GEOLOGICAL AND GEOPHYSICAL FIELD INVESTIGATIONS FROM A LUNAR BASE AT MARE SMYTHII

Paul D. Spudis[1]

Branch of Astrogeology
U.S. Geological Survey
Flagstaff AZ 86001

Lon L. Hood

Lunar and Planetary Laboratory
University of Arizona
Tucson AZ 85721

Mare Smythii, located on the equator and east limb of the Moon, has a great variety of scientific and economic uses as the site for a permanent lunar base. Here a complex could be established that would combine the advantages of a nearside base (for ease of communications with Earth and normal operations) with those of a farside base (for shielding a radio astronomical observatory from the electromagnetic noise of Earth). The Mare Smythii region displays virtually the entire known range of geological processes and materials found on the Moon; from this site, a series of field traverses and investigations could be conducted that would provide data on and answers to fundamental questions in lunar geoscience. This endowment of geological materials also makes the Smythii region attractive for the mining of resources for use both on the Moon and in Earth-Moon space. We suggest that the main base complex be located at 0, 90°E, within the mare basalts of the Smythii basin; two additional outposts would be required, one at 0, 81°E to maintain constant communications with Earth, and the other, at 0, 101°E on the lunar farside, to serve as a radio astronomical observatory. The bulk of lunar surface activities could be conducted by robotic teleoperations under the direct control of the human inhabitants of the base.

INTRODUCTION

Several advanced planning studies are currently underway to identify strategies for the establishment of a permanent base on the Moon (*Mendell,* 1985). Depending upon the ultimate emphasis placed on lunar base operations, several considerations enter into the planning process, one of which includes the selection of the base site. Any lunar base site will offer something for various users. *Duke et al.* (1985) identified three separate scenarios for development of a lunar base, each having a different emphasis for ultimate base use: lunar science, resource utilization, and lunar settlement. These different thrusts are not mutually exclusive, but each could have slightly different criteria for base site selection. In fact, it is highly probable that a lunar base program will have elements of each emphasis; indeed, one of the attractions of a lunar base program is that it has so much to offer to many different users.

Although it may be premature at this stage to design detailed, site-dependent operational strategies, it is not too soon to begin considering what types of lunar base sites offer the most benefits to the most potential users. In this spirit, we here present a study of the Mare Smythii region, on the east limb of the Moon, and suggest that this location presents many advantages to all the currently identified potential base users.

[1]Now at Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058.

ADVANTAGES OF A BASE SITE ON THE LUNAR LIMB

A consequence of the Moon's synchronous periods of rotation and revolution is that the Earth is always visible at the same location in the sky on the nearside and always invisible from the farside. This presents both opportunities and problems. For normal lunar base operations, it may be desirable to maintain constant communication with the Earth, a condition satisfied by any nearside site. However, one of the prime advantages of the Moon as an astronomical observing platform is that the lunar farside is the only known place in the solar system that is permanently shielded from the extensive radio noise produced by our home planet. These two requirements are mutually incompatible, short of designing and operating two separate lunar base sites.

Because the Moon orbits the Earth in an elliptical path and the plane of the lunar orbit is not quite perpendicular to its rotation axis, the Moon wobbles slightly, or librates, in both latitude and longitude. Thus, the lunar limb (the great circle defined by the poles and the 90° meridians) is the only place on the Moon where the Earth is sometimes visible and sometimes occulted. It is in this region that a base could be established that may potentially satisfy both paradoxical requirements: that of radio access to the Earth and shielding from the Earth's radio noise. We emphasize at the outset that no single site accomplishes these goals at all times, but rather, several outposts or "sub-bases" in close proximity are required to make use of the lunar libration effect.

Several studies have advocated base sites at the lunar poles (e.g., *Burke,* 1985), either because of the availability of continuous solar power or because the continuous darkness of crater floors may have trapped volatiles (including water) over geologic time (e.g., *Arnold,* 1979). However, from an astronomical viewpoint, a major drawback to a polar site is that only half of the sky is ever visible. Moreover, the unique lighting conditions of the poles, where the sun is constantly near the horizon and the surface is either jet black or blazing white, would make both surface operations and geological exploration difficult.

For these reasons, we believe that a limb site located on the equator has many advantages over a polar site. First, the entire sky is visible from the lunar equator over the course of a month. Second, equatorial sites on the Moon are easily and constantly accessible in minimum energy trajectories from the LEO space station, the probable staging location for base establishment. The Mare Smythii site that we endorse as a lunar base site is not only on the limb, at the equator, but it is in a region containing evidence of a great diversity of geological processes as well as a variety of materials that occur in reasonably close proximity. This region can satisfy all potential lunar base users—geoscientists, astronomers, miners, and colonists.

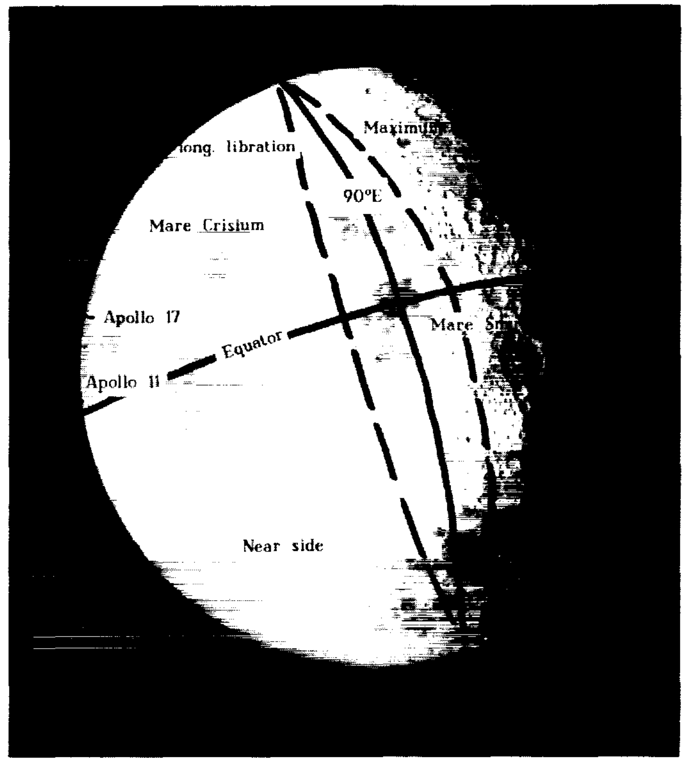


Fig. 1. Global view of the eastern limb of the Moon showing Mare Smythii and its relation to the longitudes of lunar libration. Some regional features and two Apollo landing sites are also shown. AS12-55-8226.

