No. 49 VOLCANIC SUBLIMATES ON EARTH AND MOON

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ABSTRACT

Two groups of photographs of Laimana Volcano, Hawaii, are reproduced for their relevance to lunar studies: (1) two color plates and eleven photographs of the 1960 eruption showing among others the resulting cover of sublimates on much of the mountain; (2) a set of recent aerial photographs showing numerous "secondary impact craters" that formed on Laimana's slopes, as well as remaining sublimates on the crater rims and other hot spots. The photographs of the eruption were generously made available by two Hilo photographers, Mr. L. S. Kadooka and Mr. Howard Pierce; the recent aerial photographs were especially taken for this publication by Mr. Lyman Nichols, Hawaii State Biologist at Hilo. The two sets together well illustrate the process of secondary crater formation and also the production of a sublimate cover as an accompanying feature of the volcano-building process. This observation and the recent discovery of white mountains of igneous origin on the moon suggest a close geochemical parallel.

Some of the glowing ejecta seen in the eruptive column were apparently liquid and solidified in free fall. These led to extremely vesicular rock masses called reticulite, 1–10 cm in size, of bulk density 0.1–0.2, and crushing strength 1–3 kg/cm^2. Also present were blocks of ultrabasic rock, varying from a few kg to perhaps a ton in weight, which remained solid during the eruption and which caused the secondary impact craters here illustrated. A discussion of the impact craters is deferred to a later *Communication* that will also contain the results of the field study of Laimana.

The author's (1965a) *Ranger VII* Scientific Report makes reference to geological and geochemical experience that appears relevant in the interpretation of the *Ranger* records of the moon. The following categories of terrestrial phenomena are among those of direct interest: (a) the formation of primary impact craters of all sizes; (b) the formation of secondary craters from the primaries, down to rock and dust deposits; (c) the formation of recognizable lava flows, their terminal walls, collapse depressions, pressure ridges, rilles, etc.; (d) the formation of lava-filled basins or lakes not covered with recognizable individual flows; (e) the formation of individual volcanic mounds or mountains.

These parallels will be examined or re-examined in a series of papers, with the present paper mainly concerned with certain aspects of item (e) and (b).

There appear to be two types of igneous deposits on the moon: (i) the dark maria and flooded craters; (ii) the white mountains, often with small craters aligned on their crests, and lacking much structural detail on the slopes as if covered with a snow-like substance (Kuiper, 1965b). This substance is tentatively assumed to be *sublimate,* deposited on the surface by sublimation of vapors exhaled during, or soon after, the eruption(s) that caused the mountain itself.

The possibility of the lunar white mountains being covered by a sublimate was forcibly suggested to me by the appearance of Laimana Crater, Hawaii, immediately after its 1960 eruption. Accompanied by Messrs. Strom and Whitaker of this Laboratory and Mr. Lyman Nichols, State Biologist at Hilo, Hawaii, I made a field trip to this crater on February 1, 1965, in connection with the secondary impact craters that had been observed on its slopes (cf. Kuiper, 1965a, pp. 53–54), and through the courtesy of Dr. K. Noda, Director of the University of Hawaii Branch at Hilo, contacts were established with several persons in Hilo who had secured photographs of the Laimana events in 1960.

Several excellent photographs in color of the 1960 eruption had been taken by Mr. L. S. Kadooka at Hilo, two of which are reproduced herewith. The ejection contained numerous clods of glowing lava which, from the nature of the deposits, were found to have been liquid during ejection and to have solidified in free fall. The bulk density of this material is about 0.10–0.18. In addition, blocks of olivine basalt from about 10 to 500 kg were carried up in solid state, and these caused the "secondary" impact craters on Laimana's slopes already referred to.

A fine collection of black and white photographs of the 1960 eruption was made by Mr. Howard Pierce of Hilo. The Figures 1–11 are all due to him. Figure 1 shows the eruption on 31 January 1960. The surge appears to be almost entirely a massive shower of ejecta, shot up nearly vertically. Figure 2 shows the eruption later on the same day, from about 45° to the left. On February 3, 1960, the ejection was still continuing (Fig. 3), but on February 14 the entire mountain, now overlain with new deposits, was steaming (Fig. 4). The central vents were still active, as seen in Figures 5–8 taken on February 17, 1960, which are of interest also for indicating the frequency distribution of ejecta diameters. Seen from afar, the entire mountain and its suroundings were engulfed in haze and steam (Fig. 9, also taken on Feb. 17).

When the steam had mostly cleared away, Laimana had taken on a new appearance (Figs. 10, 11). A few days later, when heavy rains came, the white deposits mostly disappeared and only locally continued to form where the surface was still hot and the subsurface layers very hot. This was found to be the case even in February 1965 when our party of three examined Laimana. Similar material collected by Mr. W. K. Hartmann at the summit vent of Mauna Loa was analyzed by Dr. Stanley W. Buol and Mr. Rollin C. Jones of this University and found to be mostly gypsum, $CaSO_4 \cdot 2H_2O$.

According to Rankama and Sahama's text *Geochemistry,*

> "... the chlorides of sodium, potassium, ammonium and ferric iron probably are the most common and most abundant volcanic sublimates. Silicofluorides and alkali carbonates also are of considerable abundance, and sulfates of the alkali metals, like glaserite (aphthitalite), $NaK_3[SO_4]_2$, have also been met in the sublimates. Alkali chlorides are abundant in hot-spring waters.
>
> "Iron as ferric chloride, hematite, pyrite, or pyrrhotite is often connected with fumarolic activity. The heavy metals occur in the fumarolic incrustations as oxides, chlorides, oxychlorides, hydrated chlorides, and carbonates. Some metals may be characteristic of certain volcanic areas. Thus copper is considered to characterize the fumaroles of Etna and lead those of Vesuvius, even though the two metals are found in the fumaroles of both areas.
>
> "The following elements are reported in the fumarole deposits of the volcano Stromboli in the Tyrrhenian Sea:
>
> Fe (abundant hematite, α-Fe_2O_3; magnoferrite, $MgFe_2O_4$; soluble compounds)
> S, Se, Te
> Li, Tl (sulfates)
> I
> P
> Zn, Sn, Pb, Bi, Cu (soluble compounds)
> B (boric acid)
> N (sal ammoniac)
> As (realgar; soluble compounds)
> K, Rb, Cs (alums)
> Na (mirabilite, $Na_2[SO_4] \cdot 10H_2O$; glauberite, $Na_2Ca[SO_4]_2$)
> Ca (glauberite)
>
> "Zies (1924) presented evidence on the concentration of elements in volcanic areas through vapor-phase activity and through the solvent action of acid or alkaline aqueous solutions. He reported the presence of heavy metals in many fumarolic deposits collected, in 1919, in the Valley of Ten Thousand Smokes in Alaska. Here the volcanic activity is caused by the intrusion of rhyolite under the valley floor. Lead, zinc, and tin were found in nearly all incrustations of the vigorously active fumaroles. The interaction of the acid gases and other volatile compounds, such as HCl, HF, H_2S, SO_2, S, and NH_4 salts, released by the fumarolic activity, with the extruded pumice produced a notable mineralization in the pumice. The fluorine content ran as high as 3.8 per cent. Several tons of well-crystallized fumarolic magnetite, evidently produced in the reaction between iron halogenide vapor and water vapor, were visible in a series of fissure vents. The magnetite was analyzed chemically and spectrochemically for its minor constituents. The analysis is presented in Table 5.41.
>
> "According to Zies (1938), the analysis of other incrustations revealed the presence of Bi, Ga, Tl, B, Ge, As, Se, and Te. Molybdenum was often present as the hydrated oxide ilsemannite (molybdenum blue), which colored areas covering several thousand square meters.
>
> "In 1923 the temperature and general activity of the fumaroles had decreased to a point where the condensation of water vapor took place. The acid gases were in solution, all the magnetite was decomposed, and in its place covellite, CuS; chalcocite, Cu_2S; galena, PbS; pyrite, FeS_2; and sphalerite, ZnS, were found, along with cotunnite, $PbCl_2$, and hematite, α-Fe_2O_3. Ammonium chloride, sulfur, borates, and fluorides had also been deposited."

Reference is also made to an analysis of sublimates discovered in Nyiragongo Volcano (Kiva, Congo) by Herman et al. (1961). They consist mostly of gypsum ($CaSO_4 \cdot 2H_2O$), aphthitalite $(K,Na)_2 \cdot SO_4$, thenardite (Na_2SO_4), and other sulphates (of Al, Mg, NH_4); and fluorides of Na, K, Al, Si, Co, and Mg.

The rain water that dissolves most of the terrestrial sublimates is, of course, absent on the moon. However, the effects of the lunar vacuum will be destructive in a different way, many of the sublimates having a finite vapor pressure at lunar temperatures, $T \leq 100°$ C. This is not true of all sublimates. Some, such as $PbCl_2$, would presumably substantially remain as long as 4.10^9 years, and some of these are white. A program of infrared spectroscopy of sublimates has been started at this Laboratory in an effort to find spectroscopic criteria for the identification of the white lunar surface deposits.

