Base Surge in Recent Volcanic Eruptions *

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Abstract

A base surge, first identified at the Bikini thermonuclear undersea explosion, is a ring-shaped basal cloud that sweeps outward as a density flow from the base of a vertical explosion column. Base surges are also common in shallow underground test explosions and are formed by expanding gases which first vent vertically and then with continued expansion rush over the crater lip (represented by a large solitary wave in an underwater explosion), tear ejecta from it, and feed a gas-charged density flow, which is the surge cloud. This horizontally moving cloud commonly has an initial velocity of more than 50 meters per second and can carry clastic material many kilometers.

Base surges are a common feature of many recent shallow, submarine and phreatic volcanic eruptions. They transport ash, mud, lapilli, and blocks with great velocity and commonly sandblast and knock down trees and houses, coat the blast side with mud, and deposit ejecta at distances beyond the limits of throw-out trajectories. Close to the eruption center, the base surge can erode radial channels and deposit material with dune-type bedding.

Introduction

During the 1965 phreatomagmatic eruption of Taal Volcano, Philippines, a series of debris-laden eruption clouds moved out radially from the base of the main explosion column (MOORE *et al.*, 1966). These clouds carried blocks, lapilli, and ash suspended in water vapor and gases and moved outward with tremendous velocity. They shattered and obliterated all trees within one km of the explosion center and sandblasted objects up to 8 km distant.

A review of other volcanic eruptions of recent date shows that such clouds are common, particularly during eruptions where ocean water, lake water, or copious ground water has access to the volcanic

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conduit. The resultant steam explosions commonly produce a vertical, cylindrical eruption column hundreds to thousands of meters high, with a collar-like, flat, horizontally-moving cloud at its base.

Very similar horizontally-moving clouds also occur at the base of shallow thermonuclear explosions both on land and sea, and have been called the *base surge* (GLASSTONE, 1950, p. 41). The term *base surge* is reserved in this paper for this characteristic, ring-shaped basal cloud which sweeps outward as a density flow from the base of the vertical explosion column. They are formed in both natural (volcanic) and artificial (thermonuclear and chemical) explosions. A base surge probably can be produced by supersonic impact explosions also. Depending on the nature of the explosion and the material available, the base surge may carry nothing but water and gases (as in a submarine thermonuclear blast) and consequently produce no permanent deposit. On the other hand, it may carry fragmental volcanic ejecta and deposit either welded or nonwelded ash layers.

Base Surge in Artificial Explosions

On July 25, 1946, a 20-kiloton nuclear device was exploded in Bikini Lagoon in the south Pacific at a water depth of 27 meters. This explosion produced a dense ring-shaped cloud which emerged from the base of the cylindrical column of spray ejected vertically from the explosion center (Fig. 1). This basal cloud or base surge was first believed to be an example of bulk subsidence in which a falling suspension of water drops in air behaved like a homogeneous fluid with a density greater than that of the surrounding atmosphere (GLASSTONE, 1950).

However, detailed mathematical analysis and study of the Bikini photographs led YOUNG (1965 b) to the conclusion that the base surge formed at the crest of a large solitary wave around the edge of the « crater » formed in the sea by expanding gases at the explosion center. Outward directed water jets from the top of this wave broke into spray and fed the base surge. This main base surge appeared before the outside of the main column had started to fall, and hence could not have been formed by bulk subsidence (YOUNG, 1965 b, p. 98). Only later did a second, smaller base surge develop inside the first by subsidence of the main column (Fig. 1).

The base surge continued outwards more than 4 km. Its initial

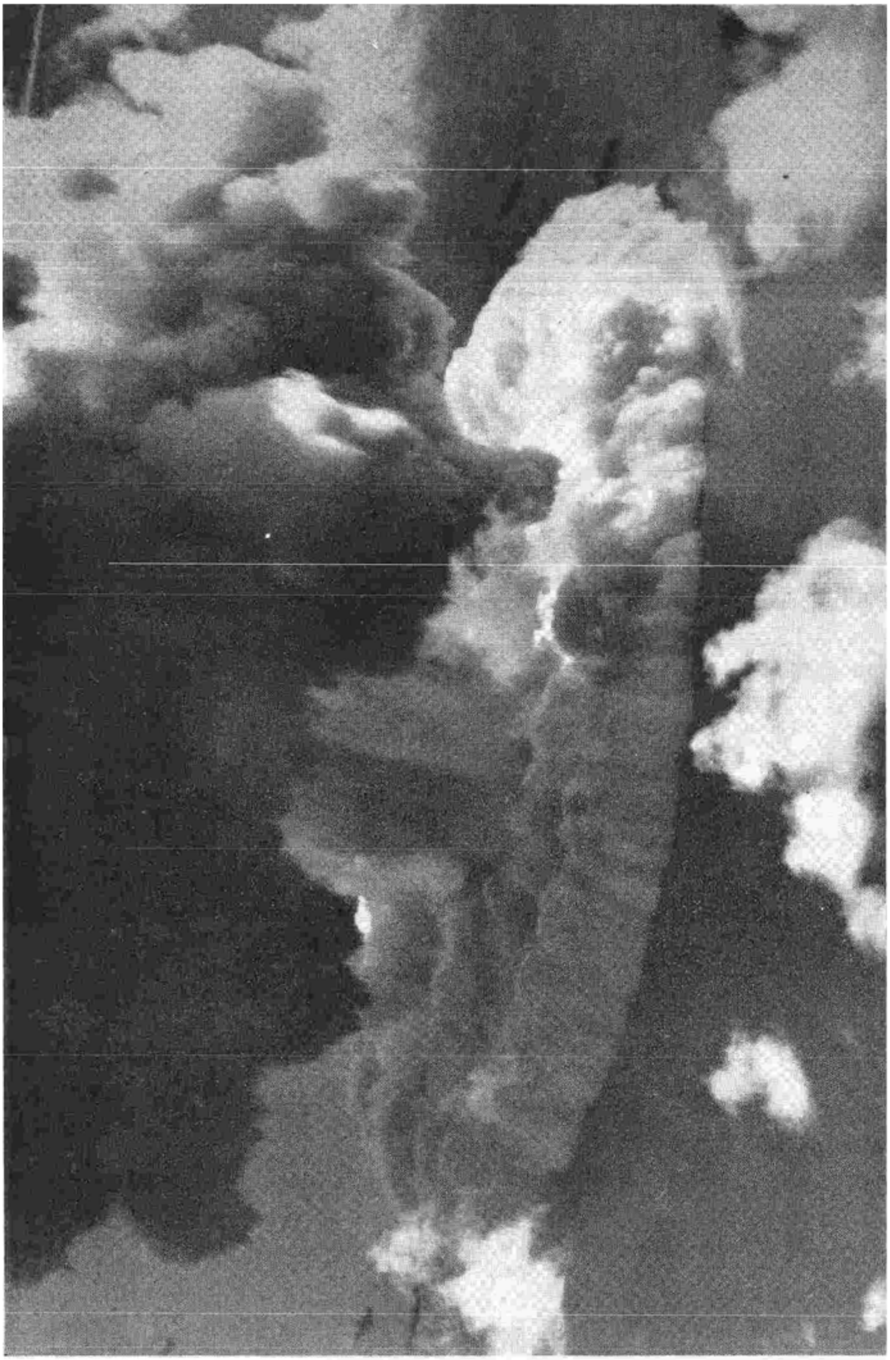

Fig. 1 - Aerial photograph taken 30 seconds after the Bikini underwater test explosion. Diameter of the outer primary base surge is about 1.8 km. The secondary, inner base surge formed by subsidence of central comlumn is visible. After Young (1965 a, slide 6).

velocity was more than 53 meters per second (118 miles per hour), and it moved at 20 meters per second (45 miles per hour) 1.4 km from the explosion center (Fig. 2).

The Bikini test was relatively shallow, but base surges have formed from an underwater test at a depth of 152 meters (1958).

Considerable study has also been directed on base surges formed during explosions of underground thermonuclear tests (ROBERTS and CARLSON, 1962, and ROHRER, 1965). The Sedan test of July 6, 1962, involved a thermonuclear device of 100-kiloton yield detonated at a depth of 194 meters in desert alluvium. This blast produced a crater 370 meters in diameter and 98 meters deep. An excellent base surge developed (Fig. 3) with an initial velocity in excess of 50 meters per second (Fig. 2). Debris carried by the base surge can be identified out to 3 km from ground zero in the upwind direction, twice the radial distance attained by ballistic debris (ROBERTS and CARLSON, 1962, p. 27).

