processes follow those of a buried magma chamber (e.g., Stillwater Complex, Skaergaard Complex). Normally, this appears to involve initial formation of high temperature minerals, their settling through the melt to the bottom of the pool, and slow differentiation of the melt as lower and lower temperature minerals are formed and withdrawn from the remaining liquid as it cools.

Phase 3
Reduction in volume with crystallization will produce sinking of the central portion of the crust. Thus, volatile constituents of the magma, which are largely excluded from the crystallized minerals, are gradually segregated near pool margins.

Volatile involved in volcanism on earth are usually H₂O, CO₂, SO₂, H₂S, HC1, and NH₃. Water is by far the most abundant component, with CO₂ second (44). Each of these volatiles may act as a carrier of other elements under favorable circumstances, and it is generally believed that many terrestrial mineral deposits are created by precipitation of a valuable element from a solution of volatiles created during magmatic processes. Creation of most terrestrial mineral deposits requires, however, several cycles of concentration and reconcentration in order to produce large deposits of any but the most common elements. Although an active volcanic past, which might provide such cyclic reconcentration, may be assumed for the moon under the volcanic theory, it is very doubtful under the meteoritic theory. Thus, Green (45) has called for relatively large deposits of various volcanic sublimates to have been formed in the highlands during the lunar degassing, and would probably call for significant amounts of rarer elements to be dissolved in the hypothesized marginal maria concentrations of volatiles. The writer, on the other hand, as a proponent of the meteoritic theory, believes that the volatiles would carry only the more common elements. It seems reasonable to assume that the major volatile carrier would be water, and that the major elements carried would be silicon, oxygen and iron. (The suggestion by Carl Sagan (46) that complex organic matter derived from the primeval lunar atmosphere and buried on the lunar surface might survive to the present day should be borne in mind as an interesting, though unlikely,
possibility). As water would probably be the most valuable of all minerals on the moon, its hypothetical high content is a desirable factor, and the search for water will be considered as the primary function of lunar resource exploration.

Having predicted from theoretical considerations that volatiles will be concentrated near the margins of the circular maria, it is necessary to look for evidence of this concentration. According to Baldwin (47), an examination of the lunar surface indicates that the lunar rilles, though subsequent to the maria, are so clearly associated with their margins that some characteristic of the lava flows must have been the cause of these features. Fig. 7 illustrates the location of these rilles. It will be noted that several rilles are associated not with the margins of maria, but with lava-filled craters such as Alphonsus, which may be considered as miniature maria. One important feature of rilles is their association with chain craters. Perhaps the best known example is a group of chain craters running N-S between the craters Copernicus and Eratosthenes (Fig. 8). Each chain crater is connected by a rille, and at the northern end of the line the individual craters begin to merge until they almost take on the appearance of a normal rille extending out into Mare Imbrium. Many other examples can be cited of rilles with similar craters spaced along their length or at their beginning and end. Fig. 9 illustrates the most prominent such rille. In discussing the origin of these features, Baldwin (48) stated, "Craters of these types rarely, if ever, show raised rims and are thus set aside as a distinct class from the majority of normal craters. There does not seem to be any question but that they are volcanic blowholes of some kind and are directly the products of gases contained in the moon's crust.". It will also be noted in Figure 7 that rilles commonly parallel the over-all conjugate fracture pattern of the lunar crust, which has been mapped by Bulow (49), Fielder (50), Hackman (51) and others.

It would seem from the characteristics of rilles and chain craters discussed above that they are probably related to each other and to gas deposits associated with the maria. The writer believes that, subsequent to maria formation and concentration of volatiles near maria margins, lunar quakes produced by meteorite impacts or internal disturbances revitalized pre-existing fractures in the lunar crust which were able to tap many of these gas concentrations. Escape of this gas produced circular blowouts along each fracture which commonly were so closely spaced as to produce a general widening of the fracture to form a rille, aided by graben-like collapse with the release of pressure.
Fig. 8. Chain craters (upper left) between Copernicus and Eratosthenes. (Mt. Wilson Observatory photograph.)
Fig. 9. The Hyginus Rille (left) and Ariadaeus Rille (right), with Mare Tranquillitatis at far right and Mare Vaporum at top left. (Mt. Wilson Observatory photograph.)
If, then, volatiles were concentrated near maria margins, and if rilles and chain craters were formed by the release of such volatiles, what conclusions may be drawn as to the location of lunar mineral deposits? First, it appears reasonable to suppose that the initial fumarolic phase of hot gas release in rille formation would slowly degenerate into a hot spring phase of liquid flow, followed by a cold spring phase and then quiescence as the more cooled and the volatiles were exhausted. This last phase would probably entail gradual sealing of the liquid flow channels with deposits of dissolved minerals, most likely quartz. Considering that the present temperature of the lunar subsurface is approximately \(-23^{\circ}\text{C}\) according to Mezger and Strassl (52), there might also be large deposits of ice sealed off beneath the surface, depending upon past and present lunar thermal gradients. Certainly considerable amounts of hydrated minerals suitable for simple water extraction would be expected. Thus, large deposits of water in some form are probably to be found beneath the chain craters and rilles, along with deposits of the other volatiles and any elements they may have carried.

