THE CHOICE OF THE LOCATION OF THE LUNAR BASE

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The development of modern methods of remote sensing of the lunar surface and data from lunar studies by space vehicles make it possible to assess scientifically the expediency of the location of the lunar base in a definite region on the Moon. The preliminary choice of the site is important for tackling a range of problems associated with ensuring the activity of a manned lunar base and with fulfilling the research program. Based on astronomical data, we suggest the Moon's western hemisphere, specifically the western part of Oceanus Procellarum, where natural, scientifically interesting objects have been identified, as have surface rocks with enhanced contents of ilmenite, a possible source of oxygen. A comprehensive evaluation of the region shows that, as far as natural features are concerned, it is a key one for solving the main problems of the Moon's origin and evolution.

INTRODUCTION

The main criteria for choosing a site for the first section of a manned lunar base are (1) the most favorable conditions for transport operations, (2) the presence of natural objects of different types in a relatively limited region (the study of these objects may provide answers to the principal problems of the Moon's origin and evolution), and (3) the presence of natural resources, primarily oxygen-bearing minerals in surface rocks, needed for ensuring the base's functioning even at the first stage.

No doubt the final selection of the base's site, as well as the final decision concerning its establishment, will call for new space flights for collecting appropriate information. However, the current level of remote sensing of the Moon and already available data of direct studies by space technology enable one to make preliminary estimates and forecasts of the most reasonable location of a manned lunar base in keeping with the above criteria.

When the lunar base project was first discussed over 20 years ago, the Moon's mare regions were considered the most suitable location for a lunar base (*Shevchenko*, 1968). At present we possess data that make it possible to substantiate this viewpoint in more detail and to determine which of the Moon's mare formations best meets the requirements.

THE MOON'S HEMISPHERIC ASYMMETRY

Upon completing the global survey of the lunar surface the asymmetry of the lunar sphere became obvious from the different structure of the near- and farside of the Moon. This asymmetry is determined by the location of lunar maria concentrated mainly within the limits of the nearside.

Analysis of the structural features and distribution of the surface rocks of the eastern and western hemispheres also showed a sharply pronounced western-eastern asymmetry. The asymmetry of the near- and farside in the complete form appeared about 3000 m.y. ago, when basaltic lavas of most of the modern maria erupted to the surface from the Moon's interior. This structure of the Moon's surface can now be explained qualitatively. In the final period of shaping the lunar crust's upper horizons (this period coincided with the final equalization of the Moon's periods of orbital revolution and axial rotation), the impact of terrestrial gravitation on the internal structure of the Moon increased. Between 4 and 3 b.y. ago the thickness of the solid crust within the nearside became 1.5-2 times lower than the thickness of the crust in the farside. This led to outcropping of lunar rocks predominantly within the limits of the nearside. As mentioned above, the distribution of maria constitutes the directly observed indication of hemispheric asymmetry of the near- and farsides of the Moon.

Asymmetry of the Western and Eastern Hemispheres

Over the past few years the work on the morphological catalog of lunar craters has come to an end. The catalog includes data on all craters more than 10 km in diameter (*Rodionova et al.*, 1985). This information characterizes the Moon's large-scale cratering, which relates mainly to the premare period of the Moon's history. Statistical analysis shows the differences in the density distribution of the craters in the highlands of the western and eastern hemispheres. Figure 1 is a generalizing map of the density distribution of about 15,000 lunar craters more than 10 km across (*Rodionova et al.*, 1988) and shows that the highest density distribution (120-150 craters per 10^5 km^2) occurs in the region in the northeastern part of the Moon's farside. The meridian with longitude 180° is central on the map. The western (during observations from the Earth) hemisphere takes up the map's right-hand side of the map. If one excludes the regions of maria and young ring structures similar to Mare Orientale, it turns out that the density distribution of craters is systematically higher in the western hemisphere. Hence, in the premare epoch the asymmetry of the western and eastern hemispheres with respect to the density of large craters was the decisive external sign of the structure of the Moon's surface. Most of the multiring basins and the most ancient of them—Oceanus Procellarum (*Whitaker*, 1981)—are concentrated in the western (during observations from the Earth) hemisphere.

