No. 150 MULTIPHASE ERUPTIONS ASSOCIATED WITH THE LUNAR CRATERS TYCHO AND ARISTARCHUS

by ROBERT G. STROM † AND GILBERT FIELDER *

August 1, 1968

Revised May, 1970

ABSTRACT

Numerous lava flows and other volcanic features occur within and in the vicinity of both Tycho and Aristarchus. Most of the flows associated with Tycho were more viscous and have higher albedos than those associated with Aristarchus indicating differences in composition. Numerous "lakes" occurring on the rims of both craters are thought to consist of lava erupted from vents primarily associated with the depressions in which they lie. The floors of Tycho and Aristarchus probably consist of lava; large volumes of this material probably drained back into subsurface chambers or open fissures. In the case of Aristarchus, late eruptions of lava and/or pyroclastics appear to have been responsible for obscuring certain parts of the floor detail. Widespread deposits surrounding both Tycho and Aristarchus probably resulted from base surges and indicate that in each case a very large explosion was the principal contributor to the formation of the craters.

Counts of probable primary impact craters on the various flow units, the floors and the "lakes" indicate that these features were emplaced at widely different times. Counts on the base surges indicate that Aristarchus is about 1.6 times older than Tycho but the floors and flows are roughly the same age. Confirmed observations of red glows on the rim of Aristarchus and vicinity suggest that limited volcanism may be active even at the present time.

The volcanism associated with Tycho and Aristarchus may have been triggered by large impacts which tapped a subsurface source of magma. Less likely both craters could be volcanic structures, the volcanism being the natural consequence of the development of the craters.

1. Introduction

Tycho, the well-known lunar crater 85 km in diameter, and Aristarchus, the brightest lunar crater 40 km in diameter are two of the most prominent craters on the moon. Both craters have clearly sculptured rims, are relatively deep, and are strong centers of stratigraphically recent rays: therefore, the craters have been widely regarded as recent impact structures. In addition, Tycho presents an anomalously high radar reflectivity (Pettengill, 1968) which indicates that the crater is rougher or denser than the surroundings; and during eclipse or through a lunation Tycho also follows anomalous thermal curves (Saari, 1965) which indicate that the materials of the crater are better thermal conductors than the surrounding terrain. All these observations may be explained on the impact hypothesis.

In 1967 part of Tycho and all of Aristarchus were photographed by *Orbiter V* with a ground resolution of about 5 m. In addition, *Orbiter V* took medium resolution photographs of the whole of both structures and their immediate surroundings, with a ground resolution of about 40 m. It was therefore possible to study some parts of the Tycho and Aristarchus domains in considerable detail and to link these studies through a general description of the surrounding terrain, in each case.

† Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona.

* Dept. of Environmental Sciences, Univ. of Lancaster, England.

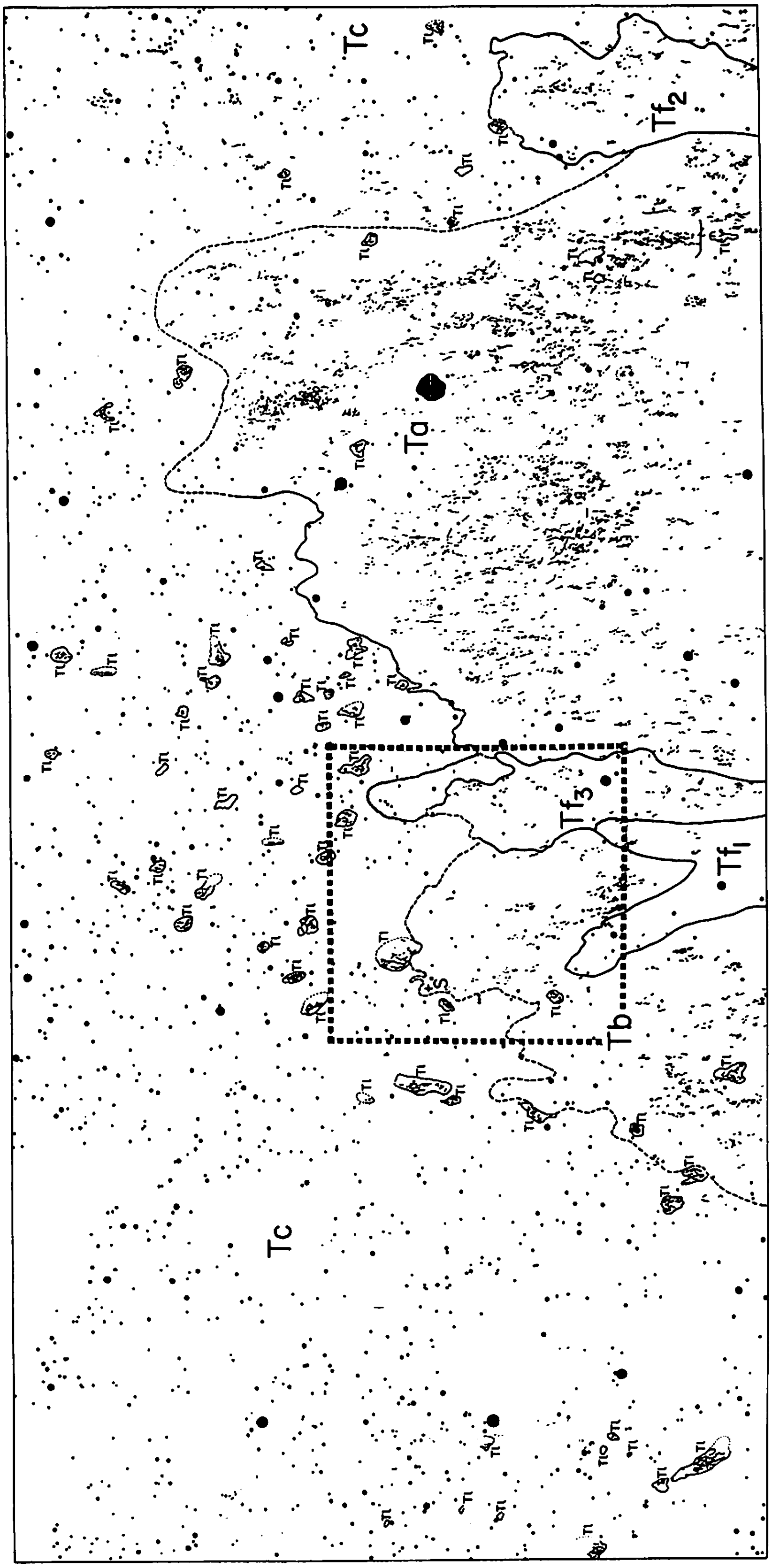

Fig. 1 Generalized map of the geologic units north of Tycho showing the distribution of craters (filled circles), fractures (fine lines) and "lakes" (T_l). The dashed outline indicates the location of the detailed geologic map (Fig. 11). The location of *Surveyor VII* is marked by S within the dashed outline. Compiled from *Orbiter V*, frame H-128.

In this paper we describe many flow units that are intimately associated with either Tycho or Aristarchus. Drawing on terrestrial analogues, and combining our results with counts of probable primary impact craters on the various geologic units, we conclude that there has been extensive volcanism in and around Tycho and Aristarchus.

2. *Tycho: Geologic Units*

The region north of Tycho shown by the *Orbiter V* frame H-128 consists of various deposits with distinct surface morphologies. Figure 1 is a *generalized map* of the different geologic units compiled from frame H-128, and Figure 2 is a mosaic of three medium resolution photographs showing the location of the area mapped in Figure 1. Units Tf_1 and Tf_2 are relatively thick, massive bodies with a ropey or ridged surface containing numerous open fractures and abundant blocks (Figs. 3 and 4). Judging by the shadows cast by the fronts of the units Tf_1 and Tf_2, they are on the order of 40 and 20 meters thick, respectively. The margins have raised rims very similar to the natural levees associated with lava drainage channels. In fact, the eastern edge of unit Tf_2 forms a well-defined front which has overflowed the channel rim and spilled onto the adjacent terrain. Since the height of the rim ($\sim$60 m) is considerably greater than the thickness of the flow front, it appears that this unit is only the latest of several flows or surges which have issued from the channel and built the natural levee. Both units Tf_1 and Tf_2 have higher albedos than the adjacent area as shown in Figure 5. Unit Tf_3 is similar to units Tf_1 and Tf_2 but is thinner ($\sim$12 meters), has a lower albedo, and is somewhat less ridged (Fig. 3). The ridging on these units is indicative of pressure ridging formed by the flow of a viscous fluid, and is similar to the surface of viscous lava flows on earth (see Figs. 24 and 25). The units Tf_1, Tf_2 and Tf_3 overlie units Ta and Tb, and are therefore younger than them. Also Tf_1 overlies Tf_3 and is therefore younger than that unit. The surface texture, the well-defined flow fronts and the flow channels strongly suggest that all these units are lava flows which were relatively *viscous*. Since units Tf_1 and Tf_2 appear to have been more viscous and have a higher albedo than other units in the area — particularly the one on which *Surveyor VII* lies — it is likely that they are more acidic than the unit for which *Surveyor* indicated an anorthositic composition.

Units Ta and Tb are characterized by a high density of fine fractures shown as fine, short lines in Figure 1, and by a semi-blocky, slightly ridged appearance. The units are generally smoother than units Tf_1, Tf_2 and Tf_3. In the southern portion of the mapped area the texture is similar to that of units Tf_1, Tf_2 and Tf_3, but somewhat more subdued. The texture gradually grades in a northerly direction into the smoother portion of these units. Both Ta and Tb overlie and are topographically higher and less cratered than unit Tc, and therefore must be younger than that unit. The fracturing on these units is primarily associated with the crests of ridges and, although fracturing sometimes occurs in the troughs between ridges, it is much less intense and more widely spaced. This seems to indicate that the fracturing is due to the uplift of the ridges possibly resulting from the hydrostatic pressure of fluid lava beneath a solidified crust. It should be noted that this type of fracturing is strongly developed on units Ta and Tb, weakly developed on units Tf_1, Tf_2 and Tf_3, and practically absent on unit Tc. All the above characteristics suggest that units Ta and Tb are volcanic flows. They are probably composed of numerous flow units.

Unit Tc is a relatively smooth, hummocky material largely devoid of fractures, and more densely cratered than the other units. All other mapped units overlie it and therefore this is the oldest unit in the area. Two sets of closely spaced ridges occur locally. The more prominent set is roughly concentric with Tycho while the other, weaker, set is approximately orthogonal to the first set. This type of ridging is absent or only locally very weakly developed on the other units. It is possible that the concentric ridges are dunes deposited by a base surge. Concentric dunes are characteristic of base surge deposits surrounding terrestrial artificial and natural volcanic explosions (Moore, 1967). However, as these dune-like structures are traced back to the crater rims at several localities near the rims of both Tycho and Aristarchus they become progressively more scarp-like until very near the rims they show definite displacements of the surface. This indicates that *much of the concentric ridging near the crater rims is fracturing resulting from subsidence or slumping of the crater rim and surroundings.* However, some of the more distant ridging may be base-surge duning. The set of ridges that is sub-radially oriented with respect to Tycho probably owes its origin to fracturing. Several large sharp craters on unit Tc as seen from *Surveyor VII,* are not surrounded by blocks, whereas other smaller, sharp craters in the vicinity of the large craters have very blocky rims. This indicates

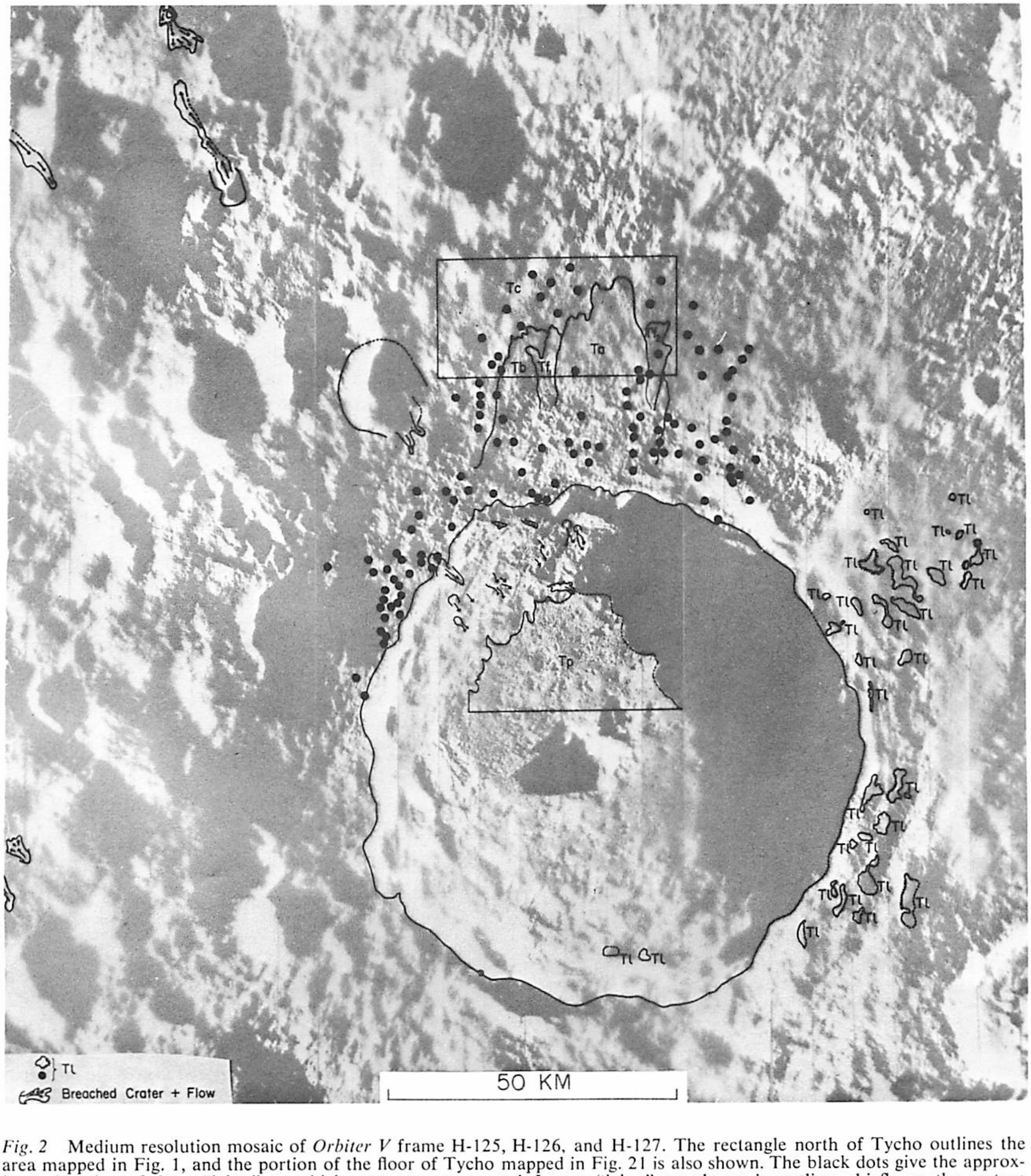

Fig. 2 Medium resolution mosaic of *Orbiter V* frame H-125, H-126, and H-127. The rectangle north of Tycho outlines the area mapped in Fig. 1, and the portion of the floor of Tycho mapped in Fig. 21 is also shown. The black dots give the approximate location of those "lakes" on which craters were counted. Larger "lakes" are shown in outline, chiefly on the eastern rim of Tycho. Finally, the principal flows outside the mapped areas are sketched, and the direction of flow is indicated by arrows.

Fig. 3 Flow units Tf_1 and Tf_3. Notice the ropy or ridged texture and well-defined fronts of these units, and the open channel on unit Tf_1. (Portion of *Orbiter V*, H-128).

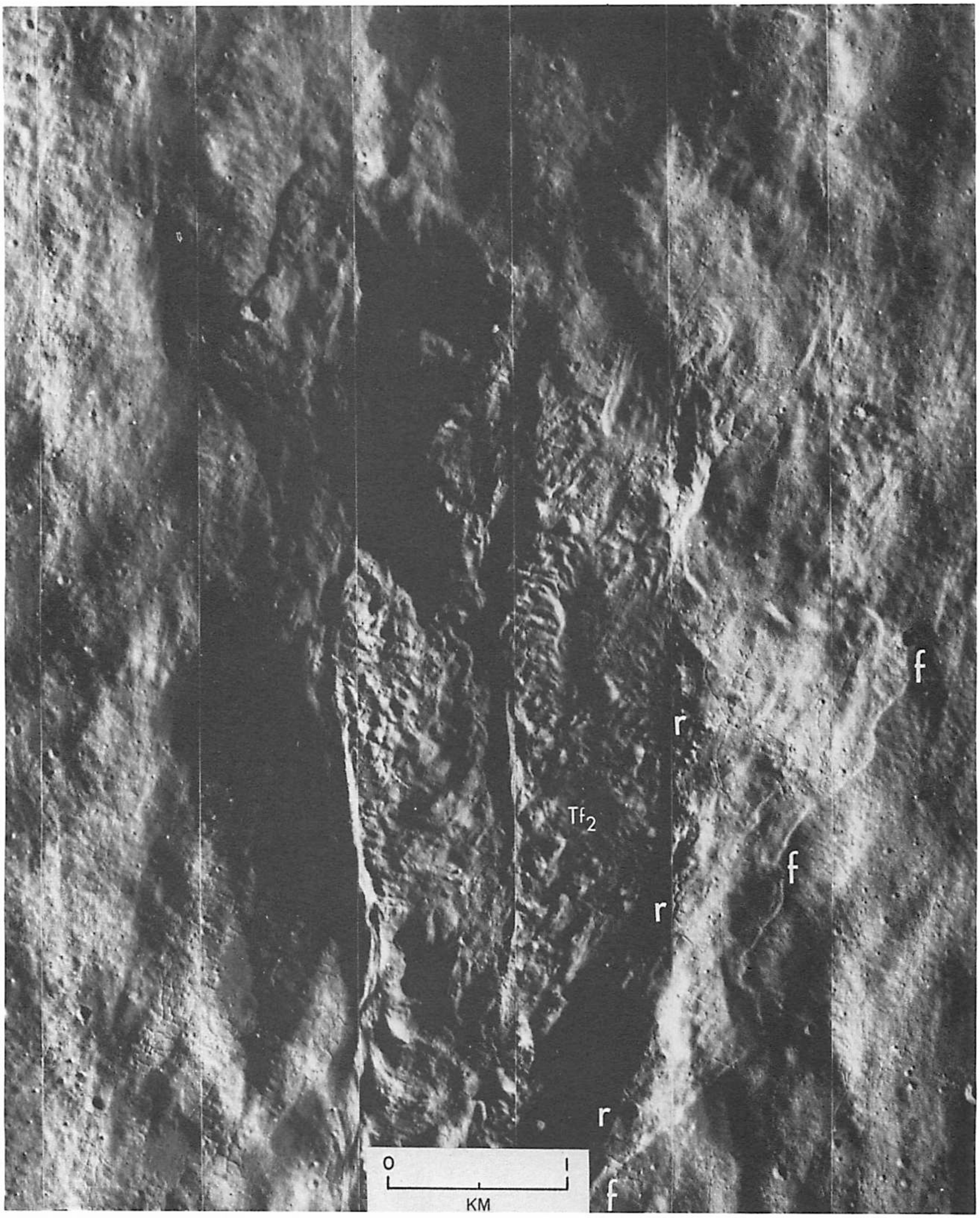

Fig. 4 Flow unit Tf_2. The flow has overridden the channel rim (*r*) — probably a natural levee — and spilled onto the adjacent terrain to the east forming a well-defined front (*f*). (Portion of *Orbiter V*, H-128).