The results of the field trip to Laimana referred to above, will be published in a later *Communication.* However, we are reproducing here a selection from the beautiful aerial photographs obtained by Mr. Nichols on 27 January 1965 just prior to our field trip. This trip had been organized upon receipt of three remarkable photographs that Mr. Nichols had taken on 31 December 1964. In his letter of 1 January 1965 he wrote: "In the course of some flying around the island of Hawaii, I noticed a small volcanic scene which may be of interest to you. In order to get the photographs ready for mailing promptly, I used a Polaroid camera which did not do the best job, but at least you can get the idea clearly enough. The photos, which I took from the air yesterday, are enclosed.

"The numerous small craters shown in the photos are located at the base of a large cinder cone which was the site of the eruption several years ago at Kapoho, Hawaii. They are in an extensive bed of cinders at the base of the cone, and appear to have been formed by the falling of lava spatter or lava 'bombs' onto the cinders during the eruption. I would guess that they range in size from one or two feet to perhaps 10 feet in diameter.

"When I first noticed these craters, they struck me as being remarkably similar to those shown in the Ranger photographs of the moon. Therefore, I thought perhaps you might be interested and so snapped these photos on a later flight. I'm sure you've considered cinders as well as lava when you theorized the surface of the moon was volcanic in origin, but perhaps such a scene as the enclosed hasn't been noticed elsewhere . . ."

Two of Mr. Nichols' photographs are reproduced as Figures 12 and 13. Both show remaining sublimate-covered areas on crater rim and slopes; and Figure 13 shows several secondary craters.

On 8 January 1965 I wrote Mr. Nichols, in part: [The photographs] "are of distinct interest in connection with the *Ranger VII* report I am preparing for NASA, and I would like to include one or both photographs. Would it be possible for you to arrange for some additional photography which might give somewhat bigger scale? It would be of special value to the *Ranger* report if such photographs could be taken with the sun about 23 degrees above the horizon, which was the sun angle for *Ranger VII.* Aerial photographs taken nearly straight-down, but with the sun 20–25 degrees above the horizon, would be the best of all. *Ranger* looked down at an angle 70 degrees above the horizon or 20 degrees from straight-down, somewhat in the direction in which the light was shining. In other words, opposite the sun in azimuth. Anything you can do in this direction will be much appreciated. Some observations from the ground, close up, would be of interest also." Mr. Nichols took these additional photographs on 27 January 1965, and nearly all of them are reproduced in Figures 14–24 because of their unusual interest and exquisite quality. Much additional information and pictorial coverage was obtained during the field trip on 1 February 1965 on which the Laboratory staff was the guest of Mr. Nichols. This material will be published in a later *Communication* which will also review more fully the aerial photographs of Figures 12–24.

Acknowledgments. Since the substance of this paper is composed of its illustrations, the credit is due to the authors of the photographs. Mr. L. S. Kadooka contributed the two color plates; Mr. Howard Pierce, Figures 1–11; and Mr. Lyman Nichols, Figures 12–24. My sincere thanks go to Dr. K. Noda, Director of the University of Hawaii Branch at Hilo, to Mr. M. Akiyama, Executive Secretary of the Hilo Chamber of Commerce, and to Mr. Lyman Nichols, State Biologist at Hilo, who all rendered important advice and assistance to our program. Dr. Stanley W. Buol and Mr. Rollin C. Jones assisted our work by determining the crystal structure of the collected Hawaiian sublimates with an x-ray diffractometer, and the chemical composition with an x-ray emission spectrograph.

This program is supported by Contract No. 95077 with the Jet Propulsion Laboratory (*Ranger* Program).

REFERENCES

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Kuiper, G. P. 1965a, "Interpretation of Ranger VII Records," *Ranger VII, Part II. Experimenters' Analyses and Interpretations,* Technical Report No. 32-700, Jet Propulsion Laboratory, chap. 3, pp. 9–73.

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Rankama, K. and Sahama, Th. G. 1950, "Geochemistry of the Lithosphere," *Geochemistry* (Chicago: University of Chicago Press), pp. 187–188.

Plate 49.1.

Plate 49.2

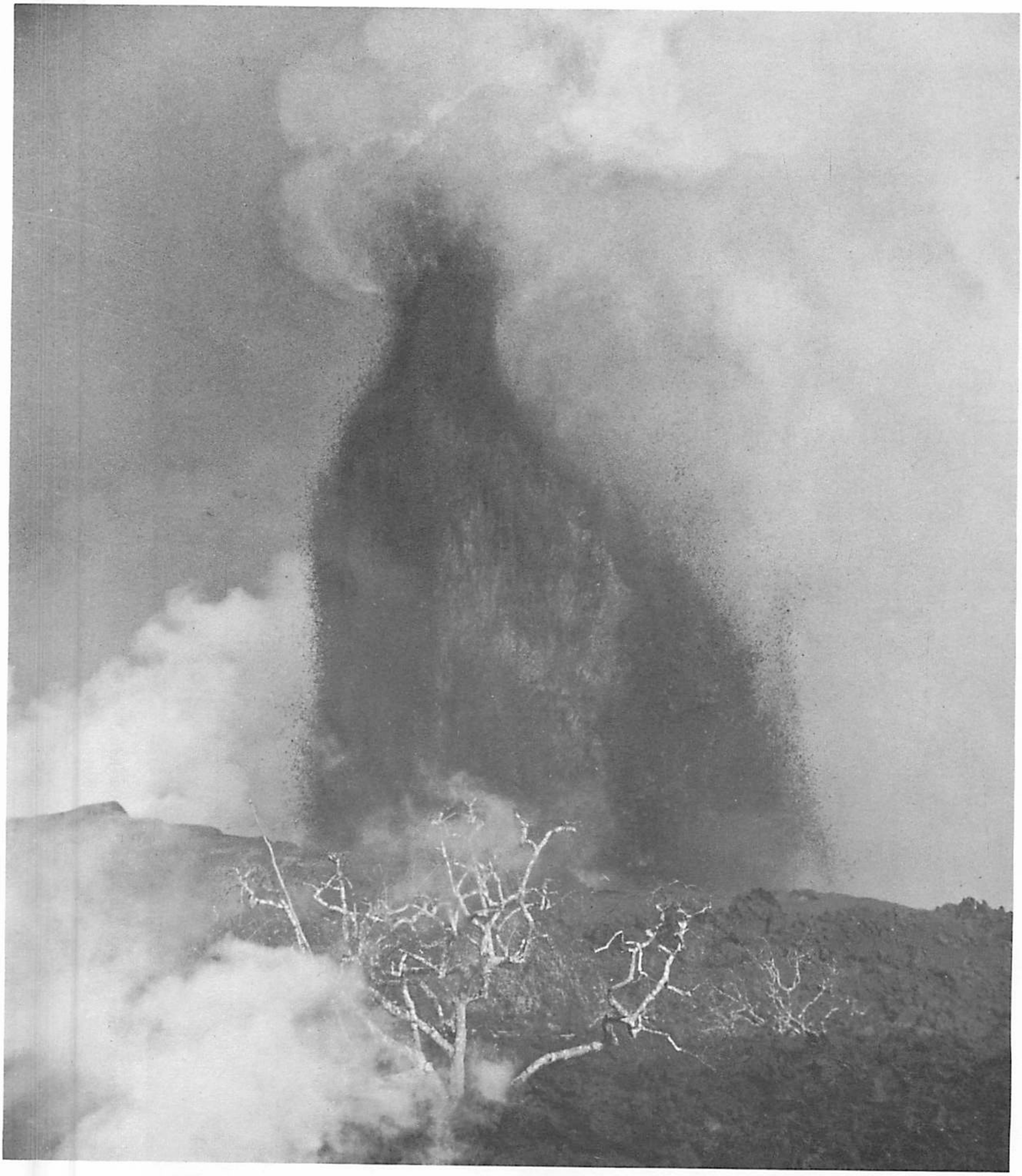

Fig. 1 Eruption of Laimana Crater, Hawaii, January 31, 1960 (Figs. 1–11 by Mr. Howard Pierce, Hilo, Hawaii). Dark material is in form of tremendous near-vertical shower.

Fig. 2 Same as Figure 1 from about 45° to the left. Dwellings in foreground part of village of Kapoho, destroyed during the eruption.