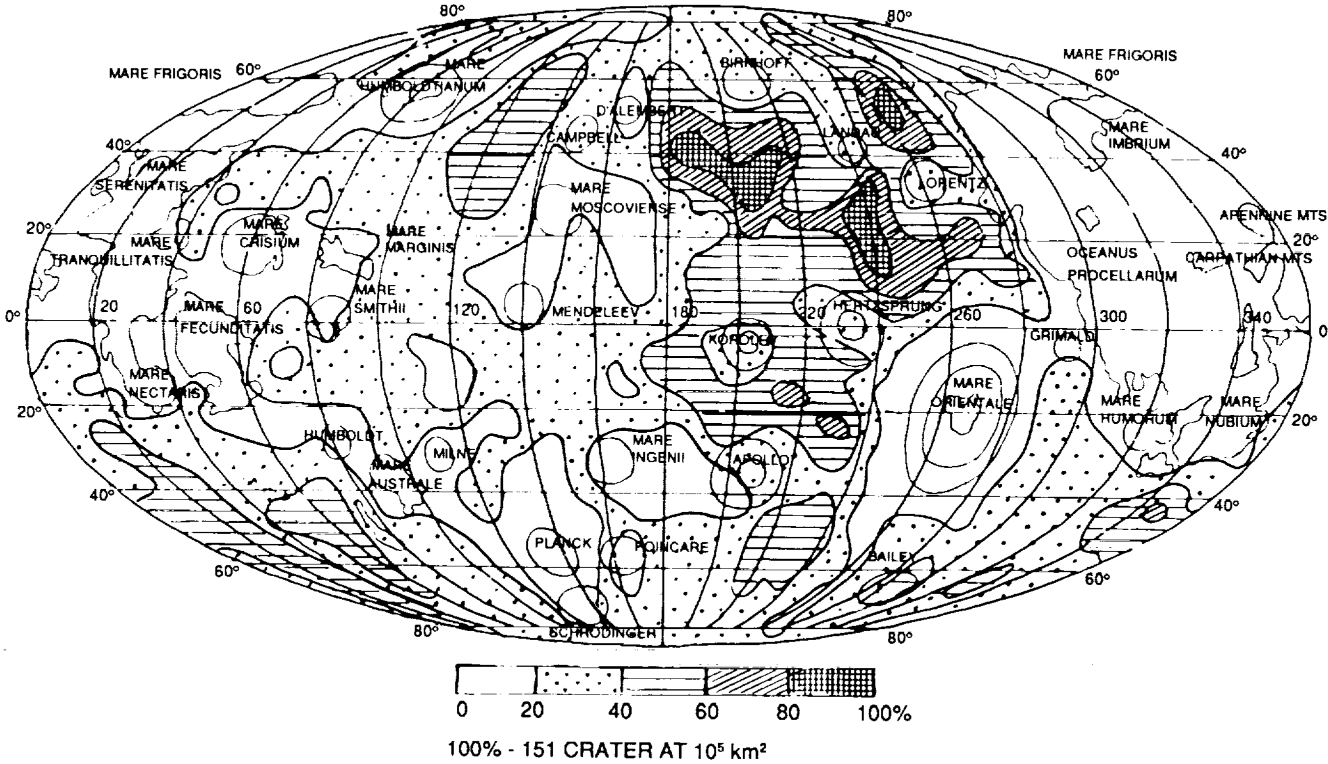

Fig. 1. The density distribution of lunar craters on the entire surface of the Moon.

On the basis of data on the Moon's reflectivity obtained by space vehicles and ground-based telescope, the albedo of 80% of the lunar surface, including the farside, was measured. When the character of the albedo distribution and the data from the orbital X-ray photography from Apollo 15 and 16 were compared, it was established that the distributions of the albedo correspond to the different chemical composition of the basic types of lunar rocks. The distribution of lunar rocks, based on available data, is given in Fig. 2 (*Schevchenko,* 1980). Excluding the relatively small regions of mare basalts, we again detect the asymmetry of the western (left) and eastern (right) hemispehres. It is worth noting that maria are within the regions of prolific lunar norites, i.e., the supposed product of premare volcanism. Hence, in the premare period the asymmetry of the western and eastern hemispheres manifested itself in the abundance of brighter (anorthositic) and darker (noritic) rocks on the surface of the Moon's single continental shield.

Gamma-ray spectrometry from lunar orbit by Apollo 15 and 16, revealed iron concentrations in the surface layer along mission routes (*Metzger et al.,* 1974). Analysis of these data also leads to the conclusion on the existence of western-eastern asymmetry. Highland rocks of the eastern hemisphere predominantly contain 6.5 to 9.5 wt% of iron, while the surface layer of the highlands of the western hemisphere contains less than 6.5% of iron. Since the rocks of these regions formed more than 4 b.y. ago this asymmetry characterizes the structure of the Moon in the premare period of lunar history.

Thus, the western-eastern asymmetry of the Moon relates to the earliest and the least understood period of the Moon's history and the evolution of terrestrial-type solar system bodies. The study of this period is of prime importance for understanding the origin and evolution of the solar system in particular and for lunar sciences in general. That is why the choice of the site for the lunar base requires that the western-eastern asymmetry of the hemispheres be taken into account. The enhanced concentration (density) of craters and multiring basins in the western hemisphere presupposes a vast and sample-rich field of ejecta from different depths. The task of selecting such samples in their natural bedding cannot be solved by automatic devices due to its complexity; a specialist's direct participation is needed to conduct such studies. Hence, taking into consideration the features mentioned above, it can be concluded that on a global scale the western hemisphere should be preferred for implementing scientific programs at the first stage of the functioning of a lunar base.