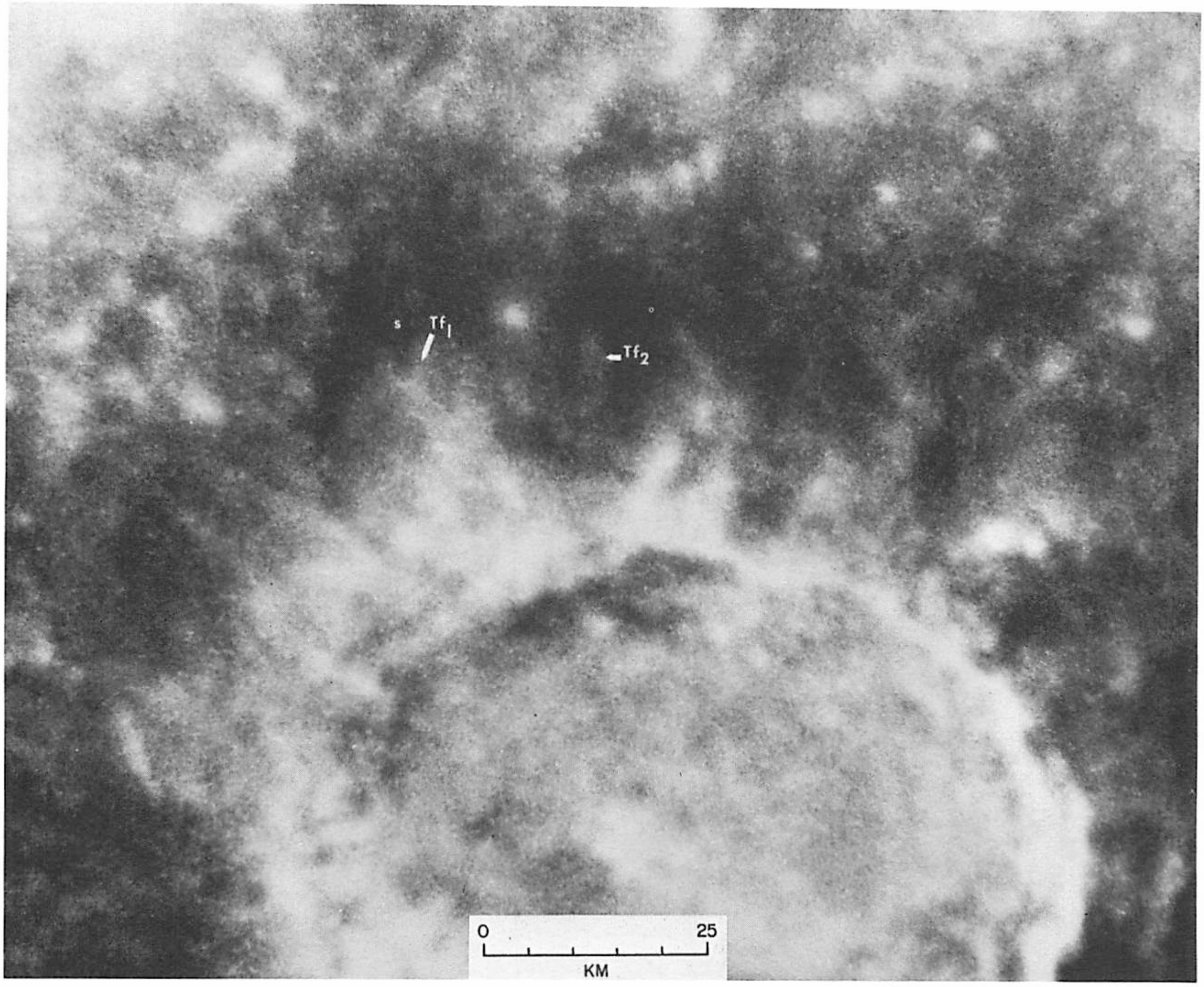

Fig. 5 Full-moon photograph of the northern part of Tycho and vicinity showing the high albedo units Tf_1 and Tf_2, and the approximate location of *Surveyor VII* (*S*). (61″ Catalina Obs. Photo.)

that unit Tc consists of more or less randomly distributed areas of fine, weakly cohesive material and hard, dense, coarse or massive material; while unit Tb consists entirely of dense material overlain only by a thin layer of fragmental debris. The hummocky smooth surface, the lack of well-defined fronts, and the apparent patchy distribution of lithology suggests that unit Tc is probably a base surge deposit resulting from an explosion originating from Tycho.

In addition to the above units, there are numerous "lakes" consisting of relatively dark smooth material and exhibiting fine fractures. They are situated in circular to irregular depressions and are concentrated within 20 km of the rim of Tycho. The fracture pattern on many of the lakes (Fig. 6) is remarkably similar to that found on lava lakes in Hawaii (Fig. 7) where the pattern results from tensile stresses caused by thermal contraction during cooling of the lava. Notice that the polygons formed by the fracture patterns are conspicuously convex in both the lunar and terrestrial lakes. According to Peck and Minakami (1968) the terrestrial polygonal hummocks result from the accumulation of gases trapped beneath the crust near centers of polygons, and the escape of gases from marginal parts which cause upbowing of polygon centers and downsagging of margins. The similarity in pattern and shape of the lunar and terrestrial polygons strongly indicates that the lakes in the vicinity of Tycho have cooled from originally molten material. Several of the larger lakes have distinct fronts where they contact the sides of the depressions in which they lie, and in a few cases the lakes have spilled over low portions of their confining basins forming short,

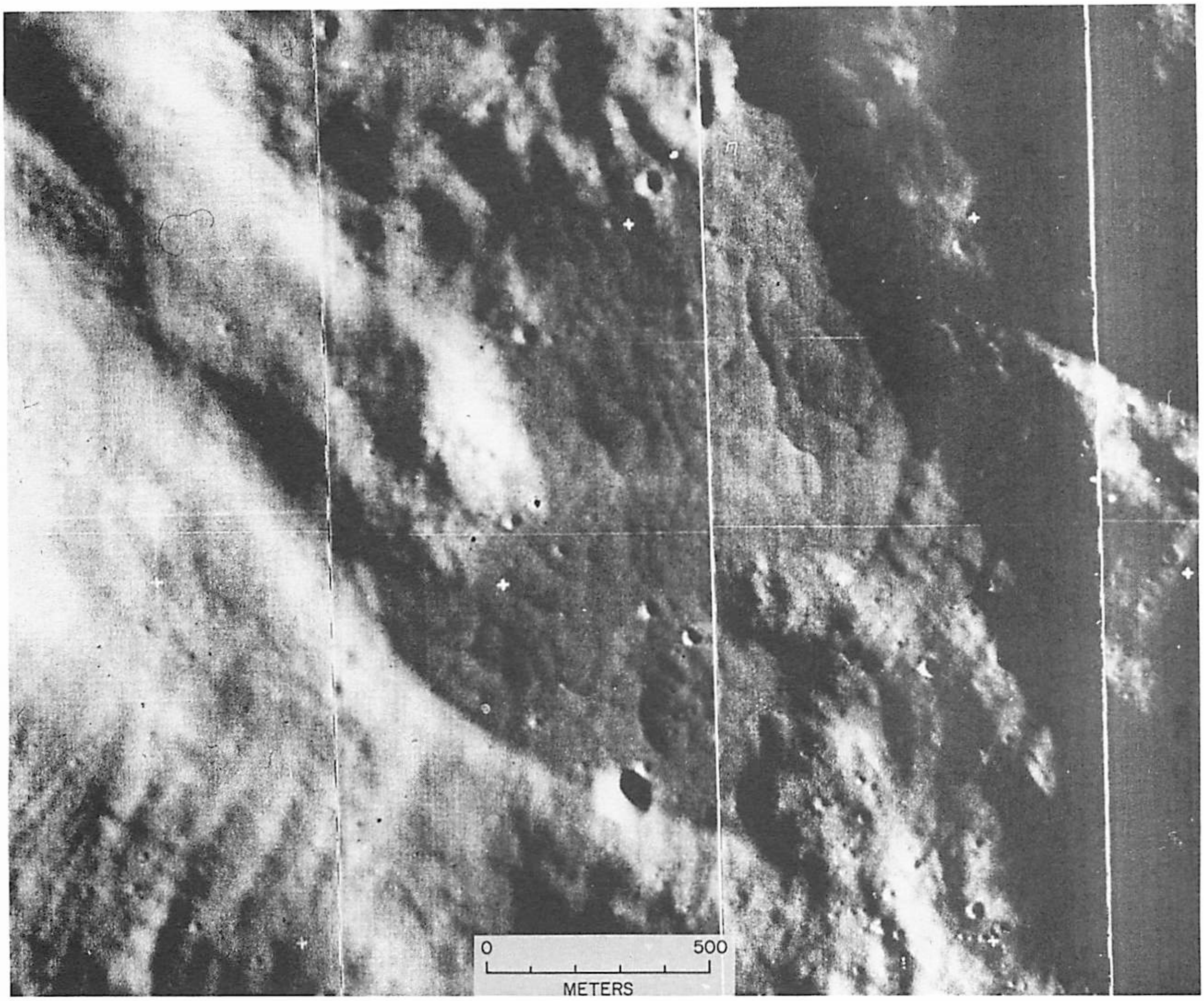

Fig. 6 "Lake" near Tycho showing fracture pattern. (Portion of *Orbiter V*, H-127.)

elevated flows in the adjacent terrain (see Figs. 8 and 9*a* and *b*). At least one lake has apparently experienced two periods of eruption as evidenced by a secondary flow superposed on the lake surface and indicated by the arrow in Fig. 9*a*. The secondary flow appears to have issued from vents or fissures at the northeastern edge of the lake. All the above facts strongly suggest that *the lakes consist of lava which has found egress to the surface through vents or fractures primarily associated with the depressions in which they lie*. The distribution of the lakes near the rim of Tycho indicates that they are intimately associated with its *formation*. Furthermore, *a small lake 350 meters in diameter occurs in an irregular crater near the crest of the main central peak of Tycho* (Fig. 10). The morphology of the lake is similar to that of the other lakes and even displays fractures or crater chains on its surface. It seems likely that the lake formed in the same manner as the others, and if this is so, then it is probable that the crater containing the lake is a volcanic vent connected by a conduit with a magma source. In this event it is possible that *the central peak itself is of volcanic origin*. Since the lakes have a paucity of craters and interrupt the other units, they must be relatively recent features of post-Tycho age. Crater counts indicate that the age of the lakes is similar to that of the floor of Tycho. However, since the total area of the lakes examined is small (22 km^2) and represents the sum of the areas of 124 individual lakes, the crater counts merely show that, *on average, the age of the lakes is close to the age of the floor*. Any individual lake may be appreciably younger or older than the floor or units Tf_1, Tf_2, Tf_3, Ta and Tb. However, all lakes

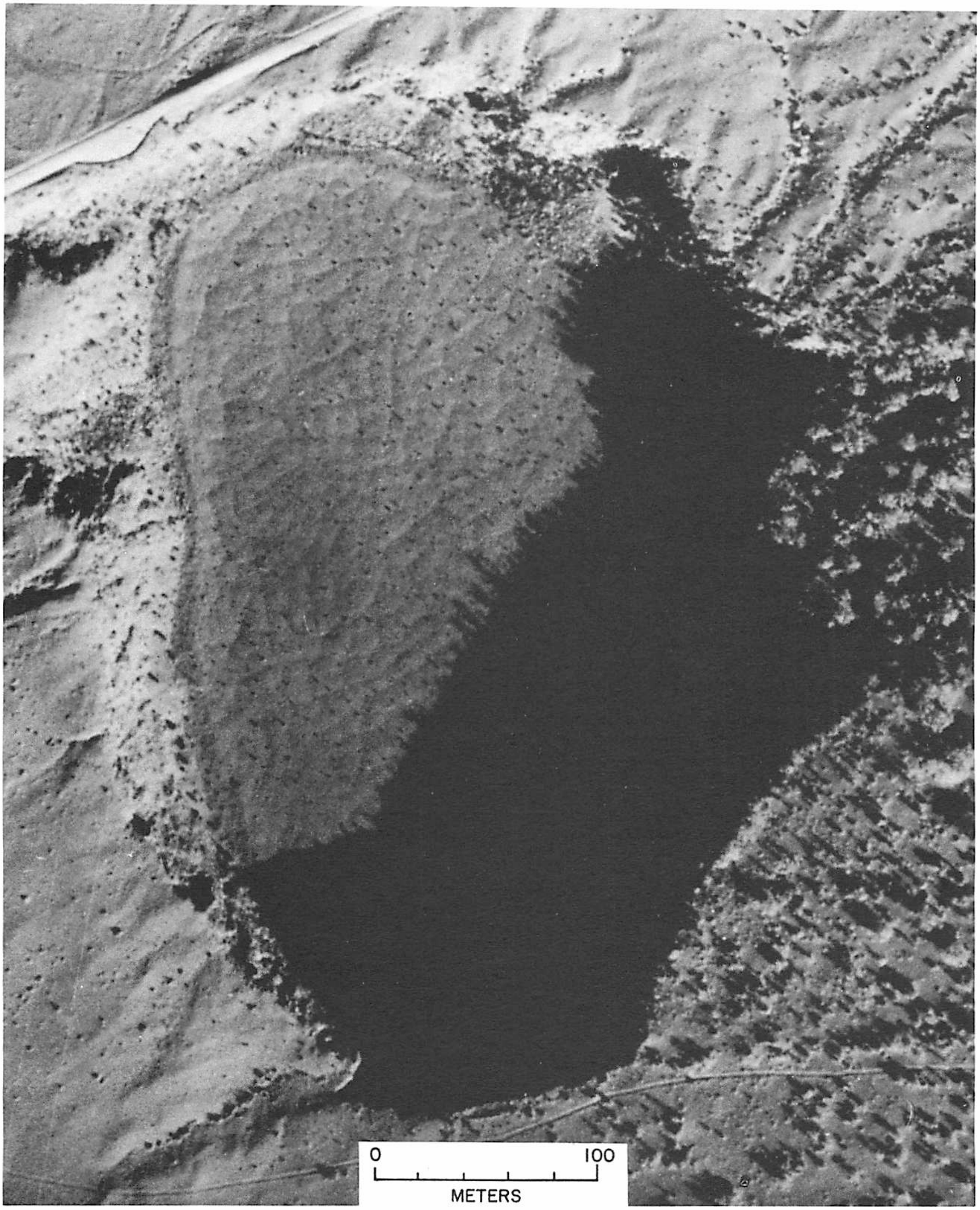

Fig. 7 Keanakakoi crater, Hawaii showing the pattern produced by cooling cracks on the lava lake. The floor is covered by about 15 cm of pyroclastics from the 1959 eruption of Kilauea Iki. (U.S. Government photo.)

Fig. 8 "Lakes" on the northeastern rim of Tycho. Notice the well-defined fronts indicated by *f* in two of the lakes. The material of two "lakes" (*A* and *B*) has apparently originated at a higher level and cascaded down-slope to form flow fronts on lower terrain (Arrow). One of these flows overlaps a pre-existing lake (*B*). (Portion of *Orbiter V*, M-128.)

must be younger than unit Tc because the lakes interrupt this unit which is the oldest unit in the mapped area.

Figure 11 is a map of the area in the immediate vicinity of the *Surveyor VII* spacecraft. The map may be located by the dashed outline in Figure 1. It shows in detail the various geologic units and the distribution of rocks, craters, and fractures. Units A and B are the same as units Tf_1 and Tf_3 and have been discussed previously. Units C, D, and E are the same as Tc. Detailed mapping of this area has shown that unit C has a unique morphology, overlies unit E, and therefore should be separated from Tb. The stratigraphic position of these units is well-defined and shows that (1) A is the youngest unit and overlies B, C and E, (2) B is older, overlying D and C, (3) C is still older and overlies E, (4) E overlies F, and (5) F is the oldest unit. The stratigraphic position of D relative to units C and E is not clear, but the surface morphology suggests that it may be related to, and of the same age as unit E.

The relationship of unit C to the largest lake in the area has a strong bearing on the age and origin of units A, B and C. Figure 12 shows that the northern terminus of unit C overlaps and extends about 400 meters onto the southern portion of the lake. There appear to be several collapse depressions (d) near the end of the unit where it covers the lake. Since the lake interrupts unit F and must be younger than that unit, then unit C, which overlaps the lake, must be younger than unit F; and units A and B, which overlap unit C, must be still younger. As previously indicated, all lakes are obviously post-Tycho in age, and therefore units A, B and C must also be of post-Tycho age. This indicates that these units, at least, are *volcanic flows which were erupted after the formation of Tycho.*

Table I lists the number density of blocks over about 4 meters in diameter on the various units in Figure 11 compared with the number of craters per km² greater than 20, 40, 60 and 80 meters in diameter.

TABLE I
ROCK FREQUENCY AND CRATER DENSITY PER KM²
ON UNITS SHOWN IN FIG. 11

UNIT	CR. ≥ 20m	CR. ≥ 40m	CR. ≥ 60m	CR. ≥ 80m	ROCKS ≥ 4m
B	11.89	2.01	0.51	0.38	34
C	10.02	1.45	0.36	—	19
D	22.54	4.64	2.50	0.71	67
E	21.32	3.10	0.80	0.10	39
F	33.32	4.32	1.12	0.42	19

The blocks on unit A are not included because of the difficulty in recognizing these small objects on the many overexposed and shadowed areas of this unit. It is apparent that the blocks are not randomly distributed with respect to the different geologic units. Unit D has about twice as many blocks as units B and E and about 3.6 times as many as units C and F. Units B and E have about twice as many blocks per unit area as units C and F. Furthermore, there appears to be a negative correlation between the number of blocks on a given unit and the density of craters on the unit, e.g., unit F has one of the greatest crater densities but one of the least block densities. This indicates that the majority of blocks greater than about 4 meters in diameter *are not ejecta from the mapped craters* on the various units. Also, it is doubtful whether blocks of this size could be produced by such small craters. Areas photographed by *Orbiter* in the maria containing more and larger craters have fewer blocks of a given size, relative to the numbers in the Tycho areas studies. Therefore, *the blocks are probably a combination of* (1) ejecta from Tycho and (2) blocks of lava broken up and carried by the flow process. The later possibility may explain the non-random distribution of blocks with respect to the various units, although it is possible that the flowage of material has resulted in a sorting mechanism by which the ejecta has been concentrated on some units relative to others. Certainly the blocks on units A, B and C cannot have been ejected from Tycho onto these units because they are of post-Tycho age. However, since unit C is estimated to be relatively thin (2-3 meters), it is possible that the larger blocks on this unit were in place prior to the flow and that they represent blocks which the flow engulfed. This explanation cannot be true for units A and B because of the thickness of these units (~40 and 12-18 meters, respectively). If the blocks on these units were to represent engulfed ejecta, then the great bulk of the blocks would be hidden beneath the flow. This would mean that the actual size of the blocks was some 5 to 10 times larger than other blocks in the mapped area and that the blocks were concentrated only in the areas covered by these flows. This is extremely unlikely. Also it is difficult to understand why, if the blocks are engulfed ejecta, unit B has twice as many blocks as unit C, which unit B overlies. It therefore seems probable that the majority of visible blocks on units A and B, and many blocks on units C, D and E *are lava broken up by the flow process.* Figure 13 is a (computer processed) picture of a rock slab ap-

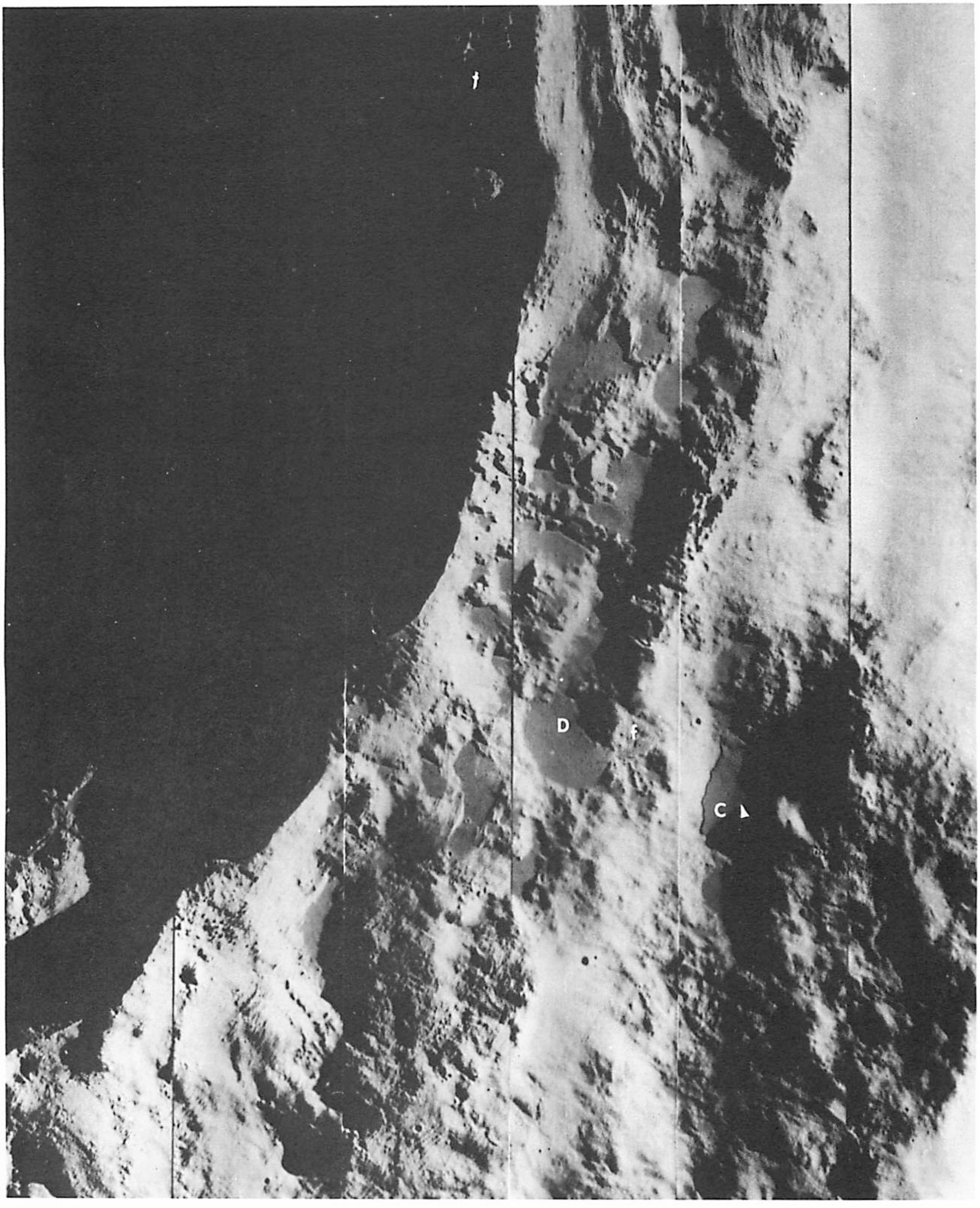

Fig. 9a "Lakes" on the southeastern rim of Tycho. Notice the well-defined fronts and the secondary flow (arrow) superposed on the surface of lake *C*. A short flow with a steep front (*f*) has issued from lake *D* through a low section of the confining basin. (Portion of *Orbiter V*, M-125.)

