A SEARCH FOR INTACT LAVA TUBES ON THE MOON: POSSIBLE LUNAR BASE HABITATS

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We have surveyed lunar sinuous rilles and other volcanic features in an effort to locate intact lava tubes that could be used to house an advanced lunar base. Criteria were established for identifying intact tube segments. Sixty-seven tube candidates within 20 rilles were identified on the lunar nearside. The rilles, located in four mare regions, varied in size and sinuosity. We identified four rilles that exhibited particularly strong evidence for the existence of intact lava tube segments. These are located in the following areas: (1) south of Gruithuisen K, (2) in the Marius Hills region, (3) in the southeastern Mare Serenitatis, and (4) in eastern Mare Serenitatis. We rated each of the 67 probable tube segments for lunar base suitability based on its dimensions, stability, location, and access to lunar resources. Nine tube segments associated with three separate rilles are considered prime candidates for use as part of an advanced lunar base.

INTRODUCTION

Early observations indentified many meandrous channels, or sinuous rilles, on the lunar surface (*Schröter,* 1788). Since then, numerous studies have shown that these features formed as a result of the extrusion of hot, fluid, low-viscosity basaltic magma (e.g., *Hulme,* 1973; *Wilson and Head,* 1981; *Coombs et al.,* 1987), some of which may have evolved into lava tubes when segments of the channels roofed over (e.g., *Oberbeck et al.,* 1969; *Greeley,* 1971; *Cruikshank and Wood,* 1972; *Hulme,* 1973; *Coombs et al.,* 1987). The prospect of using the natural cavity formed by a drained intact lunar tube for housing a manned lunar base has long been the subject of speculation (e.g., *Brown and Finn,* 1962; *Henderson,* 1962).

In his discussion of lava tubes as potential shelters for lunar habitats, *Hörz* (1985) noted that the lunar lava tubes would be ideal for locating the lunar base because they (1) require little construction and enable a habitat to be placed inside with a minimal amount of building or burrowing; (2) provide natural environmental control; (3) provide protection from natural hazards (i.e., cosmic rays, meteorites and micrometeorite impacts, impact crater ejecta); and (4) provide an ideal natural storage facility for vehicles and machinery.

A lava tube may form when an active basaltic lava stream or leveed flow develops a continuous crust. More specifically, depending on the rate of flow and the rheology of the lava, a lava tube may form by one of several methods (e.g., *Cruikshank and Wood,* 1972; *Greeley,* 1987): (1) An open channel may form a crust that extends from the sides to meet in the middle and may eventually thicken and form a roof; (2) in more vigorous flows, the crustal slabs may break apart and raft down the channel; as pieces are transported down the channel they may refit themselves together to form a cohesive roof; (3) periods of spattering, sloshing, and overflow may form levees that may eventually build upward and inward and merge into a roof; or (4) lava tubes may also form by the advancement of pahoehoe lava toes (see *Wentworth and McDonald,* 1953). Under the conditions of lunar basaltic eruptions (lower gravity field, no atmosphere), such processes would have produced lunar lava channels and associated tubes at least an order of magnitude greater in size than those found on Earth (*Wilson and Head,* 1981). Such lunar lava tubes could be tens to hundreds of meters wide by hundreds of meters deep and tens of kilometers long. These dimensions make lunar lava tubes ideal sites in which to house a lunar base habitat.

Swann (personal communication, 1988) has raised the question of the existence of open, evacuated lunar lava tubes. He contends that the lunar lava tubes may have been filled in upon cessation of the eruption that formed them. Here, we present evidence to the contrary and show that it is entirely possible that open lava tubes were left on the Moon and that it is very likely that they still exist. Work done by *Hulme* (1973, 1982), *Wilson and Head* (1980, 1981), and others has shown that lunar sinuous rilles are products of low-viscosity, high-temperature basaltic lava flows, and that these features are very similar to terrestrial basaltic lava channels and tubes. With the lack of extensive field evidence from the Moon, terrestrial lava tubes have often been studied as examples of what the formation process would have been like for the lunar features (e.g., *Greeley,* 1971; *Cruikshank and Wood,* 1972). Although there is an order of magnitude size difference between lunar and terrestrial tubes, the formational processes appear very similar.

Terrestrial evidence indicates that a tube may or may not become plugged with lava depending on the viscosity, temperature, supply rate, and velocity of the lava flowing through it. Numerous terrestrial lava tubes have been observed during their formation (e.g., *Greeley,* 1971; *Cruikshank and Wood,* 1972; *Peterson and Swanson,* 1974). Of the tubes observed during the process of formation, most did not become congealed and solidify into hard tubular masses of rock at the time of their origin (*e.g., Greeley,* 1971; *Cruikshank and Wood,* 1972). It has been noted that as the supply rate of lava diminished during an eruption, the level of liquid in the tube dropped, leaving a void space between the top of the lava flow and the roof of the tube (*Peterson and Swanson,* 1974). At the end of an eruption most of the lava was

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observed to drain out of the main tube to leave an open tunnel of varying dimensions (e.g., *Macdonald et al.,* 1983). However, the tubes may later act as conduits for younger lava flows erupting from the common source vent. These later flows may partly or completely fill the older lava tube depending on their supply rate and amount of material flowing through. While we cannot discount that similar occurrences may have happened during the formation of the lunar lava tubes, it is unlikely that it happened to a high percentage of them. Field observations of several volcanic terrains in Hawaii indicate that the majority of lava tubes formed remain partially void, that is, less that 30% of the tube has been (partially) infilled by later flows. Fewer than 1% of the lava tubes observed in the field by *Coombs et al.* (1989) are completely filled in by later flows (e.g., Makapu'u Tube, Oahu, Hawaii). Of the several hundred lava tubes known to exist on and around Kilauea, more than 90% are open or void; less than 30% of the tube has been filled in by later flows. In those tubes that have been partially infilled, the lava toes extend inward from the tube walls. Very few lava tubes are completely filled and, in fact, only one, Makapu'u Tube, on Oahu, Hawaii, was observed by the authors to have been completely filled in by later flows (*Coombs et al.,* 1989).