INDIVIDUAL OBJECTIVES OF THE LONG-TERM STUDY

Although the Moon's farside is very interesting, it seems that at the first stage of establishing a lunar base we should limit ourselves to the nearside due to simpler conditions of transport

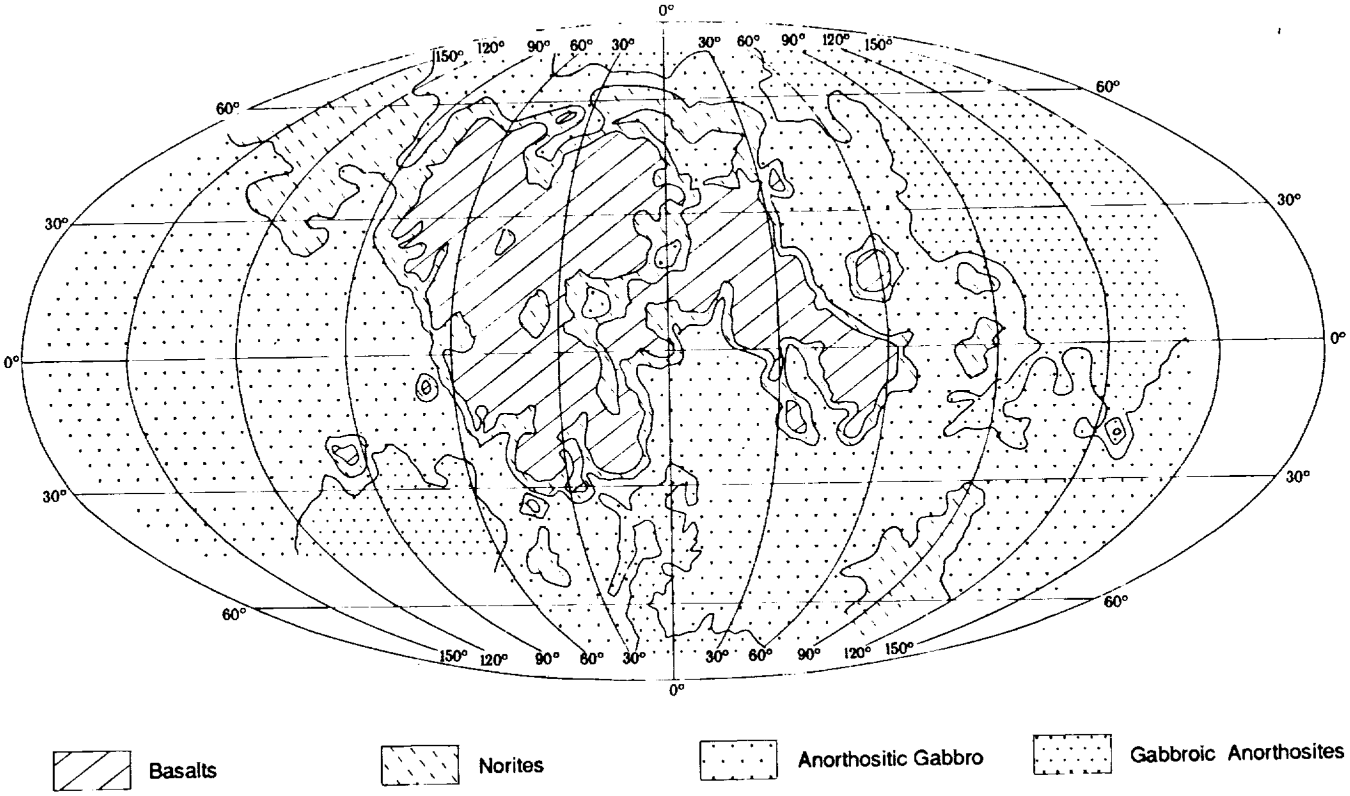

Fig. 2. A map of the distribution of lunar rocks according to photometric data.

and radio-television communications. From this point of view, let us consider primarily Oceanus Procellarum and highland regions closest to it (*Shevchenko,* 1986).

Large impact structures in this part of the Moon are of great interest. The study of samples from the lower part of the crust and ancient intrusions will help identify the age of the Moon's old rocks and determine the change in the rock composition with the bedding depth. Such samples can certainly be found in material ejected by an explosion from a depth of up to 20 km during the formation of the Moon's giant multiring basins. Apparently these basins were formed in the early stage of lunar history, 4.25-3.85 b.y. ago. If samples from the deepest layers of the crust affected by an impact explosion are identified amidst ejecta material, it will be possible to judge the time and composition of the formation of the Moon's primordial crust, the processes that took place in the era of giant impacts, and their effect on the subsequent volcanic activity during the formation of lunar maria. It is obvious that such a unique search can be carried out by a researcher in the course of long on-the-spot studies of objects and samples on the basis of preset parameters.