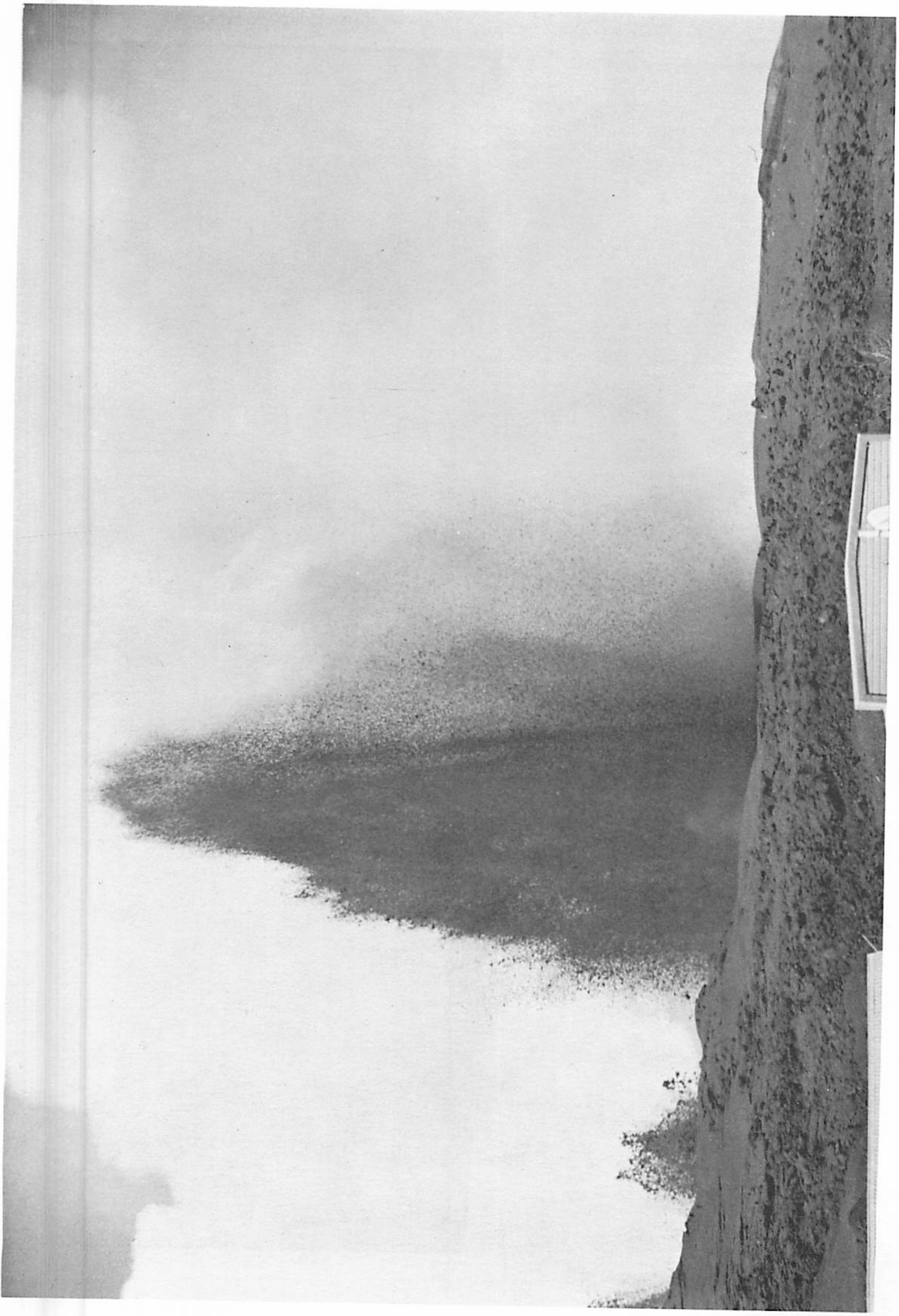

Fig. 3 Eruption as of February 3, 1960, seen from Kapoho.

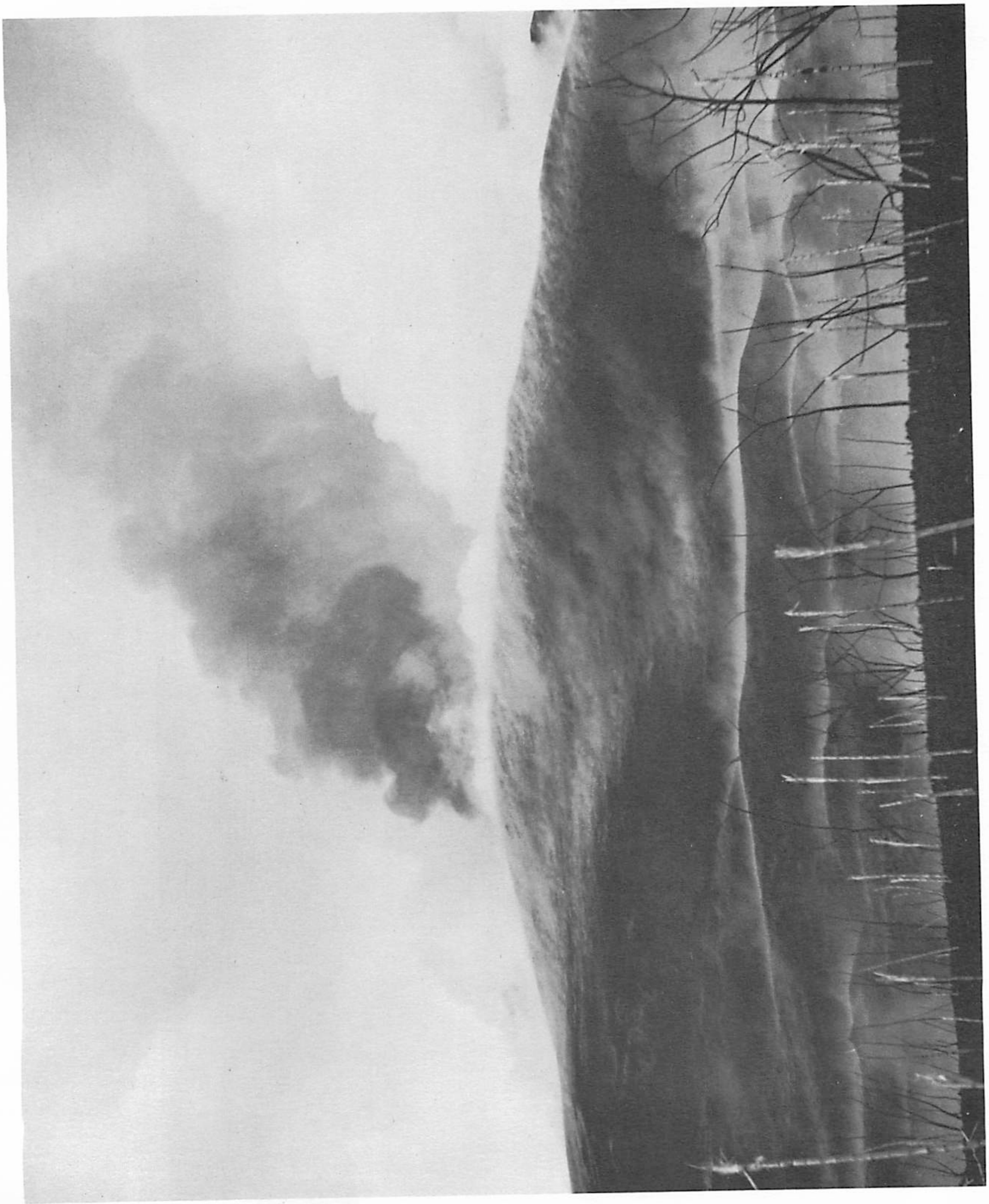

Fig. 4 Steaming mountain after the deposit of hot ejecta and small lava streams, February 14, 1960.

Fig. 5 Continued fountaining of ejecta from main vent, February 17, 1960, with interior of vent still glowing and lavas in foreground right, steaming.

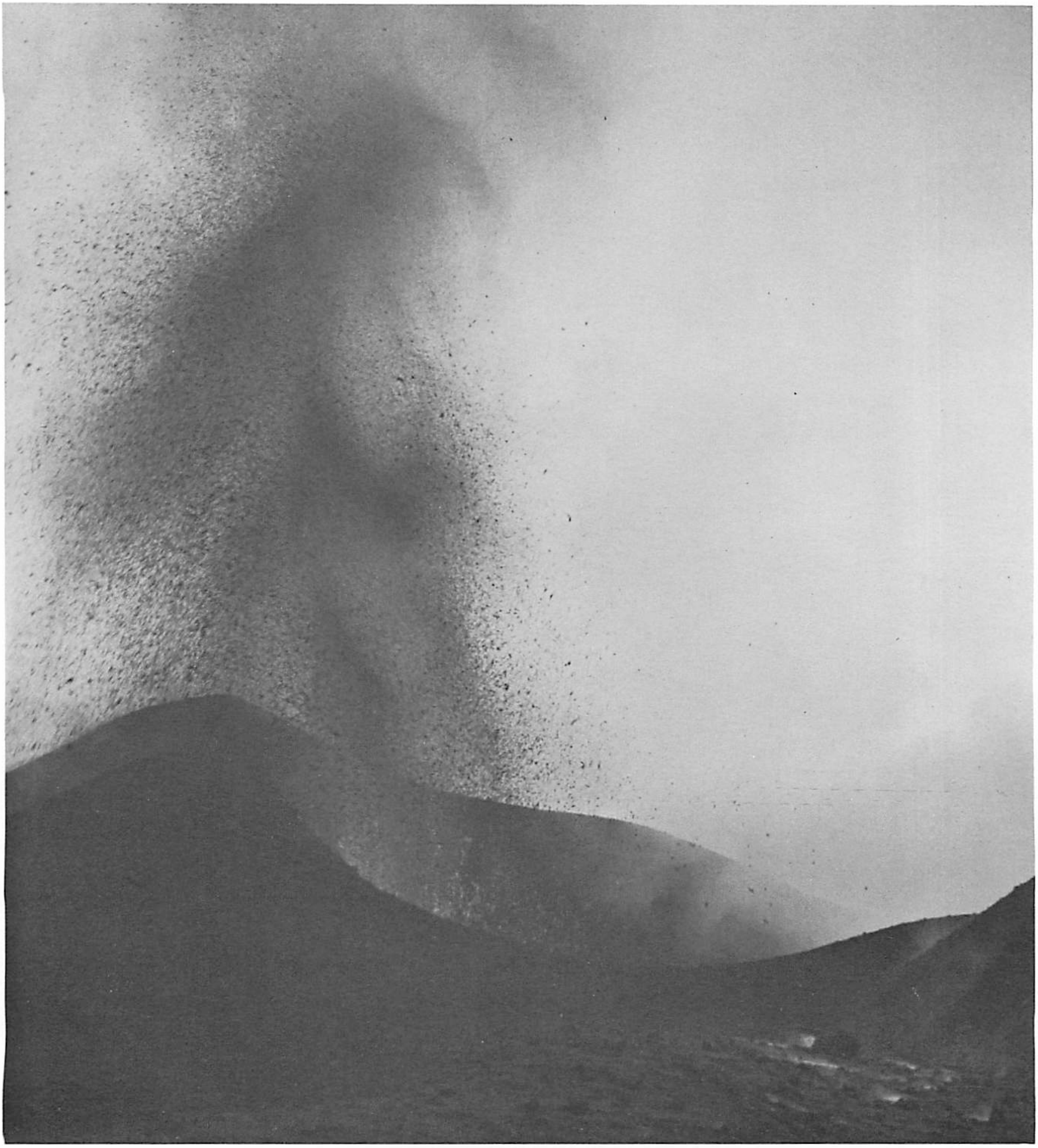

Fig. 6 Continued from Figure 5, same date.