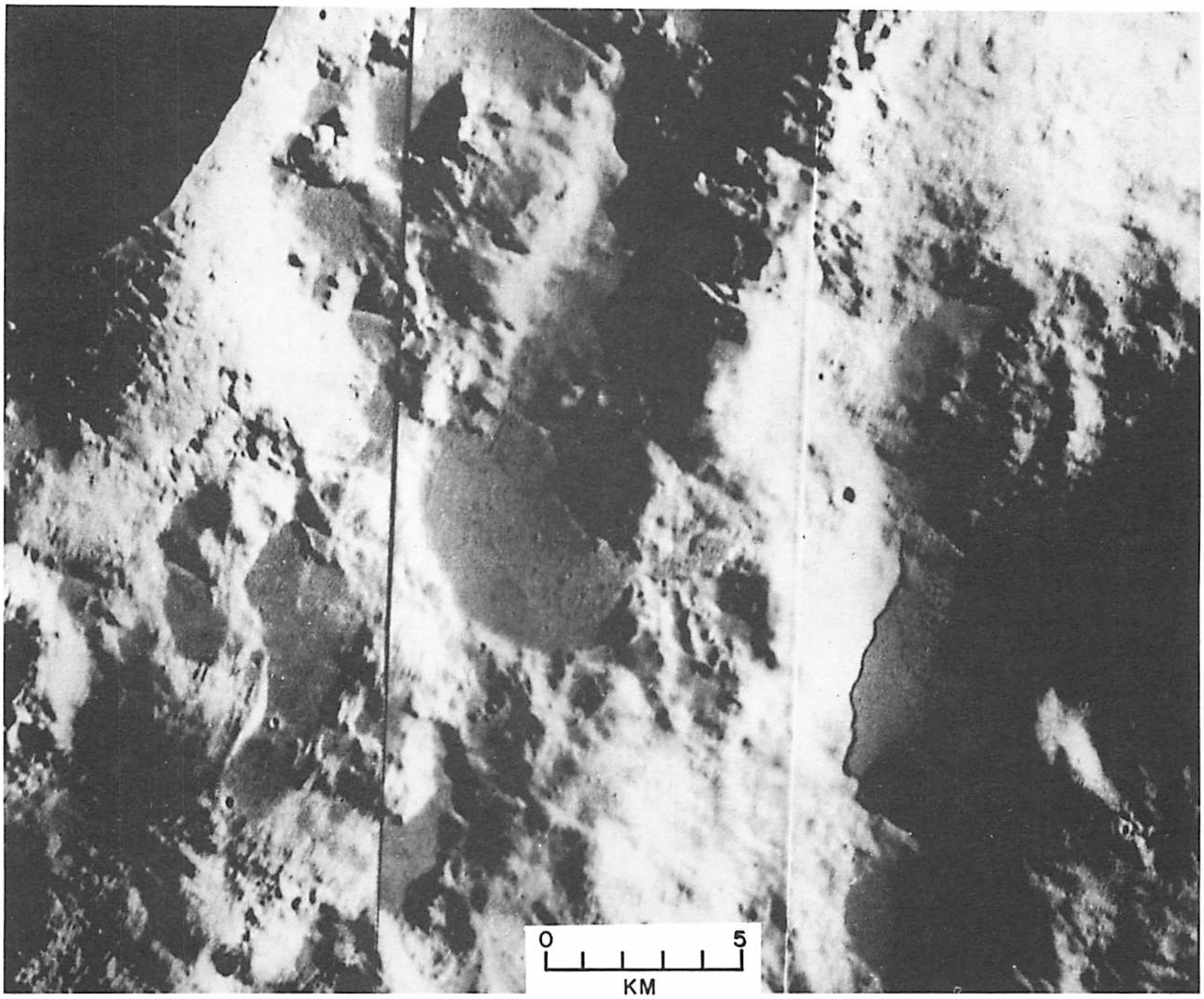

Fig. 9b Enlarged portion of Fig. *9a*.

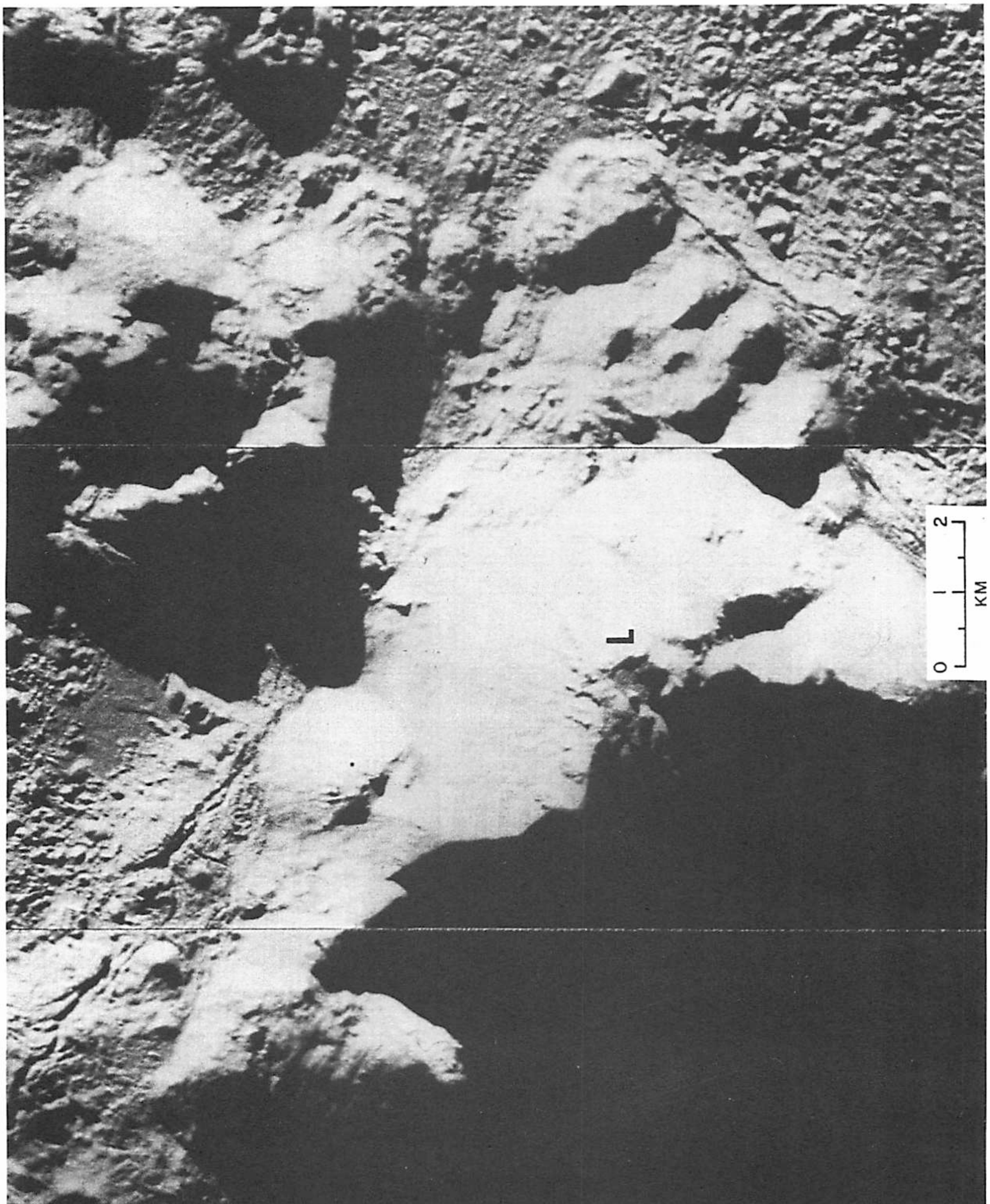

Fig. 10 Small lake (L) near the crest of the main central peak of Tycho. (Portion of *Orbiter V*, M-125.)

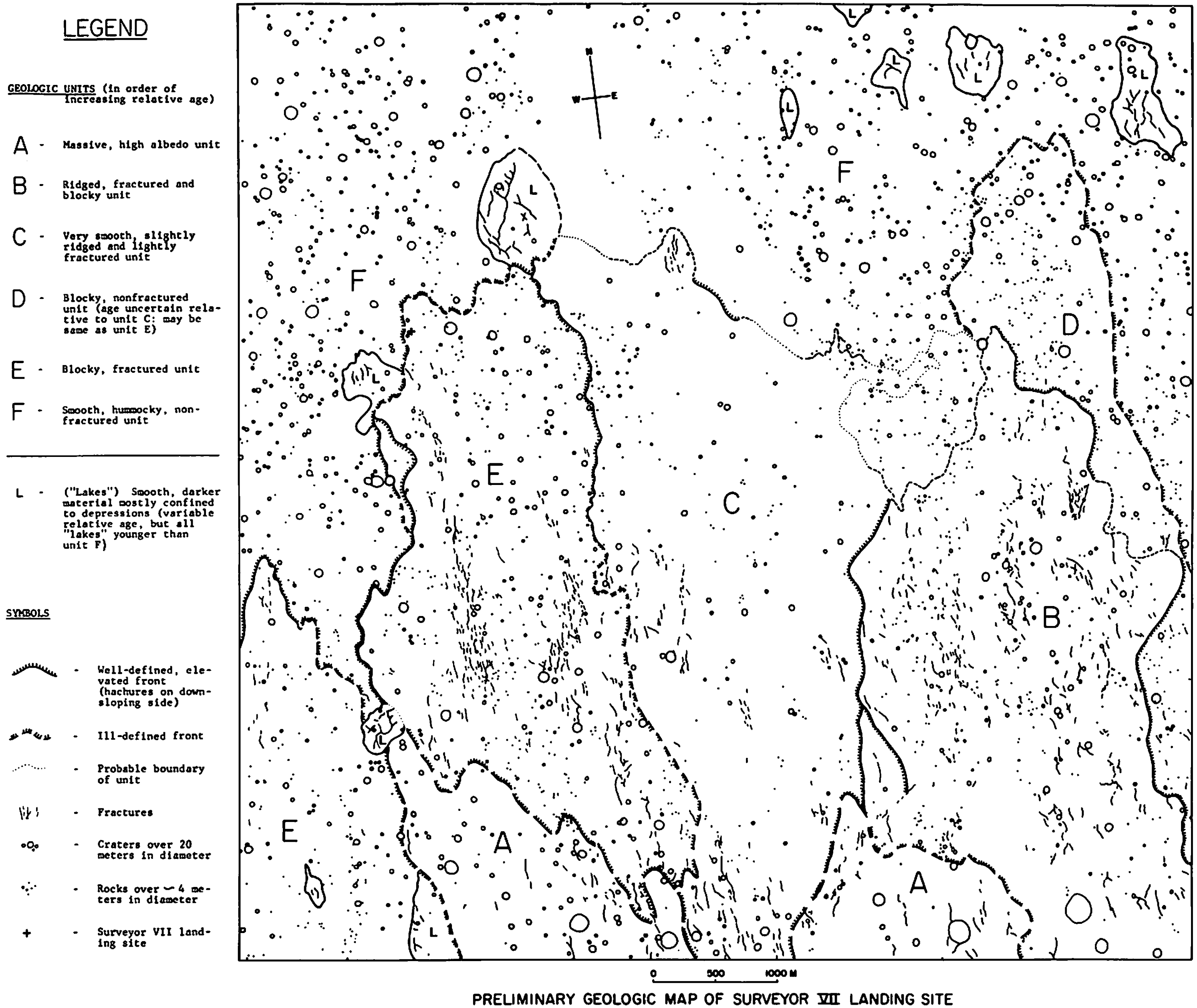

Fig. 11 Detailed geologic map of the area in the immediate vicinity of the *Surveyor VII* spacecraft as located by the dashed outline in Fig. 1.

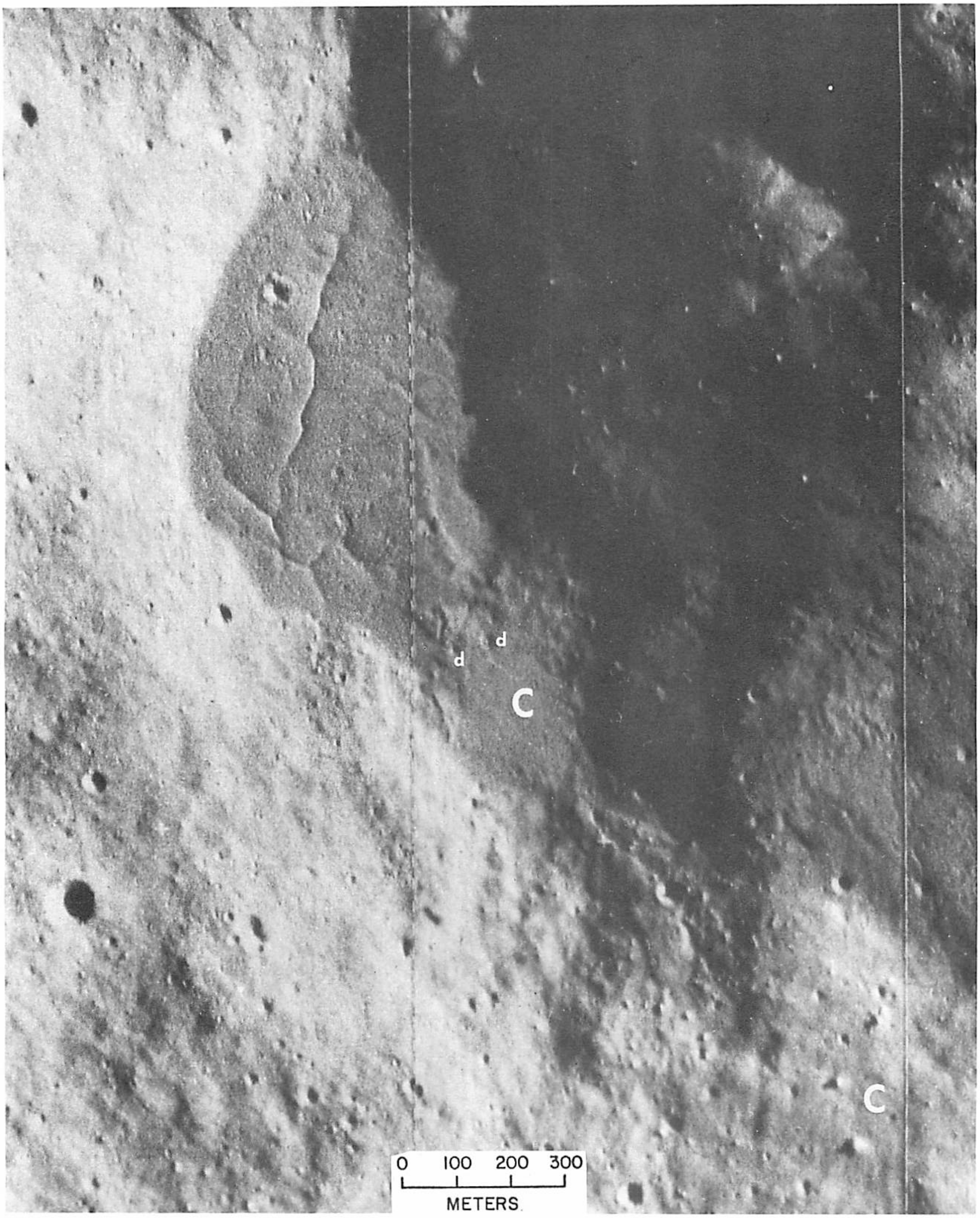

Fig. 12 Portion of *Orbiter V* frame H-128 showing the terminus of unit *C* overlapping a lake. Notice the well-defined front and possible collapse depressions (*d*) near the end of the flow.

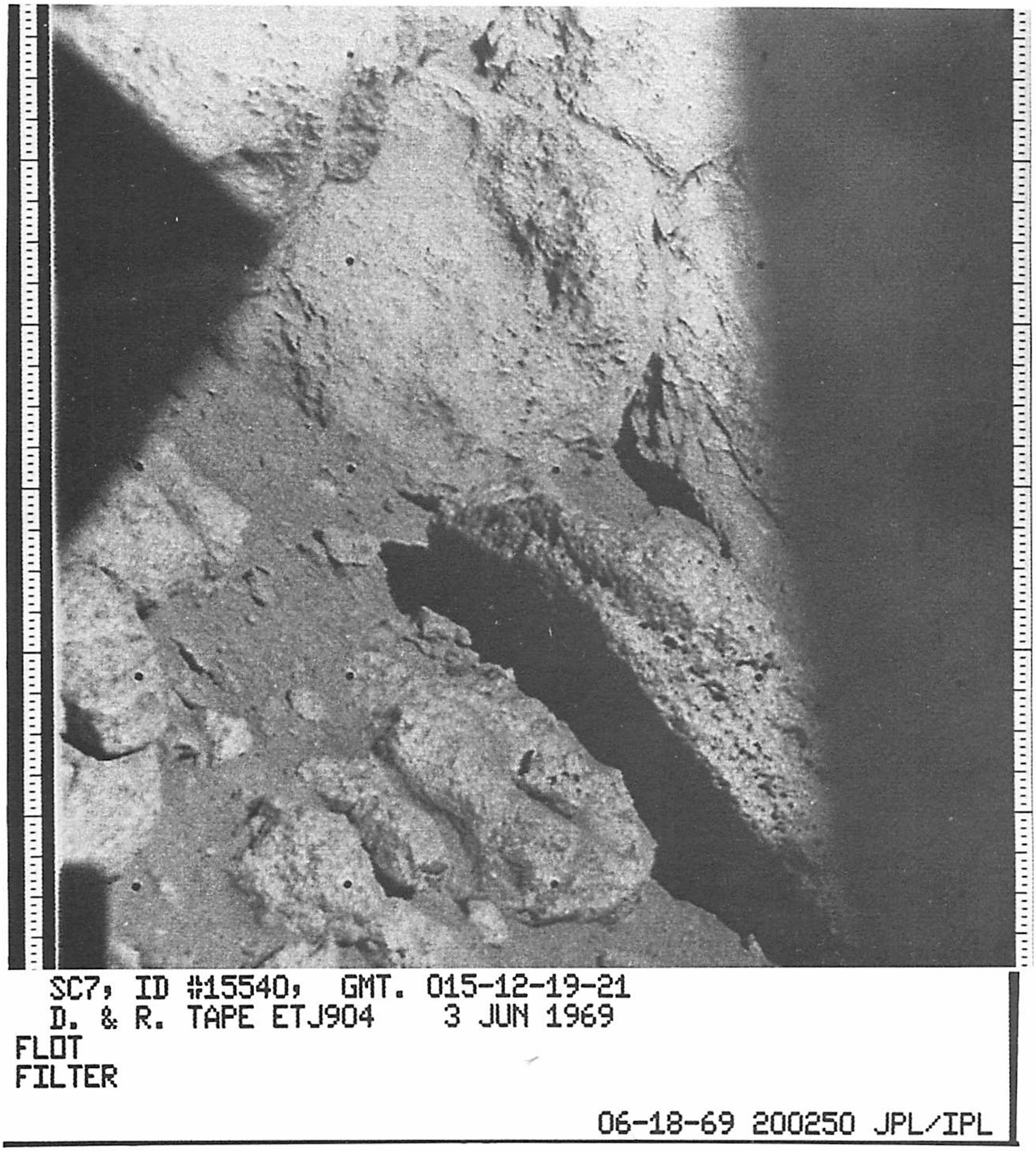

Fig. 13 Possible slab of lava photographed by *Surveyor VII* on flow unit *E*. Notice rows of vesicles on edge of slab. (Kindly computer-processed by JPL, Pasadena.)