Of special interest in the region under consideration is the large crater Grimaldi situated within the highland near the western boundary of Oceanus Procellarum. The floor of the crater is flooded by lava rocks with a very low albedo. The outer rim is 237 km in diameter; the flooded part of the crater is about 170 km across. According to morphological classification by the degree of preservation of the crater's rim (*Rodionova et al.,* 1987), Grimaldi belongs to the pre-Imbrium period of formation. Later, approximately 3.85 b.y. ago, the crater was lavishly overlapped by ejecta from the multiring depression of Mare Orientale and apparently was destroyed to a great extent. Still later, in the Imbrian period, the dark covering of the Grimaldi floor appeared. It is also worth noting that the flooding of the crater's floor by dark lavas was multiphase, which can be traced in the photometric picture of the region obtained by processing a photograph brought back to Earth by Zond 6 space probe (*Shevchenko,* 1980). The regions of equal brightness in this picture have a sharply pronounced asymmetric structure. The center of the darkest area of the lava inside the crater is observed to the south.

The change in the reflective capacity of covering material is unambiguously correlated with the geometry of the rim's topography and the adjacent crater floor. To the north, where the rim is partly destroyed and the topography is gently sloping, the gradual brightening of the surface takes place along several dozens of kilometers making up the width of the transitional zone. In the crater's southern part the rim is fully preserved with the considerable and rather sharp change of height between the rim's crest and the floor. The sharp boundary between the darkest region of the surface of the intercrater filling and the bright highland surroundings of Grimaldi correspond to this. In all likelihood, the general form of identified regions of different brightness is the result of the dynamics of lava flows occurring at different times during the filling of the crater by mare-type material. Despite the proximity of this formation to the western boundary of Oceanus Procellarum, photometric analysis of the structure of the crater and its surroundings belies the surface flooding of Grimaldi by lava from neighboring mare regions. The source of dark material lies inside the crater, presumably in its southern part. This conclusion is supported by the anomaly of gravity inside the crater (*Phillips and Dvorak,* 1981). The photometric structure of Grimaldi Crater is shown in Fig. 3. Albedo percentage is indicated for equal reflectivity lines (*Shevchenko,* 1986). Thus, Grimaldi Crater contains traces of different epochs of lunar history from the most ancient period to the final stage of global volcanism that resulted in the formation of lunar maria.

Some 500 km away from Grimaldi Crater is another structure that deserves close attention and detailed study. This is an albedo anomaly coinciding with the Moon's largest magnetic anomaly, Reiner Gamma (*Shevchenko,* 1980). Studying the photometric properties of this formation shows that the brightening of the surface belongs to a very thin layer, in all probability modified by mechanical processes. The polarization properties and the presence of reflection indicate an enhanced density that is not inherent in the typical lunar surface. The sites of the artificial compaction in the uppermost layer of the lunar regolith possess similar properties.

The map of the albedo of the Reiner Gamma magnetic anomaly is given in Fig. 4. The albedo of the main part of the brightness structure is 1.86 times higher than that of the surrounding surface. A similar result was obtained by photometry of the trace of Lunokhod 2's light-track-measuring wheel (*Shevchenko,* 1982). The rover's wheel compacted, without mixing, the uppermost surface layer by its pressure on the Moon's soil. This light compaction increased the brightness of the trace of the ninth wheel by 1.82 times when compared with the surrounding background. At the same time, reflection appeared on this trace, the increase in brightness at large phase angles being typical of the Reiner Gamma magnetic anomaly. A similar phenomenon can be seen, for instance, in the pictures of the light tracks of the rover used for manual cargo carriage in the Apollo 14 expedition (*Apollo 15 Preliminary Science Report,* 1972). A similar effect has been recorded when soil is subject to the impact of gas jets of sufficient density. The pictures of the Apollo 15 landing site taken before and after the spaceship's landing on the Moon show that in the latter case a bright halo around the landing site appears on the surface (*Apollo 15 Preliminary Science Report,* 1972).

The described properties of the formation of the Reiner Gamma magnetic anomaly enable us to speculate that this anomaly originated from the gas ejections of a dense coma surrounding a comet's active nucleus, which formed the albedo structure by compacting the Moon's uppermost soil layer. In this case it is possible to assess the anomaly's absolute age. The photometric properties of surface material are determined by a very thin porous soil layer. This layer is 1-2 cm thick with a density of 0.2-0.3 H/cm^2. Calculations have shown that due to the pressure of the gas jet of descent engines the value reached is about 0.689 H/cm^2 (*Apollo 15 Preliminary Science Report,* 1972), which is quite enough for destroying the high porosity of the surface layer through the compaction of soil. The natural level of porosity and, hence, the typical photometric properties can be restored as a result of the long effect of micrometeoritic erosion, the rate of which is 0.5 mm/10^6 yr. Hence, the recovery of the 2-cm thick porous layer will take not more than 40 m.y. This time is the absolute age of the Reiner Gamma formation, a very young large structure on the Moon linked perhaps with the era of global catastrophes in the internal part of the solar system.