Fig. 7 Continued from Figures 5 and 6, same date.

Fig. 8 Continued from Figures 5, 6, and 7, same date.

Fig. 9 Distant view of Laimana, February 17, 1960, with entire countryside enveloped in steam and haze.

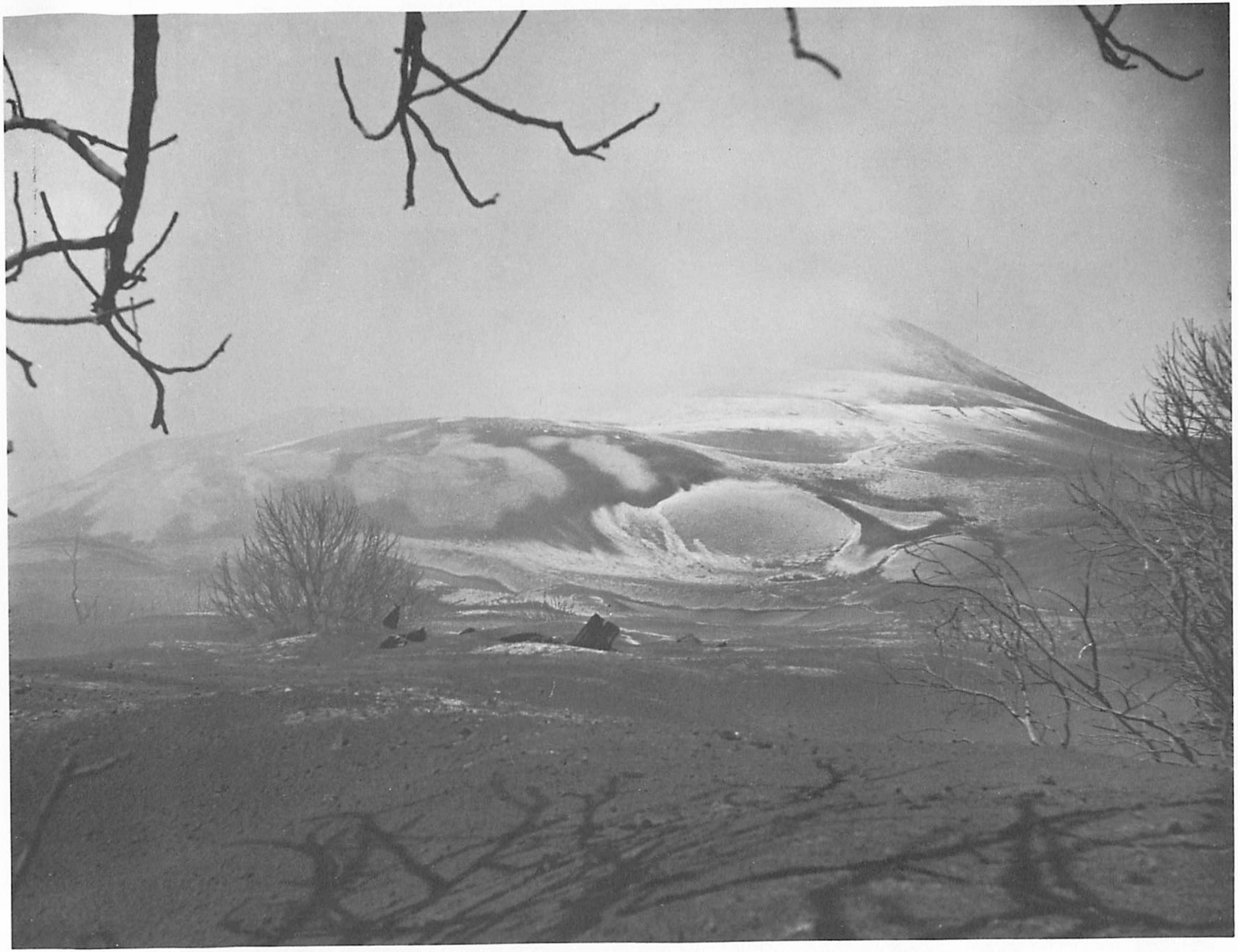

Fig. 10 Deposit of white sublimates on Laimana after most of vapors had cleared.

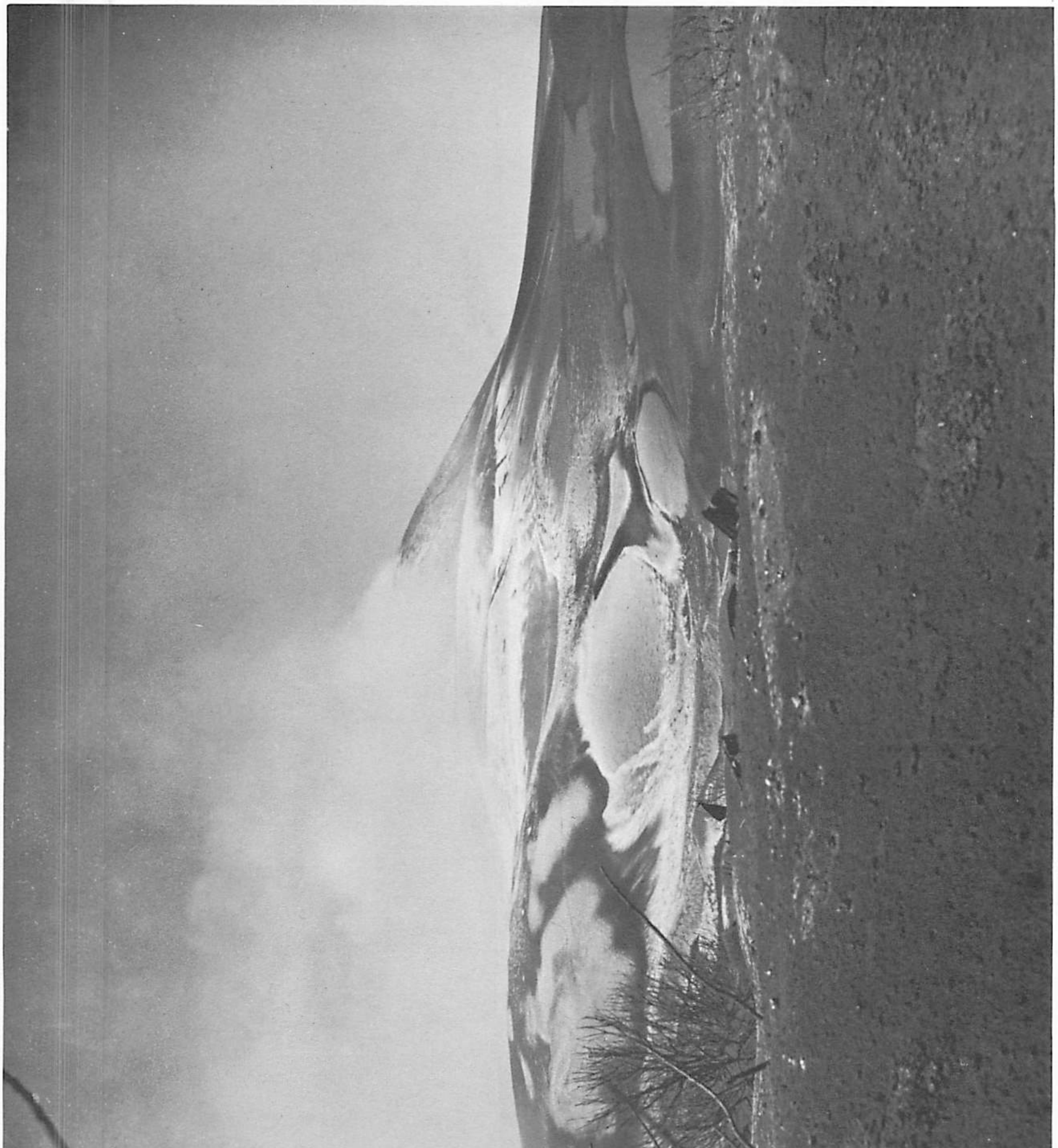

Fig. 11 Continued from Figure 10, same date.