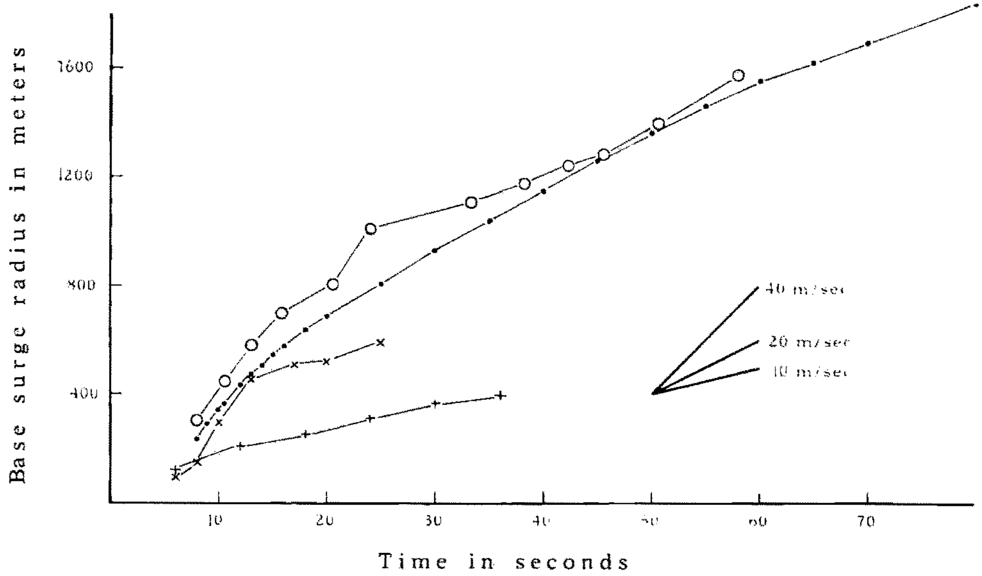

FIG. 2 - Radial distance of travel of base surge vs. time for 2 test explosions and 2 explosive volcanic eruptions. Circles, Sedan thermonuclear test in alluvium, 100 kilotons, (Robert ROHRER, written communication, 1965); dots, Bikini thermonuclear test in ocean, 20 kilotons (YOUNG, 1965 b, p. 274); crosses, Myojin Reef eruption of 13:12, September 23, 1952, assuming first photograph was taken 6 seconds after burst (MORIMOTO, 1960, pl. 1); plus signs, Anak Krakatau eruption of January 24, 1928, assuming first photograph was taken 6 seconds after burst and eruption column height is 1000 m in sixth photograph (STEHN, 1929, photo 16).

An interesting feature of the Sedan test is that a series of ejecta dunes were formed concentric to the explosion crater. These are best developed outside low portions of the crater rim, and closely resemble the dunes formed at Taal Volcano, but are much smaller, having a wave length of 3 to 4 meters.

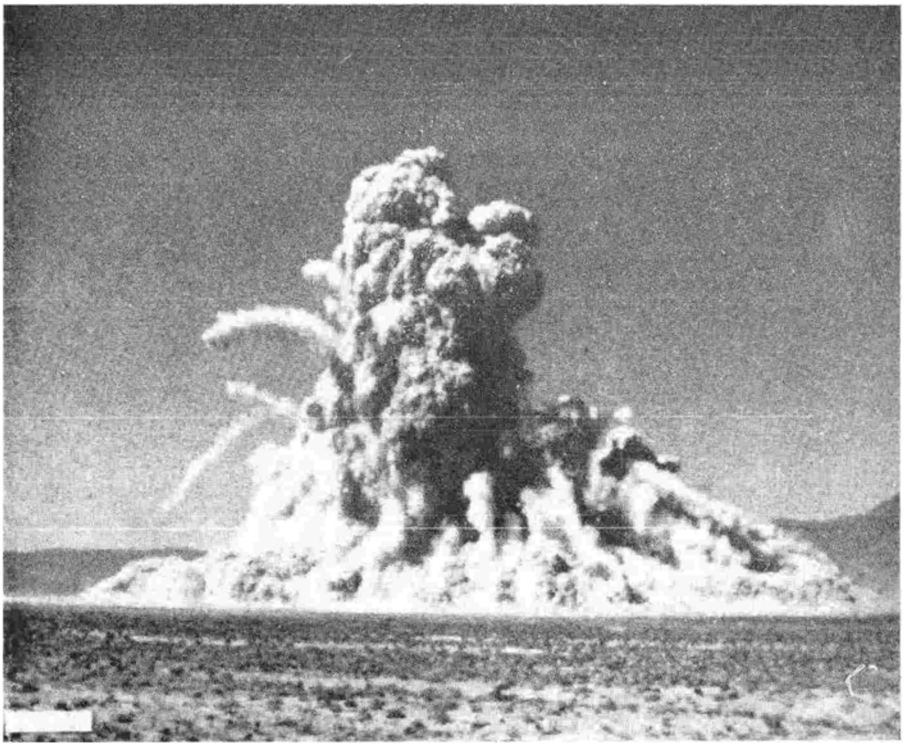

FIG. 3 - Sedan thermonuclear test explosion taken 39 seconds after burst. Height of the explosion column is 1.5 km, and diameter of emerging base surge is 2.7 km. Bar is approximately 300 meters long. After NORDYKE and WILLIAMSON, 1965, fig. 1.2.

An interesting effect of topography on the movement of the base surge was noted by KNOX and ROHRER (1963, p. 18) when studying the results of a shallow underground 220-kilogram chemical explosion. In this test, a subradial trench was present in the area covered by the explosion-induced base surge. They note that « When the surge cloud intercepted the trench a portion of the surge cloud aerosol moved down and outwards in the trench at a mean speed of about

30.5 m/sec, as determined by time lapse photographs. This down-trench mean speed exceeds the maximum radial speed acquired by the surge cloud of about 9 m/sec. The physical interpretation of this reported phenomena is that the dust aerosol, with a density exceeding atmospheric density, will move as a turbidity current over or down topographic features with the change in potential energy accounting for changes in the kinetic energy of the aerosol ».

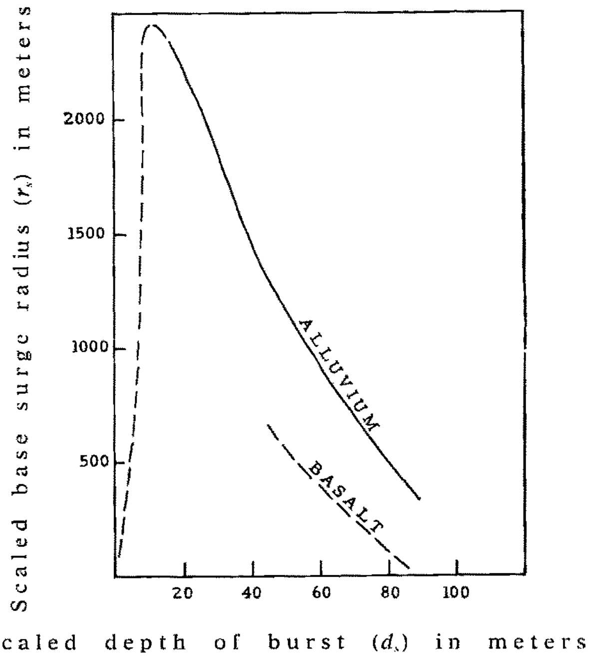

FIG. 4 - Scaled radius of base surge (r_s) in meters vs. scaled depth of burst (d_s) in meters for explosions in alluvium and basalt (after ROHRER, 1965). $r_s = r/(Y)^{0.3}$ and $d_s = d/(Y)^{0.33}$ where r is actual radius of base surge in meters, d is actual depth of burst in meters, and Y is yield of explosion in kilotons of chemical explosives.

KNOX and ROHRER (1963) and ROHRER (1965) have related the radial distance attained by the base surge with yield and depth of shot and type of surrounding material (Fig. 4). They find that the maximum radial distance to which a surge will travel varies as the 0.3 power of the yield of the burst. The optimum depth for production of the largest possible base surge is considerably shallower than that for production of the largest crater. For a 1-kiloton burst this depth would be 10 to 15 meters. Explosions from a greater depth would

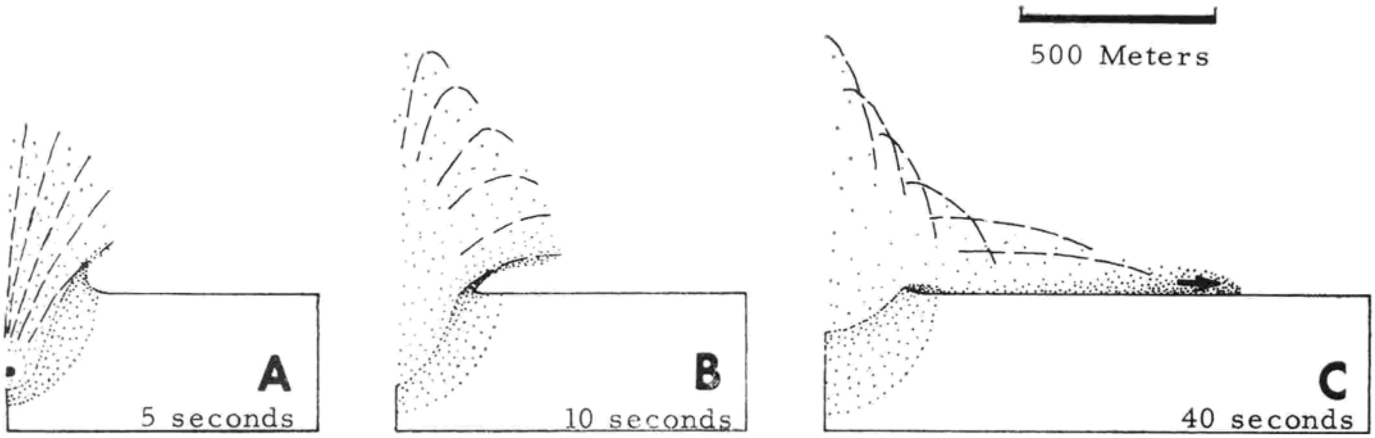

FIG. 5 - Sequential diagram, with approximate time after burst, showing apparent formation of base surge during underground explosion equivalent to 100 kilotons of chemical explosives. (A), 5 seconds, rock is brecciated around explosion center and expelled generally in a vertical direction forming the vertical explosion column. (B), 10 seconds, crater enlarges and wall surrounding it is overturned allowing outward expansion of gases and ejecta which tear material from overturned flap and feed base surge. (C), 40 seconds, larger ejecta thrown out by explosion has reached the ground, but base surge continues moving outward as a density flow aided by downslope if present. Modified from SHOEMAKER (1960, fig. 4) and YOUNG (1965 b, fig. 6.1 and written communication, 1966).

dissipate more energy in lifting the overburden, and shallower explosions would dissipate more energy into the atmosphere without mixing ejecta and gases at the crater lip.