ADVANTAGES OF THE MARE SMYTHII SITE

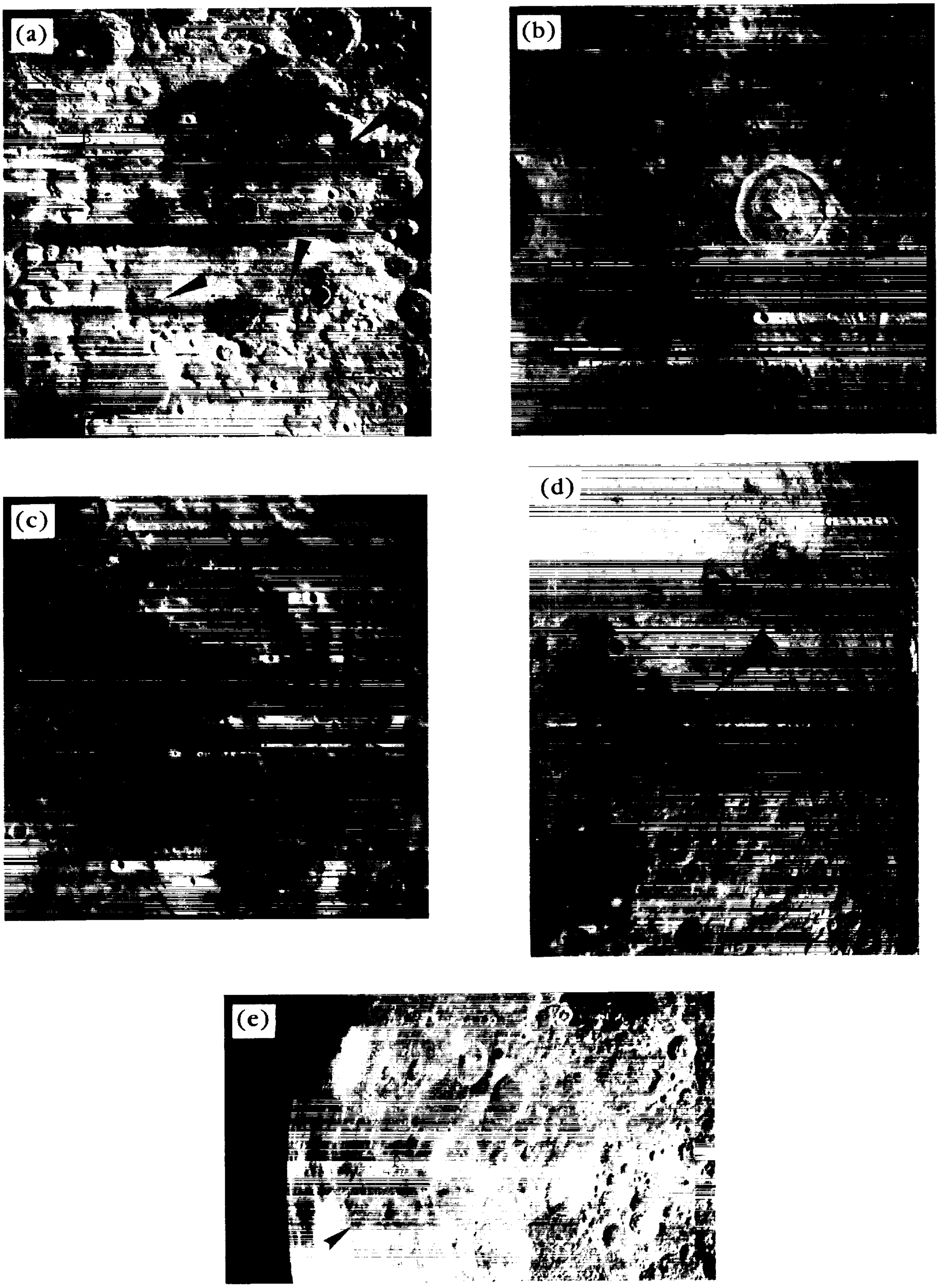
Mare Smythii is a dark lowland on the east limb of the Moon (Fig. 1). The region is well covered by orbital remote-sensing data; analysis of these data suggests that the region is probably one of the most diverse on the Moon (Figs. 2 and 3; Table 1). (For a concise summary of our current understanding of lunar geoscience, see *Lunar Geoscience Working Group,* 1986.) In the following paragraphs, we briefly discuss the advantages of the Mare Smythii region from the perspectives of several potential lunar base users.

Geological Considerations

The Mare Smythii region displays the two principal geological units found on the Moon: maria (the dark, smooth plains) and terrae (the rugged, heavily cratered highlands). Mare Smythii consists of dark lava flows that partly fill a much older, multiringed impact basin. The Smythii basin is one of the oldest lunar basins that retain recognizable ring structure; it is composed of three rings 370, 540, and 740 km in diameter. Basins were formed by the impact of asteroid-sized bodies on the Moon before about 4 b.y. ago; the study of the mechanics of their formation and their geological effects on crustal materials is one of the primary tasks of lunar geoscience.

The dark, smooth maria are known from Apollo results to consist of basaltic lava flows; the ages of mare basalt samples returned by Apollo range from 3.9 to about 3.1 b.y. The ages of mare lava flows not visited by Apollo may be estimated by examining the density of superposed impact craters. Results of this exercise for Mare Smythii are shown in Fig. 4; the astonishing result is that the lava flows of the Smythii basin are among the youngest on the Moon. The position of the crater frequency curve of Mare Smythii relative to that of dated Apollo site lava flows indicates that the Smythii basalts are probably 1 to 2 b.y. old. (A more precise estimate is impossible because the cratering history of the Moon over the last 3 b.y. is only approximately known.)

Fig. 2. Geological features of and near the Smythii basin. **(a)** Regional view of the Smythii basin. Dark smooth area (M) is Mare Smythii, consisting of high-Ti mare basalts. Smythii basin rim (B) is 370 km in diameter and is composed of anorthositic rocks. Dark mantle (arrows) is pyroclastic ash produced by fire fountain eruptions of basaltic magmas. Many floor-fractured craters (F) are visible on the basin floor. Large, mare-filled crater at upper left is Neper (N), 137 km in diameter. AS15-95-12991. **(b)** Western part of the Smythii basin floor. The prominent floor-fractured crater (F) is Schubert C (31-km diameter). Mare basalt flows (M) fill the highlands terrain (H) of the basin. Dark mantle deposits are associated with irregular volcanic vents (arrows) in this area. LO I-5 M. **(c)** Eastern part of the Smythii basin floor, showing lava flows (M) of Mare Smythii, highlands basin rim (H), and floor-fractured crater Purkyne U (F; 51-km diameter). Young rayed crater (arrow) overlies lava fill of Purkyne U. LO I-19M. **(d)** Regional view of terrain northeast of Mare Smythii (S). Basalts of Mare Marginis (M) are relatively young (about 2-3 b.y. old) and rich in KREEP. Swirls within Marginis (big arrow) are associated with large surface magnetic anomalies. Dark-halo impact craters (small arrows) are associated with buried ancient mare basalts, common in this area. Large rayed crater at top (G) is Giordano Bruno (22-km diameter), possibly the youngest large crater on the Moon. Portion of AS16-3021. **(e)** Regional view of terrain southwest of Mare Smythii (S). The mottled light plains (P) of the Balmer basin display dark-halo craters (arrow) and are KREEP-rich. Large crater near bottom center is Humboldt (207-km diameter). Portion of AS17-152-23293.


(a)
(b)
(c)
(d)
(e)