Other evidence, derived from the study of lunar volcanic features, suggests that not all lunar tubes are plugged with congealed lava and that void lava tubes exist on the Moon. Many lava channels have been identified on the lunar surface (e.g., *Oberbeck et al.,* 1969; *Cruikshank and Wood,* 1972; *Masursky et al.,* 1978; *Schaber et al.,* 1976; *Greeley and King,* 1977). These channels do not appear to be filled with solidified lava along most of their lengths. The same is true for most lunar sinuous rilles. *Greeley and King* (1977) demonstrated that thin lunar flow units typically were emplaced by lava tubes. It appears that the low-viscosity lunar lavas drained from large segments of the identified channel-tube systems and sinuous rilles. Finally, it should be noted that there are numerous instances where several tube candidates are located along sinuous rilles and where these tube segments are bounded at each end by open, deep rille segments. Since these open, deep rille segments are not filled with congealed lava, we suggest that the roofed portions of the rille (i.e., the tubes) are not filled and are likely to be void or partly void tubes.

A great deal of discussion has centered around the strength and durability of existing lunar lava tubes (*Oberbeck et al.,* 1972). Whether or not the tube roofs are structurally stable enough to withstand prolonged meteoroid impact and sufficiently thick enough to provide protection from cosmic radiation have been pressing questions (*Hörz,* 1985). The results of calculations by *Oberbeck et al.* (1969), as well as terrestrial field evidence, support the concept that many of these features are evacuated and have remained intact during the billions of years of meteoritic bombardment and seismic shaking to which they have been subjected since their formation. *Oberst and Nakamura* (1988) have examined the seismic risk for a lunar base but have not dealt specifically with the effects of moonquakes on lunar lava tubes.

Many intact lava tubes exist along the east and southwest rift zones of Kilauea Volcano on the Big Island of Hawaii. Two of the largest of these tubes are Thurston Lava Tube (Keanakahina), which was formed 350-500 years b.p., and an unnamed tube on the floor of Kilauea Caldera that was formed during the 1919 eruption of Halemaumau. The respective average dimensions of these two lava tubes are 4.90 m wide × 2.20 m high and 8.60 m wide × 3.73 m high. Both of these lava tubes have maintained their structural integrity while constantly being shaken by local seismic tremors. On any given day the summit area of Kilauea may experience as many as 300 or more earthquakes of magnitude 4 or less (*Klein et al.,* 1987). The frequency and magnitude of these earthquakes intensifies immediately prior to the onset of an eruption. Much greater magnitude earthquakes are also common to the area as evidenced by two fairly major earthquakes that occurred in the recent past. The 1975 Kalapana and 1983 Kaoki earthquakes, with magnitudes of 7.5 and 6.6 respectively, appear to have had no effect on these two lava tubes. In summary, a long and varied seismic history has had minimal effect on the lava tubes in the Kilauea area and elsewhere on the island of Hawaii. It is possible then, that many of the lunar lava tubes have remained intact over the billions of years of the seismic shaking generated by meteorite impacts and tectonically originated moonquakes.

Oberbeck et al. (1969) determined that the ratio of roof thickness to interior tube width in terrestrial lava tubes ranges from 0.25-0.125. When applied to lunar conditions, they calculated that a 385-m-wide tube roof would remain stable providing the roof was 65 m thick. They further noted that the effect of roof arching, common in terrestrial lava tubes, would allow even thinner 385-m-wide roofs to remain intact and, if the lunar rock is assumed to be more vesicular than that on Earth, the maximum stable width could reach 500 or more meters. Thus, stable tube roofs could exist on the Moon provided that they span a width of no more than a few hundred meters and that the larger tubes have roofs that are at least 40-60 m thick.

As *Hörz* (1985) pointed out, these estimates are also in agreement with other important observations. He noted, for example, that impact craters a few tens of meters to 100 m across are supported by uncollapsed roofs of identified lava tubes. With depth/diameter ratios of small lunar craters ~1/4-1/5 (*Pike,* 1976), the excavation depths of these craters superposed on the lava tubes could reach 25 m. Hörz estimated further that the roof thickness must be at least twice any crater depth, otherwise a complete penetration of the tube roof would have occurred.

In this paper we propose a set of criteria for the identification of intact lunar lava tubes. A survey of all known sinuous rilles and channels, as well as other selected volcanic features, was conducted in an effort to locate lava tube segments on the lunar surface. In addition, we have attempted to assess the potential of the identified lava tubes as candidates for lunar base sites. This paper presents the results of our survey.

METHOD

We conducted a survey of all available Lunar Orbiter and Apollo photographs in order to locate possible intact lava tubes. The criteria used to identify tube candidates were (1) the presence of an uncollapsed, or roofed, segment or, preferably, a series of segments along a sinuous rille; (2) the presence of uncollapsed segments between two or more elongate depressions that lie along the trend of the rille; and (3) the presence of an uncollapsed section between an irregular-shaped depression, or source vent, and the rest of the channel.

The above criteria were applied to all previously identified lunar sinuous rilles (e.g., *Oberbeck et al.,* 1969; *Schultz,* 1976) and others identified from the survey of all available Lunar Orbiter and Apollo photographs. Other volcanic features such as endogenic depressions, crater chains, and other types of rilles were also examined as some may be associated with a lava tube. Exogenic crater chains were distinguished from the partially collapsed tube segments by the lack of crater rays and herringbone patterns in the vicinity of the latter. Also, exogenic crater chains are commonly composed of closely spaced or overlapping round to oval craters, while the craters in endogenic chains are elongate or irregular in form. Further, secondary craters within a chain are often deeper at one end than the other and downrange craters are commonly superposed on uprange craters. Endogenic craters are more uniform in depth and generally do not exhibit systematic overlap relationships.

The locations of the identified lava tube segments and various measurements that were made for each tube are given in Table 1. Maximum tube widths were estimated by projecting the walls of adjacent rille segments along the roofed-over segments. Tube lengths were measured from the Lunar Orbiter and Apollo photographs. An estimate of the depth to each tube, or roof thickness, was made, when possible, following the crater-geometry argument presented by *Hörz* (1985) whereby the largest impact crater superposed on an uncollapsed roof may yield a minimum measure of roof thickness. To calculate this minimum roof thickness the following equation was used

$$d \cdot 0.25 \cdot 2 = t \qquad (1)$$

where d is the maximum crater diameter superposed on the tube segment and t is the estimated minimum thickness of the tube segment. This equation provides a conservative estimate of the

TABLE 1. Lava tube candidates.