They show further that base surges from explosions in alluvium travel roughly twice as far as those in basalt, other factors being equal. This is apparently due to the larger amount of noncondensible gas produced from the moister alluvium, the larger particle size of the basalt causing it to fall out of the dust-aerosol quicker, and the greater energy required to disaggregate the basalt.

According to studies of the base surge at the Bikini test (YOUNG, 1965 b), the base surge forms at the crest of a large solitary wave ringing the explosion-induced central cavity formed in the sea by expanding gases. Outward expansion of gases tears spray from the inner side and top of this wave, forming jets which feed the base surge.

In an underground shot (Fig. 5) expanding gases at the explosion center first vent vertically, pushing up and out a « wall » of nearly coherent roof material. This wall is pushed out and overturned to produce the overturned syncline described not only in large explosion tests (RICHARDS, 1964), but also in impact craters such as Meteor Crater, Arizona (SHOEMAKER, 1960). 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 outwards 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.

Base Surge in Recent Volcanic Eruptions

Taal Volcano, Luzon, Philippines

The eruption of Taal Volcano of September 28-30, 1965, produced a series of base surges which caused extensive damage and loss of life (MOORE *et al.*, 1966, and MOORE, 1966). The eruption began at 2:00 A.M. on the 28th with explosive ejection of incandescent blocks and cinders from the area of the new explosion crater on the southwest side of Volcano Island in Lake Taal (Figs. 6 and 7). The major explosive phase, apparently caused by lake water gaining access to the magma conduit, began at 3:25 A.M. and continued until 9:30 A.M. During this time enormous eruption clouds developed which were clearly visible from Manila, 60 kilometers to the north. These clouds reportedly rose to heights of 15 to 20 kilometers and were continually laced with lightning. At the base of the main cloud column, flat turbulent clouds spread out, radially transporting ejected material with hurricane velocity (Fig. 8).

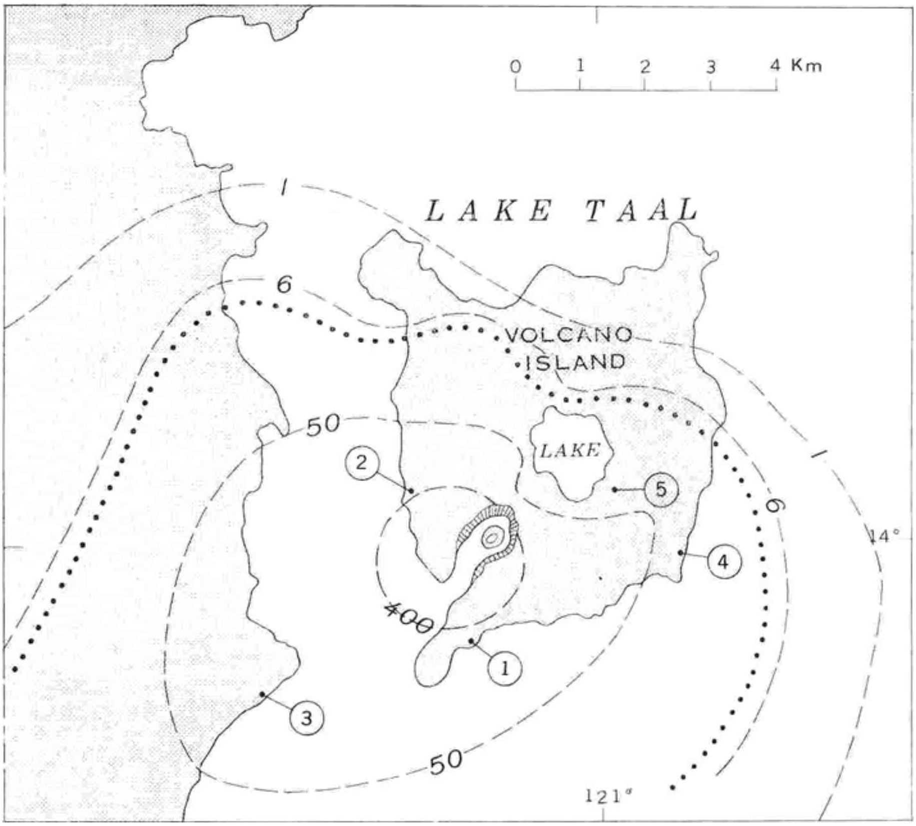

FIG. 6 - Map of Taal Volcano showing ejecta from 1965 eruption. Dashed lines, thickness of ejecta in centimeters; dotted line, outer limit of accretionary lapilli. Circled numbers are location of ash sections shown in Figure 10.

The explosion crater formed during this period is 1.7 km long and 0.8 km wide. It is open to the lake on the southwest and is now occupied by an arm of Lake Taal. Cliffs on the northeast side of the crater are about 150 meters high. The volume of the explosion crater above lake level is estimated to be about 25 million cubic meters, and soundings show that the deepest part of the new bay is about 50 meters deep. Hence, the total volume of material removed from the explosion crater is probably about 40 million cubic meters.

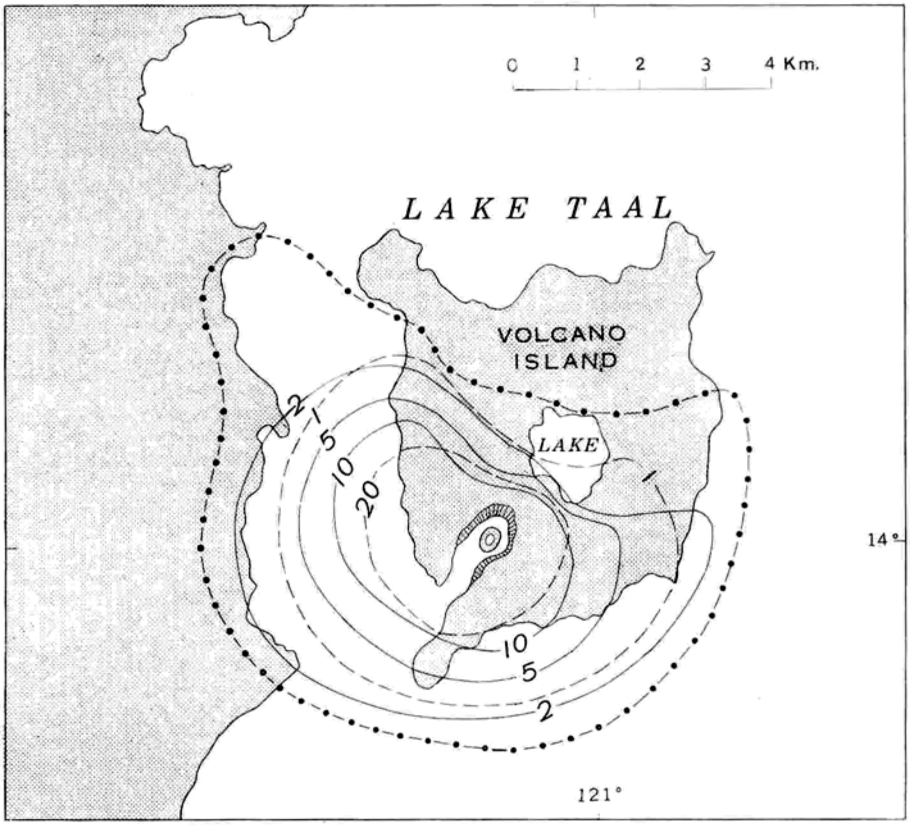

FIG. 7 - Distribution of base surge deposits at Taal Volcano. Dash-dot line, outer limit of base surge as determined by faint sandblasting. Solid lines, contoured maximum thickness in centimeters of mud coating on vertical objects. Dashed lines, maximum diameter of lapilli in centimeters.