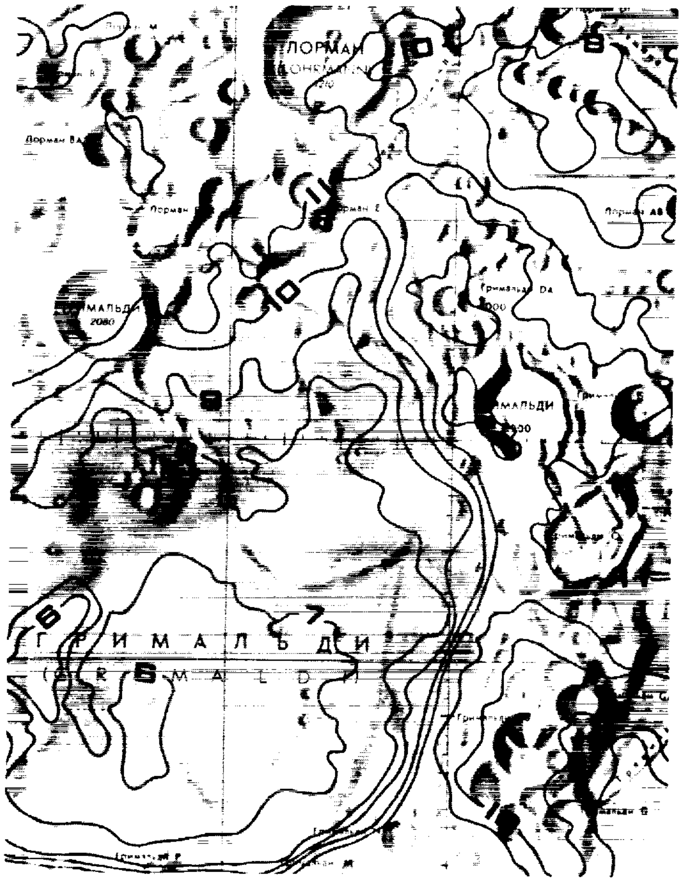

Fig. 3. A map of the albedo of Grimaldi Crater.

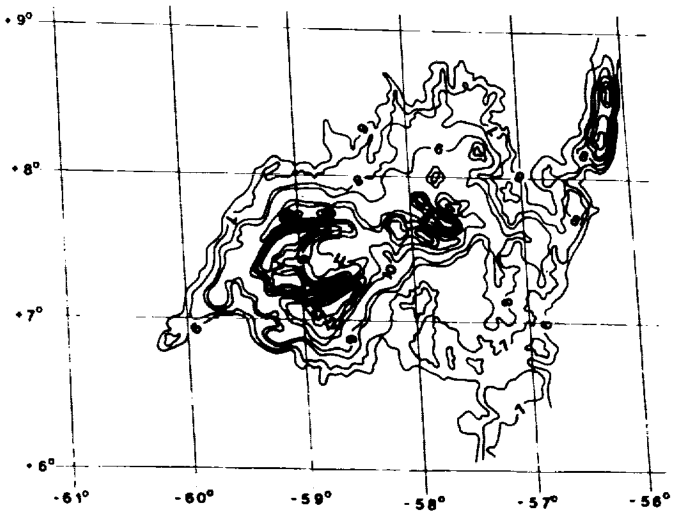

Fig. 4. A map of the albedo of the Reiner Gamma magnetic anomaly.

THE PRESENCE OF ILMENITES—OXYGEN-BEARING MINERALS

The presence of ilmenites—oxygen-bearing minerals—is essential for the choice of promising areas on the Moon for detailed studies and landing (*Shevchenko,* 1986). Ilmenite is an ore mineral and its greatest abundance (up to 20%) is recorded in highly titaniferous mare basalts. Ilmenitic basalts abound in some lunar areas whose genesis is insufficiently studied. Predicting ilmenitic basalt regions is feasible with the use of planetary astrophysics and remote sensing. According to most predictions ilmenitic basalts seem to be spread in the central and western parts of Oceanus Procellarum, in addition to the Apollo 11 and Apollo 17 landing sites, where they were detected in the samples taken back to Earth. There are relatively small areas in the northwestern part of Oceanus Procellarum that, according to the data of photography from the Earth and measurements from the Zond 6 spacecraft, have the lowest albedo on the lunar surface—less than 6%. In albedo and spectral zone characteristics, these regions have greater titanium content in the surface rocks (*Shevchenko,* 1986). Methods of remote identification of lunar rocks with enhanced titanium oxide content continue to be improved.