ID No.	Latitude	Longitude	Orbiter Frame No.	Tube Length (km)	Tude Width (km)	Crater Width* (km)	Roof Thickness† (m)	Rank‡ (A = Prime, B = Good, C = Possible)
A1	22°00′ N	30°30′ W	IV-133-H_3	2.20	0.55	0.44	110	B
2				1.10	0.55	0.22	110	A
3				0.55	0.33	0.22	110	C
B1	22°00′ N	29°oo′ W	IV-133-H_3	0.88	044	022	110	B
2				1.10	0.55	0.55	276	C
3				4.40	0.03	0.22	110	B
4				0.55	0.33	0.44	220	C
5				1.10	0.33	0.11	56	C
6				5.50	0.44	0.44	220	B
C1	35°00′ N	43°00′ W	V-182-M	0.90	0.72	0.06	30	A
2				1.20	0.97	0.09	46	A
3				0.66	0.60	0.27	136	B
4				0.54	0.60	0.12	60	A
5				0.60	0.45	0.09	46	A
6				0.60	0.82	0.09	46	A
7				0.51	0.82	0.09	46	A
D1	36°00′ N	40°00′ W	V-182-M	0.90	0.15	0.06	30	C
E1	36°00′ N	40°00′ W	IV-158-H_2	4.92	1.20	0.80	60	B
2	47°30′ N	57°00′ W		1.20	0.36	—	—	B
3				2.40	0.48	0.24	120	B
4				1.32	0.60	0.24	120	B
F1	30°00′ N	48°30′ W	IV-158-H_1	2.40	1.20	0.60	300	C
G1	27°00′ N	41°45′ W	V-191-M	2.37	0.32	0.38	190	B
2	26°30′ N	42°00′ W		1.87	0.23	0.75	375	C
3	27°00′ N	42°00′ W		0.88	1.25	0.20	100	C
H1	15°30′ N	47°00′ W	IV-150-H_2	1.65	0.88	0.22	110	C
I1	10°30′ N	49°00′ W	IV-150-H_2	1.32	0.88	—	—	B
2				1.32	0.77	0.22	110	C
3				6.60	0.66	—	—	C
4				4.60	0.55	0.33	165	C
Ja1	15°00′ N	57°00′ W	V-213-M	0.25	0.33	0.08	40	B
2				0.25	0.34	0.25	125	B
3				0.25	0.25	0.03	15	B
4				0.13	0.33	0.05	25	C
b5				0.35	0.37	0.08	40	B
6				0.25	0.32	0.05	25	B
7				1.63	0.33	0.15	75	B
8				1.63	0.38	0.08	40	C
9				7.37	0.47	0.25	125	C
10				0.37	0.28	0.08	40	C
11				0.75	0.48	0.08	40	C

TABLE 1. (continued).

ID No.	Latitude	Longitude	Orbiter Frame No.	Tube Length (km)	Tude Width (km)	Crater Width* (km)	Roof Thickness† (m)	Rank‡ (A = Prime, B = Good, C = Possible)
K1	12°00′ N	53°00′ W	IV-157-H_2	6.60	0.55	0.33	165	C
2				10.45	1.03	1.10	525	C
3				8.80	0.88	0.66	330	C
4				2.75	0.66	0.11	55	B
5				1.10	0.33	—	—	B
6				5.50	0.55	0.22	110	C
L1	2°00′ N	44°00′ E	IV-66-H_1	3.30	1.32	—	—	C
2				6.60	1.32	—	—	C
M1	4°00′ N	28°00′ E	IV-78-H_1	7.70	0.88	—	—	C
2				4.40	0.55	—	—	C
N1	11°00′ N	20°00′ E	IV-85-H_2	17.60	0.77	0.99	495	C
2				2.53	1.10	0.33	165	C
C				4.62	0.99	—	—	C
O1	18°00′ N	26°00′ E	IV-78-H_2	0.77	0.51	0.07	35	B
2				0.32	0.51	0.05	25	B
3				0.32	0.48	0.05	25	B
4				0.88	0.48	0.03	15	B
5				0.77	0.46	0.08	40	B
P1	51°00′ N	8°00′ W	V-129-M	0.84	0.21	0.13	65	B
2				1.26	0.21	0.17	85	C
3				1.68	0.29	0.13	65	C
Q1	16°00′ S	37°00′ W	IV-137-H_2	1.65	0.44	—	—	C
R1	29°00′ N	29°00′ E	IV-85-M	1.32	1.10	—	—	A
2				7.15	0.55	0.66	330	A
?1	20°00′ N	30°00′ E	IV-78-H_3	—	—	—	—	C
?2	1°00′ N	28°00′ E		—	—	—	—	C

*Crater width = maximum crater diameter measured on top of tube segment.
†Roof thickness = minimum tube roof thickness from depth of largest superposed crater (after *Hörz,* 1985).
‡Refers to the suitability of a particular tube segment for locating the advanced manned lunar base.

roof thickness, whereby the maximum crater depth is approximately one-quarter the crater diameter (0.25d) and the roof thickness (t) is at least twice that depth (after *Hörz,* 1985).

As part of the assessment of the suitability of the identified tube segments for housing an advanced lunar base, several factors were considered. The usefulness (presence of scientific targets near the base site, geologic diversity) of the locality, whether or not the site would be readily available (minor excavation and construction) for habitation, and its location were considered. The presence of potential lunar resources (e.g., high-Ti mare basalt or pyroclastics) in the region and ease of access to these deposits were important considerations, as were the proximity and ease of access to all features of interest in a region. Localities were sought in which little or no degradation appears to have occurred along and adjacent to the tube segments. The preferred sites exhibited few impact craters and/or young ridges that may indicate the presence of a fault system. It has been demonstrated that a more central location (near the equator) on the lunar nearside would provide a better site for the mass driver to launch various payloads to L_2 (*Heppenheimer,* 1985). Finally, base sites were sought where the rille/tube was located in a very flat region for greater ease of mobility and where tube widths and roof thicknesses were thought to be within the constraints determined by *Oberbeck et al.* (1969).