Much of the finer ejected material was blasted to great heights and carried by the winds toward the southwest to be deposited as fine ash as much as 80 km distant. Some of this finer material, moistened by condensing steam and copious rain which accompanied the eruption, fell as accretionary lapilli (MOORE and PECK, 1962). Accre-

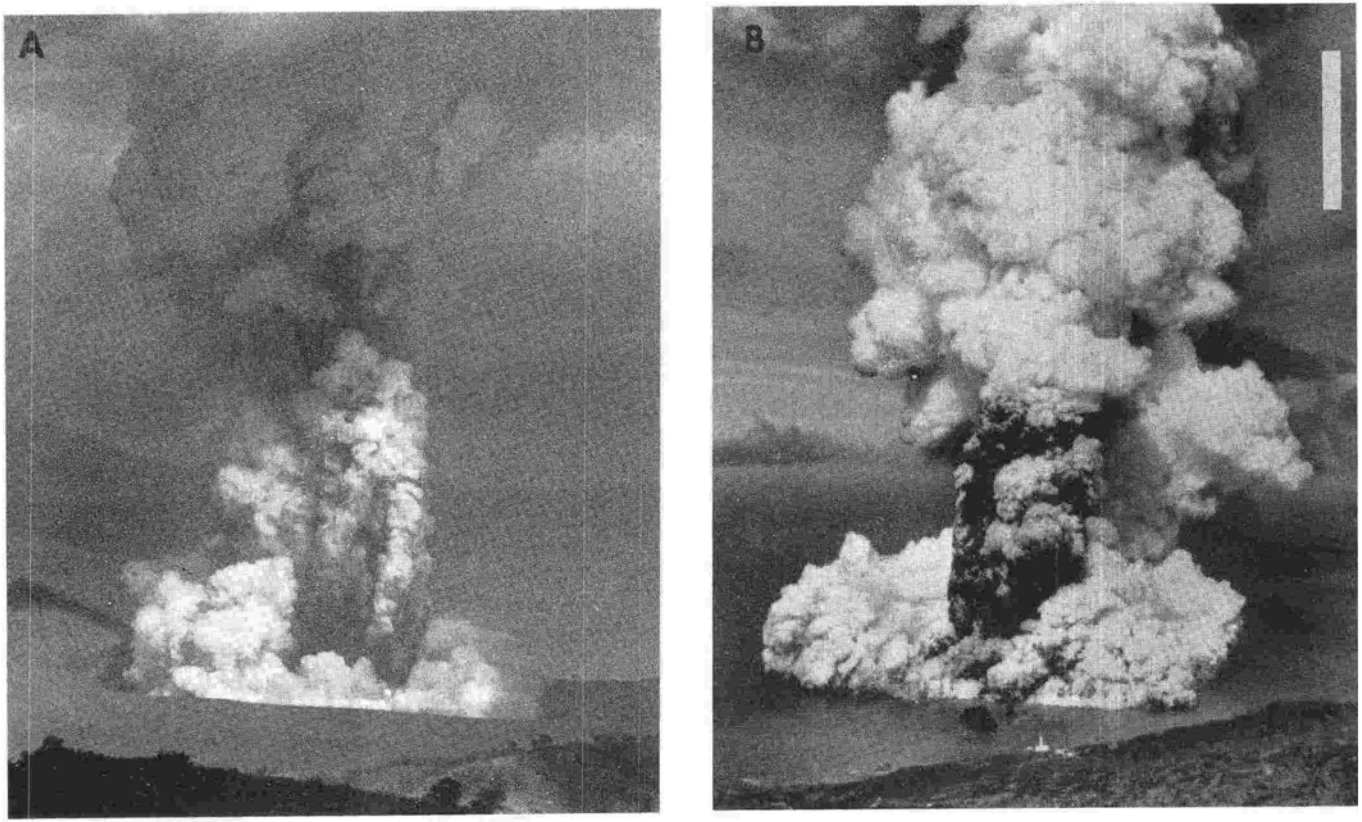

Fig. 8 - Similar explosive eruption clouds with well-developed base surge clouds at (A) September 30, 1965, eruption of Taal Volcano, Philippines (Photograph by L. E. Andrews), and (B) early October, 1957, eruption of Capelinhos Volcano, Azores (U. S. Air Force photograph). The white bar in ech photograph is approximately 500 meters long.

tionary lapilli fell as far as 9 km downwind from the explosion center (Fig. 6). The airfall ash and admixed accretionary lapilli make up the dominant part of the ejecta outside the zone of base surges.

The large steam explosions which excavated the new explosion crater early in the morning of September 28, 1965, produced ash and debris-laden clouds which closely resemble the base surges of thermonuclear explosions. These clouds sandblasted objects out to 6 km from the explosion center, totally removing all trees from ½ to 1 km from the explosion center. For about ¼ km beyond the ½ to 1-km-wide zone, the trees remain, but are strongly sandblasted and have little or no coating of mud. The sandblasting has removed more than 15 cm of wood from trees, but only on the side facing the crater — the other side of many trees is still bark-covered. In the next zone outward, all the trees show the effects of sandblasting and are coated on the side toward the crater with mud which forms aerodynamic, parabolic coatings. Some coatings are as much as 40 cm thick (Fig. 9).

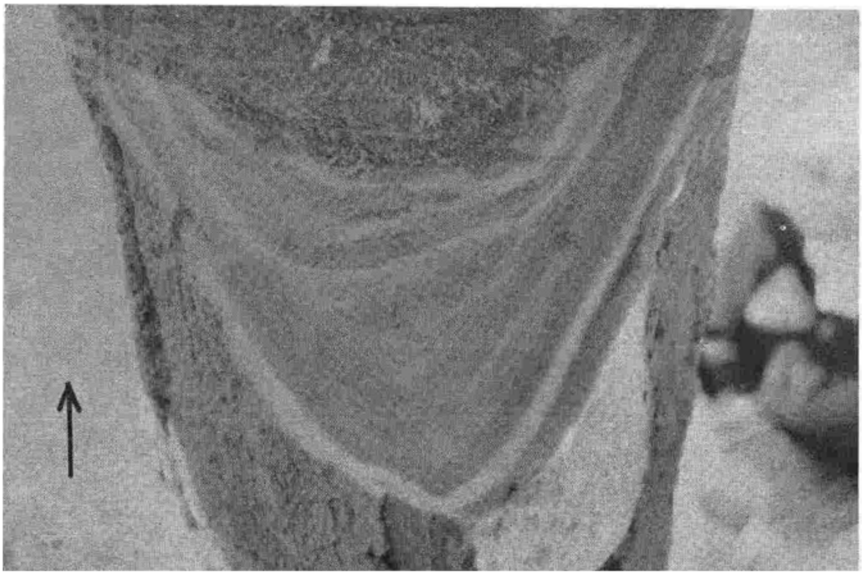

FIG. 9 - Cross-section of mud coating about 16 cm thick on palm tree 1.5 km north of Taal Volcano explosion crater. Mud coating (now dry ash) has been sectioned with a knife back to the shredded outer bark of the tree at the top of the photograph. General direction of movement of the surge clouds is shown by arrow. About 7 main layers are visible, generally beginning with fine ash (light) and ending with coarser ash (darker). Note unconformities caused by erosion of previous layer and by change in azimuth of surge cloud movement.

The mud coating is 10 cm thick 2.5 km from the explosion center and 2 cm at 3 km (Fig. 7).

When the mud coatings are carefully sectioned they are found to consist of several layers, each grading from fine silt-size ash closest to the tree out to coarse sand-size material. On some trees many such layers can be identified (Fig. 9), each partly truncating the one below and swelling to greatest thickness at slightly different places. Hence, the blasts which deposited the mud coating had the ability to erode part of the previous layer and traveled slightly different paths from the explosion center to the tree in question.

Outward from the crater toward the limit of blast effects, the blast direction is recorded not only by the mud coatings, but successively, by stripping of the bark of trees, the breakage direction of stands of bamboo, tilting and deroofing of houses, stripping of palm-tree fronds on the blast side, and faint scarring of the bark of small bushes.

In the entire area affected by the base surges, neither trees nor shredded wood in the ash are charred or burned. In the zone of mud plastering, the temperature of the debris-laden clouds would have been below 100°C, judging by the viscosity of the mud, which must have been mixed with water, not steam, to have been so sticky. The narrow inner zone of trees not covered with mud may have been blasted by steam clouds slightly hotter than 100°C.

Measured sections of the basaltic ejecta from Taal Volcano (Fig. 10) include material that was (1) thrown out directly from the explosion center, (2) transported by the surge clouds, and (3) blasted to high elevations, blown by the winds, and carried to earth commonly by mud rains. The first, which is restricted to a zone close to the explosion crater, is made up largely of blocks with intermixed ash and lapilli including small juvenile bombs at the base of the section at localities 1 and 2 (Fig. 6). The third type of material, which is most easily recognizable several kilometers from the crater, is fine, commonly well-sorted and well-bedded ash which is distributed as much as 80 km downwind from the vent. Many ash layers contain abundant accretionary lapilli. At the bottom of a bed the accretionary lapilli generally are smaller and more broken than those higher in the bed.