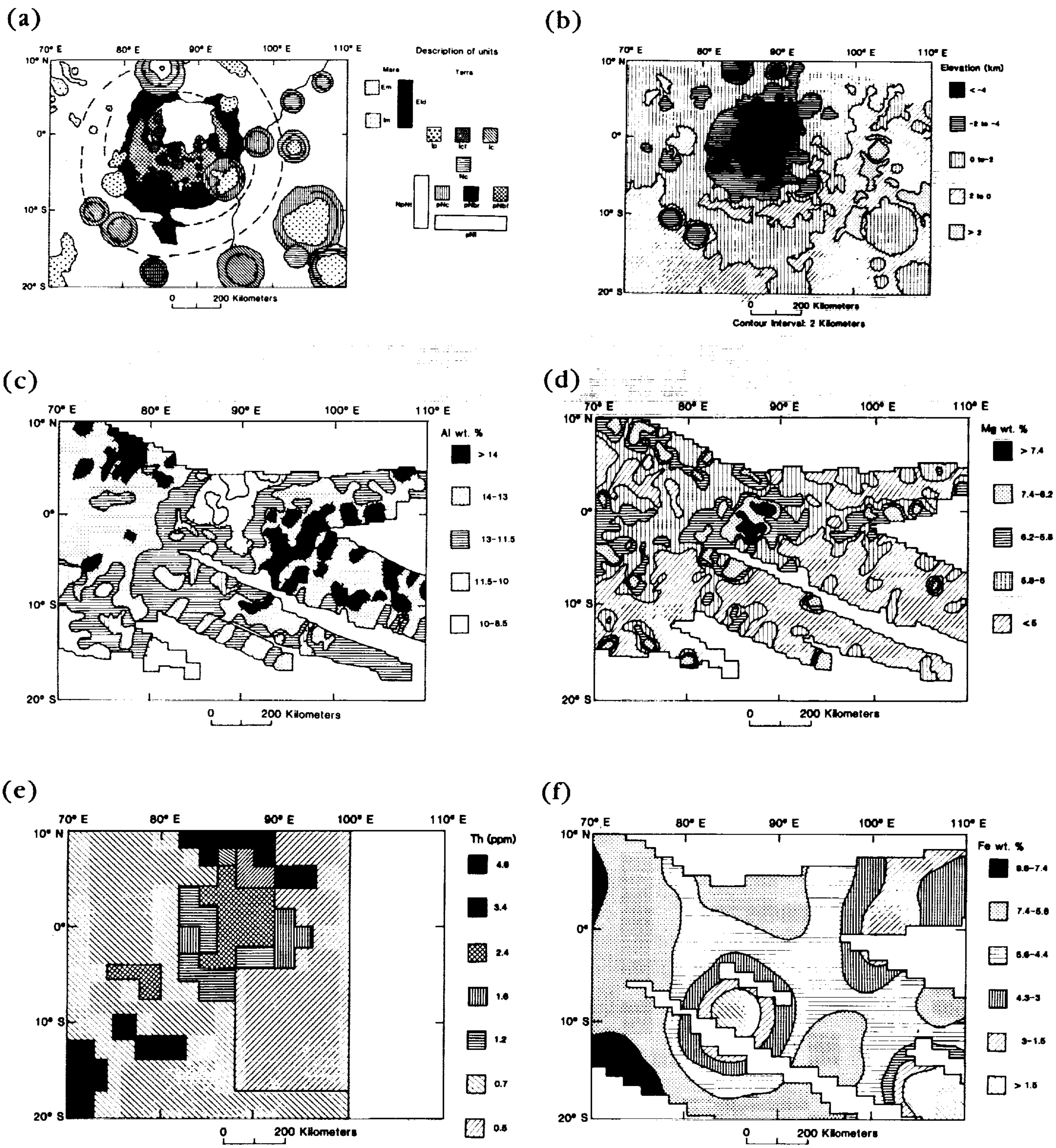


Fig. 3. Maps of geologic, topographic, and chemical remote-sensing data for the Smythii region. All geochemical data were obtained from the orbiting Apollo 15 and 16 spacecraft and, except for the thorium data, are from *La Jolla Consortium* (1977); chemical composition of major geologic units is summarized in Table 1. All maps are Mercator projection. **(a)** Geology, modified from *Wilhelms and El-Baz* (1977). Relative ages indicated by capital letters: E—Eratosthenian, I—Imbrian, N—Nectarian, pN—pre-Nectarian. Units: Em—basalts of Mare Smythii; Im—other mare basalts; EId—pyroclastic dark mantle deposits; Ip—smooth plains, some displaying dark-halo craters; Icf—floor-fractured craters; pNbr—Smythii basin rim material; pNbf—Smythii basin floor material; Ic, Nc, pNc—impact crater materials; NpNt and pNt—undivided terra (highlands) material. Dashed lines indicate basin rings. Smaller circular features are impact craters; lines with ticks indicate crater rims. **(b)** Regional topography from Apollo metric photographs by U.S. Geological Survey (unpublished, 1982). Elevations based on global datum of a spherical Moon 1738 km in radius. **(c)** Aluminum concentration (in weight percent). **(d)** Magnesium concentration (in weight percent). **(e)** Thorium concentration (in parts per million; from *Haines et al.,* 1978). **(f)** Iron concentration (in weight percent).

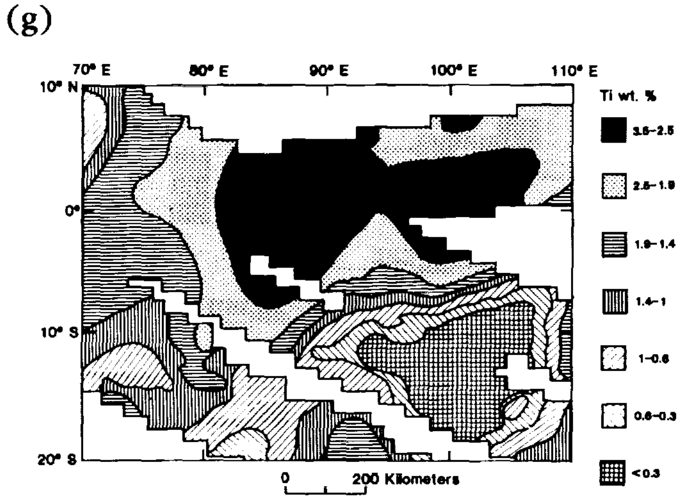


Fig. 3. (continued) **(g)** Titanium concentration (in weight percent).

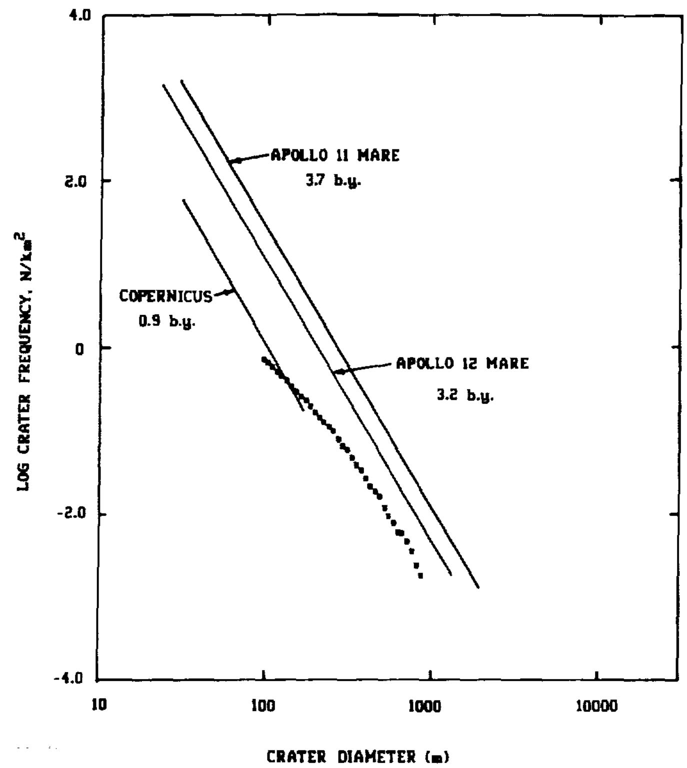


Fig. 4. Crater-frequency distribution for the mare basalt flows of Mare Smythii (squares), shown in comparison to those of the Apollo 11 and 12 landing sites and the crater Copernicus (from *BVSP,* 1981). Position of the Smythii curve indicates that these lava flows are significantly younger than those of the Apollo 12 site (the youngest sampled lunar lavas); the age of the Smythii flows is probably about 1 to 2 b.y.

Although very old by terrestrial standards, these are among the youngest lunar volcanic products; their study will greatly aid the reconstruction of the volcanic and thermal history of the Moon.

In addition to the lava flows within the basin, several localities exhibit dark mantling deposits (Fig. 2a-c). We know from the Apollo results that lunar dark mantles are composed of volcanic, pyroclastic deposits, such as the Apollo 17 orange glasses and black beads. Lunar pyroclastic glasses form in Hawaiian-type "fire fountaining" eruptions; moreover, the composition of these glasses indicates that they undergo little chemical modification during their ascent from their source regions in the lunar mantle. Thus, study of pyroclastics is important to understand lunar volcanism and the composition of the lunar mantle.

In addition to lava flows and pyroclastics, several craters inside the Smythii basin appear to be modified by internal processes (Figs. 2a-c, 3a). These features, floor-fractured craters, are not uncommon on the Moon and many are associated with the margins of the maria and other sites of volcanic activity. One hypothesis for their origin is that the subfloor zones of impact craters become sites of magmatic intrusions; the continuing injection of magma has uplifted the crater floor in a doming action that fractured them (*Schultz,* 1976). The Smythii basin, containing at least eight of these features in different states of development, is an ideal area in which to study the process of internal modification of impact craters.

The lunar terrae or highlands make up the vast bulk of the lunar crust. The crust appears to be composed largely of rocks rich in plagioclase (a silicate mineral rich in aluminum and calcium); such rocks are called anorthosites. One of the early ideas concerning the origin of the lunar crust was that the amount of plagioclase in the crust far exceeds what could be reasonably expected to be produced by partial melting and that a former "ocean" of magma existed on the Moon. The terrae surrounding the Smythii basin contain aluminum-rich terrains that are probably largely composed of anorthosites, heavily brecciated (shattered and reassembled) by impact cratering. These highlands offer an opportunity to study the rock types that make up the lunar crust as well as the effects of impact bombardment on the highlands.

One interesting and important lunar rock type contains high concentrations of potassium, rare earths, and other incompatible elements (those that do not fit well into the crystal structure of

TABLE 1. Compositional properties of selected geological units in the Mare Smythii region.