In accordance with the calculated values of the energy of metal-metal electron transitions in ilmenite, a spectral range of the characteristic 0.5- to 0.6-mcm absorption band has been isolated, where it is superimposed on individual absorption bands of transitions in the crystalline field in Fe^{2+} and Ti^{3+} ions. This conclusion is most clearly confirmed by the results of the laboratory measurements of cleansed samples of terrestrial ilmenite. Figure 5 presents reflection spectra of four ilmenite samples (Nos. 1 to 4) extracted from a depth of 100 to 1250 m in the northwestern Ukraine (U.S.S.R.). The chemical composition of the samples is similar, and the titanium oxide content varies within 49.28 to 49.40 wt%. Sample No. 2 contains slightly more iron oxide, which explains the specific features of its spectrum. All spectra contain a characteristic absorption band that indicates the presence of titanium in rocks in all other cases (*Busarev and Shevchenko,* 1988).

For the region northwest of the crater Lichtenberg in Oceanus Procellarum, spectra in the 0.336 to 0.758 mcm interval with resolution 0.0048 mcm were obtained. Spatial resolution corresponds to 25 km on the Moon's surface. Observations were conducted in the Crimea on the Zeiss-600 telescope in May 1987. Figure 6 presents spectra for section 1 with coordinates 72.9°W, 35.0°N, for section 2 with coordinates 75.1°W, 32.7°N, and the spectrum of the Apollo 17 landing site obtained during those observations. The comparison of the spectra shows that the characteristic absorption band in the 0.5-0.6-mcm region manifests clearly enough. Individual features of the spectra also coincide well enough to indicate the enhanced ilmenite content in the surface rocks of the region northwest of the crater Lichtenberg. The quantitative estimate based on the empirical dependence of the slope of the spectrum in the 0.400-0.565-mcm interval on the percentage of titanium oxide gives the value 5.3% for section No. 1 and 6.8% for section No. 2 (*Schevchenko and Busarev,* 1988).

The area northwest of Lichtenberg Crater is a region of presumed presence of ilmenitic basalts. (This region was preliminarily singled out in albedo and spectral zonal characteristics.) Since all these sections have similar optical properties, including the maximum degree of polarization (*Dzhapiashvili and Korol,* 1982), the estimates based on spectrophotometric data can be extended to them too as regards the enhanced ilmenite content in surface rocks.

THE MOON'S KEY REGION

It can be concluded that the western part of Oceanus Procellarum is a key region of the lunar surface whose detailed and comprehensive study is of great importance for the exploration of the Moon and for the understanding of the early history of the solar system.

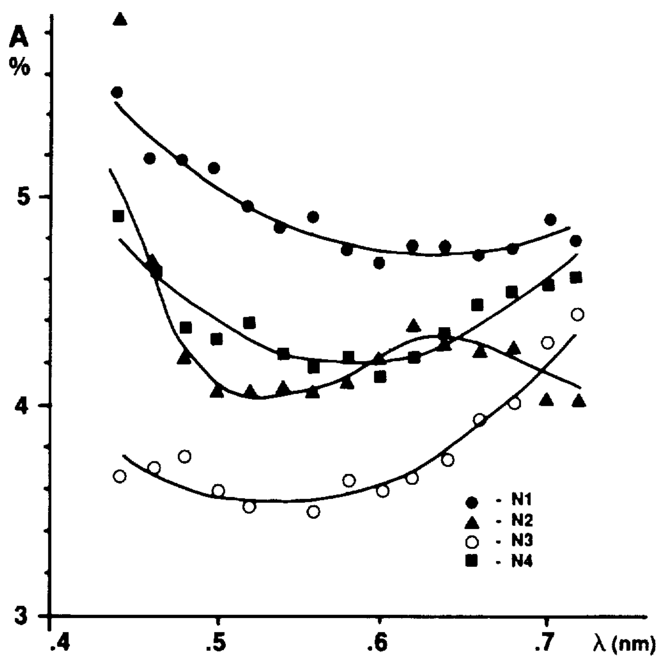

Fig. 5. Reflection spectra of the samples of cleansed ilmenite.

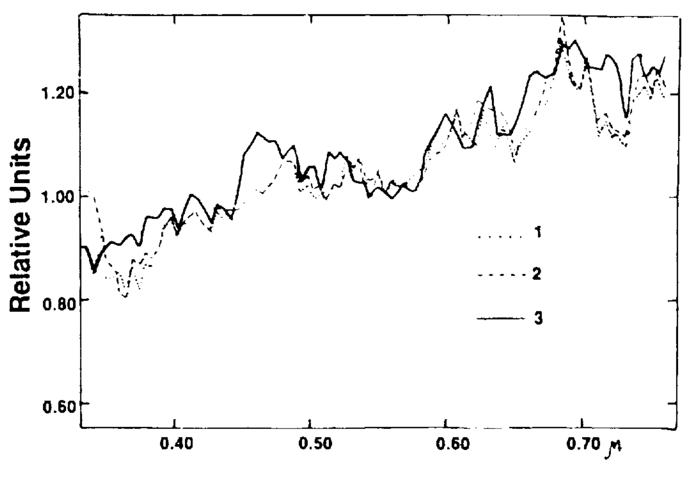

Fig. 6. Spectra of the sections of the lunar surface in the Lichtenberg Crater region (1, 2) and the Apollo 17 landing site (3).