The second type of material, the base-surge deposits, are intermediate in geographic distribution and grain size as compared with the throwout and air-fall ejecta. Base-surge deposits have lithic and glassy fragments up to nearly a meter in diameter mixed in a poorly

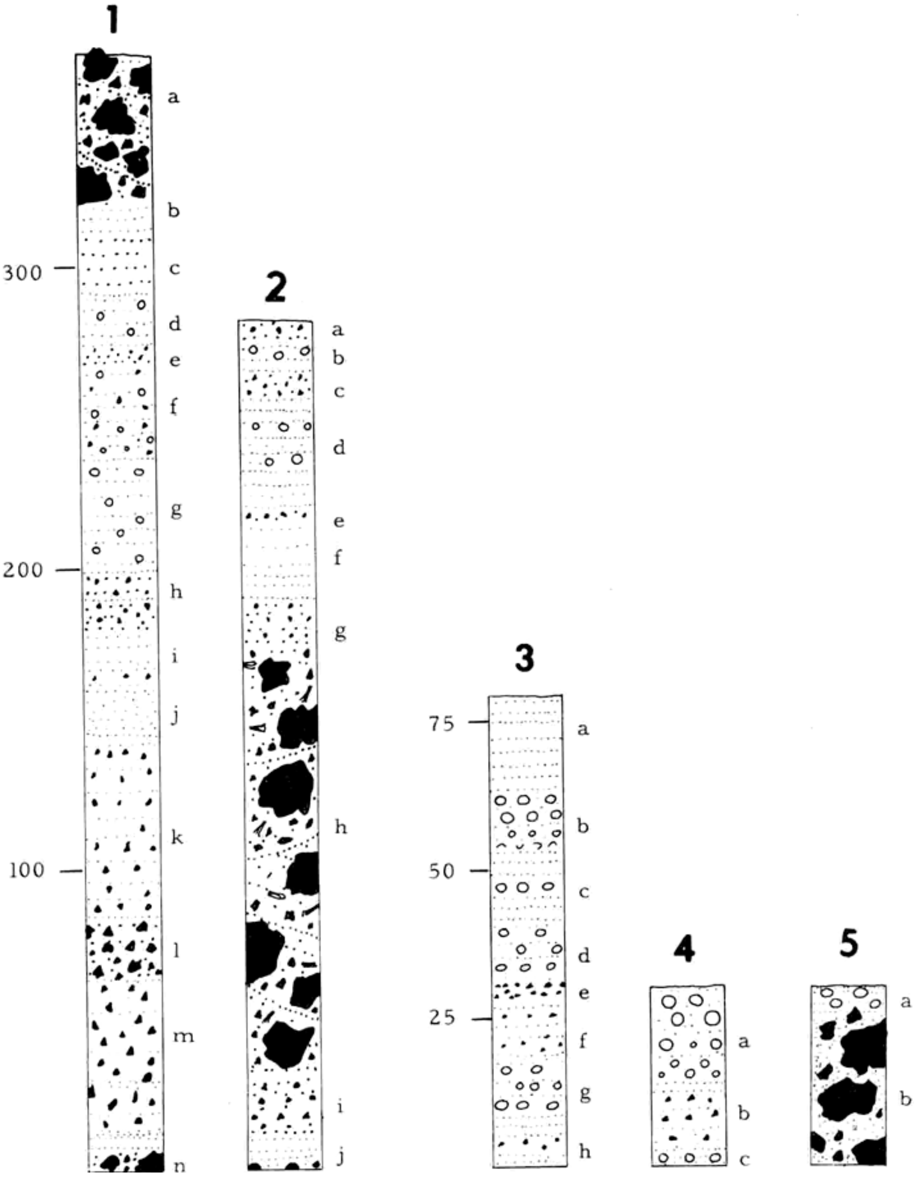

FIG. 10 - Columnar sections of ejecta from Taal Volcano. Location of numbered sections shown in Figure 6. Thickness is in centimeters.

Section number 1:

a. Coarse, angular unsorted blocks commonly up to 8 cm, some blocks up to 20 cm in size. Shredded wood. Matrix poorly sorted lapilli and ash.
b. Fine ash, no lapilli.
c. Coarser ash with lapilli up to 0.5 cm.
d. Fine ash with small, rare, accretionary lapilli.
e. Coarser ash, many fragments about 0.3 cm.
f. Fine ash with scattered lapilli up to 0.5 cm. Scattered accretionary lapilli.
g. Fine ash with scattered accretionary lapilli.
h. Coarser ash with lapilli up to 0.5 cm.
i. Fine ash with lenses of coarse sand-size ash, including one on bottom with many lapilli 0.5 cm.
j. Fine ash.
k. Thin, poorly-bedded (beds about 1 cm thick) alternating beds of lapilli (average diameter 0.5 cm) and fine ash.
l. Coarse lapilli (maxima 3 cm).
m. Alternating beds of lapilli up to 1 or 1.5 cm and finer ash beds.
n. Coarse unsorted lapilli, blocks, and some juvenile bombs in ash matrix. Overlain by rather fine-bedded ash with some lapilli up to 0.3 cm.

Section number 2:

a. Rather coarse lapilli tuff with common vesicular, vitric fragments.
b. Accretionary lapilli in fine ash.
c. Coarse ash with angular fragments up to 0.5 cm.
d. Fine ash with some delicate bedding. Finer layers contain accretionary lapilli.
e. Coarse ash with lapilli up to 0.6 cm.
f. Fine ash, no accretionary lapilli.
g. Coarse ash, many lapilli over 0.4 cm, some fragments up to 2 cm. Beds about 6 cm thick.
h. Coarse unsorted explosion breccia, some blocks up to 35 cm, many fragments 2-3 cm. Finer at top with dune-type bedding. Contains shredded wood.
i. Coarse ash and lapilli. Many lithic and vitric fragments up to 0.5 cm, some 1 cm.
j. Thin-bedded silt and sand-size ash overlying small pumiceous juvenile bombs.

Section number 3:

a. Uniform silt-size ash.
b. Silt-size ash containing abundant accretionary lapilli, more broken ones and smaller ones near bottom.
c. Uniform silt-size ash with one thin bed containing accretionary lapilli.
d. Silt-size ash containing accretionary lapilli.
e. Coarse ash with angular fragments up to 0.3 cm.
f. Silt-size and sand-size ash. Some angular fragments up to 0.4 cm.
g. Uniform silt-size ash containing abundant accretionary lapilli up to 0.6 cm in diameter.
h. Sand-size ash with layer of lithic and pumice fragments (some rounded) up to 0.4 cm.

Section number 4:

a. Silt-size ash with some fine bedding containing abundant accretionary lapilli. Accretionary lapilli are better developed and larger near top.
b. Coarse ash with many angular lithic and vesicular, vitric fragment 0.2 to 0.4 cm, some up to 1 cm.
c. Silt-size ash with accretionary lapilli.

Section number 5:

a. Silt-size ash with abundant, large accretionary lapilli.
b. Coarse explosion tuff-breccia. Many angular lithic and vesicular, vitric blocks and lapilli. Many fragments 4-5 cm, some up to 18 cm.

sorted matrix of ash and lapilli. Commonly the layers are poorly bedded, the result of slightly different average size or degree of sorting of fragments in the beds. Shredded wood and twigs from the sandblasted trees are common constituents in the base-surge deposits.

The mud coating on trees relatively close to the explosion center is much finer-grained than the main part of the base-surge deposit at that point. Apparently only the finer wet ash was able to stick on the trees. Since each mud layer is finer at its base, perhaps the surge cloud is graded so that fine material is first to reach a given point, then coarser material, and finally material so coarse that it cannot adhere to vertical objects as a mud coat, but rather erodes the previously deposited plaster.

Within 3 km of the explosion center the base-surge deposits are characterized by crude dune-type bedding (MOORE *et al.*, 1966, Fig. 8). The dunes are oriented roughly at right angles to the direction of movement of the base surges (Figs. 11 and 12). They are steeper on the blast side and are eroded and scoured on that side. The dune crests in each overlying bed are slightly displaced away from the explosion center as the deposit was built up by deposition from successive base surges.

The dunes are largest adjacent to the explosion crater (Fig. 12) where they attain wave lengths up to 19 meters. They systematically decrease in wave length away from the crater and are about 4 meters in wave length 2.5 km distant. Northeast of the crater where the terrain slopes up to 300 meters elevation, the dunes are poorly developed and decrease in wave length more rapidly with distance. Here the surge clouds were no doubt slowed down by this uphill gradient and could not carry enough suspended material to produce the larger dunes.

The experimental explosion data of ROHRER (1965) on maximum base-surge radius permit some rough approximations of energy release at the Taal Volcano eruption center. Such comparison of volcanic and thermonuclear-chemical test explosions can only be approximate because of the greatly different processes acting at the explosion center and throughout the history of the base surge. The test explosions are conducted on level ground, from a point source in a relatively homogeneous medium. Volcanic explosions occur at an unknown depth and time span below a crater of complex topography and structure. Once the surge cloud forms, it may be strongly modified by topography.

The maximum distance that the Taal Volcano base surges traveled, as indicated by damage to small bushes and trees, was 6 km. By comparing with artificial explosion data (Fig. 4) and assuming