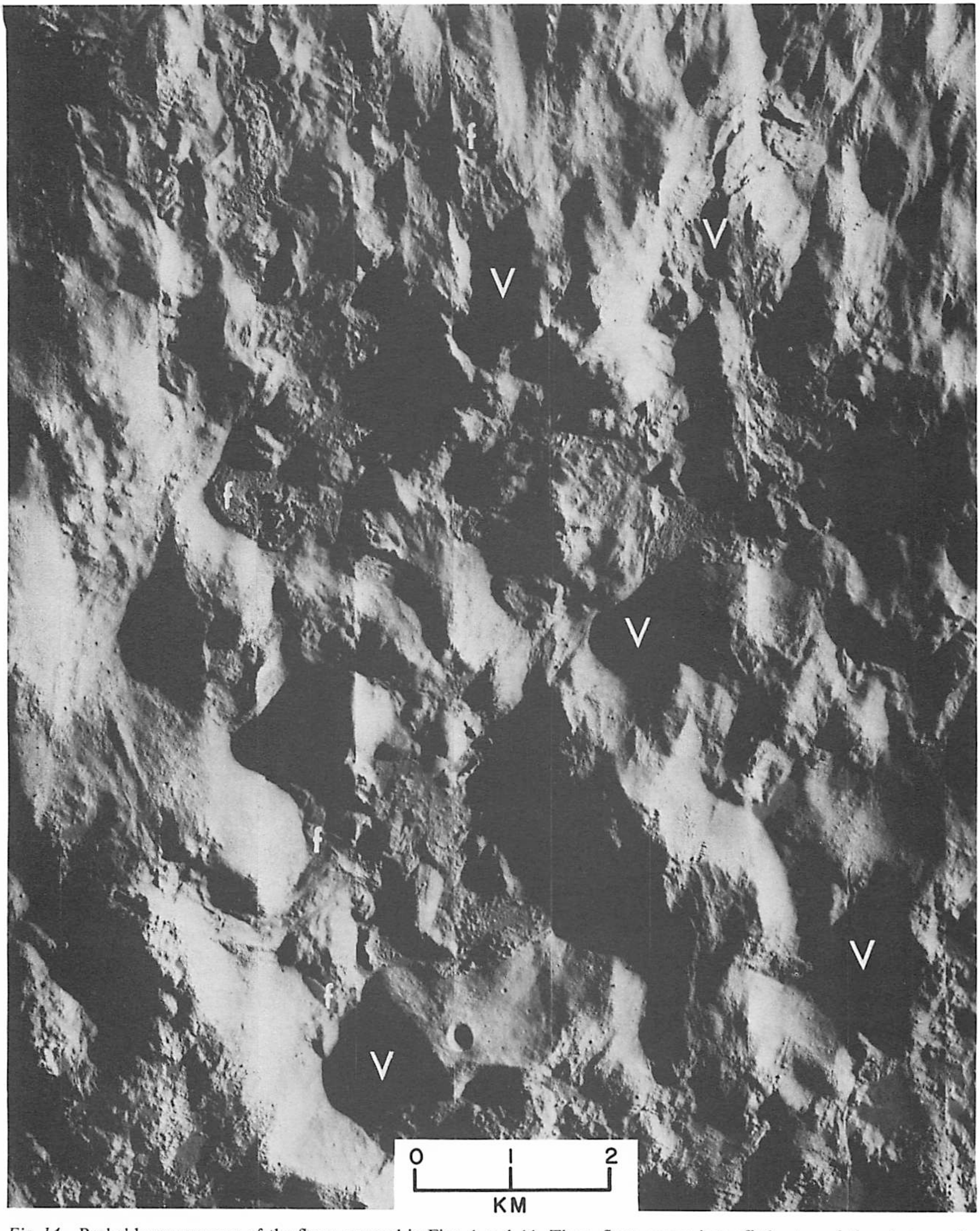

Fig. 14 Probable source area of the flows mapped in Figs. 1 and 11. These flows occur just off the top of the photograph. Several possible volcanic *vents* with their northern rims breached are indicated by *V;* and *flows* associated with these craters are designated *f*. The rim of Tycho is just off the bottom of the photograph (Portion of *Orbiter V*, H-127).

proximately 50 cm long and 15 cm thick taken by *Surveyor VII* on flow unit E, and may be one such block of lava. The block has a smooth, slightly concave underside (in shadow on this photograph) and an irregular top. Several rows of vesicles up to 1 cm in diameter parallel the long axis of the slab.

The *source of the flows* in the mapped areas appears to be the region just north of the rim of Tycho (Fig. 14). This is an anomalous area where several irregular craters 0.5-2 km in diameter have had their northern rims breached. Extensive flows with well-defined fronts are found in this area; and *the flows are associated with the breached craters.* In addition, there are *several strings of vents* from which flows have emanated. These craters, and possibly concealed *fissures,* are probably the source of the flows which have breached their walls and flowed in a northerly direction.

Several additional flow structures occur outside the mapped areas and are shown in Figures 2 and 15. They are 3-20 km long and about 1-6 km wide. The direction of flow is indicated by the arrows in Figure 2 and conforms to the slope of the terrain over which they have flowed. Several have flowed toward Tycho and others have flowed away from Tycho. *Five of these six flows have apparently issued from craters which have been breached by the flows.* Their surface texture is coarse with a wrinkled or ropy appearance and several seem to have been considerably more viscous than the flows in the maria. Fig. 15 shows a particularly viscous-looking flow with a high front ($\sim$80 meters), and arcuate and linear flow structure. This flow has apparently issued from the crater (C), partially shown in the upper left of the photograph, and has flowed toward Tycho. The general appearance of the flows and the fact that they are associated with craters indicates they are *volcanic lava flows. The most distant flows are about 100 km from the rim of Tycho* (Fig. 2) which is near the limit of the medium resolution coverage of *Orbiter V* in this area. It is quite possible that other flows occur at even greater distances. The fresh appearance of these flows, their relatively close proximity to Tycho and their similarity to flows on the rim and interior wall of Tycho suggest that they are associated with the formation of Tycho.

The *interior slopes of Tycho* also show signs of the flow of material (Figs. 16 to 18). These flows are primarily expressed as channels with raised rims, although there are several flows with well-defined fronts. In Figure 16 several flows have originated at lakes and craters on the wall, flowed down valleys in the wall and ponded in low areas of the wall or issued upon the floor. The flows display arcuate ridging and other flow structure similar to terrestrial lava flows. Their texture is also similar to that of the floor. Since several of the flows have originated at lakes and the volumes of the *flows* are large, *the lakes are almost surely volcanic centers which have experienced relatively sustained eruptions.* Figure 19 shows a flow which has issued from a pond at a higher level, flowed across part of the floor and merged with it so that the floor and flow appear as one textural unit. Peripheral fissures on the floor continue across the flow. Thus the flow reached the floor when it was still in a fluid or plastic condition and before the formation of the peripheral fissures. *Therefore the flow must be essentially the same age as the floor.* The flow channels have raised rims and several appear to begin at breached craters on the wall (Figs. 17 and 18). The channels are almost identical to lava drainage channels with natural levees built up by the overflow of lava. The similarity is strengthened by the fact that several of the channels originate at craters and at least one ends in a small "lake" which exhibits a flow front.

Finally, that part of the floor of Tycho recorded on *Orbiter V* frame H-125 forms a geologic unit which is morphologically quite different from most of the other units. It is shown in Figures 20 and 21, and is characterized by steep and gentlesided *domes* (not mapped) interspersed with terrain which displays a *highly-fractured* and *ropy pattern* similar to that of terrestrial lava. However, the size of the fractures and ridges are *at least 2 orders of magnitude greater* than similar features on terrestrial lava deposits and is probably the result of the low lunar gravity which would allow larger fractures and pressure ridges to develop. The texture and albedo of the floor is similar to units Tf_1 and Tf_2, and, therefore, they may have a similar composition; that is, more acidic than other flow units. Several gentle domes exhibit the same texture as the floor and have fissures along their crests. They are probably *updomings of the floor or tumuli* produced by the hydrostatic pressure of fluid lava beneath the solidified crust. Numerous crater chains and craters of highly irregular shape occur on the floor. Several of these features are shown in Figures 20 and 21 and attest to the widespread and intensive volcanic action to which the floor has been subjected. A set of peripheral fractures found on an inward sloping bench at the margins of the floor and central peaks, and floor material occurring at higher levels on the west-

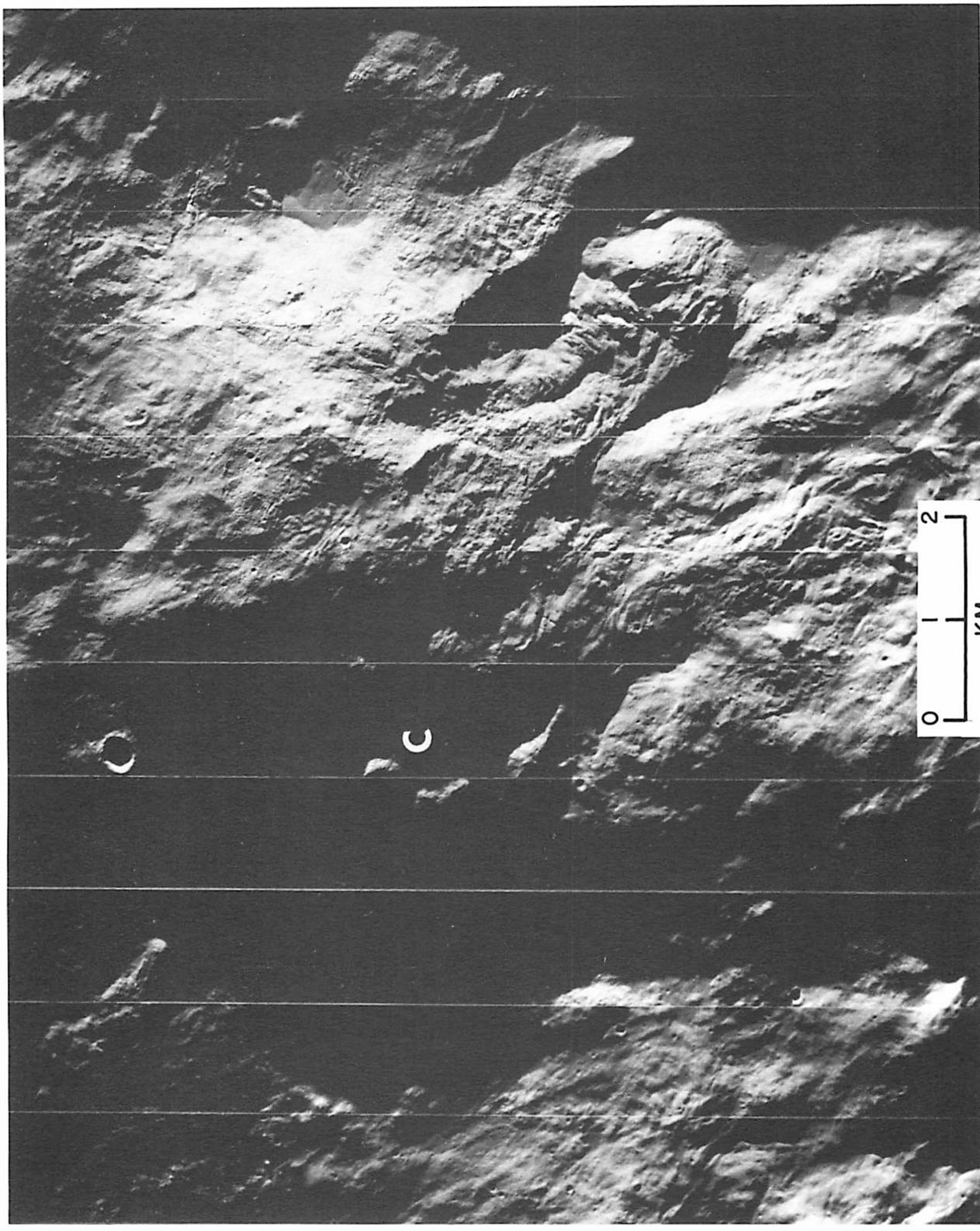

Fig. 15 Thick, viscous flow which has issued from a large crater (*C*). This flow has traveled toward Tycho. (Portion of *Orbiter V*, H-127.)

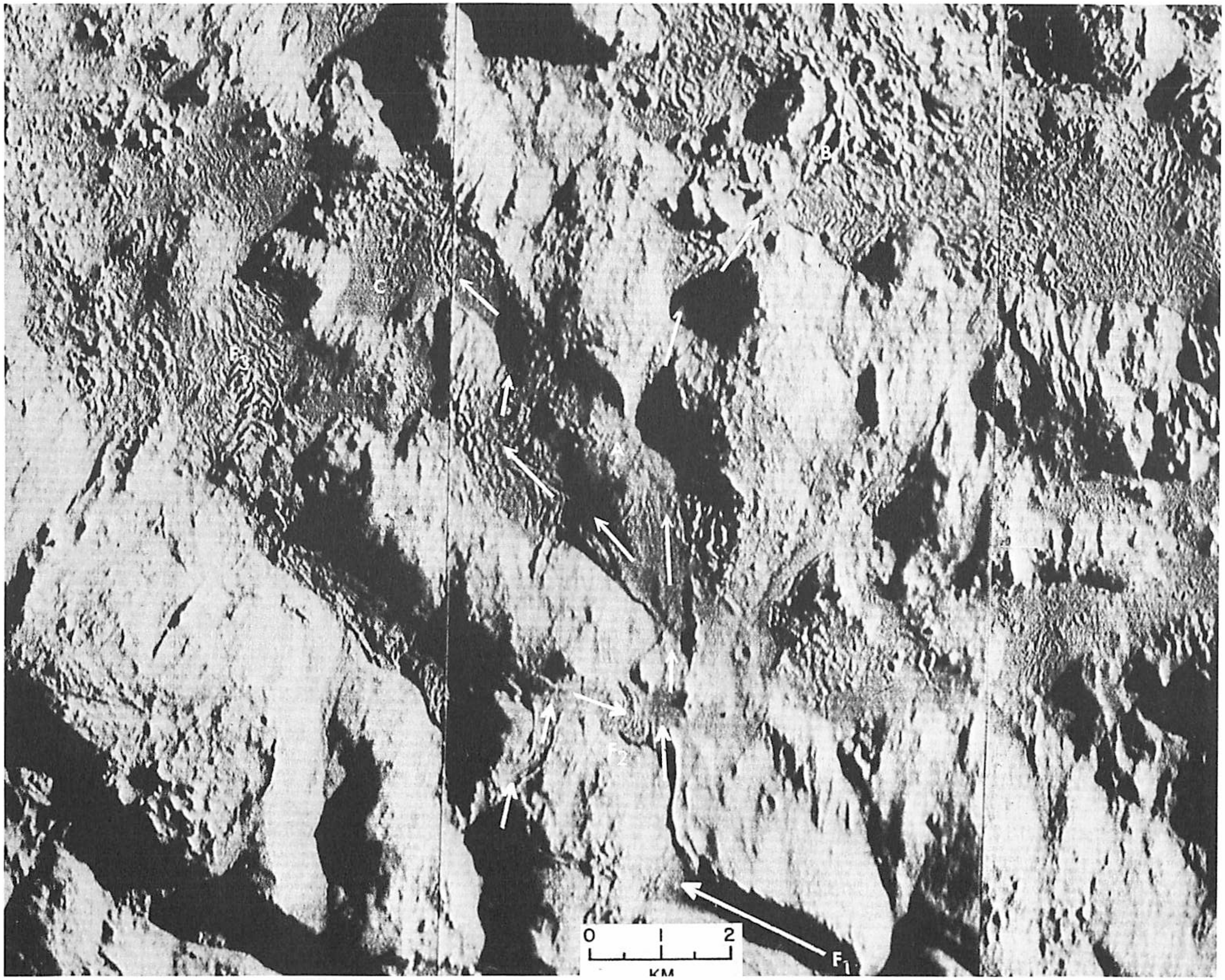

Fig. 16 Flows on the southern interior wall of Tycho. One flow (F_1) has originated at a lake on the wall off the bottom of the photograph, flowed down the wall (arrows) and bifurcated at point *A*, one half flowing onto the floor at *B* and the other half issuing onto a level portion of the wall at *C*. Other flows are indicated by F_2 and F_3. (Portion of *Orbiter V*, M-125.)

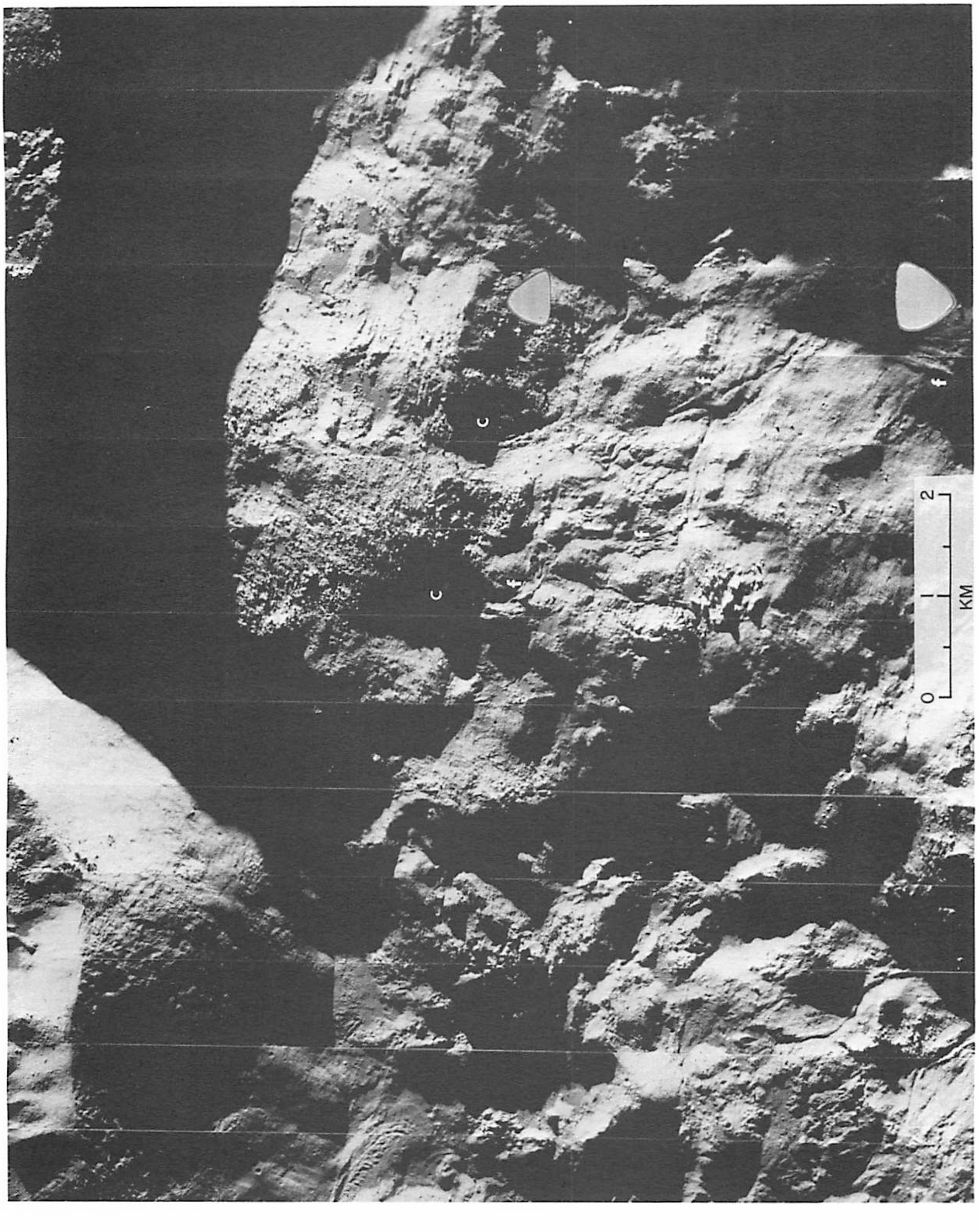

Fig. 17 Northern interior wall of Tycho showing flows and flow channels (*f*), several of which issue from breached craters (*c*). (Portion of *Orbiter V*, H-126.)