IDENTIFIED LAVA TUBE SEGMENTS

More than 90 lava tube candidates were identified along 20 lunar rilles on the lunar nearside, 67 of which were measured. These occur in four mare regions: Oceanus Procellarum, Northern Imbrium, Mare Serenitatis, and Mare Tranquillitatis (Fig. 1). Each of these rilles appears to be discontinuous, alternating between open lava channel segments and roofed-over segments. Those segments appearing structurally sound, according to the criteria discussed above, were measured and identified as tube candidates. Each of these tubes has met our tube identification criteria, is relatively close to the size constraints established by *Oberbeck et al.* (1969), and is situated in a relatively flat location. Table 1 lists each of these tube segments with its respective dimensions, location, and photographic reference frame. Of the 20 rilles examined, 4 exhibit very strong evidence for having intact, open tube segments, 2 in Oceanus Procellarum (C and J in Fig. 1; Figs. 2 and 3; Table 1) and 2 in Mare Serenitatis (O and R in Fig. 1; Figs. 4 and 5; Table 1). Each tube segment was evaluated for use as part of the structure of an advanced lunar base according to the criteria discussed above. The results of this evaluation are given in Table 1. Nine tube segments associated with three separate rilles (A, C, and R) are considered prime candidates for an advanced lunar base.

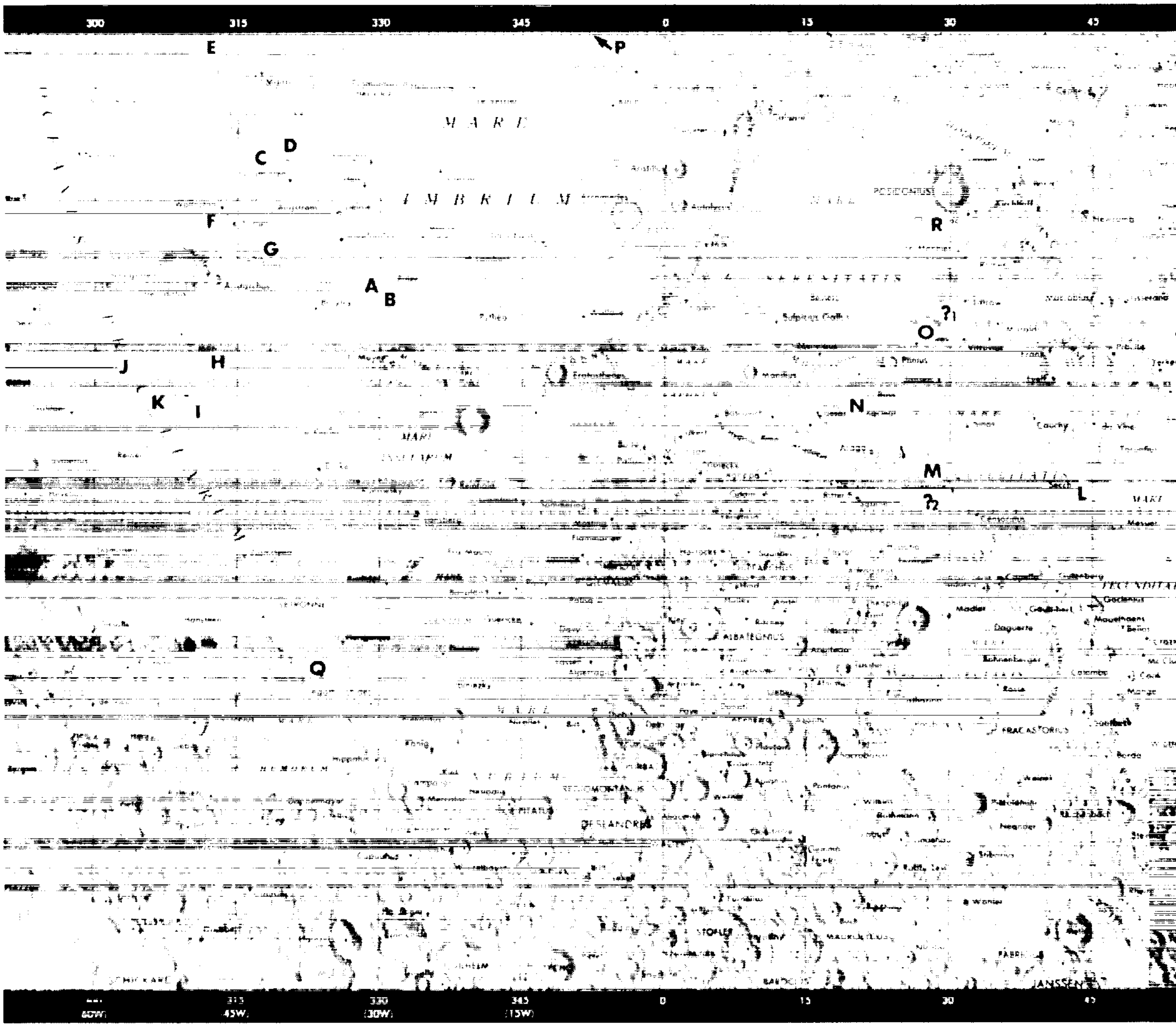

Fig. 1. Map showing the location of the 20 lunar rilles on the lunar nearside where potential lava tube candidates have been identified. Additional information concerning the location of these lava tubes is given in Table 1.

Northern Procellarum

Eleven rilles where probable intact lava tubes exist are found in the Oceanus Procellarum region; of these, two may be considered prime localities at which to find an intact lava tube or series of tubes (C and J in Fig. 1; Figs. 2 and 3; Table 1). Rille C is the classic example of a lunar lava tube and was first identified as such by *Oberbeck et al.* (1969). This rille is 60 k long and is broken into more than 15 segments, each of which may be a potential intact tube. Only seven of these were measured, however. These seven segments are longer than the others and have smaller craters superposed on their roofs. Lengths of these segments range from 510 to 1120 m, with widths ranging from 450 to 970 m. The 970-m-wide segment (as well as the other segments listed in Table 1 as > 500 m wide) was included because it appeared structurally stable in the photographs and was considered worthy of closer inspection. A variety of factors may allow tubes with apparent widths greater than 500 m to exist on the lunar surface. The largest crater on any of the segments is 270 m in diameter. The roof of the segment appears to be intact, with no sign of faults or slumping. A minimum roof thickness for this tube is 135 m.