Fig. 12 Photograph by Mr. Lyman Nichols, District Wildlife Biologist, Hilo, Hawaii, taken 31 December 1964 of Laimana volcano, 20 miles south of Hilo, Hawaii. The Pacific Ocean is shown in the background. The lava field extends to the shore at right. The volcano has several vents all lined with sublimate. Patches of white sublimate are also seen on slopes. Secondary crater field discovered by Mr. Nichols on left slope of volcano.

Fig. 13 View of Laimana volcano, similar to Fig. 12, also taken 31 December 1964 by Mr. Lyman Nichols. This view shows crater field on forward slope of volcano. Photograph also shows well lava stream from the vent at extreme right.

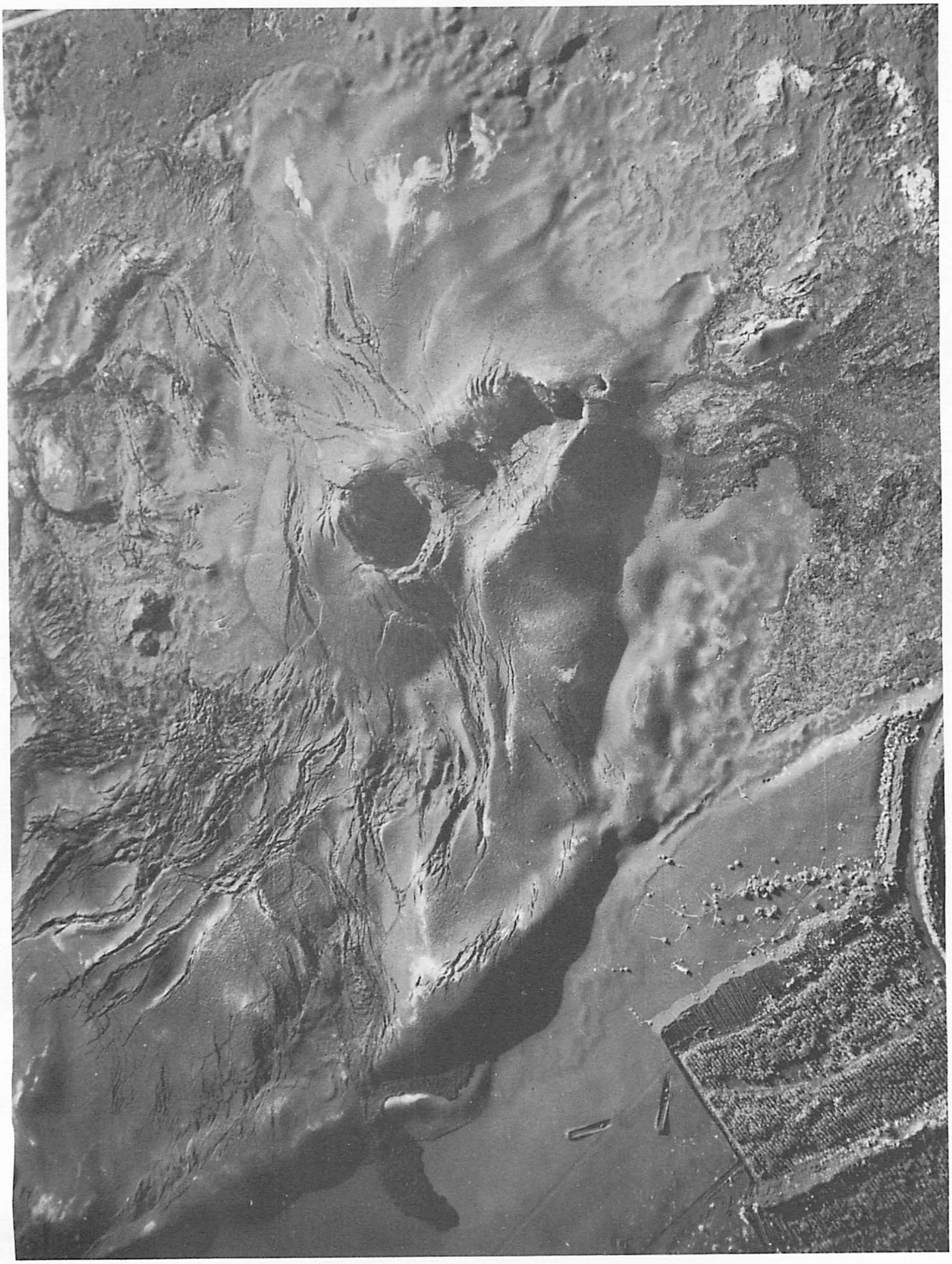

Fig. 14 A near-vertical view of Laimana, its crater field in left foreground, the lava field shown in Fig. 13 at lower right, the lava stream shown on Plate 1 at center left. Figs. 14–24 taken by Mr. Lyman Nichols on 27 January 1965.

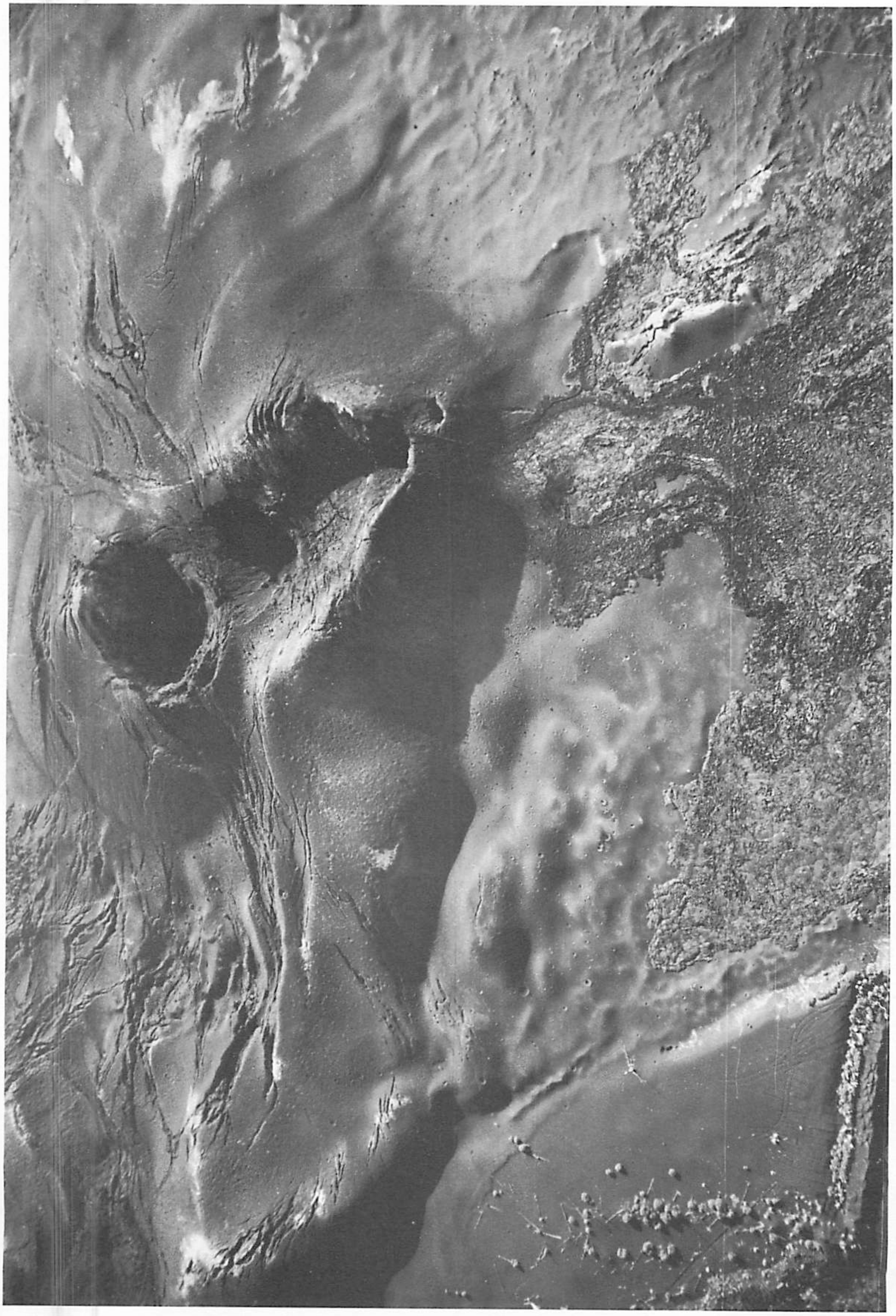

Fig. 15 As Fig. 14, closer view.