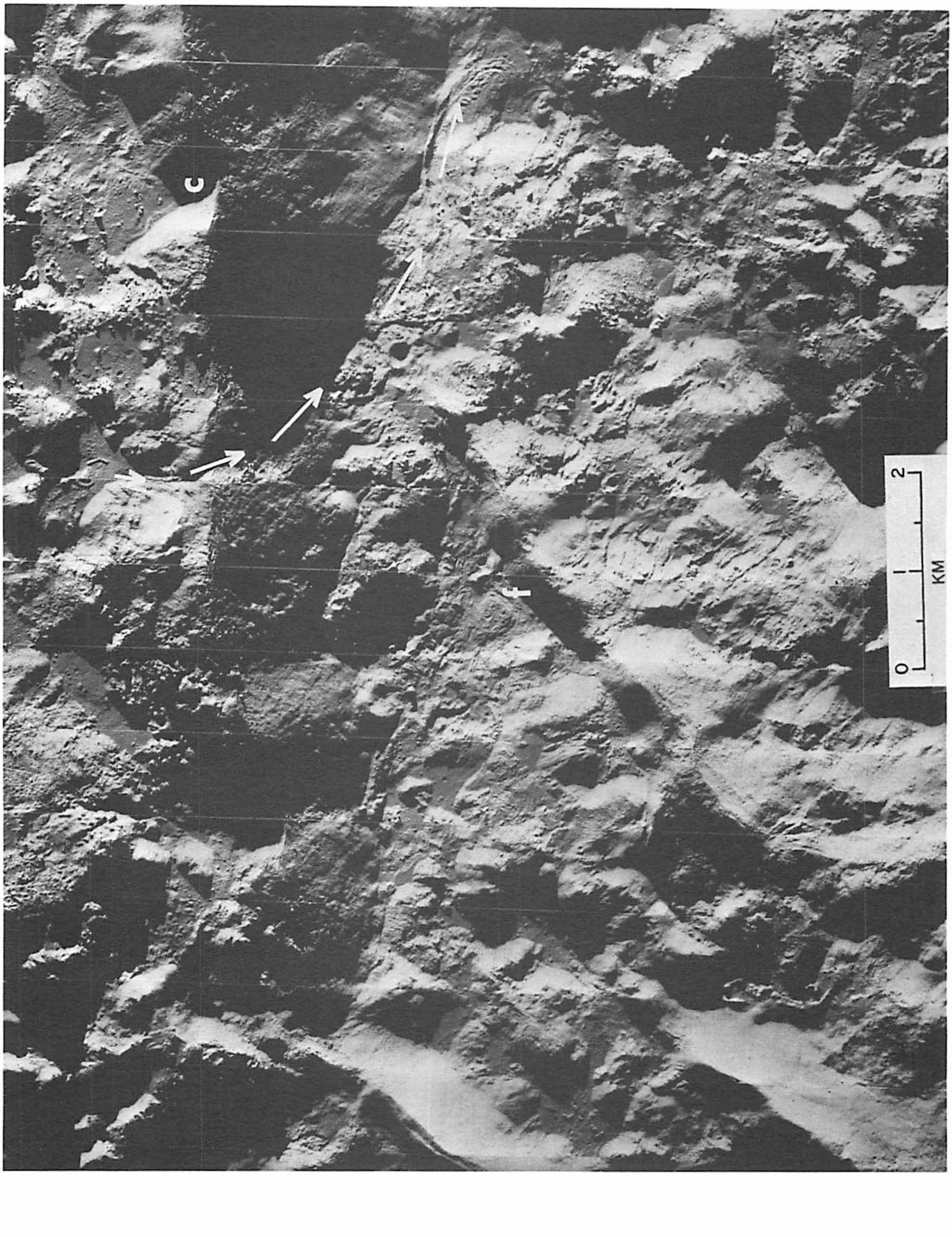

Fig. 18 Flows (*f*) on the northern interior wall of Tycho. One of the flows has apparently originated in the smooth material outside the rim and flowed down the rim scarp (arrows). The breached crater (*c*) on the rim seems to have given rise to much of the smooth material (lava) just outside the rim. (Portion of *Orbiter V*, H-126.)

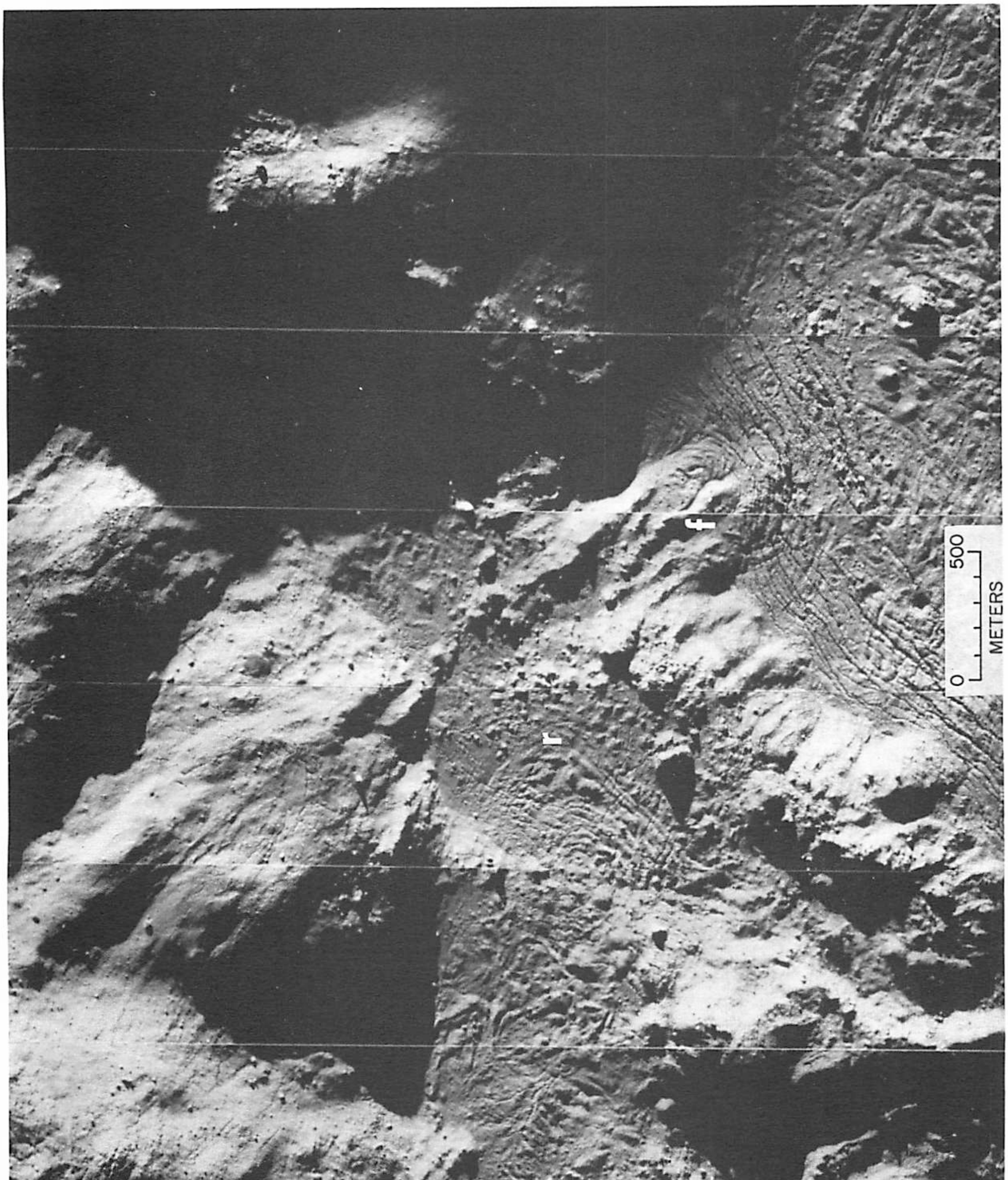

Fig. 19 Part of the ropy material (*r*) of a pond has issued onto the floor of Tycho as a short flow (*f*) which has been peripherally fractured by subsequent subsidence on the floor. (Portion of *Orbiter V*, H-126.)

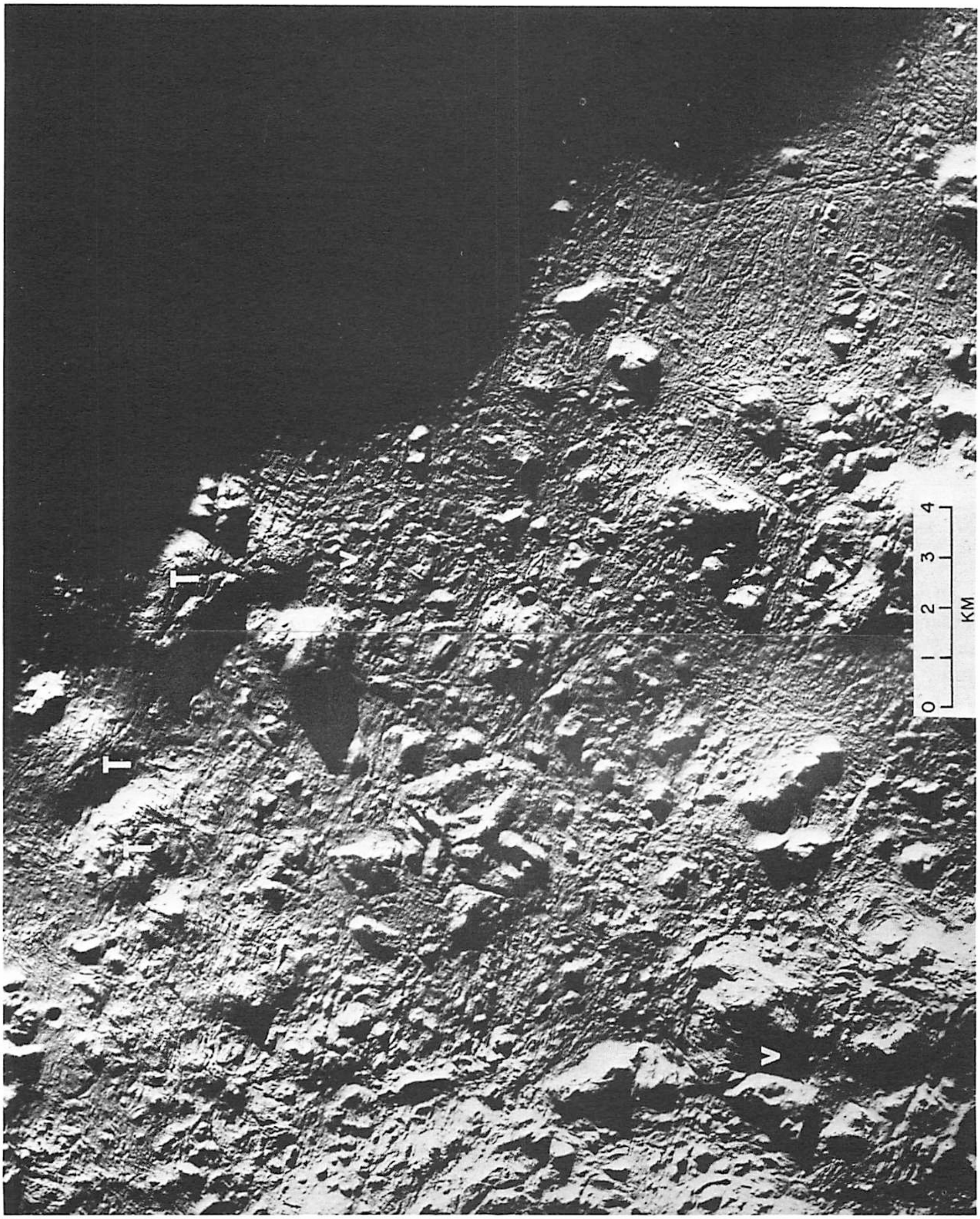

Fig. 20 A portion of the northern floor of Tycho showing the ropy or ridged and fractured texture, possible tumuli (T) and probable small volcanic vents (v). (Portion of *Orbiter V*, H-125.)

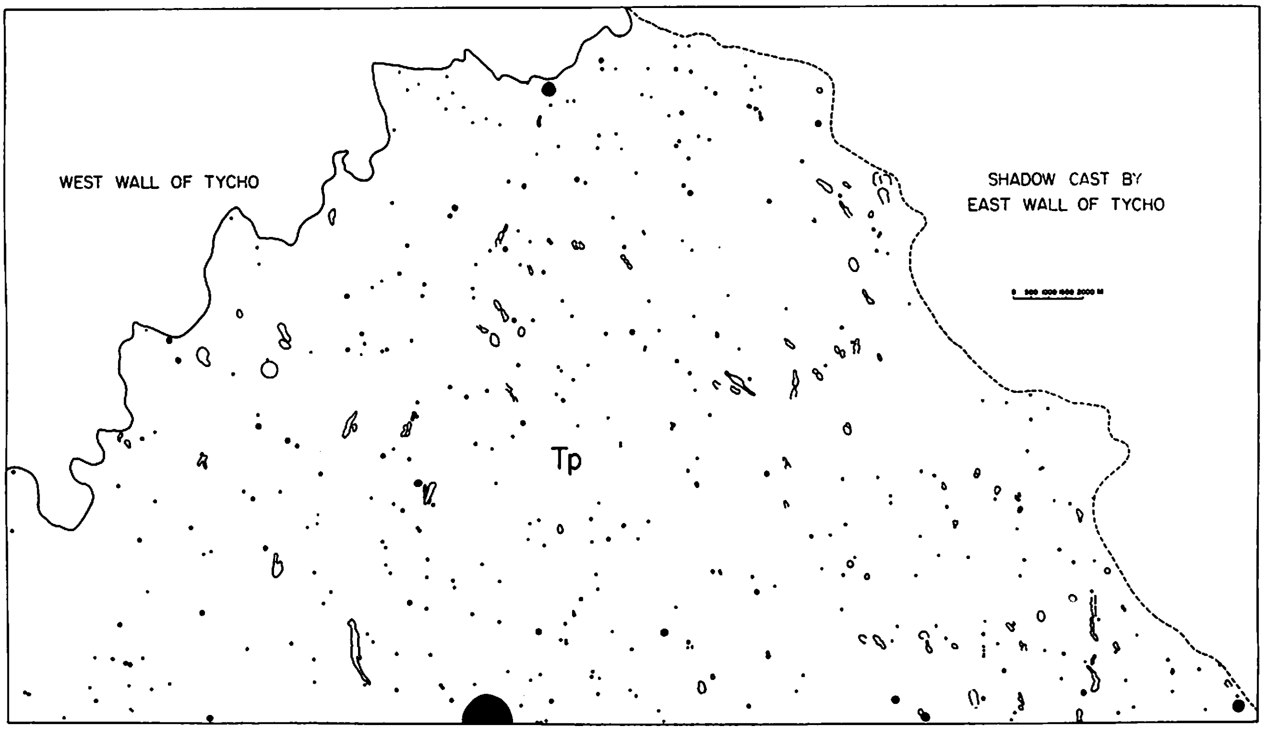

Fig. 21 Map of a portion of the floor of Tycho compiled from *Orbiter V* frame H-125. The filled circles are eumorphic craters of probable impact origin. Probable volcanic vents are shown in outline.

ern wall, indicate that *the floor was once at a higher level* than at the present time and has subsequently subsided, leaving a higher bench broken by tension fractures in the zone of maximum downbending. This type of structure is even better developed on the floor of Aristarchus and will be discussed in more detail later.

3. *Tycho: Chemical Analysis by Surveyor VII*

Surveyor VII landed on the extreme edge of flow unit E (Figs. 3 and 11), and chemically analyzed the fragmental material and one rock by an alpha scattering device (*Surveyor VII:* Patterson, *et al.* 1970; *Surveyor V:* Turkevich, *et al.* 1969; *Surveyor VI:* Franzgrote, *et al.* 1970). The results of this analysis, and those of *Surveyor V* and *VI* in Mare Tranquillitatis and Sinus Medii, respectively, are presented in Table II together with the analyses of the *Apollo 11* and *12* rocks *(Science,* 1970 *a, b).*

The chemical composition of the *Surveyor VII* site is quite different from those at the *Surveyor* sites in the maria, and the analyses of the basaltic rocks from the *Apollo 11* and *12* sites in Mare Tranquillitatis and Oceanus Procellarum. However, the composition is very similar to the small fragments of anorthosite found in the soil at the *Apollo 11* site by Wood, *et al.* (1970), and which they believe were derived from the highlands. Therefore, *flow unit E probably has an anorthositic composition.* The densities of the lunar anorthosites are between 2.8 and 2.9 g/cm^3, while the lunar basalts are about 3.4 to 3.5 g/cm^3. Anorthosites are leucocratic rocks and this may account for the higher albedo of the highlands compared to the maria. If an anorthositic composition is characteristic of the highlands then widespread chemical differentiation and/or crystal fractionation have taken place on the moon. *Apollo 12* sample 12013 (Table II) is a siliceous rock with an exceptionally high potassium content and has a composition similar to an andesite or basaltic andesite. This sample again indicates that *rather extensive magmatic differentiation has occurred on the moon.*

The volcanic flows Tf_1, Tf_2 and the flow shown in Fig. 15 have a considerably higher albedo and were more viscous than flow units E, and, therefore, are probably *more acidic in composition.* If this is the case, extensive magmatic differentiation must have been involved in the later stages of the development of Tycho.

4. *Tycho: Crater Counts*

If it is supposed that each geologic unit on the Moon is a counter of primary impact craters, then it is clear that older units will be more densely cra-

TABLE II
CHEMICAL COMPOSITION OF THE SURVEYOR V, VI AND VII LANDING SITES AND THE APOLLO 11 AND 12 ROCKS (IN PERCENT BY WEIGHT)

OXIDE	SURVEYOR V	APOLLO 11 BASALTS (AVER.)	SURVEYOR VI	APOLLO 12 BASALTS (AVER.)	SURVEYOR VII*	APOLLO 11 ANORTHOSITES	APOLLO 12 SAMPLE 12013 (ANDESITE?)
SiO_2	46.4	40.8	49.1	40.0	46.1	45.7	61.0
TiO_2	7.6	10.5	3.5	3.7	—	0.3	1.2
Al_2O_3	14.4	10.0	14.7	11.2	22.3	30.5	12.0
FeO	12.1	18.8	12.4	21.3	5.5	4.5	10.0
MgO	4.4	7.5	6.6	11.7	7.0	4.8	6.0
CaO	14.6	10.9	12.9	10.7	18.3	15.8	6.3
Na_2O	0.6	0.48	0.8	0.45	0.7	0.35	0.69
K_2O		0.21		0.06		—	2.0
MnO		0.22		0.26		0.1	0.12
H_2O		0.005					

*The rock analyzed at the *Surveyor VII* site had essentially the same chemical composition as the undisturbed soil except for a lower magnesium and higher aluminum content, and a slightly lower iron content.

tered than recent ones. In fact, the craters may belong to three different populations — primary impact craters, secondary impact craters (from either a meteoric impact or a volcanic eruption), and craters of internal origin. For the present, the results of counting all eumorphic (sharp-rimmed) circular craters as large as, or in excess of, 50 m in diameter will be presented.

The counts were performed for each geologic unit separately and the total area of each unit was measured with a planimeter. Parts of all photographed areas were overexposed or shadowed, so that the actual areas on which craters were counted were less than the total areas measured. Corrections to the actual areas where the craters were counted were applied using planimetric and square-counting methods.

Although the counts of craters on the floor of Tycho are restricted to eumorphic craters, the position of many at the apices of hills and on fissures suggest that they may be volcanic rather than impact in origin: therefore, the count on this unit (Tp) represents a maximum. The measured areas and counts for the different units are given in Table III.

TABLE III
CRATER COUNTS ON TYCHO UNITS

UNIT	AREA EXAM. (KM^2)	CORR. AREA (KM^2)	CRATERS $\geq$ 50m	CRATER DENSITY (FLOOR = 1)
Lakes	22	22	17	0.9
Floor	460	400	347	1.0
Tf_1+Tf_3	24	19	30	1.8
Tf_2	19	15	22	1.7
Ta	185	136	278	2.4
Tb	51	42	81	2.2
Tc	463	342	1324	4.5

The geologic units Tf_1, Tf_2 and Tf_3 are alike and, indeed, are found to have the same crater density, within the limits to be expected from the method. Again, the apparently similar units Ta and Tb have similar number-densities of craters. A less obvious result of the crater counts is that the "lakes" (T1), indicated by filled circles in Fig. 2, and the floor (Tp) are cratered to a similar number density (Table III). Unit Tc has 4.5 times as many craters per unit area as the floor of Tycho, 2.6 times as many as units ($Tf_1 + Tf_2 + Tf_3$) and twice as many as unit (Ta + Tb).

Consistently, *more craters per unit area are found on stratigraphically older units.* It would appear probable, therefore, that the majority of the eumorphic craters are *impact craters.*

In Fig. 22 the data are represented logarithmically as cumulative numbers per 1000 km^2 of surface against crater diameter in meters. The more significant points are joined with continuous lines, the less significant points with broken lines. "Significance" was judged qualitatively, using three criteria. The more significant points were defined as those satisfying three conditions simultaneously: (a) points relating to counts on areas generally larger than about 20 km^2; (b) points in which the number of craters counted was $>$ 10; (c) points in which observational incompleteness was believed to be essentially absent. Item (c) was ascertained after maps of craters had been cross-checked by a second observer.

Because the ratio between the crater densities of units ($Tf_1 + Tf_2 + Tf_3$) and (Ta + Tb) was only 1.3 at the 50 m size (Table III), and was not based on the most significant data, we took sample counts

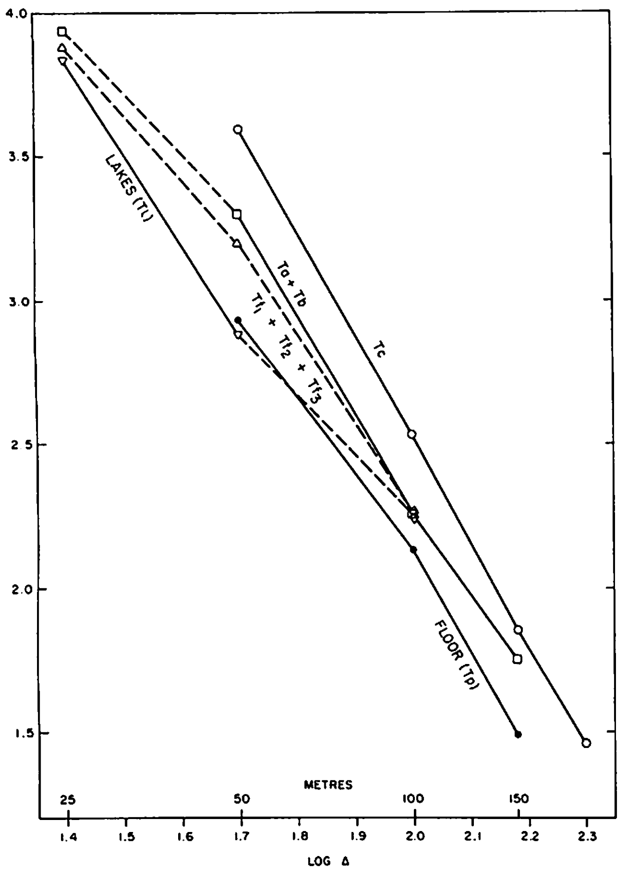

Fig. 22 Number (N) of craters $\geq \Delta$ meters in diameter/ 1000 km^2 of surface, for the geologic units shown in Figs. 1, 2 and 21.