Rille C, unnamed by previous mappers, begins at Gruithuisen K, a kidney-shaped depression at the top of the photograph (Fig. 2). This rille trends north-northwest, parallel to the major ridges in Procellarum, and is slightly sinuous. It is interpreted to be Eratosthenian in age (*Scott and Eggleton,* 1973). The highlands terrain just north of Gruisthuisen K is composed of primary and secondary impact material of the Iridum Crater and possible volcanic domes (*Scott and Eggleton,* 1973). Any or all of these

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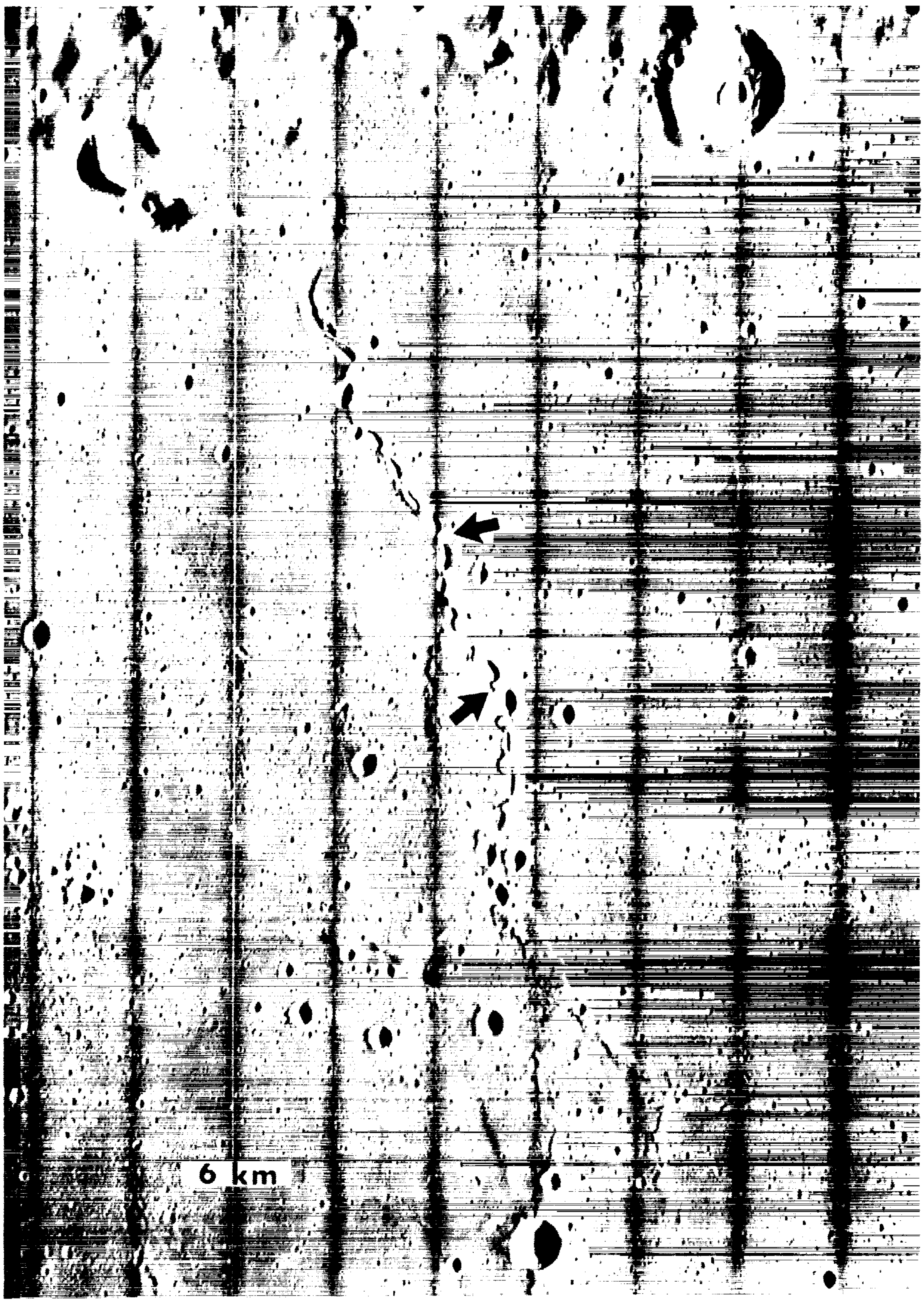

Fig. 2. This partially collapsed tube is located just west of the crater Gruithuisen. This is rille C as identified in Table 1 and is considered a prime candidate for finding an intact, vacant lunar lava tube. (LO-V-182-M)

