hemisphere could be understood as due to a different material or a faster destruction of glass on Mercury than on the moon.

No doubt many more facts will come to light concerning the lunar surface, and perhaps this phenomenon as well, in the analysis of the lunar samples brought back by Apollo 11. A rapid publication of these findings was nevertheless indicated by the urgency to make the best possible scientific preparations for the next Apollo flights. A more complete review of this and other information contained in the close-up pictures will be published later.

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## Bed Forms in Base-Surge Deposits: Lunar Implications

Abstract. *Undulating dunelike deposits of surface debris, widespread over parts of the lunar landscape, are similar in form but greater in size than base-surge deposits found in many maar volcanoes and tuff rings on Earth. The bed forms of base-surge deposits develop by the interaction of the bed materials with those in the current passing overhead. Therefore the "patterned ground" produced differs from that formed by ballistic fallout.*

As pointed out by Moore (*1*) explosive events such as shallow phreatic volcanic eruptions, large chemical or nuclear explosions, or hypervelocity impacts may give rise to turbulent debris-laden density flows somewhat similar in flow behavior to nuées ardentes. The density flows, known as base surges, expand radially outward from the base of a vertically rising explosion or eruption column and sweep laterally across the underlying surface at high velocities. Because base surges can develop by such diverse processes, it seems reasonable that they may have been important in dispersing and depositing debris on the lunar surface, irrespective of the kind of cratering mechanisms. Accordingly, the characteristics of base-surge deposits are of concern to lunar explorers. They must be considered in any interpretation of the origin of lunar fragmental debris, estimates on the thickness of the deposits, and the "mirroring" of buried structures within the underlying basement.

Although direct observational data of base-surge deposits on Earth are few, the surface configurations (bed forms) of layers which were shaped during such deposition appear to be of two kinds; low-amplitude bed waves with long axes approximately perpendicular to current directions, and planar, rather featureless surfaces. However, the distinction between these different bed forms becomes increasingly difficult as the wavelength of the undulation increases. For example, the surface of a low-amplitude, long wavelength bed form would appear to be planar when viewed up close, but may easily be recognized as part of a wave when viewed from a greater distance (compare different layers in Figs. 1 and 2).

Although maximum velocities of base surges are several times greater than those of water flowing in alluvial channels, base surges do develop bed forms similar in shape to those developed by debris-laden streams (*2*). Thus, we use similar terms. Low-amplitude bed waves with stoss- and leeside slopes inclined at angles less than the angle of repose are antidunes or sinusoidal waves; relatively flat, featureless surfaces are referred to as plane bed forms. With concurrent deposition and migration of bed forms, accompanied by changes in velocity of the current overhead, depositional sequences containing a succession of low-angle antidune foreset and backset cross laminae will be interspersed with plane beds and with dunelike bed forms of different wavelength (Figs. 1 and 3).

Base surges from the 1965 phreatic volcanic eruption of Taal Volcano, Philippines, deposited dunelike forms with wavelengths which progressively decrease from 19 m close to the eruption center to about 4 m at 2.5 km distant (*1*). This reflects the reduction in velocity. Internal structures show cross-bedding caused by wavelike transfer of debris in the current direction. Dunelike forms were also deposited by a base surge which developed from the 100-kiloton underground thermonuclear Sedan test of 6 July 1962.

Recently, it was suggested (*3*) that the uppermost layer of sand around Meteor Crater, Arizona, was deposited from a "dense suspension" during crater evisceration, rather than by later reworking of airfall debris. The sand layer exhibits sedimentary structures resembling water-laid deposits.

Bedding characteristics of base-surge deposits may be studied in the rim ejecta of volcanoes built mostly by phreatic eruptions. Of particular importance are partially dissected maar volcanoes; geologic evidence shows that nearly all maar volcanoes formed in environments where surface or subsurface water had access to the volcanic vents. The rim ejecta of most maars, especially those with broad, low ramparts which surround shallow, wide craters, have bed forms indicating emplacement by surge-flow processes (Fig. 3). Directional features around the craters show that the depositing currents spread out radially from the vents at high velocity.