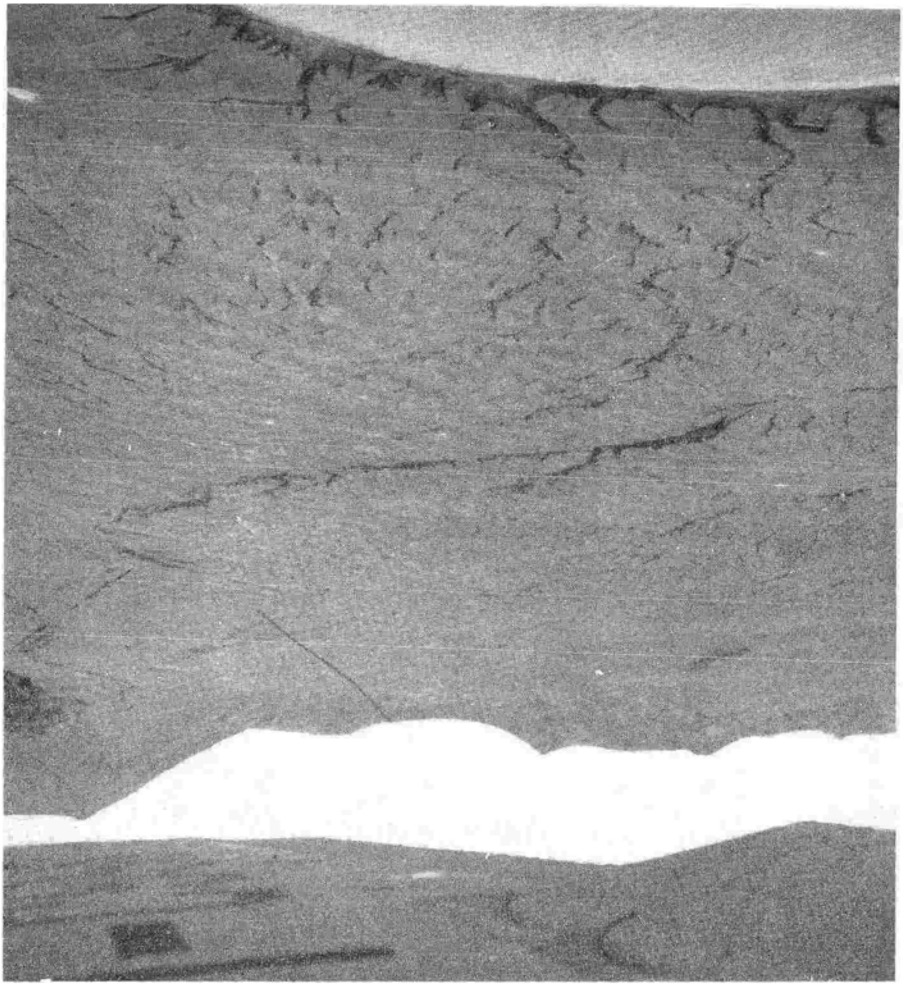

FIG. 11 - Aerial photograph toward the east showing new explosion crater of Taal Volcano on the extreme right. Ash dunes concentric to explosion crater are visible in foreground. Photograph by Robert MOXHAM, May 1966.

that the loose ash making up Volcano Island is comparable to alluvium and that the explosion was at the optimum depth to produce the largest possible base surge, we read off of Figure 4 that the scaled radius equals 2400 m (for the largest possible base surge). Thus, the kiloton yield of the maximum base surge at Taal Volcano with radius of 6 km can be calculated from the expression $r_s = r/(Y)^{0.3}$ (ROHRER, 1965), where r_s is the scaled radius of the base surge in m; r is the actual radius of the base surge in m; and Y is the yield of the explosion in kilotons of chemical explosives. The calculated yield is 21 kilotons.

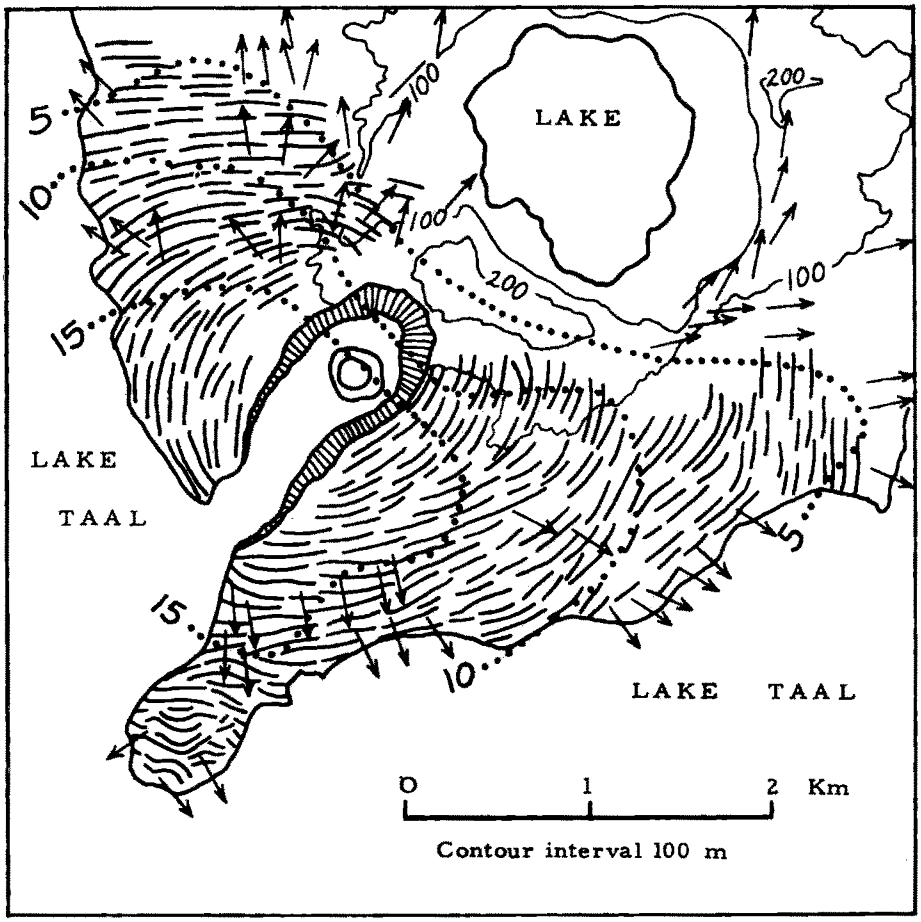

FIG. 12 - Map of the southwest part of Volcano Island, Taal volcano, showing the new explosion crater and the trend of dune crests as mapped from aerial photographs. Dotted contours are wave length of dunes in meters. Fine lines are topographic contours in meters. Arrows show direction of major base surge movement as measured in the field by direction of sandblasting, tilting, and mud coating of trees and houses.

Actually the material of Volcano Island was more compact than alluvium, and the explosion center undoubtedly was not at the optimum depth (the peak of the curve in Fig. 4). Therefore, the explosion that produced the most far-reaching base surge must have been much larger than 21 kilotons. By comparison, the 100-kiloton Sedan explosion, buried deeper than optimum for base-surge development (scaled depth of abouth 43 on Fig. 4), produced a base surge that traveled 4.0 km (NORDYKE and WILLIAMSON, 1965, p. 9). The Sedan test produced a crater 0.37 km in diameter, whereas the many explosions at Taal Volcano produced a crater 1.7 km long and 0.8 km wide.

The total kinetic energy released (in ergs) at Taal Volcano may be approximated by the equation $E = MV^2$ when M is the mass of ejecta in grams and V, its average velocity in cm/sec. The measured density of the ejecta (most of which is old tuff blasted from the explosion crater is about 1.3 gm/cm^3, and volume of ejecta is 90×10^6 m^3 or 90×10^{12} cm^3. Hence, the mass of ejecta is 1.2×10^{14} gm. Assuming an initial velocity of 100 m/sec or 10^4 cm/sec the total kinetic energy would be $1.2 \times 10^{14} \times (10^4)^2$ or 1.2×10^{22} ergs. Since 1 kiloton equals 10^{12} calories or 4.2×10^{19} ergs (NORDYKE and WILLIAMSON, 1965, p. 4), then the one base surge calculated above (21 kilotons) would approximate 8.8×10^{20} ergs. The total kinetic energy as calculated above could account for $(1.2 \times 10^{22}) / (8.8 \times 10^{20})$ or 14 base surges of the large optimum type defined above. Actually the mud coats on the trees record about 7 large base surges.

In most volcanic eruptions the kinetic energy released is only a small part of the total energy, since most is released as heat. If we assume that 10 percent of the ejecta was originally at magmatic temperatures (1000°C), then the heat energy could be approximated by $E = MTH$, where E is energy in calories, M is mass of hot material in gm, T is temperature above ambient in °C, and H is specific heat, assumed to be 0.2. Then $E = 1.2 \times 10^{13} \times 1000 \times 0.2$ or 2.4×10^{15} calories or 1.0×10^{23} ergs. Hence the heat energy exceeds the kinetic energy by $(1.0 \times 10^{23}) / (1.2 \times 10^{22})$ or by a factor of 8. On the basis of these approximate calculations, the energy of the seven recorded base surges represents about 5 % of the total energy of the eruption.

Capelinhos Eruption, Fayal Island, Azores

The Capelinhos eruption (basaltic) began as a submarine flank eruption of Fayal Volcano on September 27, 1957, and continued for about 13 months. The early phase of explosive activity was characterized by bursts of tephra with sharp, pointed jets (MACHADO *et al.*, 1962). The wreath-like base-surge clouds that formed around the base of the main eruption column resembled to a remarkable degree the surge clouds of the 1965 Taal eruption (Fig. 8).

Myojin Reef, Japan

The eruption (dacitic) of Myojin Reef, in the Pacific Ocean 420 km south of Tokyo, Japan, began in the early morning of September 16, 1952, and continued for many months. Frequent submarine explosions occurred; one sank the *No. 5 Kaiyo-maru*, a research vessel, on September 24, 1952, and all 31 scientists and crewmen were lost.

During the explosive phases of activity, excellent photographs were obtained of base-surge development (MORIMOTO, 1960, and NIINO, 1954) (Fig. 13). As some of the photographs were taken at definite intervals, it is possible to study the rate of growth of the base surge. The base surge accompanying the explosion of 13:12 September 23, 1952 (MORIMOTO, 1960, plate 1) began with an initial velocity of more than 65 meters per second. About one second after the burst broke the water surface, the vertical velocity of ejecta was about 115 meters per second.

In the first several seconds, the growth of the base surge compares closely with that of the 20-kiloton Bikini blast (Fig. 2). At 20 seconds, however, the base surge was much slower than that of Bikini, possibly due to the greater depth of many of the Myojin Reef explosions. The central column was not nearly so high as that of the Bikini test or of the Taal or Capelinhos eruptions.