Material	Age*	Al wt%	Mg wt%	Ti wt%	Fe wt%	Th ppm	Comments
Mare Smythii	E/1-2	8.5-10	5->7.4	2.5-3.5	5.6-7.4	2.4	High-Ti mare basalts, thin with admixed highlands debris
Dark mantle	EI/3.5-1	10-11.5	5.8->7.4	2.5-3.5	4.4-5.6	1.2-2.4	Mafic, pyroclastic glasses, probably high-Ti
Basin rim	pN/~4.0	11.5->14	<5-5.8	0.6-1.9	<1.5-4.4	0.5-0.7	Anorthositic debris, breccias
Balmer plains	IN/3.9	10	6.2-7.4	1.4-1.9	7.4-9.6	4.0	Thin mantle of terra debris overlying KREEP basalts
Terra, west of basin	NpN/~4	11.5-13	<5-5.8	1-1.9	5-7.4	0.7	Anorthositic norite breccias
Terra, east of basin	pN/>4	13->14	<5	<0.3-1.4	<1.5-3	0.5	Anorthositic to pure anorthosite breccias

*Relative ages: E—Eratosthenian, I—Imbrian, N—Nectarian, pN—pre-Nectarian. Absolute ages (in billion years) are rough estimates.

common rock-forming minerals). This rock type, called KREEP, may represent the final stages of the crystallization of the original global magma system. KREEP is not uniformly distributed around the Moon, but in the Mare Smythii region, both Balmer and Mare Marginis contain KREEP-rich rocks (Figs. 2e, 3e; Table 1). At Balmer, KREEP basalts apparently underlie a thin covering of highlands debris, whereas at Marginis, the high KREEP appears to be associated with the mare lava flows. Thus, the Mare Smythii region offers the opportunity to study the occurrence and nature of KREEP-rich rocks in two entirely different geologic settings.

In short, the Smythii basin offers a wide variety of geologic units and processes for detailed investigation from a lunar base. From a centrally located base site, a series of traverses can be designed to explore this diverse terrain, as will be discussed below.

Geophysical Considerations

Structurally, the Smythii basin is of geophysical interest because (1) it is similar in size and depth to the younger Orientale basin (*Wilhelms,* 1987) and (2) it formed on a crust thought to be thicker (about 60 to 80 km thick) than that beneath the Apollo 12 and 14 landing sites (45-60 km thick). This thicker crust is inferred from the relative absence of strain-induced grabens in the Smythii region, which implies that subsidence was minimized by a thicker ancient lithosphere (*Solomon and Head,* 1980). Because the lithosphere and the more plastic asthenosphere were probably identical with the differentiated crust and mantle at the time of basin formation, a thicker crust is expected. A regional seismic network near a base in Mare Smythii would test this expectation directly and provide a determination of subsurface wave-velocity structure in a thick crustal zone to complement the Apollo results.

The Smythii and Orientale basins are also structurally similar in that they contain relatively thin mare basalt flows and strong gravity anomalies that imply the existence of subsurface mass concentrations or "mascons." The mascons are caused partly by the surficial mare basalt flows and partly by impact excavation of less dense crustal material, followed by rising of the denser mantle to compensate isostatically for the excavated crustal material. The existence of a relatively thick ancient lithosphere beneath Smythii is believed to have assisted in the preservation of a mascon beneath this basin despite its relatively thin mare fill. Geophysical characterization of the subsurface density structure under the Smythii basin (inferred from seismic and gravity surveys) will therefore provide a general test of models for the structure of mascon basins.

Mare Smythii is adjacent to a large group of swirl-like albedo markings north and east of Mare Marginis (Fig. 2d). Although the origin of these swirls is poorly understood, they are similar to markings found elsewhere on the Moon and are closely associated with strong magnetic anomalies detected from lunar orbit (Fig. 5). A base in Mare Smythii would therefore afford an opportunity to investigate the magnetic anomaly sources. In addition to establishing the nature of the swirls, such an investigation would further constrain the origin of lunar paleomagnetism, an enigma raised by the Apollo data (see *Lunar Geoscience Working Group,* 1986). The swirls have been suggested to be either surface residues of relatively recent cometary impacts or zones of the lunar surface that have been shielded from the ion bombardment of the solar wind by the associated strong magnetic fields. In the latter model, solar-wind hydrogen is considered a necessary part of the process that results in darkening with time (or "optical maturation") of lunar surface materials (*Hood and Williams,* 1988). To complicate matters further, it is likely that transient plasmas produced during hypervelocity impact are responsible for generating short-lived magnetic fields that magnetized some lunar surface materials. Geologic and magnetic investigations at a lunar base may verify this process in detail for the benefit of future paleomagnetic investigations of the Moon and similar bodies in the solar system.

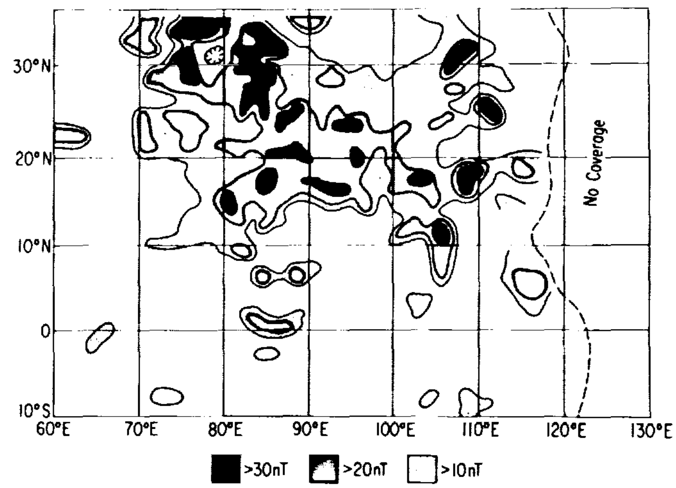


Fig. 5. Amplitude of near-surface magnetic fields in the region of Maria Smythii and Marginis as deduced from the reflection of low-energy electrons (from *Hood and Williams,* 1988).

At a lunar base, it will be important to obtain new heat flow measurements *in situ* to supplement the two Apollo measurements. A determination of the global mean heat flow is important for constraining not only the thermal state of the interior but also the bulk lunar composition (through the inferred abundance of heat-generating radioactive elements such as uranium and thorium). A major deficiency of the Apollo 15 and 17 heat flow determinations is that both were obtained near mare-terra boundaries, transitions between a surface with a thick, insulating megaregolith layer (the highlands) and a surface with a very thin insulating layer (the maria). Because heat flow at such boundaries is expected to be anomalously large, the Apollo measurements may not be representative of the Moon as a whole (*Warren and Rasmussen,* 1987). Although indirect orbital measurements of lateral variations in heat flow may be made prior to the establishment of a lunar base, direct Apollo-type heat flow determinations at additional sites around the Moon will be required to establish the absolute magnitude of global lunar heat flow. Measurements at sites in and around Mare Smythii (or any other circular mare) would allow an evaluation of heat flow as a function of megaregolith thickness. Mare Smythii is also known to be higher in radioactivity than the surrounding highlands (Fig. 3e); heat flow measurements in the Mare Smythii region, combined with orbital measurements of lateral heat flow and of surface abundance of radioactive elements, would therefore contribute ground truth for a more accurate evaluation of mean global heat flow.

Astronomical Considerations

The uses of a permanent lunar base for astronomical observations have been described in detail (*Burns and Mendell,* 1988; *Smith,* 1988). Here we will note the advantages offered by the Mare Smythii site for an astronomical observatory.

As discussed above, it is highly desirable to establish a radio astronomical observatory somewhere on the lunar farside, out of view of our electromagnetically noisy home planet. Perhaps the greatest advantage of the Smythii site is that the radio observatory could be near the main base, but out of Earth radio range. Moreover, the equatorial location of a Smythii site would ensure that the entire sky would be visible over the course of each lunar day (about 28 terrestrial days). The potential for astronomy at wavelengths other than radio is as exciting in this region as at any site on the Moon.