Sedimentary structures in maar ramparts, such as those at Zuni Salt Lake, New Mexico (*4*), Salt Lake Craters, Hawaii, Cerro Colorado, Sonora, and the Macdoel, California, tuff rings (Fig. 3), exhibit broad undulations instead of uniform primary dips. We conclude that such low-amplitude structures, preserving the form of broad waves, were developed by base-surge flow. Wavelengths may attain many meters, or be only a fraction of a meter.

On vertical exposures cut radially into maar rims, large-scale undulations are not easily discernable. Instead, the conspicuous structures consist of dozens of thin-bedded or laminated tuff and lapilli-tuff layers, some of which show low-angle foreset and backset cross laminae. Thus these deposits pre-

Fig. 1. Large-wavelength antidune forms. Internal continuous laminae consist of thin beds which repeat the large wave form, and a laterally continuous zone of repeated small antidunes. The beds were deposited by density currents moving over the surface toward observer out of Ubehebe Crater, California, which can be seen in background.

serve the form of much smaller sinusoidal waves interspersed with nearly flat plane beds (see Figs. 2 and 3). The plane beds superficially resemble airfall layers, but their large-scale undulations and transition into smaller antidune cross laminae support the contention that most were emplaced by flow. So does the common appearance of turbulent bedding streaks on the downstream ends of large fragments embedded within some of these flat beds.

An exposure at Ubehebe Craters, Death Valley, California (Figs 1 and 2), illustrates the association of small antidunes with large-scale antidunes, and the vertical gradations between plane beds and wavelike forms. At the largest crater there are two broad antidune crests and an intervening trough with a wavelength of about 42 m and an amplitude of about 1.5 m (Fig. 1). Although it is possible that this large wave form reflects the underlying topography and thus could be interpreted as draped airfall ejecta, it seems fortuitous that the amplitude-to-wavelength ratio is the same order of magnitude as most other large-scale wave forms (*5*). Moreover, the beds within this wave are mostly continuous smooth-surfaced layers which repeat the large wave form. Within this sequence, however, is a laterally continuous zone about 0.5 to 1 m thick which consists of small antidune forms ranging in wavelength from 1 to 2 m and in amplitude from 5 to 20 cm (Fig. 2). Cross laminations and other directional structures show that the depositing current moved outward from the crater, as do cross laminae at several other places around the crater.

Plane beds beneath the smaller antidune sequence are composed mainly of coarse-grained tuff and lapilli tuff. Upward, however, with the appearance of finer-grained tuff, undulations that resemble standing waves begin to form (Fig. 2). At amplitudes of about 5 cm, some of the leeside laminae become truncated, and stoss-side laminae begin to stack up with a slight increase in slope. Although the foreset laminae are commonly truncated, many laminae are continuous from the stoss- to leesides across the crests (Fig. 2). The upward growth of the cross-laminated antidune forms is terminated by the appearance of a continuous and symmetrical 2- to 3-cm thick sinusoidal bed that is followed immediately by coarser-grained tuff and a rapid upward gradation to plane beds. The amplitude-to-wavelength ratios of the small wave forms are between about 1 to 7 and 1 to 15 in contrast to a ratio of about 1 to 30 for the large-scale antidune in which they occur.

Simons and Richardson (*2*) discuss the important variables operating during dynamic interaction between bed materials and a current which passes overhead. Among them are the flow velocity or magnitude of shear stress exerted on the bed materials, and the median fall velocity (a function of size, shape, and density) of the particles. With other factors held constant, an increase in velocity and shear stress or both on the bed results in a predictable series of bed forms—ripples, dunes, plane beds, and antidunes in succession. Essentially, the wave forms steadily increase in wavelength with respect to amplitude.

As shown by Kennedy (*6*) from theoretical considerations, the wavelength of antidunes formed by flowing water is directly proportional to the square of the velocity and inversely proportional to the force of gravity. If somewhat similar relations hold for base-surge flow, hypervelocity impacts on the lunar surface could give rise to high-velocity base surges that would produce deposits with extremely broad undulations near the crater. If wavelengths are proportional to velocity as predicted by Kennedy, a progressively more fine-sculptured concentric ridge and valley pattern should appear with increasing distance from the impact crater.