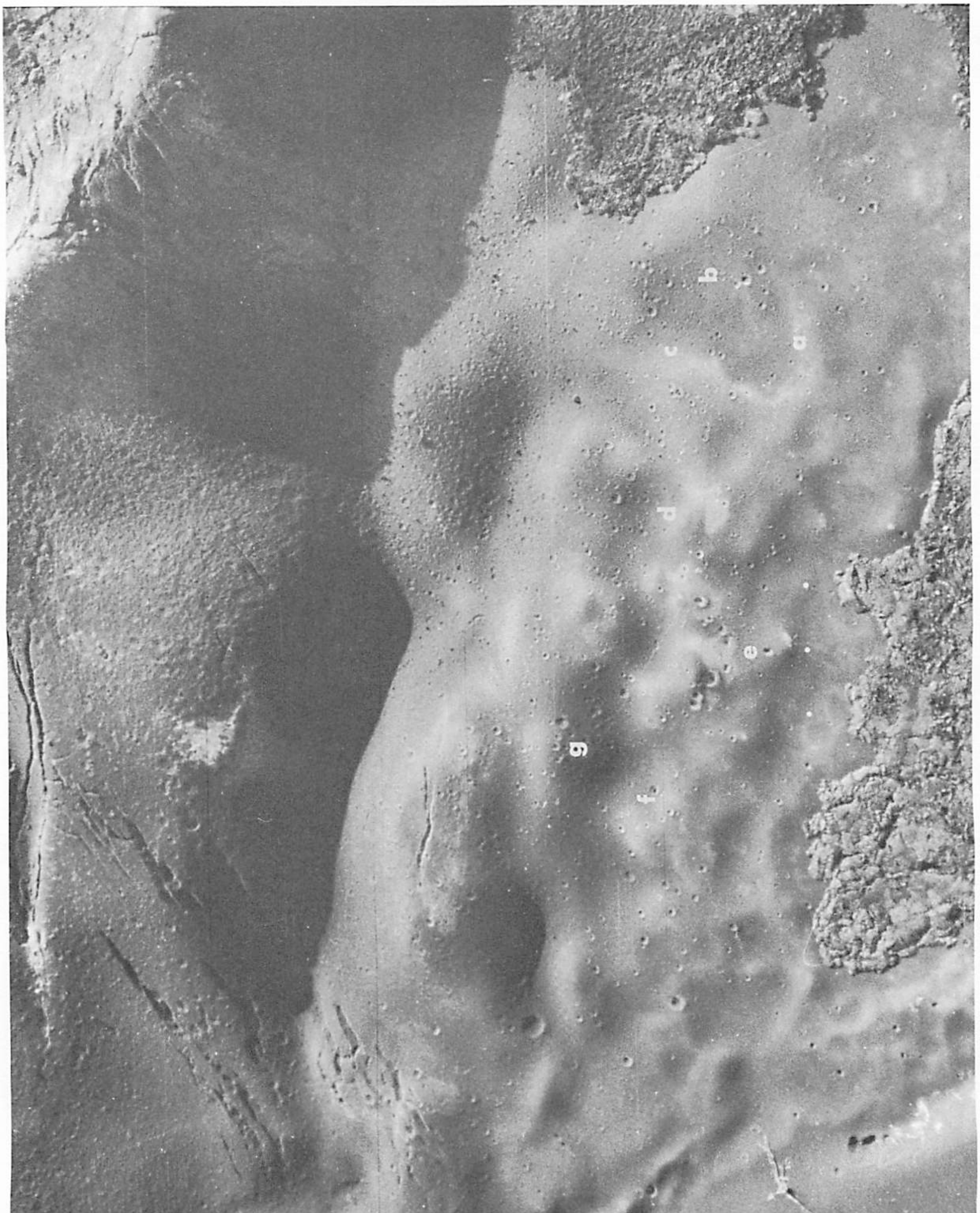

Fig. 16 Enlargement of lower central section of Fig. 15, with centers of close-up views in Figs. 18–24 designated *a* to *f*. Approximate scale entered in foreground; three dots below *e* separated by 10 meters.

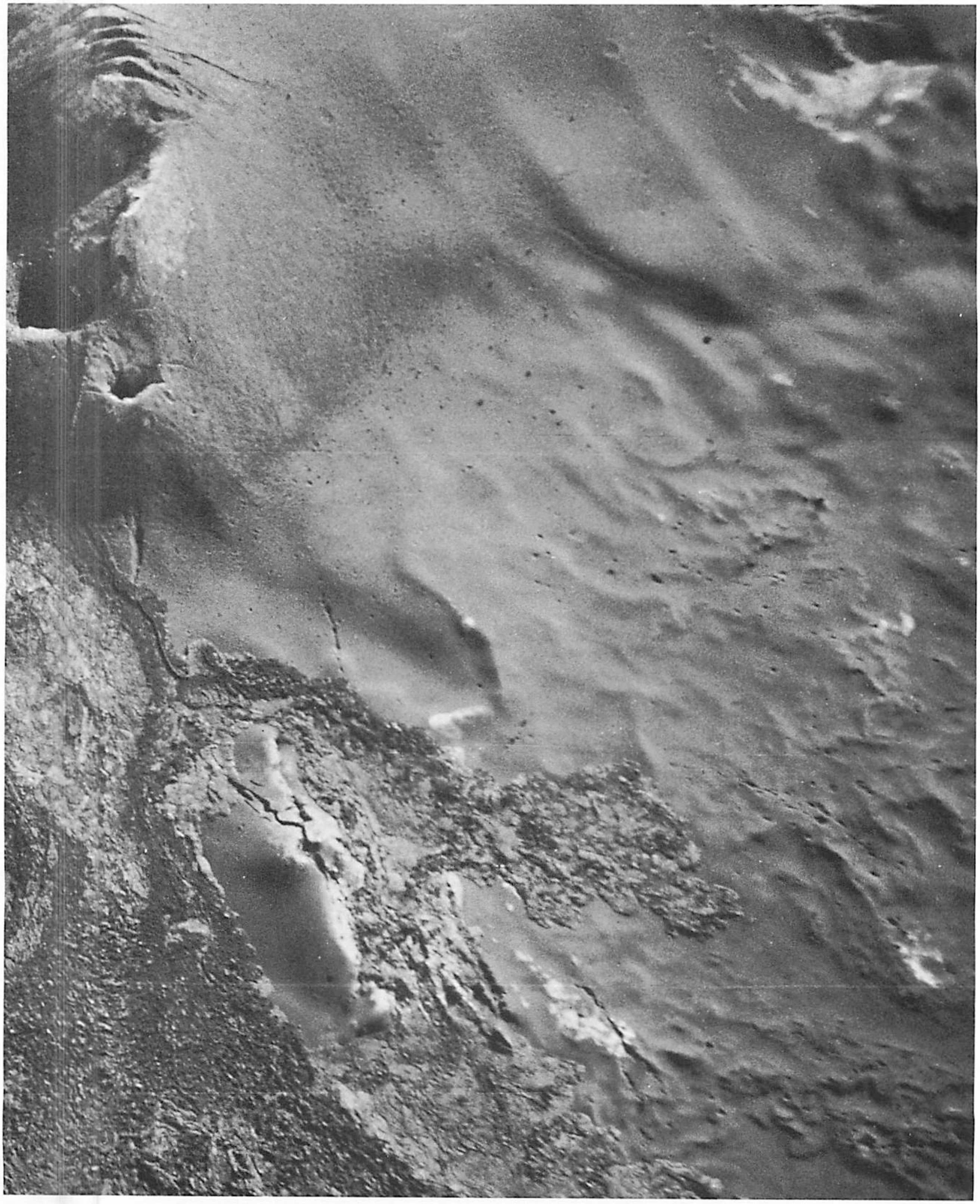

Fig. 17 Enlargement of right-hand central section of Fig. 15, showing numerous sink holes, fissures, small crater chains, and a few secondary impact craters in upper margin.