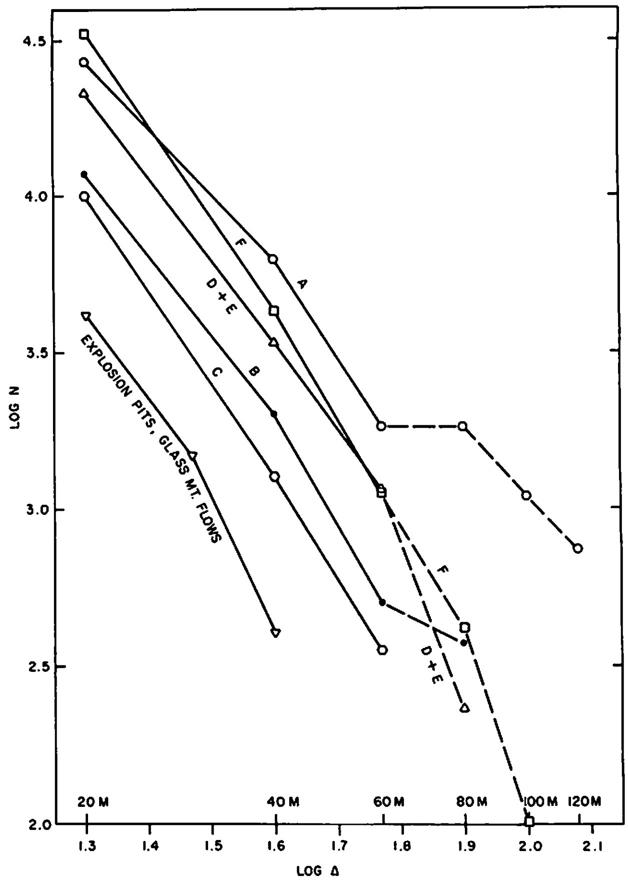

Fig. 23 Logarithmic plot of the cumulative number of craters per 1000 km^2 of surface (N) against minimum crater diameter (Δ) for the geologic units in Fig. 11.

in these regions of craters smaller than 50 m but larger than 25 m to see if the same difference persisted. The result (Fig. 22) shows a similar difference in crater density, although we suspect some observational losses in the counts of the smallest craters since the terrains are rough and the graphs bend downward relative to the graph of the "lakes," where equally small craters were seen easily.

The fact that ($Tf_1 + Tf_2 + Tf_3$) is younger than (Ta + Tb) comes from stratigraphic evidence. The counts are insufficient by themselves to establish the relative ages of these particular units even if the craters counted are all impact craters; but, once again, the counts do not conflict with the geologic information. Again, therefore, we must conclude that the majority of the eumorphic craters which we have used in this analysis are not of internal origin.

5. *Tycho: Counts of Small Craters in the Surveyor VII Area*

Fig. 23 shows the cumulative number of craters per 1000 km^2 against crater diameter, for craters $\geqq$ 20 meters shown in Fig. 11. The plot shows that with the exception of units A and B, the number densities accord with the stratigraphic position of the units; that is, the older the unit the more craters per unit area. However, units A and B have an excess of craters in the diameter range of 20-60 meters. The youngest, unit A, has more craters per unit area than the oldest, unit F; and the next youngest, unit B, has more craters than unit C, which it overlaps. However, it was shown in the previous section that counts of craters over 50 meters in diameter on the large areas shown in Figure 1 gave crater densities which were in agreement with observed stratigraphic relationships. Since the unit areas in Fig. 11 are very small (2-7 km^2), it is possible that the excess craters are due to random fluctuations in crater density. Alternatively, they could be of internal origin. In this connection, it is of interest that the excess is found only on the two most viscous appearing units and that unit A, the more extreme case, also has the greatest excess of craters. If the excess is of internal origin, it would seem likely that they are explosion pits resulting from volatiles contained in the flows. It was pointed out previously that the flows in question have a surface morphology (flow ridging) similar to viscous flows on earth. Also unit A has a higher albedo than the other units. Terrestrial flows of acidic and intermedaite composition often contain large

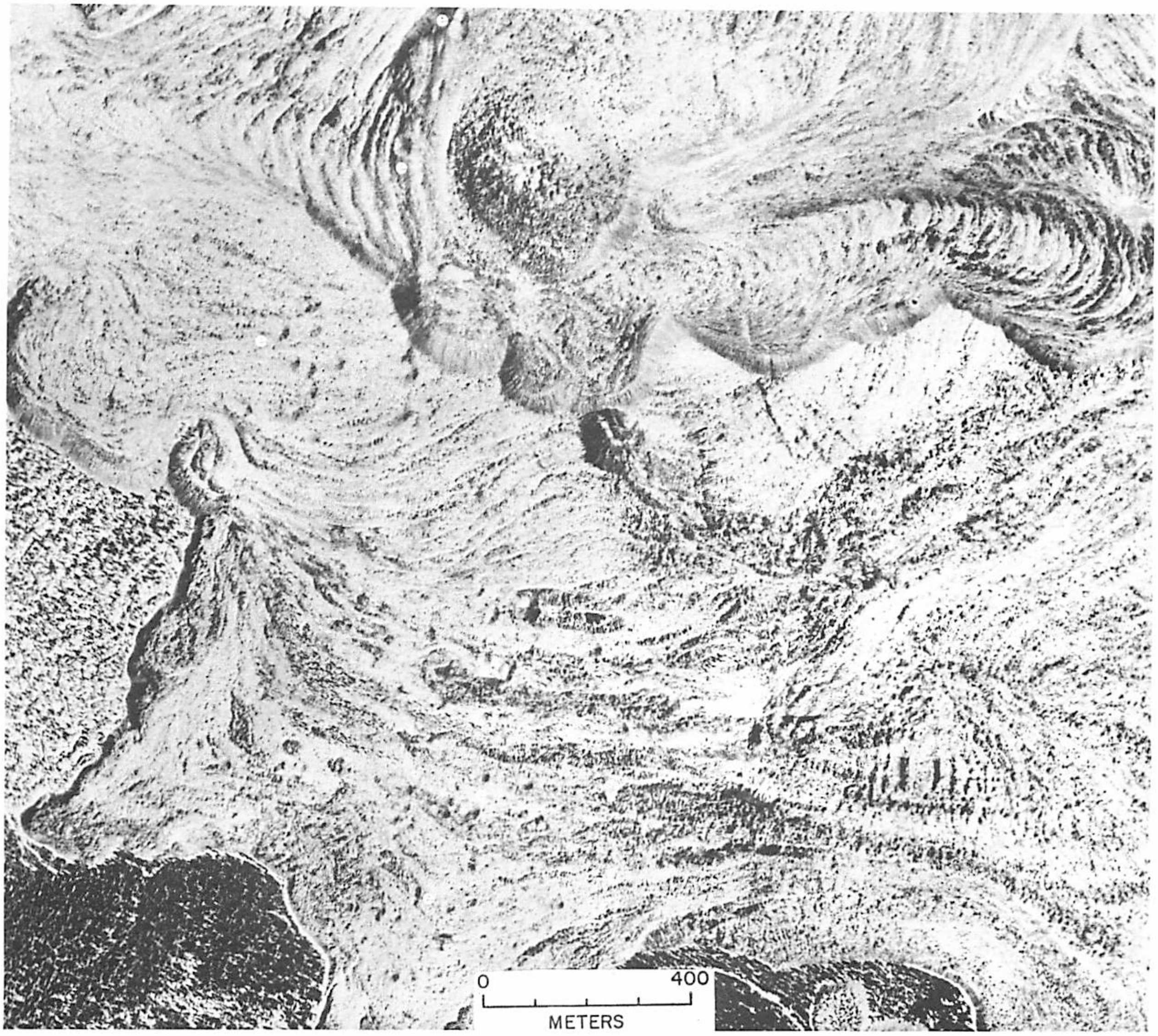

Fig. 24 Aerial photograph of a portion of the Glass Mountain rhyolite-dacite flows, Siskiyou Co., California, showing numerous explosion pits. Several of the larger explosion craters are indicated by *e* (U.S. Government photo).

amounts of volatiles which escape violently to form explosion pits. Figure 24 is an aerial photograph of the Glass Mountain rhyolite-dacite flows in Siskiyou County, California, and Figure 25 is a map, compiled from stereo photographs, showing the flow structure and distribution of explosion craters on these flows. If the excess craters on the lunar flows are of internal origin, then the slope of the diameter-frequency curve should be similar to that of the terrestrial explosion pits. In Figure 23 the cumulative frequencies of the terrestrial explosion pits on the Glass Mountain flows are plotted in the same manner as that of the lunar sample. It is seen that the slopes are indeed similar (about -3). The log N intercept of the Glass Mountain curve could be adjusted upwards, into the lunar domain, by the addition of impact craters. The fact that the excess of craters on unit A is greater than that on unit B may be due to unit A's having a higher volatile content. This possibility is substantiated by the more massive character and higher albedo of A relative to B.

6. Tycho: Summary of Facts

In this section, we list the facts relevant to the interpretation of Tycho and leave much of the interpretation of these facts to a later discussion. In what follows, reference should be made to Figs. 1-25.

1. Counts (Table III) of craters $\geqq 50$ m in

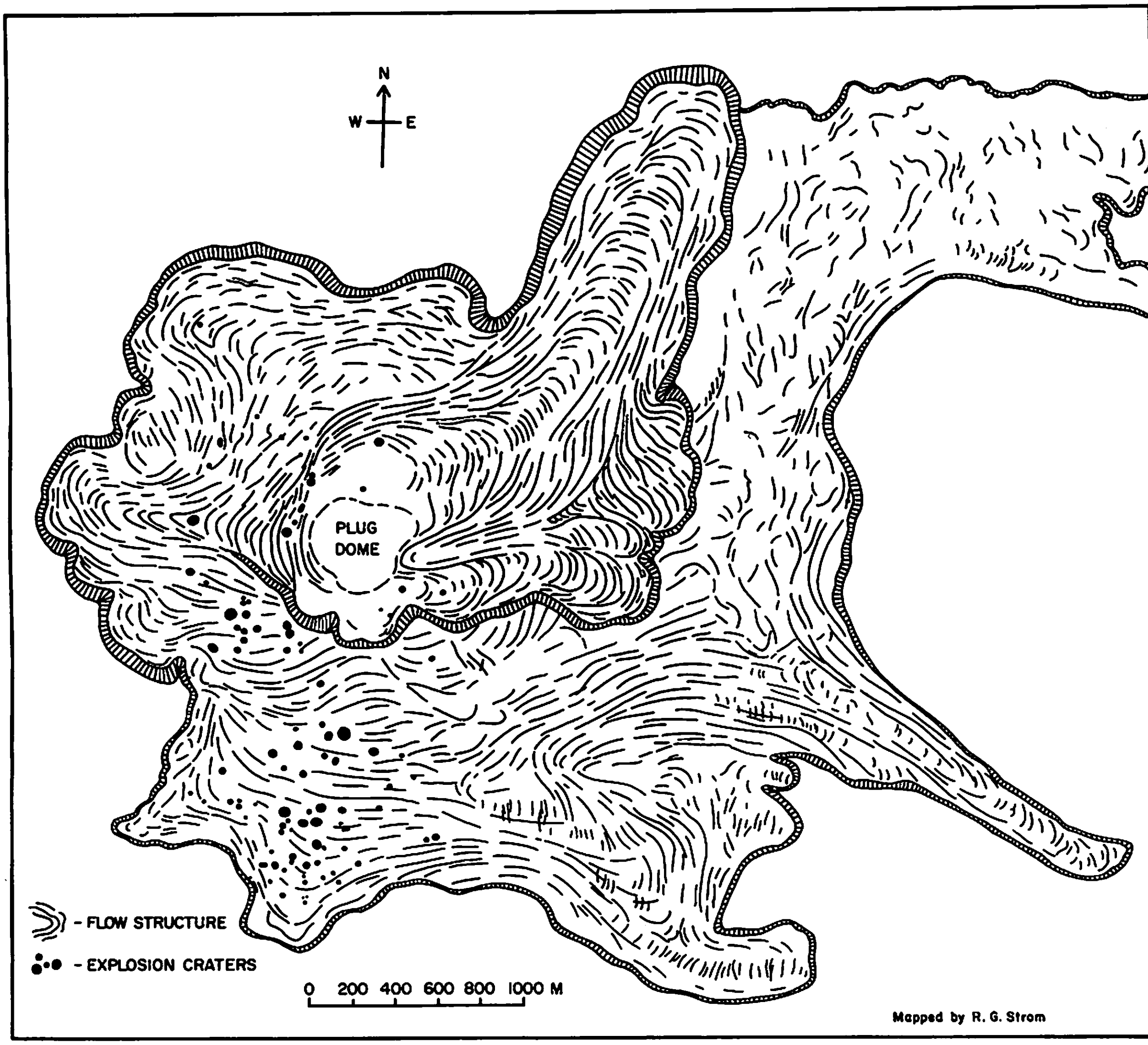

Fig. 25 Map of the Glass Mountain flows showing the distribution of explosion pits (filled circles) and flow structure.

diameter on the various geologic units demonstrate without exception that stratigraphically younger units contain fewer craters. Therefore it is probable that the majority of these craters are either primary impact craters or secondary impact craters. On two viscous appearing flows there is an excess of small craters ($<$ 50 meters diameter). The excess craters may be internal explosion pits.

2. The number of craters $\geqq$ 50 m in diameter per unit area of the floor unit (Tp) of Tycho is essentially the same as the average number per unit area on the lakes (Tl) outside the walls of Tycho. The floor and the lakes may therefore have the same average age.
3. Major flows occur in the Tycho region. They are up to 20 km or more long and 4 to 12 km wide. Some appear to have been more viscous than others, and these have a higher albedo than the others. Generally, the apparently more viscous flows are the later ones.
4. The floor of Tycho has, in peripheral localities, an inward sloping bench containing fractures. A similarly fractured bench surrounds the central peaks. In both cases the fractures concentrate in the zone of maximum curvature. They are probably tension fractures induced by the stretching of the margins of the floor, the lowest parts of which appear to have subsided as a whole.

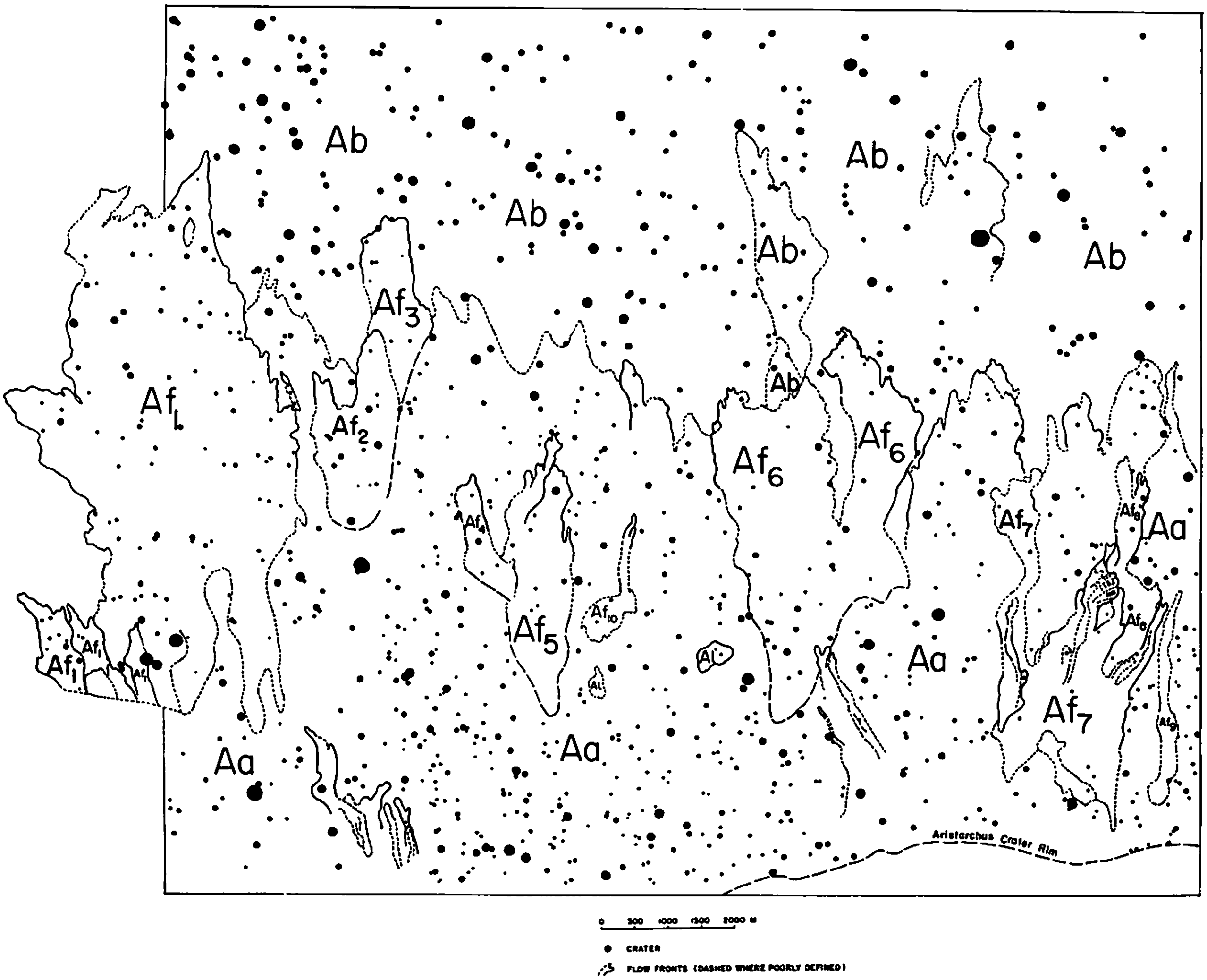

Fig. 26 Generalized map of a portion of the north rim of Aristarchus showing the various geologic units and the distribution of craters greater than 28 meters in diameter on units Aa and Af_1-Af_9, and greater than 56 meters on unit Ab. (Compiled from *Orbiter V*, H-201.)

5. One flow, found on the inner wall of Tycho, is the same age as the floor: The flow merges with the material of the floor and peripheral fractures following the floor bench also traverse the flow.
6. At least five flows have originated in, and breached, craters in the Tycho region. Several of these flows commence at distances of about 100 km from the rim of Tycho. Other, less well-defined flows occur in the vicinity of the rim of Tycho. Like the major flows, some of the flows from craters near Tycho, and from craters in its rim appear to have been more viscous than others. They are from 3 to 20 km long and up to 6 km wide.
7. Of the "lakes," the major ones are concentrated in a relatively narrow zone on the eastern outer flanks of Tycho. Many of these lakes exhibit flow fronts. In at least two cases the lakes have overriden low places in the wall of their otherwise confining depressions and formed distinct flows. In several "lakes" there are younger flows with fairly well-defined secondary fronts superimposed on the main flow. One lake occurs near the crest of the main central peak.
8. Different units have marked differences in texture. The floor (Tp) has a characteristic crenulated appearance. It is fractured and has many domes and hills. Units Tf_1 and Tf_2 are, in some respects, similar to the floor material but have a ridged appearance typical of a flow pattern. Units Ta and Tb are highly fractured, whereas very few fractures are found in unit Tc.

7. *Aristarchus: Geologic Units*

The northern rim of Aristarchus contains flow units similar in disposition to those on the northern rim of Tycho. However, the surface morphology of these units is somewhat different from those near Tycho. Figure 26 is a generalized map of a portion of the northern rim of Aristarchus compiled from *Orbiter V* frame H-201. It shows the various geologic units and the distribution of craters greater than 28 meters in diameter on units Aa and Af_1-Af_9, and greater than 56 meters on unit Ab.

Units Af_1-Af_9 are discrete, well-defined flows which overlie and are therefore younger than, units Aa and Ab. They are exceptionally smooth flows with very little fracturing or ridging (Figs. 27 and 28). The units generally have well-defined, lobate fronts, but are unusually thin, ranging from less than 1 meter to about 9 meters in thickness. Several have formed channels with raised rims along their centers, and at least one has weak arcuate ridging at its terminus indicative of flow ridging (see Fig. 28). Lakes similar to those in the vicinity of Tycho appear to have been the source of several flows, and a row of vents is apparently the source of another flow (Figs. 29 and 30). Other flows appear to have originated at small, irregular, flat-floored depressions, and still others have no evident source. Although the resolution of earth-based full moon photography is not high enough to distinguish these flows, it is obvious that the general area in which they occur has a low albedo similar to that of the maria (see Fig. 31). All the above characteristics suggest that the flows were extremely fluid and probably have a basaltic composition similar to the maria.