Because of the many variables that control the development of bed forms, and the lack of experimental data on the fluid and flow parameters of base-surge density flows, the principles learned from studies of alluvial channel bed forms may apply only in a general way. Our observations indicate that the wavelike forms of volcanic base surges are broader and flatter than alluvial channel bed forms. It is to be expected that the base-surge bed forms developed by hypervelocity impact on the moon would show even greater wavelengths.

The similarity in flow behavior of different kinds of density flows, including base surges and nuées ardentes, suggests that their deposits may show somewhat similar characteristics. However, the formation of impact base surges is independent of rock composition, whereas large-scale nuées ardentes are normally derived from salic magmas by explosive vesiculation. Even if pyroclastic salic rocks are absent or minor in amount within the lunar crust, large-scale base-surge flows formed by impact are capable of creating the undulating flat surfaces photographed on parts of the lunar terrain.

Photographs of the lunar surface

show abundant large- to small-scale wavelike forms. Some occur within the maria, others on terra slopes, and some are clearly associated with crater ejecta. Within the Rümker quadrangle (*7*), mare plains mapped at 100-km and 10-km scales are horizontal to very gently undulating, but they also show rolling surfaces with a relief of a few tens of meters. Terra plains on 10-km and 1-km scales show many gently undulating areas. Moreover, the rim materials of some craters up to 10 km across show low rounded ridges which are slightly curved, tend to be short, and are arranged subconcentrically around the crater.

On an even smaller scale are ridges and mounds with intervening troughs in a pattern likened in some instances to the bark of the ponderosa pine (*8*). Shoemaker refers to these features as *lunar patterned ground*. Individual ridges or mounds range from 5 to 30 m in width and from 15 to 200 m in length. Their heights are estimated to be from 10 cm to several tens of centimeters, therefore their slopes are very low. These features of the patterned ground suggest bed forms developed by flow. Moreover, the patterned ground overlies different units of the terrain without changing the pattern. Also, where patterned ground crosses crater rims, it is deflected as if influenced by slopes. Close inspection shows many curving elements. The "tree-bark" pattern could be the result of interfering wave forms developed by a younger flow moving in a different direction across an already patterned surface, or by refraction of a flow front as it moves around an obstruction. If basement lineaments are prominent, the flow directions of a density current would necessarily be refracted by their trends. The landscape surrounding Mare Orientale is replete with much coarser bed forms and interference patterns that record the passage of a catastrophic debris-laden surge from this large impact crater. These patterns may be examined on high-resolution photographs (*9*).

Studies of the outer rim material of the crater Tycho (*10*) from Orbiter V and Surveyor VII photographs revealed a belt from 80 to 100 km wide with various undulating features. The zone closest to the rim crest, about 10 to 15 km wide is characterized by irregular hummocks and contains many lobate tongues, some as long as 8 km. The zone from 15 km to about 40 km is marked by subradial ridges and valleys which Shoemaker believes to reflect underlying topography. Individual ridges are 2 to 5 km long and 0.5 to 1 km wide. Still farther from the crest of Tycho, the outlines of ancient craters are more easily seen, but they too are blurred by subradial ridges and valleys out to a distance of 100 km.

Surveyor VII landed about 30 km north of the rim of Tycho on the edge of a lobate flow in an area marked by large-scale swales with superimposed subradial ridges. The local relief is 160 m.

The observed lobate deposits are interpreted (*10*) as lava flows and cold or hot debris flows resulting from im-