Figure 7 presents the map-diagram of the western part of Oceanus Procellarum. The areas identified according to ground-based remote sensing data are assumed to have an enhanced titanium oxide content in surface rocks. This conclusion is drawn from the low albedo (less than 6%), increased reflectivity ("blue" rays revealed in the course of spectrozonal photography on wavelengths 0.37 and 0.61 mcm), a higher maximum degree of polarization, and lastly, spectral characteristics. Sections in the region northwest of Lichtenberg Crater for which spectra are obtained (see Fig. 6) are denoted by asterisks. Similarly, the surface rocks on the floor of the darkest southern part of Grimaldi Crater can be assumed to be ilmenitic basalts.

According to the stratigraphic diagram of Oceanus Procellarum (*Whitford-Stark and Head*, 1980) the regions in the western part of Oceanus Procellarum coincide with the sites of regional lava flows originated in small craters and with a system of rilles indicating the direction of the movement of these flows. It seems that the lava flows and their sources identified by the above authors were the entryways of ilmenitic basalts to the surface. On the other hand, these features are indicative of the traces of lunar volcanism that deserve special close study.

Maria hills situated on the territory bewteen the Reiner Gamma structure and Marius Crater are also such objects. As volcanic structures, these objects relate apparently to the epoch of late postmare volcanism on the Moon, the traces of which, due to the limited spread of this process, are very rare.

Mention should also be made of the fact that in the region under review there are objects near which nonstationary processes have been recorded many times. They are linked with the manifestations of modern lunar volcanism (*Shevchenko*, 1986). These sites, denoted on the diagram by the sign V, are hypothetical sources of volatiles of endogenic origin. Nonstationary phenomena on the Moon have not been studied enough because of specific features of their manifestations. Hence, a detailed study of the places where nonstationary phenomena have repeatedly been observed on the surface is important for understanding the evolution of the Moon and other minor bodies of the solar system and the nature of modern volcanism on planets and satellites. It is probable that the detection of the sources of the intensive outgassing from the Moon's interior will be of great importance for the functioning of a lunar base.

Thus, in the given region, according to preliminary data, we have natural resources in the form of ilmenitic basalts suitable for obtaining oxygen and in the form of volatiles—products of the eruption from the Moon's interior. The same sites of nonstationary phenomena and the traces of the late volcanism of the postmare period are the major aim of studies. Grimaldi Crater, lying near this region, contains numerous traces of the multistage process of the formation and evolution of lunar highlands and maria, including intercrater volcanism. Finally, this region has the youngest large formation on the Moon—the anomalous Reiner Gamma structure, the study of which opens up an opportunity to detect the traces of cometary impacts against the lunar surface that perhaps belong to one of the latest epochs of catastrophic events in the solar system.

The highland adjacent (from the west) to Oceanus Procellarum undoubtedly contains ejecta relating to different periods of impact phenomena, from the earliest, when the region of the highest