Bárcena Volcano, Islas Revillagigedo, Mexico

The eruption (trachytic) of Bárcena Volcano on San Benedicto Island, 400 km south of the south cape of Baja California, began on August 1, 1952 and lasted until the end of February, 1953. RICHARDS, in his excellent description of the eruption, mentions that, in its early stages, the horizontal spread of the eruption column resembled the base surge of an atomic explosion (1959, p. 89). Several of the photos published by Richards show clouds which resemble base

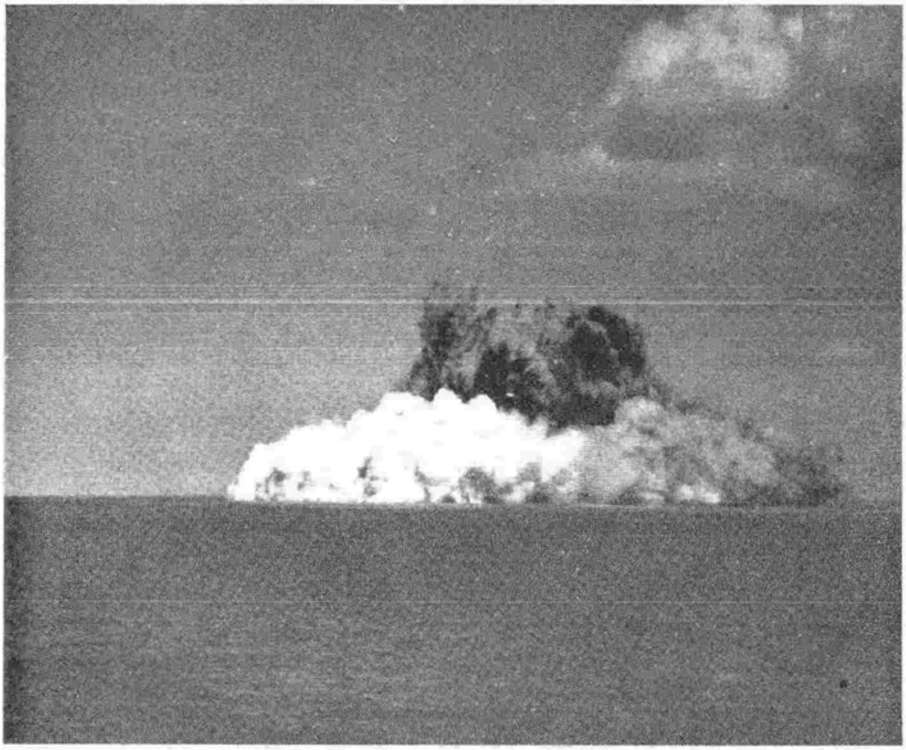

FIG. 13 - Explosive submarine eruption of Myojin Reef at 13:40 September 23, 1952. Photograph taken 15 seconds after water dome broke the surface. Eruption cloud is 500 m high and base surge is 1400 m in diameter. After NIINO, H. (1954, plate 17).

surges developed at Taal Volcano and Miyojin Reef (RICHARDS, 1959, plates 4, 5, 6).

A very interesting feature of the Bárcena eruption was the production of numerous furrows on the flank of the main cone (Fig. 14). These furrows are 3 to 7 meters wide, up to 430 meters long, and are best developed below the low areas of the crater rim. They have been slightly modified and incised by rainfall. They extend directly down the outside of the cone and are assumed by RICHARDS (1959, p. 112) to have been eroded by tephra avalanches.

At the lower end of the furrows, at the break in slope, an excellent pattern of dunes is developed (Fig. 14). These dunes apparently formed where change in slope impeded the base-surge density flows, resulting in cessation of erosion and beginning of deposition. The dunes at the base of the furrows have a wave length of up to 11 meters, and are thus comparable to the dunes at Taal Volcano. Other dunes which are preserved on the ridge crest south of Bárcena Volcano are about 5 meters in wave length (Fig. 14). Still other very small ones of only a few meters in wave length are present directly on the crater

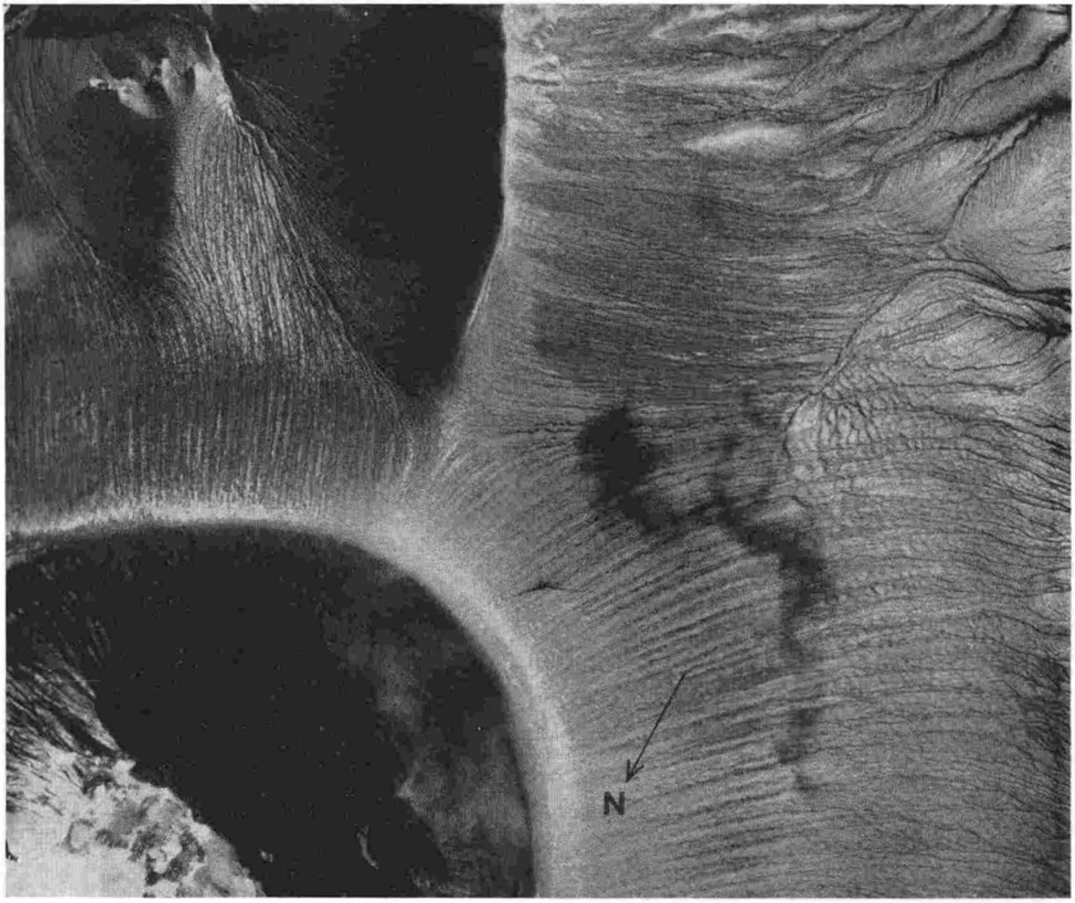

FIG. 14 - Aerial photograph of southwest side of Bárcena Volcano, Islas Revillagigedo. Main crater is about 750 m in diameter. Furrows eroded by surge clouds radiate from the main crater, and have been slightly modified and incised by rainfall. Furrows on the west side change downslope to dunes (wave length about 10 m) at change in slope where surge clouds lost some of their erosive ability and began deposition. Smaller dunes are also visible on ridge crests south of crater where they are protected from erosion. Very small dunes (almost invisible) are present on crest of crater rim and their crests are parallel to rim. After RICHARDS (1959, plate 24. U. S. Navy photograph).