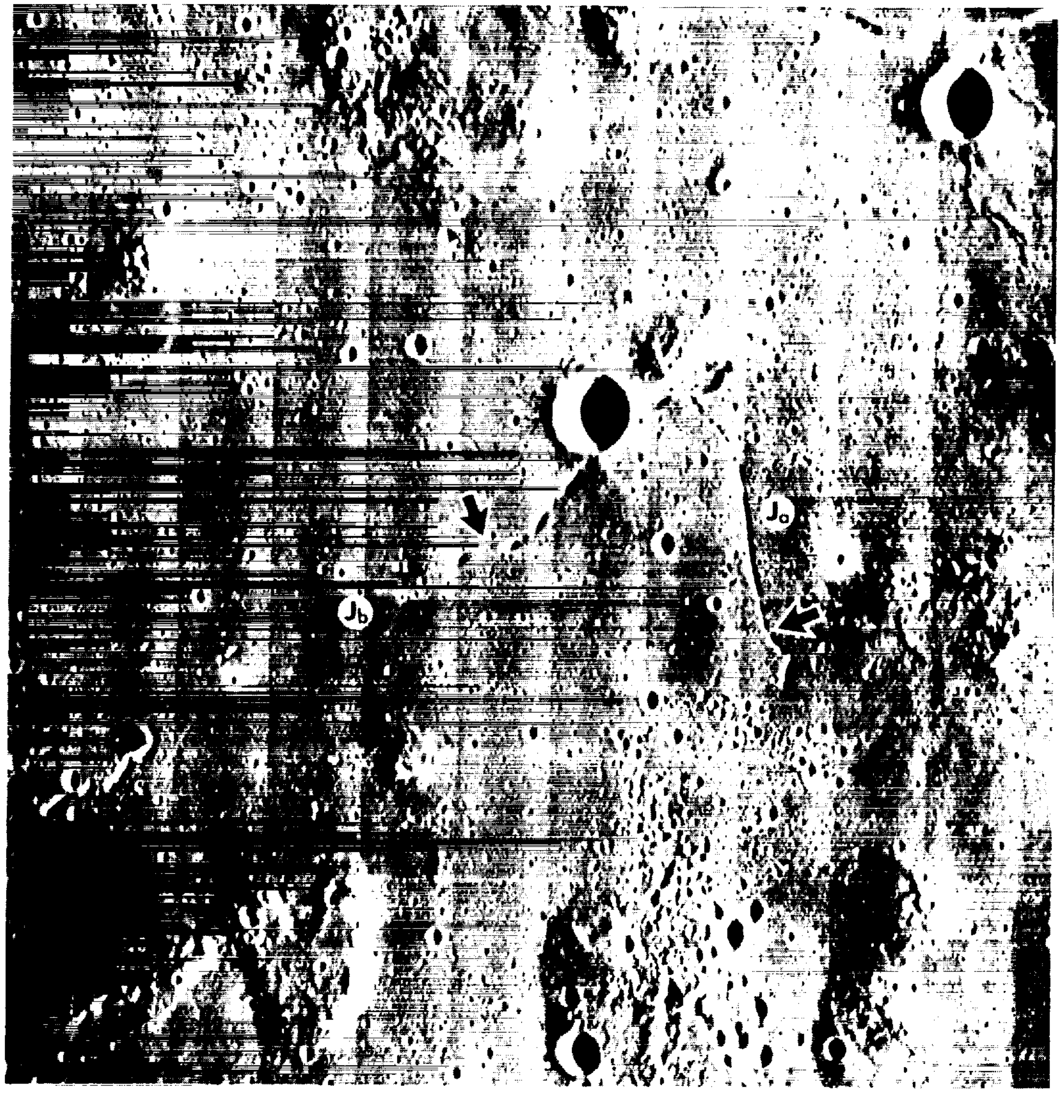

Fig. 3. Lava tube candidates in the Marius Hills region (J of Table 1 and Fig. 1). Two segments (J_a and J_b) meet at right angles at what may have been the source vent for them both. (LO-V-213-M)

tube segments would provide easy access to mare materials and the volcanic dome material just north of the rille.

Rille J, located in the Marius Hills region of Oceanus Procellarum (Figs. 1 and 3; Table 1), also exhibits extremely strong evidence for the existence of an intact lava tube. Rille J is actually a combination of two rilles that meet at right angles at an irregularly shaped depression that may have served as a common source vent (Fig. 3). Rille J_a trends north to south, is 15.5 km long, and is divided into seven segments, four of which were measured. The tube lengths range between 130 and 250 m, and the widths between 250 and 340 m. The maximum crater depth along rille J_a is 20 m, suggesting a minimum roof thickness in this area of 40 m.

Rille J_b is 42 km long, trends southwest, and is broken into more than 15 segments. Eleven of the best defined segments were measured. Here the lengths of the tube segments range between 250 and 1630 m and the widths vary between 270 and 480 m. One other tube segment along this rille varies radically from the others (J9, Table 1). This segment is 7370 m long, 270 m wide, and has a maximum superposed crater diameter of 250 m, or a minimum roof thickness of 125 m. The existence of a tube segment here is considered a strong possibility as the tube does appear to continue to the southwest. Whether or not an open tube is continuous along the entire length is difficult to determine. Closer inspection of this segment will be necessary in order to accurately determine its potential for human habitation.

The Marius Hills region is the product of a complex volcanic history. Northeast- and northwest-trending wrinkle ridges represent the intersection of two major structural trends (*Schultz*, 1976), while thick layers of lava flows and extrusive domes mark the sites of previous major volcanic activity. The Hills themselves are interpreted to be composed of pyroclastic and volcanic flow material that erupted and flowed over older mare material (*McCauley*, 1967). Both the pyroclastic debris and mare basalts in this region could be used as sources of lunar resources.