It should also be noted that other features of the maria, especially the domes, may have been formed by some process related to the release of trapped volatiles. The writer has suggested in a previous paper (53) serpentinization (hydration) of olivine by slow water leakage from the interior as the cause of lunar domes. Urey (personal communication) has extended this concept to apply also to wrinkle ridges. These features may, therefore, also be sites of large scale water deposition.

Continuing experimentation is, of course, required to verify the conclusions reached above. The seismic experiment proposed by Press et al (54) may accomplish this, or at least give rough indications of structure. It is especially important that more advanced lunar probes (Surveyor, Prospector) do some of their proposed core drilling in the vicinity of rilles for more definite information. Other techniques sensitive to water or hydrogen, such as neutron albedo measurements, would most appropriately be used over or near rilles or edges of mare.

Summary

An effort has been made to define the geological problems involved in the establishment of a lunar base, to deduce provisional solutions to these problems from the two major theories of the origin of lunar features, to point out any evidence in favor of these solutions, and to propose experiments for their final verification.
Geological problems involved in base location may be divided into three groups: 1) those concerned with subsurface structure; 2) those concerned with surface characteristics; 3) those concerned with natural resources.

**Subsurface Structure.** According to the volcanic theory, location of the lunar base in the highlands would be difficult due to the collapse hazard presented by lava caverns and caldera structures. The maria would be more favorable sites for base location because the collapse hazard represented by the vesicular surface should not be beyond the bounds of design compensation.

According to the meteoritic theory, location of the lunar base in the highlands would be permissible because the discontinuous layers of rubble, rock flour and meteoritic material overlying the highly fractured basement rock would not present a collapse hazard. The maria, on the other hand, are considered to bear near-surface cavities probably twice the size of those predicted under the volcanic theory. This added collapse hazard, when compared to the negligible collapse hazard of the highlands, makes the highlands a more favorable site for base location, and such a site is advocated in this report.

**Surface Characteristics.** The gross topography in the highlands, though quite rugged in appearance, is actually not rugged enough to hinder base location. The microtopography (on a scale of tens of feet) produced by rubble ejected from the craters also should not hinder base location, at least in the case of the meteoritic theory. Under this theory, which is considered here to be the most likely, lunar seismic waves caused by large meteorite impacts should have shaken the rubble into a maximum density packing arrangement with low relief. Under the volcanic theory, despite internal seismic disturbances, adjustment should be less complete due to the cementing action of lava flows and atmospheric processes.

Both theories predict that the microtopography of the maria should have a relief not exceeding three or four feet, and probably less.

Very different predictions have been made for the depth of the lunar dust and its behavior. It may be deep or shallow, sintered or loose, and capable or incapable of migration. Evidence points to a shallow, sintered dust, but further experiments are necessary.

**Natural Resources.** It appears that appropriate natural resources could play an even more important part in base location than structure or surface characteristics. Remnants of the lunar atmosphere and gases leaked from the interior are probably present in the shadowed zones of deep polar craters and surface fractures.
Such deposits, though common, would probably be small, scattered, and more or less random in location. It appears, on the other hand, that large concentrations of volatiles should occur near maria margins during solidification of the lava, and that these concentrations may have been tapped by revitalized fractures to form rilles, chain craters, domes and wrinkle ridges. It is probable, therefore, that large centralized mineral deposits, composed largely of H$_2$O, will be found associated with these features.

Considering the probable lunar structure, surface characteristics and natural resources, it appears that the lunar base should be located in the highlands near a rille, but not near a recent large crater such as Copernicus or Kepler. Bearing in mind also astronomical, guidance and propulsion requirements for a base near the equator and in the center of the lunar face, a location in the highlands just south of the Hyginus Rille near the crater Agrippa is provisionally proposed for the lunar base.

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References