From a geocentric viewpoint, the Moon experiences about 8° of longitudinal libration: any point beyond 98° longitude is never in radio sight of the Earth. However, diffraction effects for very-low-frequency radio waves (*Taylor,* 1988) require that the radio observatory be located an additional 75 km east of this longitude (a degree of lunar longitude at the equator is about 30 km). Thus, the prime location for a lunar radio observatory is on the equator at any longitude greater than 100.5° east or west; at these locations, Earth radio noise does not exist. We suggest that the radio observatory for the Smythii base be an outpost, largely automated, located at 0, 101°E (Fig. 6). For routine maintenance of the observatory, a road could be bulldozed and the observatory serviced by tracked or wheeled vehicles. The observatory would be about 330 km from the main base; on a prepared road, routine speeds of at least 30 km/hr could be achieved, making the transit time to the observatory about 11 hours. Transport and servicing

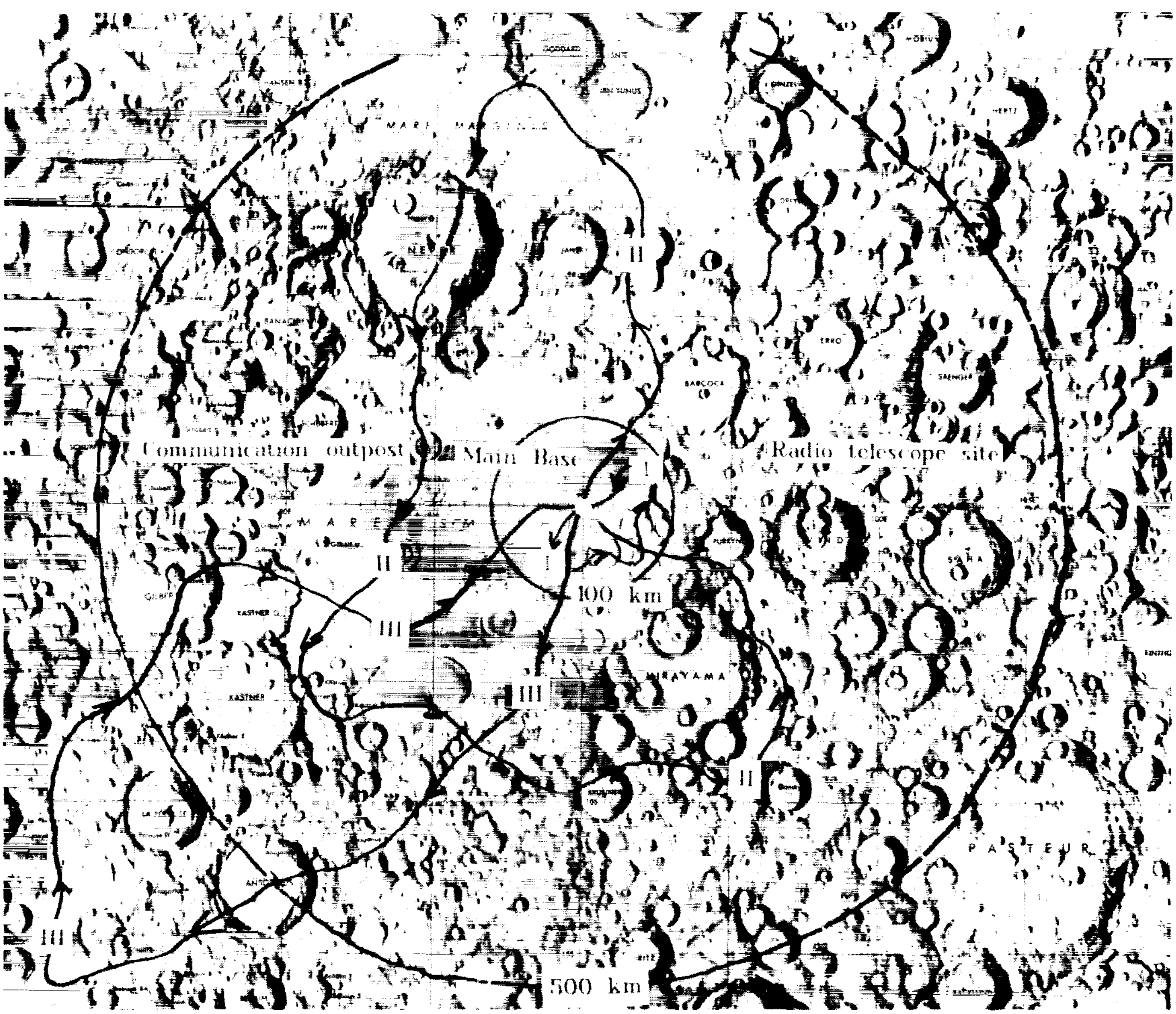


Fig. 6. Relief map of the Smythii region of the Moon, showing location of the main lunar base, the farside radio astronomical observatory, and permanent communications outpost. Circles indicate a 100-km and 500-km radius of action from the main base. Three model geological traverses (I, II, and III) are described in the text. Base is portion of LOC-2, original scale 1:2,750,000.

could be largely automated or teleoperated, thus greatly minimizing surface exposure risks to the human inhabitants of the lunar base.

The Mare Smythii site offers all the advantages of lunar-based astronomical observation. Its equatorial location would make the whole sky visible and the lunar farside is in close proximity. Other properties intrinsic to the Moon (e.g., hard vacuum, stable platform; see *Smith,* 1988) are as applicable here as at any lunar base site. In conjunction with its numerous other virtues, the Smythii site easily satisfies the criteria of lunar base astronomical users.

Lunar Resource Considerations

A wide variety of potential uses for the indigenous resources of the Moon has been identified (see sections 6, 7, and 8 in *Mendell,* 1985). Although these proposed uses differ widely by process and required feedstock materials, several lunar resources appear to be common to many different schemes. In general order of decreasing usefulness, these resources are bulk regolith, ilmenite (a Ti-rich mineral), volatiles, Al-rich highlands soils, and KREEP-rich material. Each of these materials is abundant at the Mare Smythii site.

The entire surface of the Moon is covered by a mass of fragmental material, ground up by impact bombardment, called regolith. The most important identified use of bulk regolith will be to shield surface habitats from the harsh radiation environment on the Moon (e.g., *Haskin,* 1985). This is the easiest recognized use of lunar materials; loose soil can be bulldozed to cover prefabricated living modules. Moreover, expanding human presence in Earth-Moon space will require shielding at space outposts where humans will live (e.g., in geosynchronous orbit or at the Lagrangian points). Thus, bulk lunar regolith may become one of the first economical lunar exports. Both mare and highlands surrounding the Smythii site are suitable for mining bulk regolith; the old age of the highlands suggests that the regolith is extremely thick in these areas, possibly as thick as 30 m.

The mineral ilmenite is of particular importance in schemes for utilizing lunar resources. Not only would ilmenite be useful in the production of oxygen on the Moon by a reduction process (e.g., *Gibson and Knudsen,* 1985), but ilmenite-rich soils contain high concentrations of ^{3}He, implanted on the grains by the solar wind over geologic time. This ^{3}He, used in terrestrial nuclear fusion reactors, could become the most profitable lunar export resource (*Wittenberg et al.,* 1986). Ilmenite is abundant in the mare basalts from the Apollo 11 and 17 landing sites; remote-sensing data show that these high-Ti basalts are widespread within the maria, including Mare Smythii (Fig. 3g; Table 1). Photogeological evidence suggests that the mare basalts here are relatively thin, but a significant amount of the observed soil chemistry of Mare Smythii is contributed by underlying highlands debris, added to the soils by vertical impact mixing (e.g., *Rhodes,* 1977). This observation and the observed relatively high Th content of Smythii soils (Table 1) suggest that the basalts of Smythii are similar in composition to the Apollo 11 high-K subgroup of high-Ti basalts. These basalts contain about 20% by volume ilmenite and about 7 wt% Ti (*BVSP,* 1981). Thus, the Mare Smythii basalts are prime candidates for any mining process that requires large amounts of ilmenite.

Volatile elements appear to be rare on the Moon. However, notable concentrations, including zinc, sulfur, and lead, are found on the surfaces of lunar pyroclastic glasses. Not only are these materials important for what they tell us about the indigenous lunar volatile content, but they also constitute a potential resource. As noted above, dark mantle pyroclastics are abundant in the Mare Smythii region (Figs. 2 and 3a) and are present in minable quantities on the basin floor. Because they are of small extent, we cannot be certain of their composition; however, pyroclastics found at the Apollo sites appear to be broadly similar in composition to their associated mare basalts. Thus, the Smythii pyroclastics are probably also of the high-Ti variety.