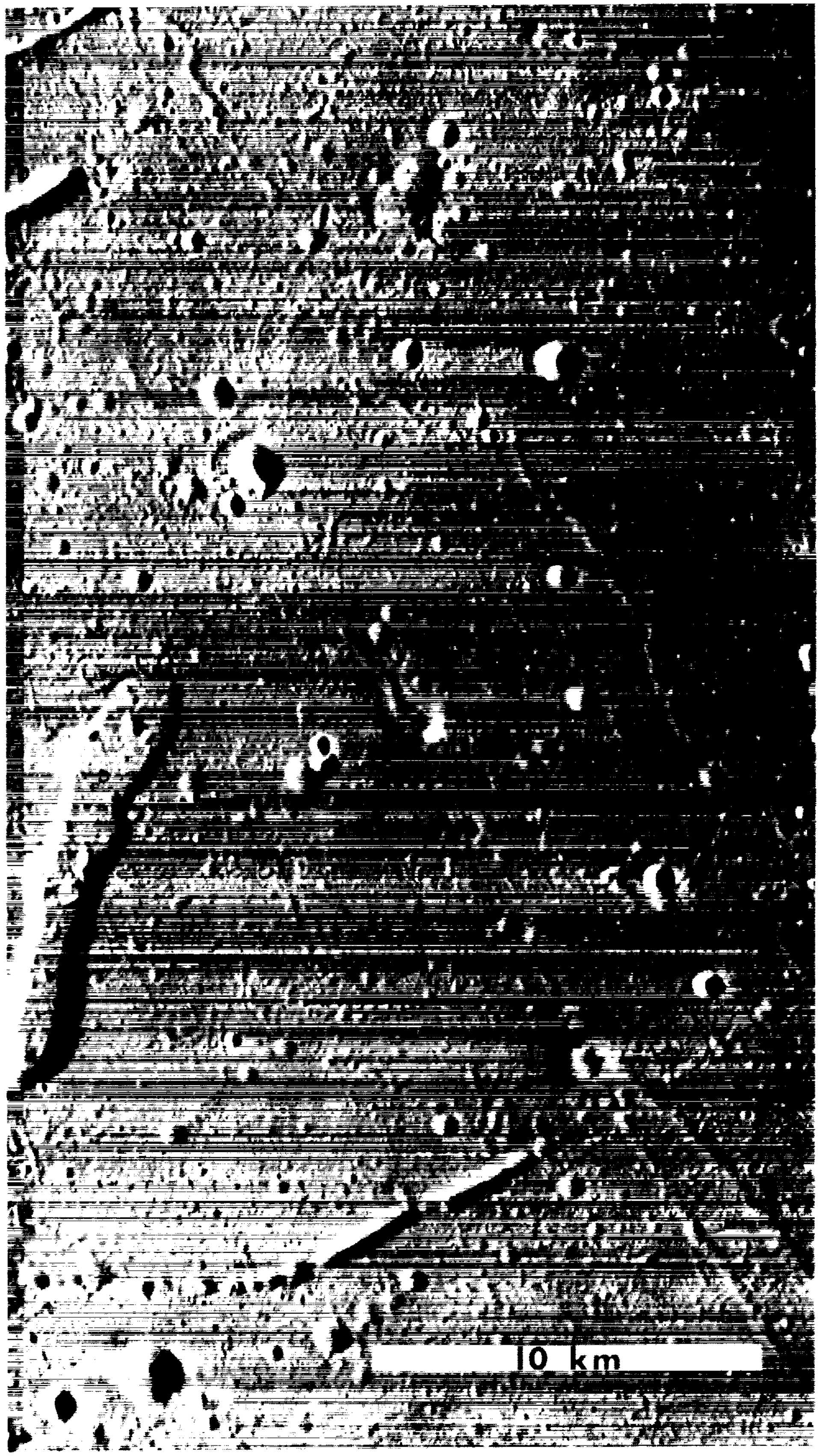

Fig. 4. Rille O, a prime candidate for having an intact lunar lava tube is located southwest of the Apollo 17 landing site in southern Mare Serenitatis. (AS17-2317)

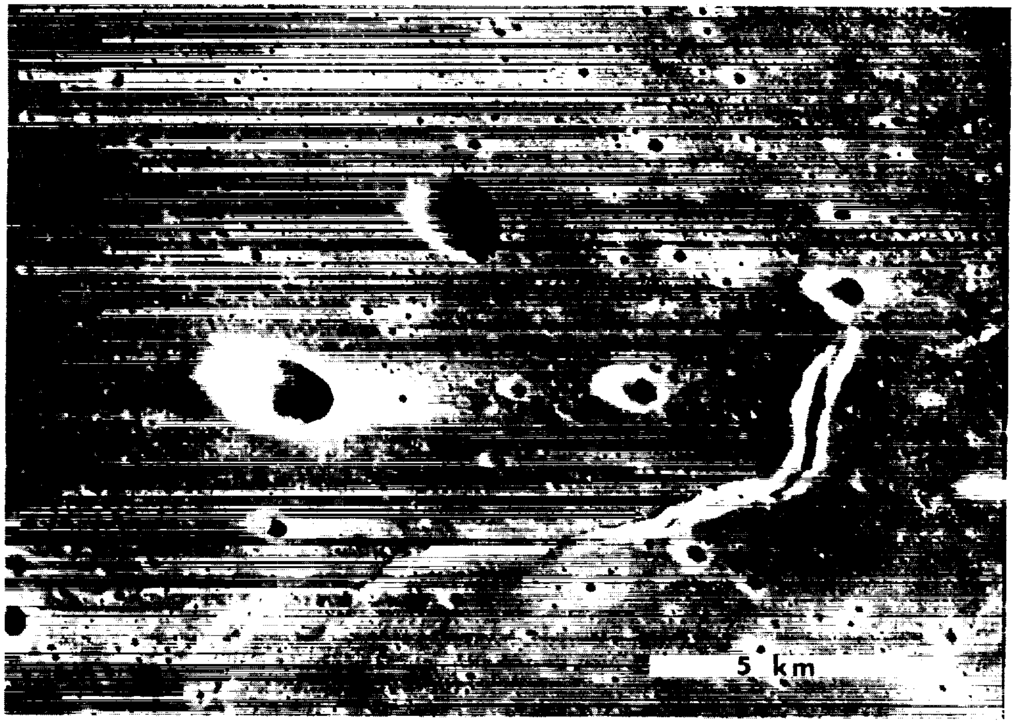

Fig. 5. Rille R, located in eastern Mare Serenitatis. This sinuous rille has retained its original levee walls and is roofed over at both its proximal and distal ends. The source crater is located at the right end of the rille, with the flow direction from right to left. (AS15-9309)

Southern Procellarum

One strong tube candidate was found in a complex of rilles north of Mare Humorum (Q in Fig. 1; Table 1). A number of very sinuous rilles that trend north-northeast are located near the boundary between Mare Humorum and Oceanus Procellarum. A tube segment was identified along one of these rilles. The tube segment is 1650 m long and 440 m wide. No measurable superposed craters were identified on the photographs available for this tube segment. The isolated, noncentral location, and presence of just one tube segment at this locality all argue against recommending this site to house the lunar base.

Northern Imbrium

Three tube segments were found along one sinuous rille in the northern portion of Mare Imbrium. This rille trends northeast and is located near the mouth of Alpine Valley (P in Fig. 1; Table 1) and, like the others, is surrounded by mare material. The three tube segments range in length from 840 to 1680 m and in width from 210 to 290 m. The maximum crater diameter supported by one of the segments is 170 m, with a potential roof thickness of 85 m. While this area may offer a variety of resources, and parts of it are flat, we do not feel that it would make an ideal locality to house the lunar base because of its noncentral location.