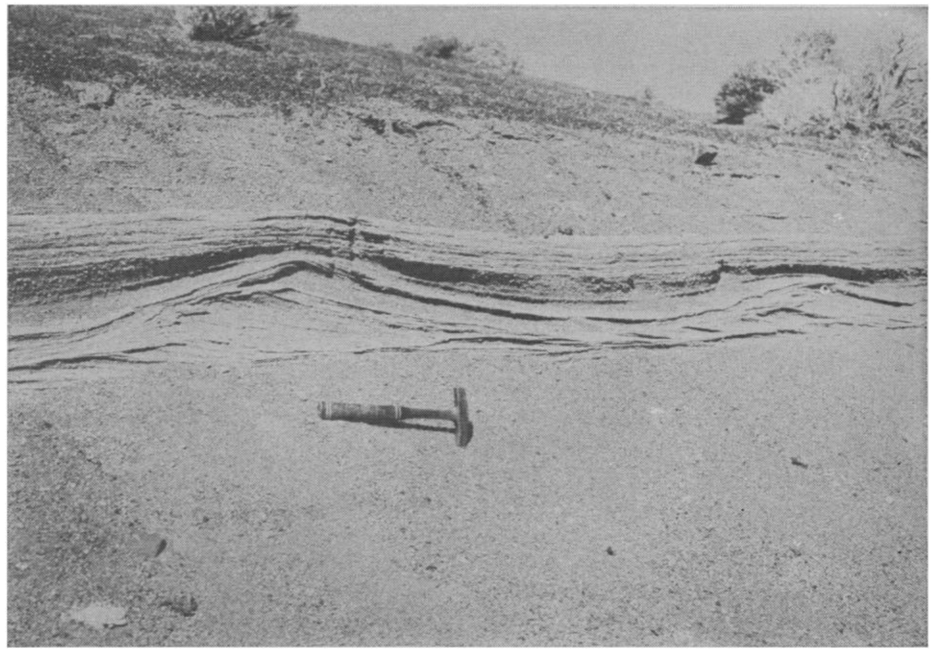

Fig. 2. Closer view showing part of the zone of small antidune forms seen in Fig. 1. They include preserved low-angle stoss- and leeside antidune laminae. Sequence grades from plane beds beneath, through the wave form sequence, and upward to plane bed forms. Hammer handle points toward crater.

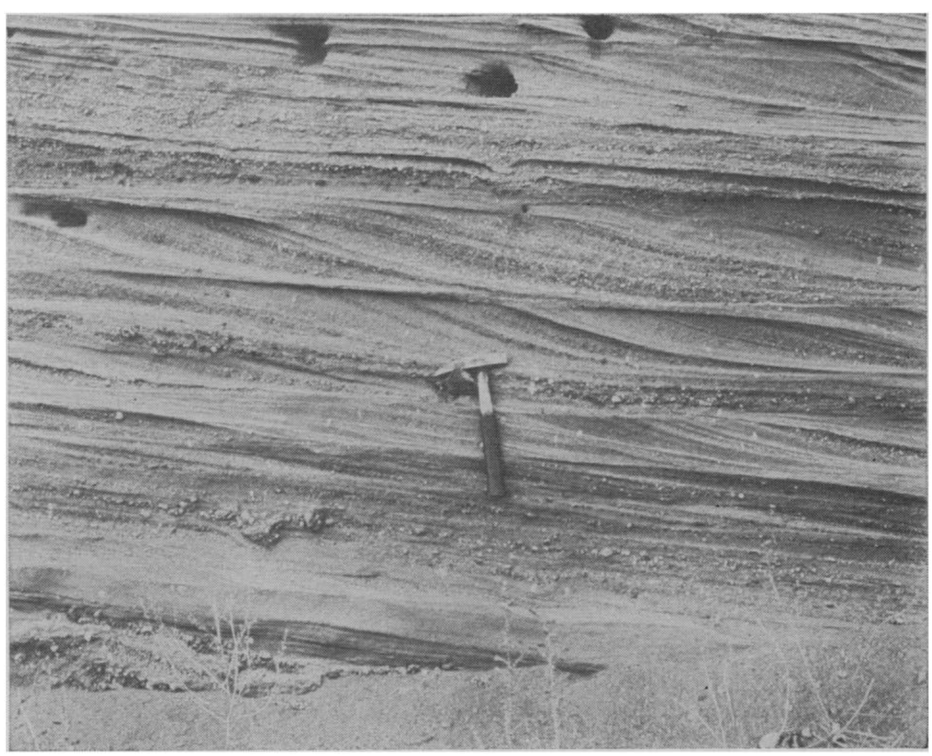

Fig. 3. Base-surge deposits on the outer slope of a tuff ring. Direction of transport to the right. Juniper Hills group of maar volcanoes near Macdoel, California.

pact, or both, but the patterned ground is interpreted as fallout material which is draped over a minutely fractured basement. Although it seems reasonable that many of the undulations observed in the Tycho rim materials are due to fallout ejecta draped over basement lineaments, it seems more probable that the definitely wavelike forms were developed by base-surge flow. In contrast to Shoemaker's interpretation, Masursky *et al.* (*11*) indicate that extensive tracts of the "patterned ground" surrounding Tycho "is probably fine ejecta deposited by base surge. The dune features may be deceleration dunes localized at concentric fractures in the underlying material."