The highlands surrounding Mare Smythii display some of the highest Al concentrations seen in the Apollo orbital data (Fig. 3c). This suggests the presence of nearly pure anorthositic soils, an Al-rich material that is readily usable for construction on the lunar surface and in Earth-Moon space. One proposed process, which requires such soils, involves fluorination of anorthite (the major mineral in anorthosites) to produce both oxygen and aluminum (*Burt,* 1988).

KREEP, a material rich in trace-elements, is also available at the Smythii site, and it may ultimately be needed for phosphorus to support lunar agriculture. Although its extraction is probably an element of the advanced lunar base, it is fortunate that significant KREEP deposits are near the proposed base site.

Virtually every use of lunar resources that has been thus far proposed can be accomplished at a base site within Mare Smythii. Thus, the geological diversity that makes the Smythii site such an attractive candidate for geoscience exploration also makes it a prime candidate for lunar resource exploration and utilization.

Summary

The Mare Smythii region has several attractive attributes for the siting of a permanent lunar base. Its location on the equator and limb combines the best of the nearside and farside base advantages and permits easy access to the lunar surface from the supporting LEO spaceport. The geological diversity of the region, which contains mare basalts, pyroclastics, KREEP-rich rocks, and aluminous highland soils, permits a wide variety of surface scientific exploration and resource utilization. The regional context of the Smythii site is significantly different from the Apollo sites, thus enabling detailed comparative geophysical studies. A base established in Mare Smythii has the potential to service the various scientific and engineering users of such a base from one central location.

GEOLOGICAL FIELD INVESTIGATIONS AT SMYTHII BASE

Having detailed the numerous merits of the Smythii region for a lunar base, we now briefly discuss some model studies that could be carried out from such a base. For the purposes of this discussion, we will tentatively place the main base site at exactly 0, 90°E (Fig. 6); this site is on the high-Ti basalts of Mare Smythii and is a good location to utilize the ilmenite resources of the mare floor for both oxygen production and possible mining of ^{3}He. Moreover, the smooth, flat surface of Mare Smythii will also be conducive to the ultimate construction of a mass driver, thus making the export of lunar material cheap and reliable. Because the Earth will be out of radio view from this site on some occasions during the libration cycle, we show a communications outpost on the west rim of the Smythii basin at about 0, 81°E (Fig. 6). Here, a radio installation will have a permanent view of the Earth for base communications purposes; communication from this outpost to the main base ultimately will be established by direct optical link. For base start-up operations, either a surface relay network or a temporary comsat will provide a continuous radio link with the Earth.

We describe below three separate strategies for geological exploration based on the distance from the main base to features of interest at ranges of <100 km, 100-500 km, and >500 km from the base (Fig. 6). For extensive traverses beyond 100 km, we envision that most geological exploration will be by teleoperated robots (*Spudis and Taylor,* 1991) that would be directly controlled by geologists who remain at the main base site or, possibly, from the Earth. These robots have many advantages over human field workers and could effectively conduct most of the exploration advocated here. Follow-up visits by human geologists are assumed; these visits would largely consist of quick sorties to minimize extensive and complex life support systems and risks from radiation. Although planning for detailed traverses and field work cannot be done until a base site is selected, the following exploration plans are offered as examples that could be undertaken from a base in Mare Smythii.

Near-Base Activities (<100-km Radius)

In the early stages of base establishment, most geological work will probably be done near the base site; also, several scientific problems lend themselves well to near-base work even after the longer traverses begin. Thus, fieldwork near the base will start at the time of base emplacement and continue into the indefinite future.

The base's location on the basalt flows of Mare Smythii will provide the opportunity to study both regolith formation and lava stratigraphy. To determine the complete history of regolith formation and evolution, it will be most useful to bulldoze a pit down to bedrock (at this site, probably no more than a couple of meters, because of the young age of the Smythii lavas). The early stages of regolith growth are still almost completely unknown; within this pit, we can study the bedrock interface and address questions of grain-size evolution and soil maturity as study proceeds upsection. The sequence of lava flows and possible changes in magma composition with time can also be studied at the base site; this study of the regional bedrock unit can be done either directly (by shallow drilling and coring of the basalt flows) or indirectly (through the sampling of the ejecta from small craters in the mare to reconstruct possible subsurface layering).

Small particles of highlands rocks are found in the soils of all Apollo mare landing sites, and the aluminous composition of Mare Smythii (Table 1) suggests that this site is no exception. Most of these particles are derived from directly beneath the surface flows by vertical impact mixing of sublava highlands terrain. Thus, even though the base will be located on the mare flows, samples of the terra basin-floor materials will be available within the mare soils. Determining the composition and history of the highlands surrounding the Smythii base site will be one of the prime long-range tasks for the base geologists.

Farther afield, both the extensive dark-mantle pyroclastics and the internally modified floor-fractured craters are within 100 km of the main base site [Figs. 2a-c, 3a, 6 (I)]. The pyroclastics should be sampled to determine their place in the general volcanic history of the Smythii region, their possible compositional affinities to the mare basalt flows, the nature of their mantle source regions beneath the crust in this area, and their potential as minable resources. The floor-fractured crater Purkyne U (Fig. 2c) lies about 60 km east-southeast of the base site; this crater has an uplifted, fractured floor, partial fill by mare basalt (erupted from within the crater interior, as demonstrated by its unbreached rim), and a partial covering of dark pyroclastic material. Detailed field study of this crater could elucidate the processes of internal modification of lunar craters and contribute to our understanding of the volcanic history of the basin.

In addition to these primary studies, several smaller-scale ones will be conducted in the near-base area. These tasks will include study of a large population of small (<1-km diameter) craters to understand their formational mechanics and the regional cratering history, the study of lateral variations in both the lava flows and the subfloor basement, and investigations of the nature of crater rays. (This area is covered by rays from distant craters and it is important to establish the exact amounts of crater primary ejecta contained in ray material). These studies alone are of significant importance and complexity to provide the base geologists with challenging exploration opportunities.

Short-Range Traverse Activities (100-500-km Radius)

The middle range of exploration traverses is illustrated by the 500-km circle of Fig. 6. In this range, almost all the diverse geological features of the Smythii region are available for study. Model traverse route II (Fig. 6) could be followed by a tele-operated robot investigating the materials and processes described below. Undoubtedly, significant discoveries made along the way will perturb the actual route, but route II as shown encompasses most of the currently identified field geology goals.

In the first leg of the traverse, the lateral heterogeneity of the young Smythii lava flows north of the base will be investigated (Fig. 6). The north rim of the basin will be sampled to determine its relation to materials of the basin floor, collected near the base site (see above). Next, the traverse will continue north into the lava flows of the Mare Marginis basin (Fig. 2d). These lavas also appear to be relatively young (about 2 b.y. old); moreover, they are enriched in Th (up to 3.4 ppm; Fig. 3e). This suggests that they are a variety of KREEP-rich mare basalt, rare in the Apollo collections, and their study could shed light on the process of igneous assimilation of KREEP into mare basalt magmas.

The traverse will continue north to sample and investigate the mysterious swirl materials of northern Marginis (Fig. 2d). As described above, these swirls are associated with large surface magnetic anomalies (Fig. 5) and field studies of their composition and local environment are required to fully understand their origin. It would also be of interest to visit the crater Goddard A, as it has been proposed that this crater may be related to the Marginis swirls.

The traverse will now turn south, across Mare Marginis to determine its lateral variations, cross the mare-filled crater Neper, and return to the Smythii basin. One goal of this leg is to examine the lateral variations of the highland deposits making up the Smythii basin rim. The trip will continue south into the basin to examine and explore the floor-fractured craters Schubert C (Fig. 2b), Haldane, and Kiess. These craters display a range of modification states, and comparative studies between them and the previously studied Purkyne U (see above) will enable a resolution of the problem of their origin. In addition, this leg of the traverse covers the most abundant dark mantle deposits and local volcanic vents of the region (Figs. 2b and 3a). Field study of these features will aid in a detailed reconstruction of the volcanic history of the Smythii basin.