Unit Aa consists of hilly, ridged terrain with numerous rocks, but is practically devoid of sharp, open fractures. At the northern margins of this unit there sometimes occur lobate sub-units, similar in form to units Af_{1-9} but usually thicker and coarser in texture. The sub-units are included in unit Aa, although it is not entirely clear whether or not they are younger than unit Aa and should be regarded as separate units.

Unit Ab is smooth, hummocky and devoid of open fractures. It is overlain by the other deposits and is therefore the oldest unit mapped. It is somewhat similar to the Tycho unit Tc. This deposit contains numerous concentric ridges which may be base surge dunes resulting from an explosion centered in Aristarchus.

Lakes similar to those surrounding Tycho are also found on the rim of Aristarchus. However, they are less numerous and many seem to define the source of the more recent flows. Several have well-defined fronts which give a bladder-like appearance to the lake (B in Fig. 29), and several of these have numerous circular to irregular depressions similar to collapse depressions on terrestrial lava flows (Fig. 32). Lakes which have given rise to flows appear to have overflowed their confining basins and then subsided to lower levels, in some cases leaving small tongues of flows at higher elevations (Fig. 29). Lakes also occur in low areas between fault scarps on the interior wall of Aristarchus and these lakes have most of the above characteristics. In Figure 33 several flows have originated at high levels and flowed down-hill to partially or entirely fill a low area in the wall and form a typical lake. Closely spaced open fractures parallel to the crater wall are common and indicate that a slight slumping of the wall took place after the formation and consolidation of these lakes.

Numerous flows, in addition to those previously mentioned, occur at other areas on the rim of Aristarchus. Several good examples are shown in Figs. 34 and 35. A series of 14 short flows have issued from small circular to elliptical craters on the southwestern rim, and are shown in Fig. 34. They range from 140 meters to 1.4 km long and 50-390 meters wide, and have a surface texture similar to the flows on the northern rim. Fig. 35 shows a long narrow flow (4.4 km long and 28-570 meters wide) which originated from a lake (L) on the southwestern rim and flowed in a southeasterly direction across the grain of the underlying deposit. It formed a channel (C) with raised rims along the first one-third of its length. The portion of the flow where it emerges from the channel displays arcuate flow ridging (r), and at the middle and near the end there are several circular, irregular and strings of subdued craters with convex inner walls (dimple craters) which resemble, and are almost surely, collapse depressions (d). The volume of the flow is considerably greater than the depression from which it issued, indicating that the flow was sustained by a continuous eruption. This is also true for many of the other flows.

As in the case of Tycho, the inner walls of Aristarchus also show evidence for the flow of material. The flows down the walls of Aristarchus are expressed primarily as channels with raised rims. Many of the rims, or levees, originate at irregular craters and in some cases flows emanate from the distal ends

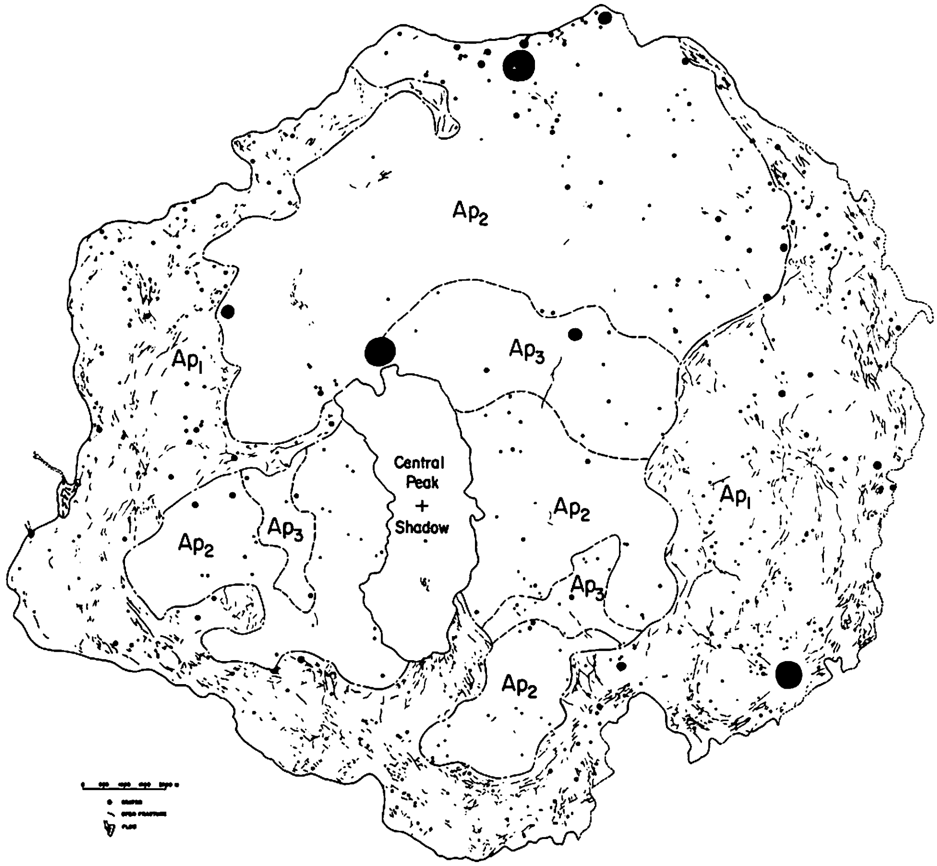

Fig. 38 Generalized map of the floor of Aristarchus showing the different geologic units and the distribution of craters and fractures. (Compiled from *Orbiter V*, H-198 and 199.)

ferent for diameters in excess of about 65 m. Another possibility is that the craters are members of inherently different populations; in which case many of them are probably of internal origin. Since the high resolution photographs of the central floor units, Ap_2 + Ap_3, show a strong deficiency of open fractures (Fig. 38) as if these units had been covered by some deposit, we adopt the first explanation, also because of the much smoother texture of the central portions compared to the floor margins.

We may now test whether such a deposit may be due to mass wasting of hill slopes. To this end, we have isolated the regions (Ap_3) of unit Ap_2 + Ap_3 which were largely devoid of hills, and performed counts of craters on Ap_3 only. The counts are included in Fig. 41 and indicate that the crater population on Ap_3 is the same as on Ap_2. In addition, there are more craters per unit area of Ap_2 than there are per unit area of Ap_3 — just the opposite of what one would expect if mass wasting of hill slopes were the mechanism obliterating craters. Therefore, *the blanketing is probably the result of flows and/or pyroclastic deposits.*

It should be noted (Fig. 41) that floor unit Ap_1 is cratered to the same density as the rim flows $Af_{2\text{-}8}$. This indicates that, on average, *the oldest floor unit* Ap_1 *was emplaced at about the same time as most of the mapped rim flows*. This is *not* the case for Tycho in which the mapped rim flows were apparently in place long before the floor formed.

In general, more craters per unit area are found on stratigraphically older units. This conculsion holds for all the sizes (28 m to 112 m) covered by the more significant points of Fig. 41. The indication, therefore, is that the majority of the eumorphic craters counted are *impact craters* of either primary or secondary impact origin.

9. *Aristarchus: Summary of Facts*

The following lists the facts relevant to the interpretation of Aristarchus. Reference should be made to Figs. 26-41.

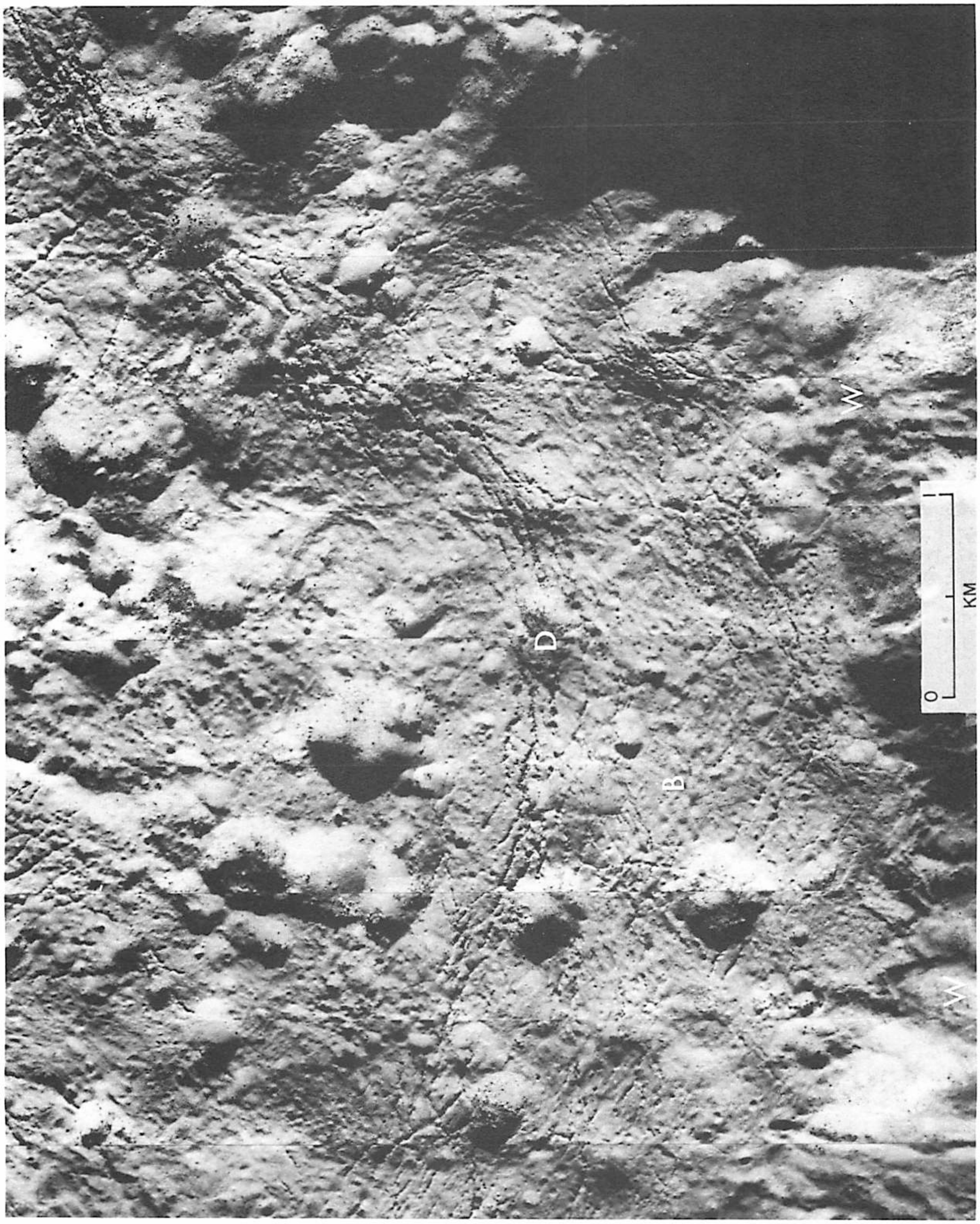

Fig. 39 A portion of the southern floor of Aristarchus at its contact with the wall (W) showing a relatively thin peripheral bench (B) with strong open fractures in the zone of maximum downbending (D). (Portion of *Orbiter V*, H-198.)

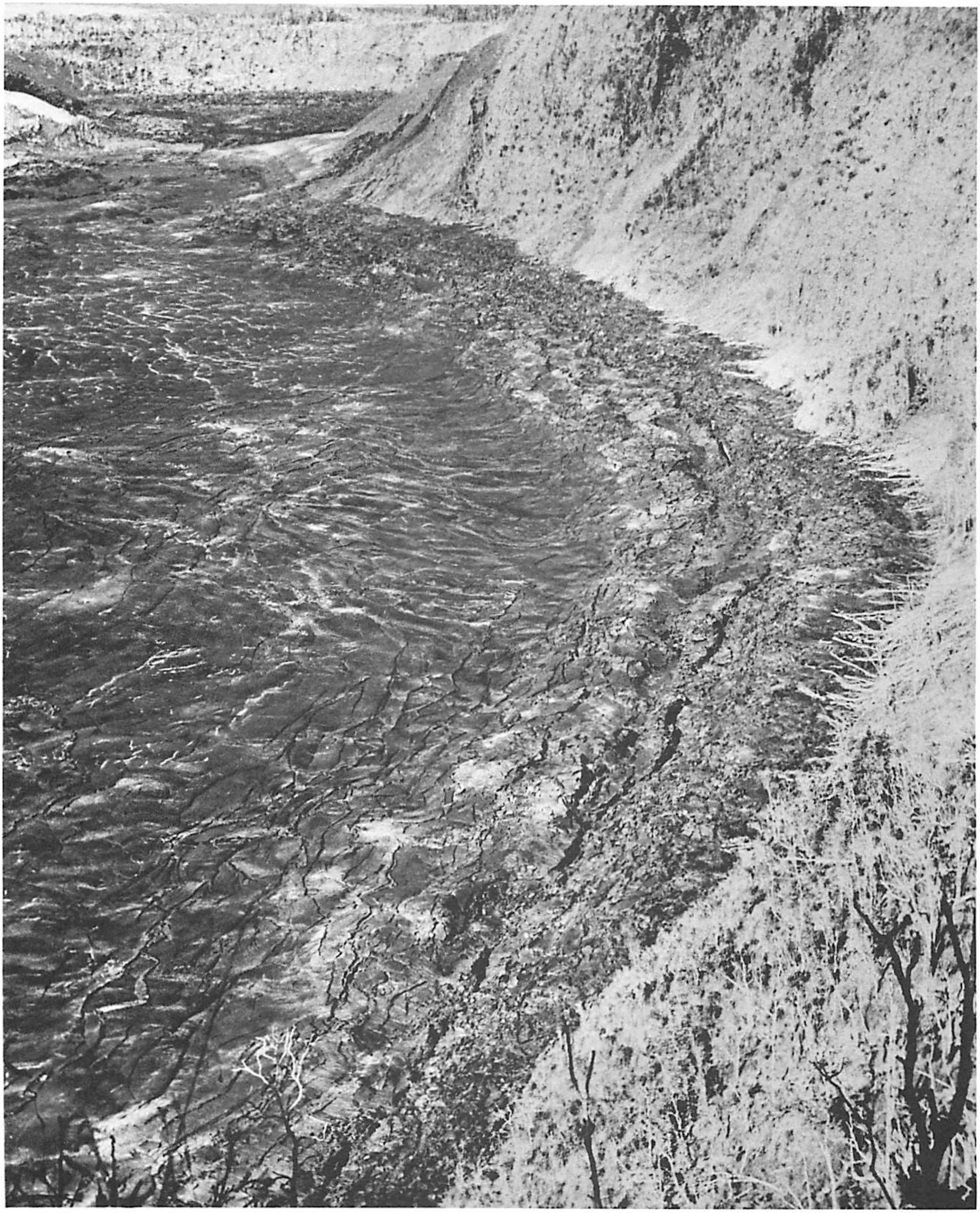

Fig. 40 Bench at the margin of the floor of Kilauea Iki crater, Hawaii, showing peripheral fracturing. The bench resulted from the drainback of the lava lake into the vent. (Photo by D. P. Cruikshank, Oct. 1967.)

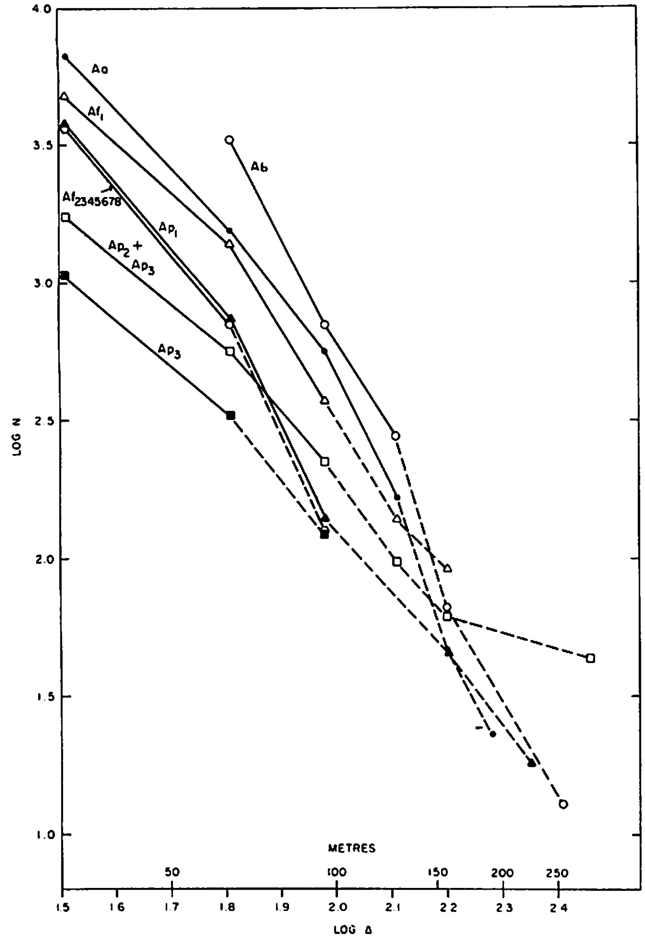

Fig. 41 Logarithmic plot of the cumulative number of craters per 1000 km² of surface (N) against minimum crater diameter (Δ) for the geologic units indicated and shown in Figs. 26 and 38.

1. Counts of craters larger than 56 m in diameter show that stratigraphically younger units carry fewer craters and that, therefore, the majority of the craters counted are impact craters.
2. The fact that there are essentially the same number of craters per unit area on the combined flows $Af_{2\text{-}8}$ as on the fractured part (Ap_1) of the floor of Aristarchus indicates that the flows are, on average, of the same age as the fractured floor unit.
3. The curves (Fig. 41) for the fractured floor unit Ap_1 and for the unfractured floor units ($Ap_2 + Ap_3$) intersect in their more significant portion. This shows that Ap_1 has more craters smaller than 65 m diameter than ($Ap_2 + Ap_3$); and, conversely, ($Ap_2 + Ap_3$) has more craters larger than 65 m diameter.
4. Portions of the floor have been designated Ap_3 by the fact that they are much smoother, and relatively free of hills, than the remainder of the floor (unit Ap_2). We find that Ap_3 carries 1.9 times fewer craters than Ap_2 yet it maintains the same slope as Ap_2 in Fig. 41, and this slope is sensibly less than that of any of the other units.
5. Many flows occur in the Aristarchus region. They are up to 9 km long and 400 m to 4 km or more wide. The widest flows may in reality be composed of coalescing flows which we are unable to distinguish from one another. Some flows are very long relative to their width.
6. There are flows on the inner wall of Aristarchus. One reached and crossed part of the floor unit and so was later than that part of the floor.
7. Near the southern rim of Aristarchus there are at least 14 craters each with a flow emanating from it: each flow is directed away from Aristarchus, apparently downslope. In another instance, a flow has started in a "lake" and flowed downhill tangentially to the rim of Aristarchus. This has been confirmed using stereo photographs.
8. Some "lakes" are found in the vicinity of Aristarchus, and several have well developed fronts with numerous collapse depressions.
9. There is an inward-sloping bench around the margins of the floor of Aristarchus. The bench contains open fractures, characteristic of a zone of maximum downbending.
10. Different units have marked differences in texture. The floor of Aristarchus is generally similar to that of Tycho, except that while, as in the case of Tycho, the peripheral parts of the floor of Aristarchus display a network of open fractures, no open fractures are found on the remaining parts of the floor. Flows $Af_{1\text{-}8}$ have smoother surfaces than the other flows and their albedo is approximately the same as the maria.

10. Comparison of Tycho and Aristarchus: Flows and Lakes

Most of the flows associated with Tycho have morphologies and structures that differ from those associated with Aristarchus. The Aristarchus flows are thinner, smoother, have more lobate margins and are not as bright as the Tycho flows at full moon. The flow designated C near *Surveyor VII* and shown in Figs. 11 and 12 is somewhat similar to those in the vicinity of Aristarchus in that it is relatively smooth and thin. However, even this flow is more ridged and has a higher albedo than the Aristarchus flows. Furthermore, many of the Aristarchus flows have issued from lakes whereas only several minor flows in the vicinity of Tycho are due to the overflow of material from lakes. All the above facts strongly suggest that, relative to the Tycho flows, *the Aristarchus flows were considerably more fluid.* They probably consist of *basaltic lava* typical of the maria whereas the Tycho flows of *intermediate albedo consist of anorthositic lava* and those of *high albedo* represent a more differentiated material that may be *higher in silica.* This is not unexpected since Aristarchus is situated in the mare and Tycho is in the highlands.

The morphology of the lakes associated with both Tycho and Aristarchus is similar. However, there are considerably more and larger lakes in the vicinity of Tycho, and usually they have remained in depressions rather than giving rise to flows. Several of the Aristarchus lakes have been the source of flows, and several lakes exhibit an abundance of collapse depressions which are not seen on the Tycho lakes. In general, however, the lakes in both areas seem to have originated by the same process.