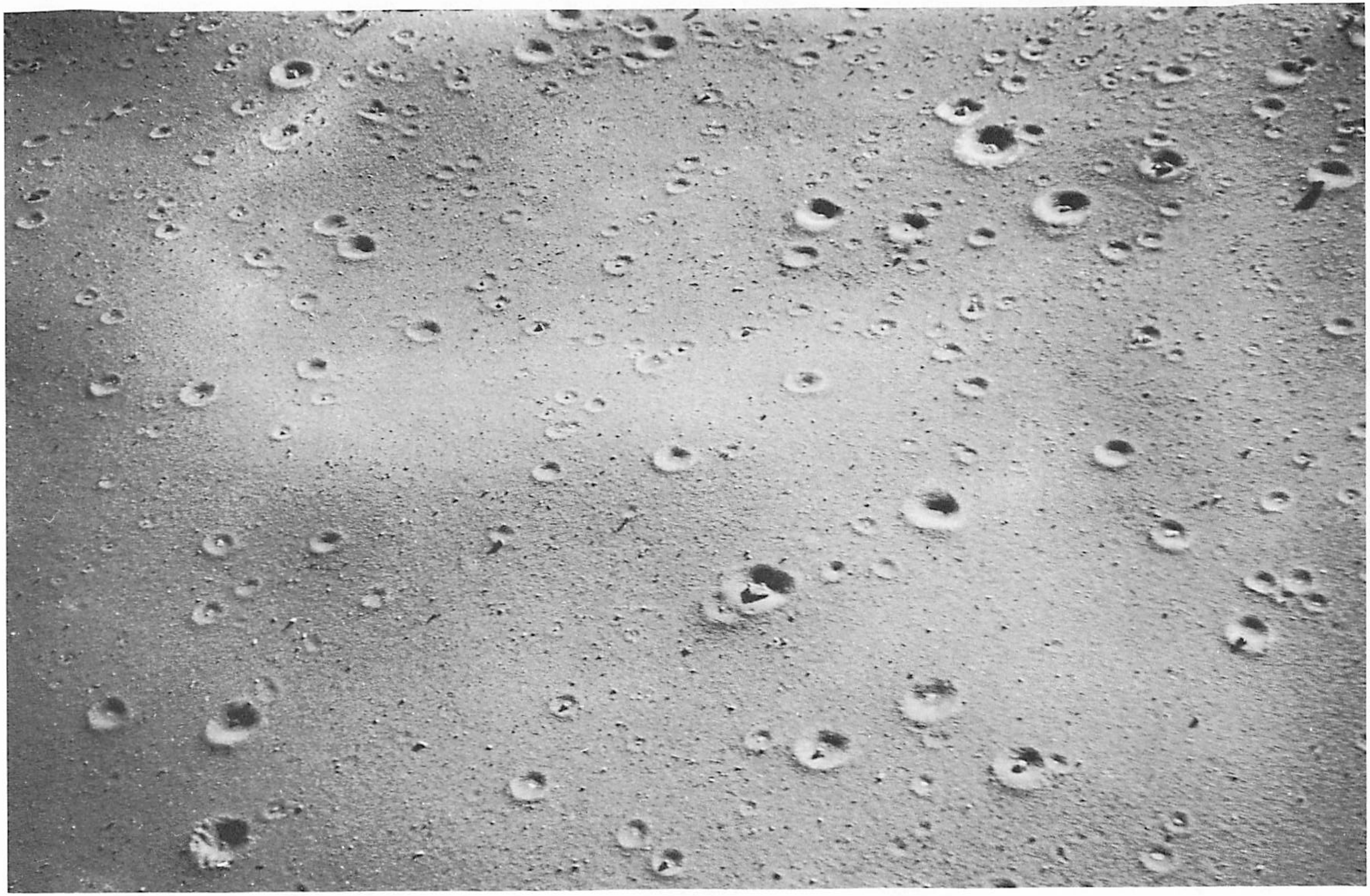

Fig. 18 Close-up of crater field centered on *a* on Fig. 16. Note lips of craters in down-slope direction; blocks of olivine basalt having caused craters and still visible, though occasionally not at crater center but displaced down-slope due to recoil. Craters not showing central rocks were usually found to contain them below the visible surface, some small erosion having taken place since impact. For scale, see Fig. 16.

Fig. 19 Near-vertical view of crater field centered on *b* of Fig. 16. Lava bed in upper right. Photograph previously reproduced in *Ranger VII* report. Comments on craters as in Fig 18.

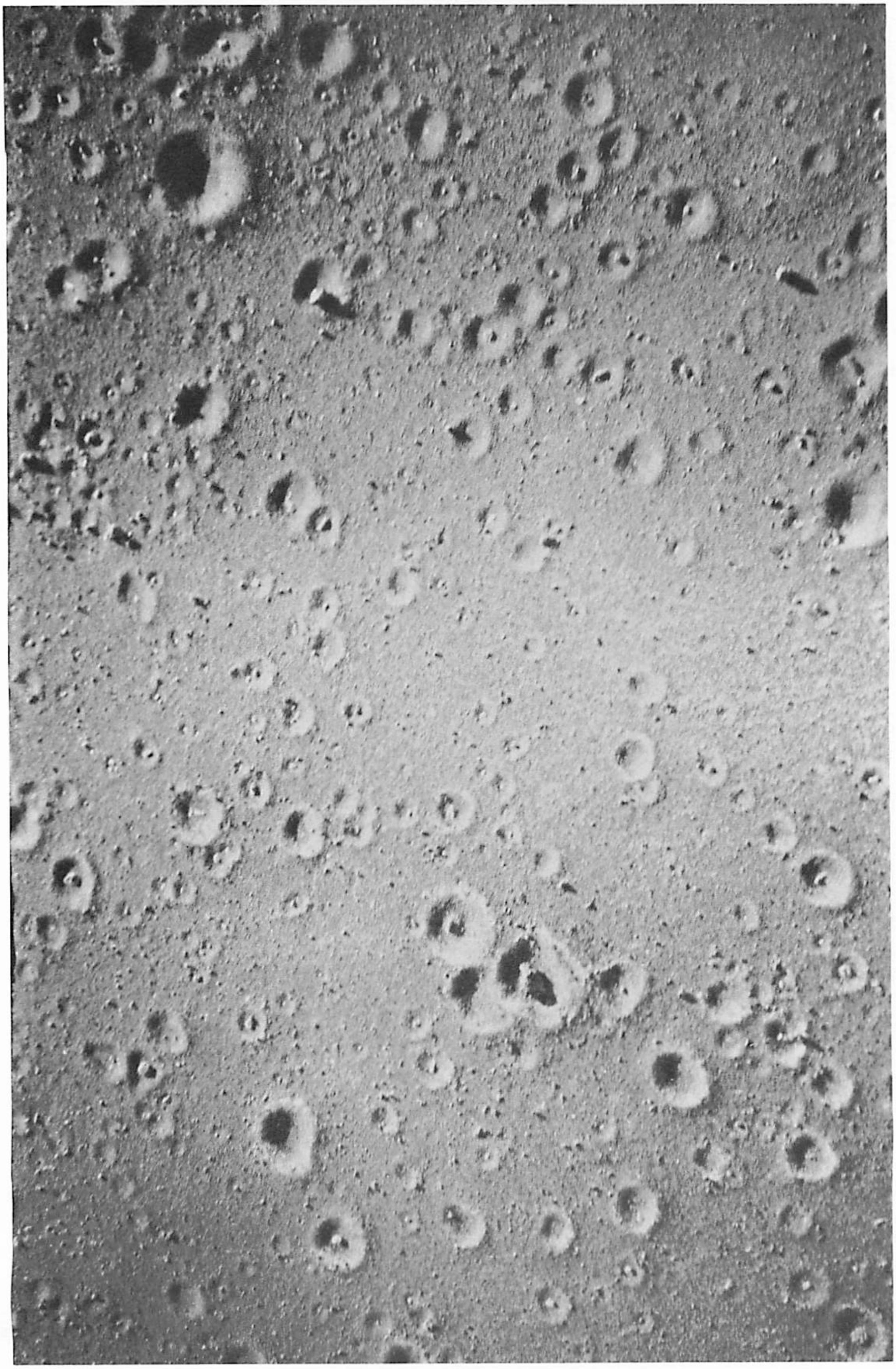

Fig. 20 Close-up view of crater field centered on *c* of Fig. 16. Comments on craters and rocks as in Fig. 18.

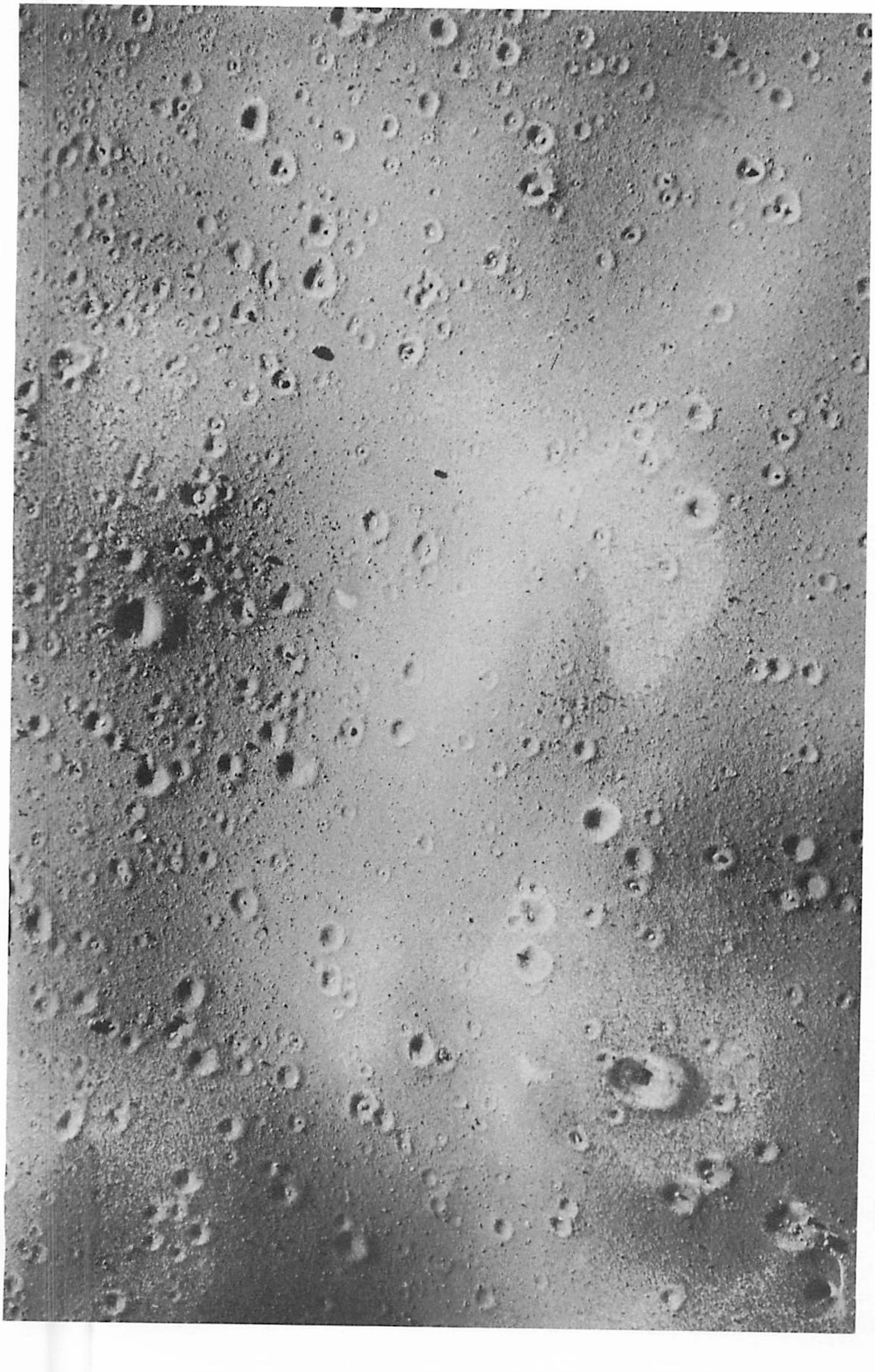

Fig. 21 Close-up of crater field centered on *d* on Fig. 16. Bright patches caused by residual sublimate cover. Collapse crater at lower left. Comments on craters and rocks as in Fig. 18.