Serenitatis/Tranquillitatis

Five rilles with probable intact lava tubes were identified in the Serenitatis/Tranquillitatis region. Two other rilles in this region were also noted as potential candidates; however, the poor quality of the available photographs prohibited us from accurately measuring them and assessing their true potential. These two rilles should be inspected, however, when better data are available.

Of the five rilles identified, two exhibit extremely strong evidence for having intact tube segments (O in Figs. 1 and 4; R in Figs. 1 and 5; Table 1). Rille O is >30 km long, is located southwest of the Apollo 17 landing site, and is divided into more than 13 segments, 5 of which were measured. This rille trends east-northeast, parallel to the structural trend in this portion of southern Mare Serenitatis. The segments measured vary between 320 and 880 m long, are 460 to 510 m wide, and support a maximum crater 80 m in diameter. The minimum roof thickness for the longer tube segment is 40 m.

This locality offers major advantages for siting the lunar base. Not only is the region relatively flat, offering easy access to many areas, it is reasonably close to the Apollo 17 landing site (high-Ti mare basalt regolith), as well as a major regional dark mantle deposit of pyroclastic origin. This site may provide a good source for building materials as well as lunar resources such as Fe, Ti, Al, and K.

Rille R, located on the eastern edge of Mare Serenitatis, is 15 km long and 1.0 km wide. The rille originates at an acircular crater approximately 1.3 km in diameter and follows a general south-southwest trend. Channel levees mark the edge of the channel along a 6-km stretch between the two segments. The shorter of the two tube segments is 1.32 km long, and the other is 6.5 km long. The largest crater superposed on this rille was 0.66 km along the longest segment. The minimum roof thickness for this tube segment is 330 m.

Many other lunar rilles were examined but were considered less viable candidates for several reasons. The rejected rilles exhibited no uncollapsed sections and/or the adjacent and superposed craters were too large. The possibility that structurally sound lava tubes exist at these and other locations on the nearside of the Moon cannot be ruled out completely, however, until much more detailed analyses are completed.

ROLE OF LAVA TUBES FOR AN ADVANCED MANNED LUNAR BASE

There are many advantages to using intact lunar lava tubes as the site for a manned lunar base. The natural tube roof provides protection from cosmic radiation. The protected area offered by the intact tubes would provide storage facilities, living quarters, and space for industrial production. The constant temperature of around 20°C (*Hörz,* 1985; W. Mendell, personal communication, 1987) is conducive to many projects and experiments, and could be altered to maintain a controlled environment for a variety of experiments as well as comfortable living conditions.

Unused or uninhabitable portions of lava tubes would also provide an additional disposal facility for solid waste products generated from the manned lunar base. Biological and industrial (i.e., mining, construction) waste may be safely discarded within these structures without diminishing the vista of the lunar surface. This method of waste disposal may provide an alternative to the crater filling, burial, or hiding-in-the-shade methods proposed by *Ciesla* (1988).

Many potential resources may be located in the vicinity of lava tubes or complexes. For example, lunar pyroclastic deposits are known to be associated with some source vents for the lunar sinuous rilles and lava tubes (*Coombs et al.,* 1987). The black spheres that dominate some regional pyroclastic deposits are known to be rich in ilmenite (*Heiken et al.,* 1974; *Pieters et al.,* 1973, 1974; *Adams et al.,* 1974). These ilmenite-rich pyroclastics may in turn be a source of Ti, Fe, and O. Also, pyroclastics and regolith found in the vicinity of some of our tube candidates may be a good source for S as well as other volatile elements. Sulfur could be used as a propellant, as a fertilizer, and in industrial chemistry as suggested by *Vaniman et al.* (1988). The volcanic material may also be used as construction materials. Big pieces of rock may be utilized as bricks while small pyroclastic debris may be incorporated in cement compounds or broken down into individual elements.

There is one major problem to consider when planning the use of a lava tube to house the first manned lunar base. That is the difficulty in confirming, absolutely, that a tube does in fact exist in a particular spot and determining what its exact proportions are. Efforts are currently underway to determine a method for identifying evacuated, intact, lava tubes on the Moon. Such methods might include initial gravity and seismic surveys with later drilling and/or "lunarnaut" and rover reconnaissance, or a portable radar system. Several such methods are being tested now in Hawaii to identify lava tubes on Oahu and the Big Island. The construction of highly detailed geologic and topographic maps for the lunar areas also would greatly enhance the efforts to accurately determine the locations, dimensions, and existence of the lunar lava tubes. Thus, until a tube or tube system is positively identified on the lunar surface, mission planners should not rely on the presence of a lava tube when designing the first manned lunar habitat. This paper, rather, points out the strong possibility of there being an intact open tube system on the lunar surface that could be incorporated into future plans for an advanced, manned lunar base.

CONCLUSION

We conclude that lava tubes were formed on the Moon and that the probability of finding an intact, open tube segment that would be suitable for housing a permanent lunar base is quite high. Criteria were established for identifying intact lava tube segments. A survey of all known sinuous rilles and channels and other selected volcanic features was conducted in an effort to locate lava tube segments on the lunar surface. All available Lunar Orbiter and Apollo orbital photography of these features was utilized. We measured 67 tube segments associated with 20 rilles in 4 mare regions on the lunar nearside. It was determined that these tube segments are likely to be intact and open. Each tube segment was evaluated for suitability for use as part of an advanced lunar base. The results of this evaluation are given in Table 1. Nine tube segments associated with three separate rilles were given the highest ranking. We consider these nine segments to be prime candidates for use as part of an advanced lunar base. Finally, it should be pointed out that the emphasis in this paper was placed on relatively large lava tubes because evidence could be obtained from existing lunar photography. Numerous much smaller tubes may be present on the lunar surface, however, and some of these may also be useful in the lunar base initiative.

More analysis of the tubes discussed here is needed before an adequate selection can be made of a specific lunar lava tube to house a manned lunar base. One thing that may be done to help identify an intact lava tube or series of tubes would be construction of detailed geologic maps, topographic maps, and orthotopophotographic maps for areas showing potential for intact, vacant lava tubes. Also, further data are needed to adequately confirm the presence of open channels and tubes. These data might include radar, gravity, active and passive seismic experiments, rover and "lunarnaut" reconnaissance, and drilling. Once the proper tube is located, the possibilities for its use are numerous.

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