11. Comparison of Tycho and Aristarchus: Floor Units

The gross features of the floors of Tycho and Aristarchus are similar and strongly suggest that, in each case, the *material has solidified from a melt.* However, the floor of Tycho apparently has not been subjected to the blanketing deposits as have the central portions of the floor of Aristarchus. It would seem that, after Aristarchus was partially filled with lava and the surface solidified, the still molten lava beneath the solidified crust drained back into a chamber or open fissures to form a peripheral bench. This was followed by the eruption of ash, possibly from the numerous hills covering large areas of the floor, which blanketed and subdued the preexisting floor structure. The fact that the central portion of the floor of Aristarchus is bluish and surrounded by a less blue peripheral zone supports this view.

12. Crater Counts and Ages: Flows and Base Surge Hypothesis

A base surge is a ring-shaped gas-charged density flow formed by expanding gases resulting from an explosion. On the earth, a surge cloud is propelled over the crater lip by the expanding gases and carries large amounts of ejecta in radial directions away from the crater and nearly parallel to the ground surface (Moore, 1967). The cloud may travel at initial velocities of over 50 meters/second and may carry fragmental material many kilometers. Base surges may result from artificial, meteoritic or volcanic explosions.

J. A. Moore (1967) describes the mechanics of base surge formation from an artificial explosion as follows: "In an underground shot expanding gases at the explosion center first vent vertically, pushing up and out a "wall" of nearly coherent roof material. Only after the wall is broken and bent down and outward can expanding gases from the explosion center rush over it, erode it, and carry material from it outward to feed the base surge. Trajectories of previously ejected material are necessarily at a high angle because of the directing effect of the wall. The early falling, larger blocks may strike in front of the base surge after it has begun to form. Such blocks are quickly overrun by the surge cloud and most other throwout material comes down later and falls into the moving cloud." Although the above description is of an artificial explosion, explosive volcanic eruptions react in similar manner. In both cases the base surge deposits exhibit dunes which are concentric and have the same center as the crater rim.

We shall now examine whether the deposits surrounding Tycho and Aristarchus are base surge deposits; and as part of the hypothesis, the vast majority of craters on the various units are secondary impact craters formed soon after their deposition. According to this hypothesis, the differences in crater frequency between the different units resulted from the decreasing amounts and higher trajectories of ejecta as the younger deposits were laid down. Although we believe that certain units surrounding Tycho and Aristarchus are base surge deposits, there are serious objections to several of the units being the result of a base surge and strong evidence indicating they are volcanic flows.

We have already indicated (Sec. 2 and 7) that the morphology of the Tycho flows Tf_1 and Tf_2 is similar to that of viscous lava flows on Earth. There are three additional points concerning the lunar flows: (a) they appear to be gravity-controlled, a few of them flowing in directions other than away from the rim of Tycho and Aristarchus; (b) other flows originate in, and emerge from, breached craters which themselves are located on, or outside, the walls of Tycho or Aristarchus; (c) the excess of crater pits (counted by R.G.S.) on several flows near *Surveyor VII* may best be explained (Sec. 5) as volcanic explosion craters. All three points as well as the morphology, indicated that the flows in question cannot be base surge deposits but are genuine lava flows.

The base surge hypothesis assumes that the bulk of the recognizable secondary craters in a particular surge deposit formed immediately after the formation of that deposit; in this way, stratigraphically-recent units are expected to be less heavily cratered than the earlier units. Furthermore, the floor of the crater from which the base surge evolved is expected to be the least cratered of all the units. This, indeed, is the situation on Tycho. By contrast, for Aristarchus we find that the floor unit Ap_1 is cratered to the same extent as exterior units Af_2-Af_8 (see Fig. 41). Thus we again find the basal surge hypothesis inadequate, by itself, to explain the facts.

Finally, the "duning" or ridging that is approximately concentric with Tycho and Aristarchus and appears outside their confining walls has been cited as one of the effects of a base surge, and it does seem probable that such duning is present. This ridging is particularly well developed around Aristarchus, but parts of it trend tangentially to the wall segments of Aristarchus and Tycho to form complex lattice patterns. Although much of the concentric ridging, particularly the more distant ridging, is probably base surge duning, we believe that the complex lattice pattern is the result of faulting in the outer walls of the large craters; possibly lavas issued from some of these fractures.

It should be noted that, while presenting a case against the base surge hypothesis for certain units, we believe that particular units — for example, units Tc and Ab — are base surge deposits. We believe that certain units are almost certainly congealed lava flows, and that the majority of the units we have mapped are probably volcanic flows.

13. *Crater Counts and Ages: Dating Tycho and Aristarchus*

We have already shown, through crater counts on stratigraphic units that may be dated unambiguously relative to one another, that the number of eumorphic craters per unit surface is, in general, a reliable guide to the age of that surface relative to others. Even so, on the base surge hypothesis it is clear that the crater populations we have counted may be compositions of at least two populations deriving from meteoroids and from secondary ejecta. Absolute dating based on counts of eumorphic craters will therefore depend on the validity of our assumption that we are dealing with volcanic flows rather than deposits from base surges. Apparently the third population, consisting of endogenic craters, does not appreciably influence the counts of the larger craters we use for dating purposes: we have shown that the apparent volcanic explosion craters are small; and we have counted only eumorphic craters so that craters of collapse, for example, are excluded from our data.

With these assumptions, our method of dating is to adopt the particle influx law which best represents all observations relating to the minor objects in the solar system. The appropriate data have been compiled by Vedder (1966) and he had proposed fitting them by means of the equation.

$$\log I = -14 - \log m, \qquad (1)$$

where I is the total number of particles of mass greater than m gm crossing one square meter of cis-terrestrial space every second. We assume that the same law of accumulation holds, at the present epoch, for the Moon. Any variations in the accumulation rate at different times in the past are not known and, because we are considering small, sharp rimmed craters that are recent compared with the age of the Moon we assume, further, that eq. (1) holds for the astronomically recent times in question.

Öpik (1962) has given equations that relate the diameter of an impact crater to the diameter of the parent meteoroid for different particle densities and velocities of impact. We adopt as a representative diameter $\Delta/15$ for a meteoroid of density 3 g cm^{-3} which forms a crater of diameter Δ; then it follows that the mass required to form a crater 50 m in diameter is 5.8×10^4 kg. Under these conditions, eq. (1) predicts one primary lunar impact crater 50 m or more in diameter per 1000 km^2 of surface every 1.8×10^5 years.

Using the cumulative number-data of Tables V and VI, it follows that the various geological units may be expected to have the ages listed in the last column of each table.

The spread of ages is large for both Tycho and Aristarchus. If the estimates are taken at face value, the time span between the formation of the Tycho lavas $Tf_1 + Tf_2 + Tf_3$ and Ta + Tb is of the order of 10^8 yr; and between the Aristarchus flows Af_{2-8} and Af_1, it is 1.5×10^8 yr. The floor of Tycho and the

TABLE V

CUMULATIVE CRATER COUNTS
ON THE DIFFERENT GEOLOGIC UNITS OF TYCHO

UNIT	N*	AGE OF UNIT $\times 10^8$ YR
Tl	759	1.4
Tp	869	1.6
$Tf_1 + Tf_2 + Tf_3$	1575	2.8
Ta + Tb	2005	3.6
Tc	3871	7.0

* N is the number of craters > 50 m in diameter per 1000 km²

TABLE VI

CUMULATIVE CRATER COUNTS
ON THE DIFFERENT GEOLOGIC UNITS OF ARISTARCHUS

UNIT	N*	AGE OF UNIT $\times 10^8$ YR
Ap_3	501	1.0
$Ap_2 + Ap_3$	841	1.6
Af_{2-8}	1259	2.3
Ap_1	1349	2.3
Af_1	2138	4.0
Aa	2630	4.6
Ab	7763 †	11.0

* N is the number of craters $\geq$ 50 m in diameter per 1000 km²
† Value found by extrapolating best fitting line.

lava lakes solidified 1.3×10^8 yr later than the lava flows $Tf_1 + Tf_2$. The floor of Aristarchus itself developed over a period of 10^8 yr and, unlike Tycho, parts of the floor of Aristarchus appear to be 10^7 yr older than the flows Af_{2-8}. The flows Af_{2-8} themselves are differently cratered and probably developed over widely different times, and hence the indication that some are more recent than parts of the floor of Aristarchus is strengthened; but because of the small aerial coverage of each component flow in Af_{2-8} we are not able to assign an individual age to it.

Gault and Greeley (1968) have applied a similar method to date Tycho and Aristarchus but have used a substantially higher flux than that given by eq. (1). Although not in possession of the facts behind their assumption, we consider that the bulk of the observations that led to the formulation of eq. (1) cannot be waived so lightly. On the other hand, the scatter in the original data that were used to construct eq. (1) is such that our ages might be in error by a factor of 10 either way. Gault and Greeley obviously arrive at the conclusion that Tycho and Aristarchus are much younger than 10^8 years. Indeed, they have proposed an age as young as 10^6 to 10^7 years for Tycho. We reserve comment on this until their full paper is published. However, even if the ages we are proposing in this paper are in error by an order of magnitude, there must still

TABLE VII

COMPARISON OF AGES
OF THE GEOLOGIC UNITS ASSOCIATED WITH TYCHO AND ARISTARCHUS

	PROPOSED AGE $\times 10^8$ YR	
	TYCHO	ARISTARCHUS
Floor	1.6	1.0 to 2.3
Flows	2.8 to 3.6	2.3 to 4.0
Principal external unit	7.0	11.0

be wide intervals of time between the formation of the various lava fields. It would, of course, be surprising were this not so. We therefore believe that multiphase eruptions characterized at least part of the formation of the structures Tycho and Aristarchus.

The development of Tycho and Aristarchus may be compared by reference to Table VII.

The floor and flow units are of the same order of age, the most recent features being the floor of Tycho and the central parts of the floor of Aristarchus. The flows appear to have started first in the case of Aristarchus and the last ones appear to have been later than those of Tycho. The biggest difference in the crater densities is encountered in the principal external units Tc and Ab: if the craters counted were mostly of primary impact origin the terrain around Aristarchus would be 10^9 years old, and 1.6 times as old as the terrain around Tycho.

14. Conclusions

The gross morphologies of Tycho and Aristarchus are similar, and it is clear that both craters originated in the same manner, although there were differences in their later development. Only small portions of the craters were studied in detail. A broader investigation of the two craters, including their ray systems, must be conducted before firm conclusions can be reached concerning their origins. However, it is clear from the present investigation that extensive flows issued from the inner and outer rims of both craters and, in the case of Tycho, several flows originated at distances of the order of 100 km from the rim crest. The morphology, sources, and temporal relationships of these flows indicate that they are volcanic lava flows.

Viscous lavas up to 40 meters thick have flowed from the zone around the rim crest of Tycho. Flows of generally lower viscosity are associated with Aristarchus, and this crater occurs in mare-type material rather than, like Tycho, in brighter highland material. These observations, when combined with independent evidence that flows in the maria were generally less viscous than those in the highlands, indicate that the viscous, high albedo flows associated with Tycho consist of more highly differentiated lavas, i.e., more acidic in composition, than the darker, less viscous flows associated with Aristarchus.

Our observations of flows from small craters in the vicinity of the Tycho and Aristarchus structures strongly suggest that these small craters are volcanic. If this indication is correct, it may be taken as established that one class of lunar volcano, at least, resembles an impact crater.

The floors of Tycho and Aristarchus are almost surely solidified lava, and the "lakes" occuring on the rims are probably lava originating from vents primarily associated with the depressions in which they lie. Thus, it appears that both Tycho and Aristarchus went through a phase of extensive volcanism. Crater counts on the various units indicate that the volcanism occurred after the formation of the craters, and continued intermittently over periods of millions of years. Furthermore, confirmed observations of red glows and other transient phenomena on the rim of Aristarchus and vicinity (Greenacre, 1965; ACIC, 1964; Hartmann, 1968), as well as unconfirmed reports of similar phenomena in Tycho (Middlehurst, 1968), strongly suggest that limited volcanic activity has continued to the present day, and that modifications of these craters still may be taking place.

Evidence of the drainback of lava and consequent subsidence of the floors of Tycho and Aristarchus suggest that the craters are underlain by chambers or extensive networks of fissures capable of receiving large volumes of magma. Magmatic differentiation seems to be required to account for the more viscous flows and, in particular, the floor lavas of both structures. This is supported by the composition of samples collected by the *Apollo 11* and *12* astronauts. In the case of Aristarchus, very late eruptions appear to have been responsible for obscuring certain parts of the floor detail; this material may be lavas and/or pyroclastic deposits.

A crater 125 km in diameter on the western limb of the moon at 36.5° N latitude and 95° W longitude shows very strong evidence of volcanism on its rim, and is mentioned here as another example of the association of volcanism with large craters. Fig. 42, taken by *Orbiter IV*, shows this crater having a pronounced linear ridge (A) forming part of the western rim and penetrating deeply into a large rim satellite crater 25 km in diameter. The satellite crater is obviously younger than the rim of the larger crater upon which it lies, but the linear ridge, which is considerably higher than the satellite rim and penetrates about 15 km into the crater, must be younger than the satellite crater. This can only be explained if the ridge is a volcanic extrusion ridge, extruded after the formation of the satellite crater. Furthermore, a large flow, about 50 km long and 12 km wide, with a well-defined flow front (B in Fig. 42) has apparently issued from one or more degraded craters (C) on the northern rim of the large crater and filled a valley adjacent to the crater. These observations show that volcanism has played an important role in the history of this crater.

Three possible causes of the volcanism associated with Tycho and Aristarchus have been suggested: (1) sufficient thermal energy was produced by an impact to generate large pockets of magma which gave rise to the volcanism, or (2) the volcanism was triggered by an impact that penetrated, or produced fractures which tapped, a potential source of magma, or (3) Tycho and Aristarchus are volcanic structures and the observed volcanism represents the natural sequence of development of the craters.

It seems doubtful that the amount, distribution and temporal relationships of the volcanic units can be accounted for on the basis of impact-generated volcanism. First, if the floor lavas were generated directly by the thermal energy of an impact, they should be the same age as, or older than, the rim units. However, the crater counts show that the number density of craters on the floors is considerably less than that of most of the rim units, and, therefore, that the floors were emplaced at a much later time than the rim units. Secondly, volcanism generated by an impact would be expected to cease within a relatively short period of time, and would not be expected to continue intermittently over periods of millions of years. At least in the case of Aristarchus, volcanic activity appears to have continued to the present time (Hartmann, 1968). Thirdly, volcanism associated with Tycho occurs at distances of at least 100 km from the rim, and it is unlikely that an impact of the size necessary to produce Tycho could generate volcanic activity at such a great distance from the parent crater. Finally, a floor melt produced by impact would seal off subsurface fractures almost immediately, and it is unlikely that large volumes of magma could drain away as indicated at both Tycho and Aristarchus. Certainly, the floor of a recent impact crater would tend to adjust

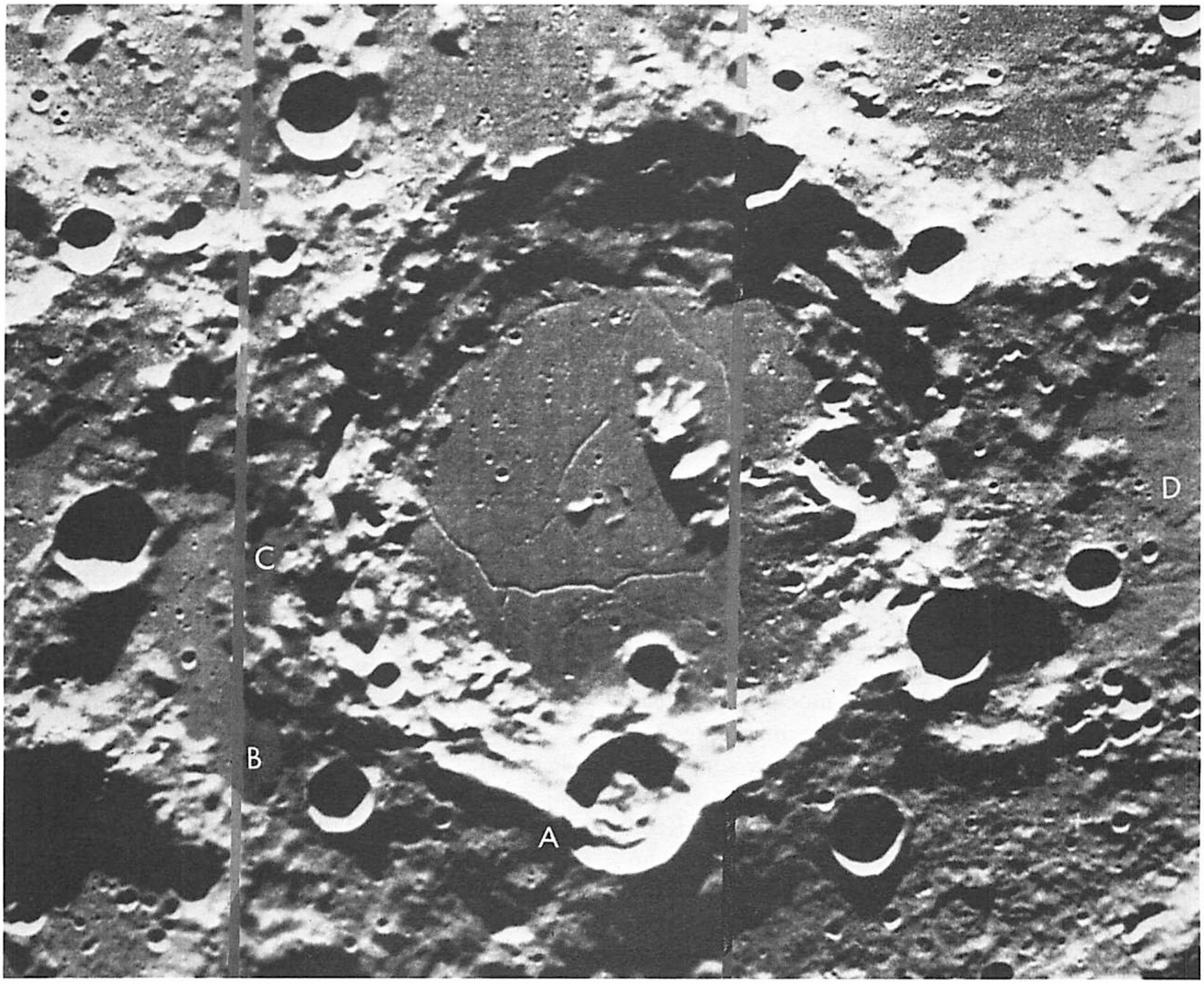

Fig. 42 A crater 125 km in diameter on the western limb of the moon showing volcanism associated with its rim. The linear ridge (*A*) is probably a volcanic extrusion which forms part of the rim of the large crater and penetrates the satellite crater. The flow (*B*) has apparently issued from craters (*C*) on the northern rim of the large crater. Another flow is indicated by *D* (Portion of *Orbiter IV*, M-189). *N* is to the left.

upwards — not downwards — under the influence of isostasy: the peripheral fractures in the downwarped benches of the floors of the structures, even if originally present on an impact hypothesis, would probably close as a result of the isostatic uplift of the lowest parts of the floors after some 10^8 years had elapsed (Fielder, 1965) — that is, in a time that was comparable to the age of either structure. Also, craters which have been completely filled, such as Wargentin (84 km, the same size as Tycho), could not possibly have had so much lava generated by an impact. The floor material of such craters must have originated from a relatively deep-seated and prolific source of lava.

It is possible to explain the observed temporal and spatial relationships of the volcanism associated with Tycho and Aristarchus by an impact triggering mechanism if it is assumed that a potential zone of magma occurred at a relatively shallow depth beneath the lunar surface. A "potential" source is one that may become an active source upon a change of physical parameters, such as pressure and temperature. In this case, an impact could produce fractures which tap a potential subsurface source of magma and give rise to volcanic activity within the crater and probably at considerable distances from the rim crest. Also this volcanism might occur intermittently and endure for a considerable length of time. It is conceivable that a large impact of the magnitude of Tycho and Aristarchus could produce fractures deep enough to give rise to volcanism.

If Tycho and Aristarchus are completely volcanic structures, the observed volcanism is explained as a natural consequence of the development of the craters. As mentioned in Section 2, 7, and 12, the oldest Tycho and Aristarchus units mapped, Tc and Ab, respectively, are probably base surge deposits resulting from an explosion centered in the craters. The extensive ray systems, numerous large blocks on the rim, and swarms of small craters (probably secondary impact craters) at distances of several diameters from the parent crater indicate that in each case a very large explosion was responsible for the formation of Tycho and Aristarchus. Although base surge deposits are characteristic of explosive volcanic eruptions, it is doubtful whether enough internal energy could be concentrated in a relatively small area to produce such large explosions. Irrespective of the mode of formation of Tycho and Aristarchus, impact or volcanism, there is compelling evidence for subsequent widespread volcanism, both within the crater walls and on the outer slopes.

Acknowledgments. We are indebted to Steve Larson and Alice Agnieray for the photography and drafting of the figures. This work was supported under NASA Grant 5601-920-271, and was greatly aided by the cooperation of National Space Science Data Center, Goddard Space Flight Center, who made available enhanced film positives of selected *Orbiter* records. These enhanced film copies showed detail that would otherwise has been missed, as e.g. the very important observation of the lava lake on the central peak of Tycho.

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