Certainly the pattern of these dune-like ridges from Tycho is not unlike the dunes we have observed around Earth maars, except in scale. Base surges would soften the outlines of small craters and other lunar landscape features and eventually cover and reduce them to ghostlike images. In any event, layered deposits of granular material and geomorphic features of the lunar landscape should be evaluated with the possibility that fragmental material may have been emplaced by flow, as well as by fallout, regardless of rock composition.

It is now widely accepted that the small lunar craters which are aligned along fissures and rills may be of volcanic origin. Many are similar in size and form to Earth maars. Thus, base-surge deposits similar in size and origin to those in Earth maars may also be present on the moon. If a permafrost layer occurs within permeable materials beneath the lunar surface as is postulated by some workers (*12*), conditions exist whereby phreatic base-surge flows could develop from lunar magma rising into ice-filled fractures. The presence of chilled sideromelane in cross-bedded antidunes might afford reliable indications of the presence of underground ice.

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## Lead: X-ray Diffraction Study of a High-Pressure Polymorph

Abstract. *An x-ray diffraction study of lead under pressure has shown that the face-centered cubic structure transforms to the hexagonal close-packed structure at room temperature and a pressure of 130 ± 10 kilobars. The volume change for the transformation is −0.18 ± 0.06 cubic centimeter per mole.*

On the basis of a 23 percent increase in electrical resistance, Balchan and Drickamer (*1*) have reported that a phase transformation in lead occurs at 160 kb and room temperature. However, the crystal structure of this high-pressure phase was not determined. A hexagonal close-packed structure was predicted for the high-pressure phase by Klement (*2*), who found a similar transition in bismuth-lead alloys. We have identified the crystal structure of the high-pressure phase in pure lead by means of an x-ray diffraction method with a polycrystalline sample compressed in a diamond-anvil high-pressure cell.

We used a high-pressure x-ray diffraction camera designed by Bassett *et al.* (*3*). The high-pressure cell of this camera consists of two ⅛-carat gem-quality diamond anvils driven by a piston screw assembly. When a polycrystalline sample is compressed between the anvil faces (~ 0.4 mm in diameter), a maximum pressure is produced at the center of the anvil area. A finely collimated x-ray beam, approximately 50 μm in diameter, of filtered MoK$\alpha$ radiation passes through one of the anvils and impinges on the central part of the anvil area where a maximum and a minimum pressure gradient exist. Diffracted rays pass out

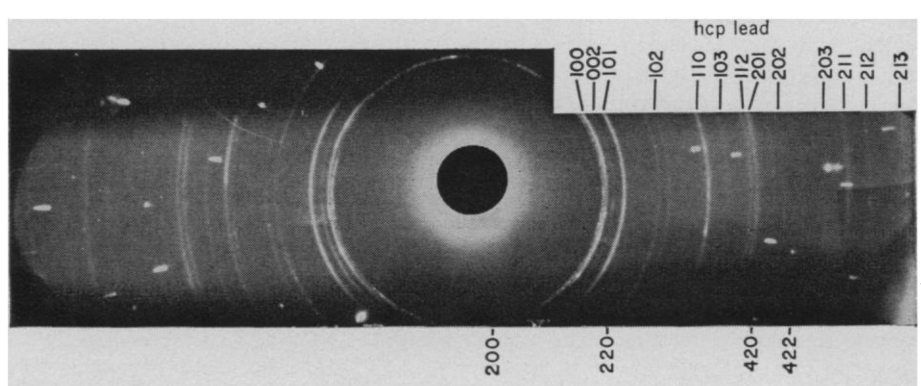


Fig. 1. X-ray diffraction pattern for the high-pressure phase of lead at 139 kb. All the diffraction lines for lead can be indexed as hexagonal close-packed. The pattern also shows the diffraction lines from the NaCl platelet placed in the x-ray beam on the back of the diamond facing the film for the purpose of monitoring the constancy of the camera geometry and film dimension. Many lines for the high-pressure phase of lead exhibit spottiness due to coarse crystallinity.