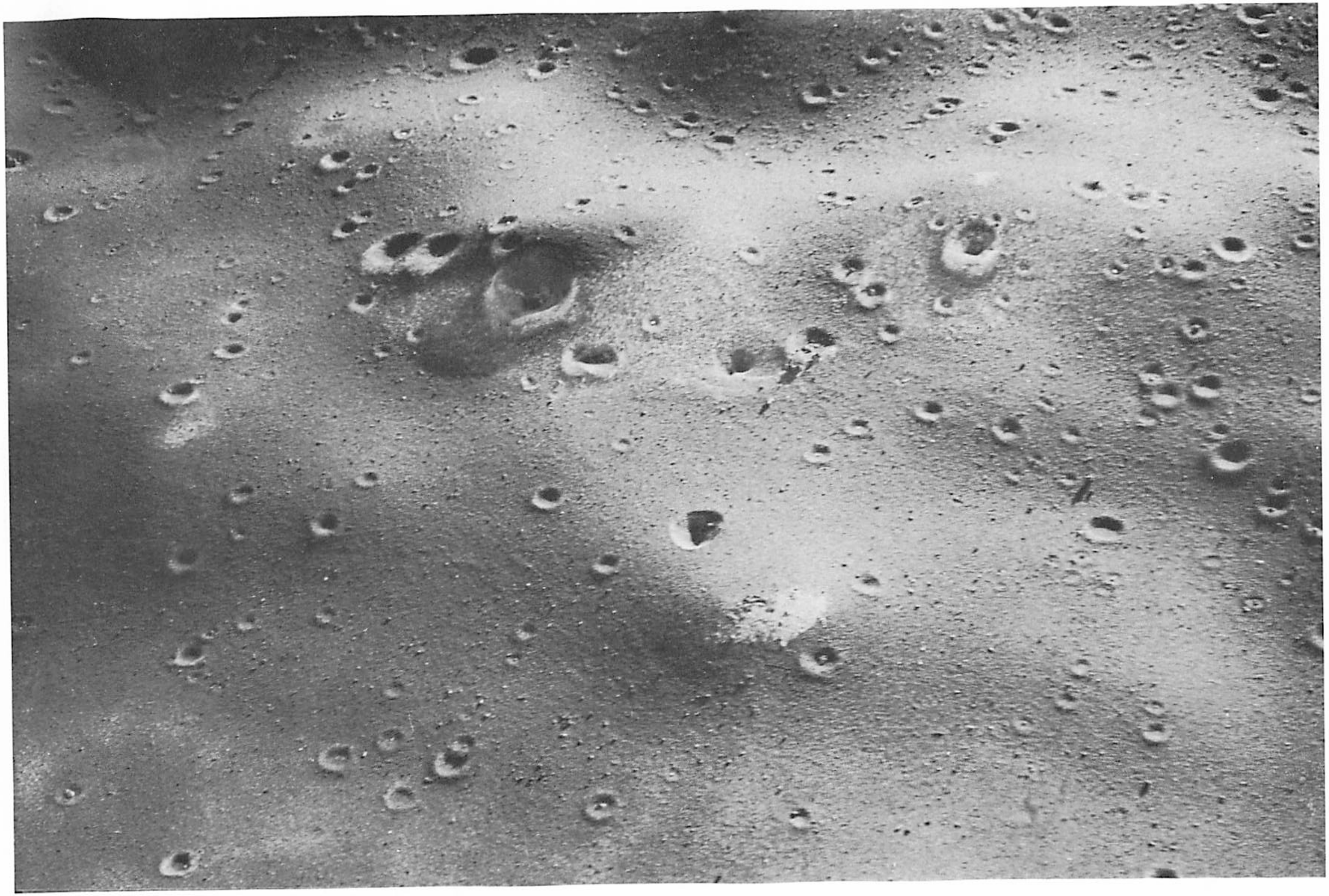

Fig. 22 Close-up of crater field centered on *e* of Fig. 16. Two drainage craters near center, both shown previously in Fig. 33 of the author's *Ranger VII* report. Note patches of sublimates. Comments on crater shapes and rocks as in Fig. 18.

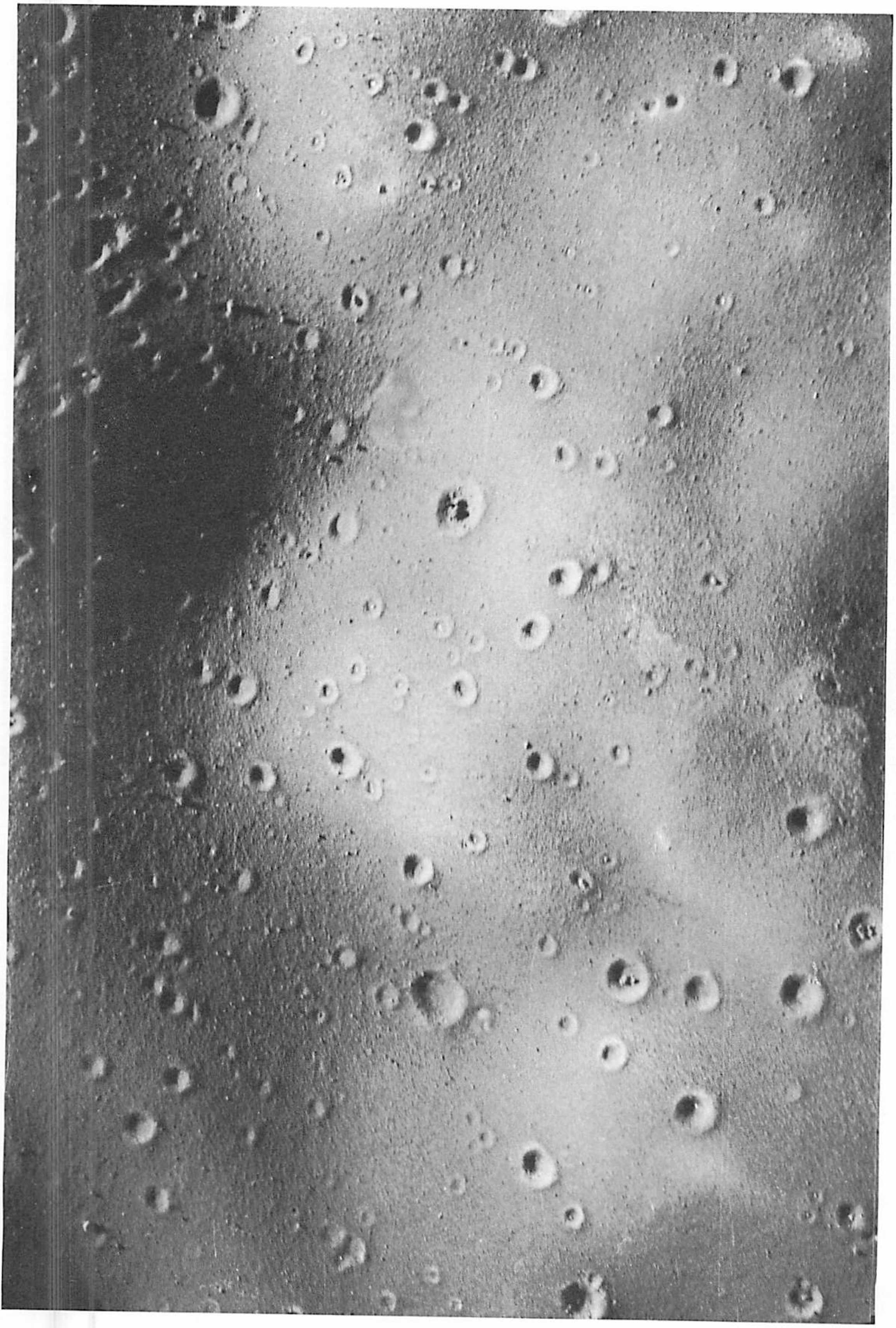

Fig. 23 Close-up of crater field centered on *f* of Fig. 16. Comments on crater shapes and rocks as in Fig. 18.

Fig. 24 Composite of two adjacent photographs, the upper one centered on *g* of Fig. 17, with the lower one showing area of Fig. 23, upper right. Note exquisite resolution for aerial photograph in lower section.

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