In the final leg of this traverse, we will study the highlands of the Smythii basin's south and west rims (Fig. 6). When this leg is completed, we will have a fairly complete knowledge of the lateral variations in basin rim deposits. We may even find evidence for large-scale compositional zoning within the basin ejecta deposits, a feature long postulated for basin geology based on incomplete and inadequate remote-sensing data, but as yet unproven on the Moon. This geological traverse provides a variety of features and processes for direct study, all within a fairly short traverse radius.

Long-Range Traverse Activities (>500-km Radius)

Beyond the 500-km limit, virtually the entire Moon beckons for detailed exploration. Indeed, one of the advantages of the teleoperated robot system is that it turns a single-site base into a "global base" by providing access to any point on the Moon (*Spudis and Taylor,* 1991). For the purpose of brevity, we here restrict our attention to a long-range traverse likely to be undertaken early in operations from the base, a mission to explore and sample the intriguing Balmer basin (Fig. 6, III).

As noted previously, Balmer is an old multiring basin apparently filled with light plains materials of Imbrian age (Figs. 2e and 3a). This otherwise unremarkable basin is worth investigating for two reasons: (1) the light plains that fill Balmer display dark-halo craters (Fig. 2e), indicating the presence of a subsurface basalt unit at least 3.9 b.y. old; and (2) orbital gamma-ray data suggest that this area is rich in KREEP (Fig. 3e), having a local Th concentration of 4 ppm. Moreover, this Th enrichment is coincident with the plains displaying dark-halo craters, suggesting that the KREEP component is associated with the underlying, ancient lava flows. In combination, these observations suggest the presence of ancient KREEP-rich basalt flows; flows of this composition have long been postulated in the lunar literature, but thus far we have identified only one example, the planar Apennine Bench formation near the Apollo 15 landing site. Because the concept of KREEP volcanism is so important to models of lunar evolution and because of the controversy over its existence, we have specifically planned this traverse to examine and characterize the volcanic fill of the Balmer basin.

The traverse begins by exploring the southwestern floor and rim of the Smythii basin, previously unvisited, to determine more completely the nature of the highlands around Mare Smythii and to provide comparative data for the previous traverses. This route includes a complete traverse of the crater Ansgarius; not only can we investigate the geology of this large, complex crater of Imbrian age, but this location also demarcates the crest of the outermost ring of the Smythii impact basin. The internal structure of this basin ring may be exposed within the walls of Ansgarius, thus making the detailed geologic structure of the ring available for study.

The traverse next proceeds to the plains of the Balmer basin. The goals in this area include characterization of the Imbrian-age light plains to determine their provenance and study of the dark-halo craters to understand their internal structure and ejecta. It is within the ejecta of these craters that we hope to find the long-sought KREEP basalts; through study of the ejecta volumes and their distribution around the craters, we can estimate the thickness of the overlying highlands debris mantle and, possibly, the thickness of the buried ancient basalts. Another important goal at this stop is study of regolith developed on the ejecta blankets of the dark-halo craters to understand how they form the strong photometric contrast seen in orbital photographs. These tasks involve intensive fieldwork; an advantage of using robots here rather than human field geologists is that as much time as is required can be spent in the field area to completely understand and solve these problems.

On the return trip to base, we will investigate the west basin rim and the light plains fill of the craters Gilbert and Kastner G (Fig. 6). At these two craters, an important question is the possible relation of their plains fill to that in the Balmer basin. If these light plains are related to the Crisium basin to the north (Fig. 1), these stops will test the concept of lateral variation in basin debris blankets and could also address the vexing question of primary basin ejecta vs. locally reworked material in highland plains materials. On the final leg, we will continue previously started field studies of the Smythii basin floor material, dark-mantle deposits and vents, and a previously unvisited floor-fractured crater, Runge (Figs. 3a and 6).

Summary

These three strategies of geological exploration demonstrate the amazing variety of geological units and processes that are available for direct exploration at the Smythii base site. The units represent the range of lunar geologic processes and absolute ages, from the ancient brecciated highlands crust to the youngest, rayed craters. Many additional traverses could be described; moreover, after a short time of base operations, many significant new discoveries will undoubtedly be made, thus altering the order of exploration priorities and planning of the actual routes. The total potential of a lunar base for geologic study is of such magnitude that it is impossible to predict the exact schedule and order of surface operations.

GEOPHYSICAL FIELD INVESTIGATIONS AT SMYTHII BASE

Following the order outlined above for geological exploration, we divide the discussion of geophysical exploration into categories depending upon the maximum radial traverse distance from the base.

Near-Base Activities (<100-km Radius)

After base establishment, the first priority for geophysical studies should be the deployment of an Apollo-type geophysical station containing such instruments as a seismometer, heat flow probe, magnetometer, and solar-wind spectrometer. These instruments should be emplaced near enough to the base to allow easy access for maintenance and recalibration but far enough away so that base activities do not add an undue amount of artificial noise to the measurements. The structure of near-surface seismic wave velocities can be determined using active sources, perhaps in conjunction with construction or mining activities. To deduce the structure at greater depths, using a single-station seismometer, will require active energy sources of increasing magnitude, comparable to those produced by the planned crashes of LM ascent modules and S-IVB stages during the Apollo program. Measurements from a single heat flow probe should be monitored for at least a year to establish the thermal properties of the surrounding regolith, which are needed for heat flow determination. The final value, if obtained away from the periphery of the mare, will provide a valuable benchmark for comparison with the Apollo values. A single magnetometer and solar-wind spectrometer will define the local crustal magnetic strength at the base site and determine the extent of deflection by this magnetic field of ions in the solar wind.

The next order of priority after establishing the base geophysical station is to conduct field geophysical measurements during the surface geological traverses. A local area network of seismic stations should be emplaced to allow passive seismic studies using meteoroid impacts and shallow moonquake sources. Active seismic sounding using artificial sources will also be very effective using this local array. Heat flow probes can be deployed at a series of sites on different megaregolith thicknesses to obtain a first determination of the dependence of lunar heat flow on this quantity. During exploratory traverses, it will be desirable to obtain direct surface gravity and elevation measurements at specific points along the route to constrain later modeling studies of subsurface density structure. These measurements will provide a ground-truth supplement to Apollo and LO orbital gravity and topography data. Also, magnetic field and solar-wind flux measurements along the traverse will provide the first direct measurements of solar-wind deflection as a function of surface magnetic field intensity and direction. The surface magnetic field measurements, combined with orbital magnetic data, will also facilitate modeling of the bulk magnetization properties of large-scale geologic units (e.g., mare basalt flows) in order to constrain the nature and origin of lunar paleomagnetism.

Short-Range Traverse Activities (100-500-km Radius)

Several important geophysical investigations can be made during the medium-range traverse discussed above (II in Fig. 6). This traverse will enable the deployment of one or more geophysical stations that will become part of a regional network designed to determine the subsurface structure and thermal state of the Smythii region. The primary instruments to be deployed at these stations will be seismometers and heat flow probes. In order to resolve basin structure, individual seismic stations should be no more than about 150 km (5°) apart, requiring at least 8 regional stations in addition to the base station. Active seismic sounding near at least one of the highland stations will allow the first direct crustal thickness determination at a highland site on the Moon. As noted previously, the crust is expected to be substantially thicker in this region than at the Apollo sites. Crustal thickness peripheral to the basin will be larger still because of the expected isostatic raising of the crust-mantle boundary beneath the basin center. Following establishment of both mare and terra seismic velocity and thickness benchmarks using active methods, the passive network will be capable of a first-order determination of the velocity structure beneath the entire basin. In combination with gravity and topography surveys, the two-dimensional velocity model will provide strong constraints on the subsurface composition and density structure of this mascon basin. Heat flow measurements will likewise establish the lateral variation of surface heat flow and probable subsurface thermal state as a function of radial distance from the basin center.