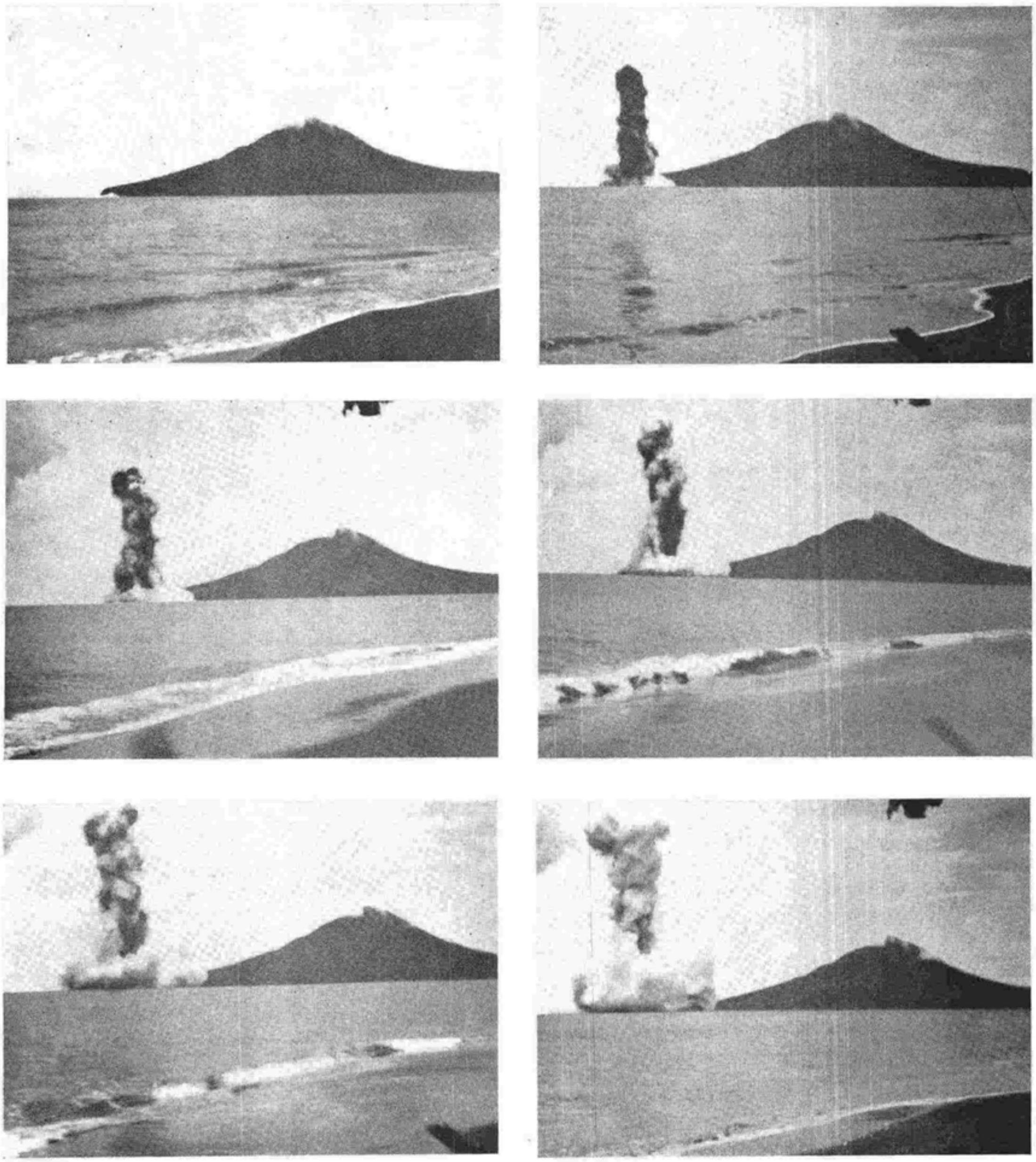

FIG. 15 - Six photographs taken at intervals of six seconds during a phreatic explosion of Anak Krakatau on January 24, 1928. Height of explosion column about 1000 m. After STEHN, 1929, photo 16.

rim crest. They were presumably formed by very late feeble surge clouds from the crater. All of the dunes are oriented at right angles to the direction of flow.

Surtsey Volcano, Vestmann Islands, Iceland

Surtsey Volcano (basaltic) began as a submarine eruption 35 km off the south coast of Iceland on the morning of November 14, 1963. As long as sea water had an easy access to the volcanic vent of the new island, frequent explosive eruptions occurred. The bigger explosions were followed by grayish-brown tephra-vapor avalanches (base surges) which rolled down the outer slopes of the volcano or through breaches in the crater wall and traveled hundreds of meters over the sea (THORARINSSON *et al.*, 1964, p. 6 and Fig. 7). Photographs of these surge clouds are remarkably similar to those of the Myojin Reef explosions (Fig. 13).

Some of the photographs of Surtsey show a curious surface pattern on the outer flanks of the volcanic cone (THORARINSSON *et al.*, 1964, Fig. 19). The ash surface appears to be lineated by small dunes whose crests are arranged parallel to the main crater rim. They may be similar in origin to the dunes at Taal and Bárcena Volcanoes.

Lassen Peak, California

Lassen Peak (dacite) underwent a series of explosive eruptions from 1914 to 1917. The activity of 1914 and early 1915 was apparently steam explosions caused by meltwater from the heavy snow cover in the crater contacting hot material in the volcanic conduit at shallow depth (DAY and ALLEN, 1925, p. 33). These explosions blasted out relatively cold ash, lapilli, and blocks in eruption columns which reached heights of 100 to nearly 4000 m.

The culminating period of activity occurred in the middle of May 1915, when a blocky lava flow spilled over a notch in the western crater rim. A few days later on May 19 and again on May 22 violent explosions shook the volcano, and horizontal blasts of tremendous force swept down the east flank of the volcano, carrying ash and blocks and laying waste to an area extending more than 4 km from the summit. Associated with these blasts were mudflows, caused by rapid melting of snow on the volcano, and perhaps condensation of steam in the eruption clouds. These blasts have been interpreted by Day and Allen (1925, p. 67) to have been directed in their horizontal path by the upheaval of the old material which acted as a plug or lid on the vent. This they compared to lifting the « lid » from the volcano which resulted in the horizontal direction of the explosions escaping from beneath.

The effects of these blasts resembled to a remarkable degree those of the base surges at Taal Volcano. The Lassen blasts blew down trees up to 1.5 m in diameter such that the fallen trees all pointed away from the crater. These trees and the remaining stumps were sandblasted and stripped of bark only on the side facing the crater. However, the Lassen blasts were somewhat hotter; they singed, but did not set fire to, the bark and foliage of the trees.

The pattern of development of the early, smaller steam explosion clouds is very similar to those of other eruptions described in this report. A series of photographs by B. F. Loomis (Day and Allen, 1925, plate 1) clearly shows a base surge emerging from the base of one of these explosion columns and rushing down the north flank of the mountain as a density flow.

Anak Krakatau, Indonesia

After a 44-year period of quiescence from the catastrophic eruption of 1883, submarine activity began anew in late 1927 at the site of the previous activity. In January 1928 a new volcano island appeared above the surface and has been intermittently active until the present time.

In his description of the 1927-1929 activity, Stehn (1929) has provided us with one of the best photographic records of base-surge formation. His photo 16, taken from a distance of 4.5 km on January 24, 1928, is reproduced as Fig. 15. These 6 frames, taken at 6-second intervals show the development of the central, dense black vertical explosion column which rose rapidly to a height of 1,000 m. He states (Stehn, 1929, p. 38) that « Immediately after its appearance above sea level, there is formed at the foot of the column, as a result of the contact of the hot mass of the ejected matter with sea water, a wreath of steam, which rapidly grows in breadth and height as the mass shoots up and plumps down again ». This wreath is similar to the base surges of Taal and Capelinhos volcanoes (compare Figs. 8 and 15).

By scaling the dimensions off the photographs (Fig. 15), the velocity of the base surge after several seconds is only 14 m/sec. Although the cloud pattern is similar, the size of this explosion is considerably smaller than that of the Sedan and Bikini tests, and the Myojin Reef eruption.

Conclusions

The base surge, which is a common feature of shallow underwater or underground test explosions, is a ring-shaped basal cloud which sweeps outward as a density flow from the base of the vertical explosion column. The base surge apparently forms as the expanding gases at the explosion center first vent vertically and then, by continued expansion, enlarge the crater and push out a « wall » of brecciated roof and crater material. After the wall is overturned to form the crater lip, outward expanding gases rush over it, tear ejecta from it, and feed the base surge. In an underwater blast, the crater lip is represented by a large solitary wave, which breaks and forms spray jets which feed the base surge. Once developed, the surge cloud moves outward as a density flow, taking advantage of topographic irregularities.

The shape and behavior of many horizontally moving clouds formed during explosive volcanic eruptions are very similar to the base surges produced in artificial explosions. Therefore it is believed that such eruptive clouds are basically of the same origin, though many additional variables are present in volcanic eruptions.

The test explosion evidence gives insight into the processes acting in volcanic explosions where close observations are vastly more difficult and dangerous and where the processes of activity are more complex. From the artificial explosions it is known that: 1) the surge clouds can form by a subsurface blast venting vertically without any specific radial component, that is without any « directed blast », 2) the surgec louds can form on flat ground (or sea surface) and do not require a down-slope gradient for development, 3) the surge clouds may form in a clean atmosphere and a « roof » of ejecta from a previous explosion is not necessary to direct the horizontal path of the surge, 4) the mobility of the surge clouds does not require the constant exsolution of gases from superheated magmatic material, 5) the surge clouds do not require the fall of vertically ejected material for their formation, and 6) the surge clouds, despite their great velocity and destructiveness, do not require high temperature, but can be relatively cool. However, it is obvious that one or all of the above factors may be important in shaping the surge clouds, in increasing their life and range, and in making them more destructive. But it is believed that such factors may obscure the true origin of these volcanic phenomena.

Most of the examples of base surges accompanying volcanic eruptions described here are associated with phreatic explosions. Hot magma coming in contact with water or water-soaked rock causes rapid generation of steam which forms an explosion not unlike that of a large chemical explosive or thermonuclear device. However, explosive exsolution of magmatic gases during rapid extrusion of large volumes of oversaturated magma may also produce a base surge. Some glowing avalanches and ash flows may originate from such base surges.

The base surge is always produced during shallow test explosions, though its size, velocity, and pattern of development is dependent on many factors. Likewise it is believed that similar surge clouds are generally produced during volcanic explosive eruptions. Whether they become an important element in the eruption depends on many local conditions such as depth and force of the explosion, character of country rock and ejecta, nature of the surrounding terrain, etc. In many cases the surge cloud is entirely confined to the volcanic crater and does not spill over the rim.

SHOEMAKER (1960) has pointed out the close similarity in structure of hypervelocity impact craters and craters formed by large explosions. Because of the similarity in the explosion mechanism, it is believed that base-surge clouds would also form at the site of such impacts (possibly also around impact craters on the lunar surface), and would carry some ejecta outward to distances much greater than the distances to which it is thrown out on ballistic trajectories.

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