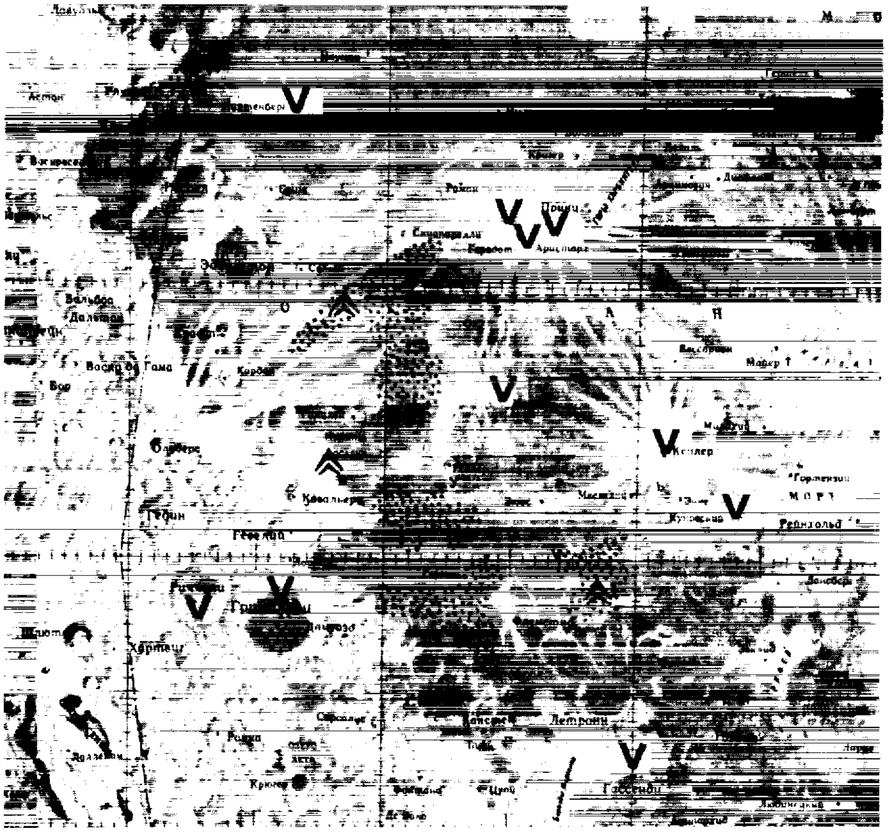

Fig. 7. A map diagram of the western part of Oceanus Procellarum.

density distribution of craters situated northwest of the region under consideration was shaped, to the latest, when the multiring basin of Mare Orientale came into existence. No doubt as a result of later impact events, these ejecta were partly transferred and scattered on the mare surface of Oceanus Procellarum. A more careful search for such fragments is needed in the overall regolith mass covering the western part of Oceanus Procellarum.

The plain-type terrain in this region provides favorable conditions for takeoff-landing transport operations of unmanned, remotely controlled, and manned spacefcraft. The typical texture of the surface is known from the pictures of the surrounding terrain taken at the landing sites of unmanned space probes—Luna 9 (Planitia Descensus), Luna 13, and Surveyor 1 (denoted on the diagram by big asterisks).

It can be concluded that expoloration by remote (ground-based) and direct (space vehicles) method should be focused on this key region on the Moon as the most suitable (as preliminary data show) for the establishment and functioning of a lunar base.

REFERENCES

Apollo 15 Preliminary Science Report (1972) *NASA SP-289,* pp. 2550-2553.

Busarev V. V. and Shevchenko V. V. (1988) TiO_2 in crater Le Monier (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* pp. 44-45. Lunar and Planetary Institute, Houston.

Dzhapiashvili V. P. and Korol A. N. (1982) *Polarimetric Atlas of the Moon.* Tbilisi. 44 pp.

Metzger A. E., Trombka J. I., Reedy R. C., and Arnold J. R. (1974) Element concentrations from lunar orbital gamma-ray measurements. *Proc. Lunar Sci. Conf. 5th,* pp. 1067-1078.

Philipps R. J. and Dvorak J. (1981) The origin of lunar mascons. In *Multi-Ring Basins, Proc. Lunar Planet. Sci. 12A* (P. H. Schultz and R. B. Merrill, eds.), pp. 91-104. Pergamon, New York.

Rodionova Zh. F., Skobeteva T. P., and Karlov A. A. (1985) A morphological catalogue of lunar craters (abstract). In *Lunar and Planetary Science XVI,* pp. 706-707. Lunar and Planetary Institute, Houston.

Rodionova Zh. F. et al. (1987) In *A Morphological Catalog of Lunar Craters* (V. V. Shevchenko, ed.), p. 174. Moscow University, Moscow.

Rodionova Zh. F. and Shevchenko V. V. (1988) The creation of maps of the density distribution of lunar craters. In *Lunar and Planetary Science XIX,* pp. 992-993. Lunar and Planetary Institute, Houston.

Shevchenko V. V. (1968) Problems of a manned lunar base. *Vestnik Akademii Nauk SSSR, 6,* 95-104.

Shevchenko V. V. (1980) *Modern Selenography.* Nauka, Moscow. 288 pp.

Shevchenko V. V. (1982) The technique and results of photometric studies in the mare-highland transition zone by Lunokhod 2. *Trudy (Proceedings) of the Sternberg Astronomical Institute, 51,* 195-207.

Shevchenko V. V. (1984) Optical properties of Reiner gamma magnetic anomaly on the Moon (abstract). In *Lunar and Planetary Science XV,* pp. 772-773. Lunar and Planetary Institute, Houston.

Shevchenko V. V. (1986) A manned lunar base project. *Vestnik Akademii Nauk SSSR, 10,* 85-98.

Shevchenko V. V. and Busarev V. V. (1988) Ilmenites in Oceanus Procellarum (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 219. Lunar and Planetary Institute, Houston.

Whitaker E. (1981) The lunar Procellarum basin. In *Multi-Ring Basins, Proc. Lunar Planet. Sci. 12A* (P. H. Schultz and R. B. Merrill, eds.), pp. 105-111. Pergamon, New York.

Whitford-Stark J. L. and Head J. W. (1980) Lunar surface morphology and stratigraphy: A remote sensing synthesis. *J. Brit. Astron. Assoc., 90,* 312-345.