A traverse to the Mare Marginis swirl belt will make possible direct surface magnetometer and solar-wind spectrometer measurements at the site of one of the largest magnetic anomalies on the Moon (Fig. 5). As stated above, simultaneous geologic investigation and sampling of the swirls should establish their origin. As a by-product of these investigations, solar-wind spectrometer measurements will determine the lateral variation of the implantation rate of solar-wind gases (mostly hydrogen and helium) into the uppermost regolith. For example, the strongest lunar magnetic anomalies are probably capable of completely deflecting bombardment by ions of the solar wind (*Hood and Williams,* 1988). This process will lead to zones of relatively low implantation rates near the centers of large surface anomalies and zones of high implantation rates in complex, curvilinear areas peripheral to the same anomalies. Measurement of these fluxes will be helpful for evaluating the volatile resource potential (i.e., the extraction efficiency of trapped solar wind gases; *Haskin,* 1985) of different source regions. Furthermore, the strongest magnetic anomalies are characterized by surface field amplitudes that probably exceed several hundredths of a Gauss (for comparison, the Earth's field near the equator at the surface is about 0.3 G). Depending upon their horizontal scale, these relatively strong crustal fields may be capable of significantly deflecting a part of the solar cosmic ray flux during flare events. If such deflection is beneficial in reducing the hard radiation environment for human activities, then it may even be desirable to locate outposts or bases within the shelter of strong magnetic anomalies.

Long-Range Traverse Activities (>500-km Radius)

When the robotic field explorations are extended to greater distances, identified geologic targets can be characterized using geophysical methods. For example, along the suggested route III of Fig. 6, small-scale seismic sounding and surface gravity measurements may be useful in delineating the thickness of subsurface basalt units in the Balmer basin and in identifying the crest of the outermost ring of the Smythii basin. More generally, remote geophysical stations may be deployed to allow seismic and electromagnetic sounding of the deeper lunar interior. These stations would be part of a global-scale network that should be established in the course of continuing field investigations. Among the major objectives of large-scale seismic and electromagnetic sounding network studies are determinations of the seismic-velocity profile of the lunar mantle and of the existence and size of a possible metallic core. Although core detection may be achieved earlier through alternative approaches, a detailed characterization of the size, mass, and physical properties of the core will probably require long-term seismic measurements using a large number of stations. Similarly, a more accurate appraisal of mantle structure and thermal state will need both long-term and large-scale seismic, electromagnetic, and heat flow measurements. Thus, the geophysical stations deployed in the course of lunar base activities and traverses will contribute significantly to an eventual accurate determination of the structure, composition, and thermal state of the deep lunar interior. Because the bulk composition of the Moon (including core size and mass) is a basic constraint of lunar origin models, such a determination will lead to a much improved understanding of the origin of the Moon.

CONCLUSIONS

We have demonstrated that the Mare Smythii region holds great promise as a lunar base site from a scientific, operational, and resource utilization viewpoint. This site enables enough flexibility to satisfy any potential lunar base user. Among its attributes are the following:

1. Its location on the lunar limb permits the establishment of a base complex that combines the benefits of a nearside base (for ease of initial and routine base operations) and a farside base (to

shield the radio astronomical observatory from the electromagnetic interference produced by the Earth).

2. Its equatorial location allows for easy base access from the LEO space station and also permits a clear view of the entire sky for astronomical observations.

3. The Smythii region abounds in a diversity of both geologic features and natural resources. This diversity permits a wide range of geological and geophysical investigations to be performed and it also provides almost the entire known range of potential lunar resources to be mined, processed, and used on the Moon and in Earth-Moon space.

Nearly all the identified lunar geoscience problems can be addressed at a base located in Mare Smythii. Some of these problems are the origin and evolution of the lunar crust and mantle, the cratering history of the Moon, the formational mechanics of large craters and basins, the nature and evolution of the lunar regolith, the origins of lunar paleomagnetism, and lunar volcanic history. Geologic and geophysical field studies conducted from the Smythii base will provide data applicable to all these problems.

Based on our study of the Smythii region, we have tentatively identified the following operational requirements for base establishment and initial operations:

1. We propose that the main lunar base be located at 0, 90°E, in Mare Smythii. This location will provide high-Ti mare regolith as a feedstock for oxygen production and possibly ^{3}He mining, and it allows easy access to a variety of important geological and geophysical exploration targets.

2. At least two installations will be required in addition to the main base. The first is a communications outpost on the west rim of the basin at about 0, 81°E. This site is in constant radio view of the Earth; the outpost will be needed as a relay station when the main base is out of contact with Earth during minimum libration cycles. The outpost will be connected to the main base by an optical link cable emplaced during base start-up; interim Earth-Moon communications can be provided by a temporary lunar comsat.

3. The second outpost could be a lunar very low frequency radio astronomy observatory. It should be located on the equator east of 100.5°E; we suggest an intercrater area at 0, 101°E, where the observatory will be permanently shielded from radio noise from the Earth. The suggested site is about 330 km from the main base; a road can be constructed to allow easy rover access to service the outpost.

4. As we envision base operations, most geological field work and emplacement of geophysical instruments can be done by teleoperated robots. Some visits by humans to sites distant from the base will be required.

Acknowledgments. This work is supported in part by the Office of Exploration, National Aeronautics and Space Administration. We thank J. Taylor for discussion of astronomy requirements and M. Cintala, B. R. Hawke, J. Whitford-Stark, and R. Wildey for their helpful review comments.

REFERENCES

Arnold J. R. (1979) Ice in the lunar polar regions. *J. Geophys. Res., 84,* 5659-5668.

Burke J. D. (1985) Merits of a lunar polar base location. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 77-84. Lunar and Planetary Institute, Houston.

Burns J. O. and Mendell W. W., eds. (1988) *Future Astronomical Observatories on the Moon.* NASA CP-2489. 134 pp.

Burt D. M. (1988) Lunar mining of oxygen using fluorine (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 43. Lunar and Planetary Institute, Houston.

BVSP (Basaltic Volcanism Study Project) (1981) *Basaltic Volcanism on the Terrestrial Planets.* Pergamon, New York. 1286 pp.

Duke M. B., Mendell W. W., and Roberts B. B. (1985) Strategies for a permanent lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 57-68. Lunar and Planetary Institute, Houston.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Haines E. L., Etchegaray-Ramirez M. I., and Metzger A. E. (1978) Thorium concentrations in the lunar surface. II: Deconvolution modeling and its application to the regions of Aristarchus and Mare Smythii. *Proc. Lunar Planet. Sci. Conf. 9th,* pp. 2985-3013.

Haskin L. A. (1985) Toward a spartan scenario for the use of lunar materials. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 435-444. Lunar and Planetary Institute, Houston.

Hood L. L. and Williams C. R. (1988) The lunar swirls: Distribution and possible origins. *Proc. Lunar Planet. Sci. Conf. 19th,* pp. 99-113.

La Jolla Consortium (1977) Global maps of lunar geochemical, geophysical, and geologic variables. *Proc. Lunar Sci. Conf. 8th,* frontispiece, 25 plates.

Lunar Geoscience Working Group (1986) *Status and Future of Lunar Geoscience.* NASA SP-484, Washington, DC. 54 pp.

Mendell W. W., ed. (1985) *Lunar Bases and Space Activities of the 21st Century.* Lunar and Planetary Institute, Houston. 865 pp.

Rhodes J. M. (1977) Some compositional aspects of lunar regolith evolution. *Philos. Trans. R. Soc. London, A285,* 293-301.

Schultz P. H. (1976) Floor-fractured lunar craters. *Moon, 15,* 241-273.

Smith H. J. (1988) Why the Moon is the best place in the solar system from which to do astronomy (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 266. Lunar and Planetary Institute, Houston.

Solomon S. C. and Head J. W. (1980) Lunar mascon basins: Lava filling, tectonics, and evolution of the lithosphere. *Rev. Geophys. Space Phys., 18,* 107-141.

Spudis P. D. and Taylor G. J. (1992) The roles of humans and robots as field geologists on the Moon. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Taylor G. J. (1989) Site selection criteria. In *A Lunar Far-Side Very Low Frequency Array,* pp. 61-63. NASA CP-3039.

Warren P. H. and Rasmussen K. L. (1987) Megaregolith insulation, internal temperatures, and bulk uranium content of the Moon. *J. Geophys. Res., 92,* 3453-3465.

Wilhelms D. E. (1987) *The Geologic History of the Moon.* U.S. Geol. Surv. Prof. Paper 1348. 302 pp.

Wilhelms D. E. and El-Baz F. (1977) Geologic map of the east side of the Moon. *U.S. Geol. Surv. Map I-948.*

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of ^{3}He for commercial fusion power. *Fusion Technol., 10,* 167-178.