PROCEEDINGS OF THE SECOND

COLUMBIA RIVER BASALT

SYMPOSIUM

15

MAAR VOLCANOES

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ABSTRACT

Examination of maar-type volcanic cones, including tuff rings, from more than 40 localities in western North America indicates that water had access to volcano orifices during their activity. The most convincing evidence is the abundance of sideromelane (chilled basaltic glass) or its palagonitic decomposition products in the ejecta. Moreover, the volcanoes we have examined erupted in basins that either contained surface water, or else they grew above highly permeable aquifers at shallow depth.

Characteristic features of maar ejecta are continuous thin beds, undulations and antidunes characteristic of base surge stratification, abundant accretionary lapilli or mud-armored rock particles, bedding sags that show soft sediment deformation, and -- in the subaqueous parts of the maar ramparts -- great piles of subtly graded thin lenses of hyaloclastic debris.

INTRODUCTION

Maar volcanoes received their name from the small crater lakes of the Eifel district in Germany (German: maare, lake).

Typically, maar craters are less than a mile in diameter, and are bordered by low rims of ejecta. The small ejecta ramparts are composed of chilled volcanic debris, chiefly sideromelane or its decomposition product palagonite. Invariably, shattered bits of the underlying bedrock are contained in these hyaloclastic rim deposits and in some layers they comprise 50 per cent or more of the bulk of the deposit. Lava flows are absent, or very sparse, but dikes may invade rim beds and crater fillings, and remnants of ephemeral lava lakes within the crater are found in a few dissected maar volcanoes.

Many dry maar craters of Pliocene and Quaternary age (Figs. 1, 2) occur in the arid parts of western North America, but our observations indicate that they formed only in basins which formerly were occupied by lakes, or they were near ocean shorelines, major streams, or other water bodies. Some have erupted upon dry land (Fig. 2), but the magma passed through highly permeable aquifers at shallow depth. Others built up subaqueously on the floors of widespread surface lakes which have since evaporated (Fig. 3). Nearly all appear to have formed where strong phreatic steam eruptions resulted from magma coming in contact with shallow lakes, marshes on flood plains, or prolific aquifers.

A significant clue to this mode of origin is the presence of abundant sideromelane or palagonite in the ejecta. Sideromelane is bits of drastically

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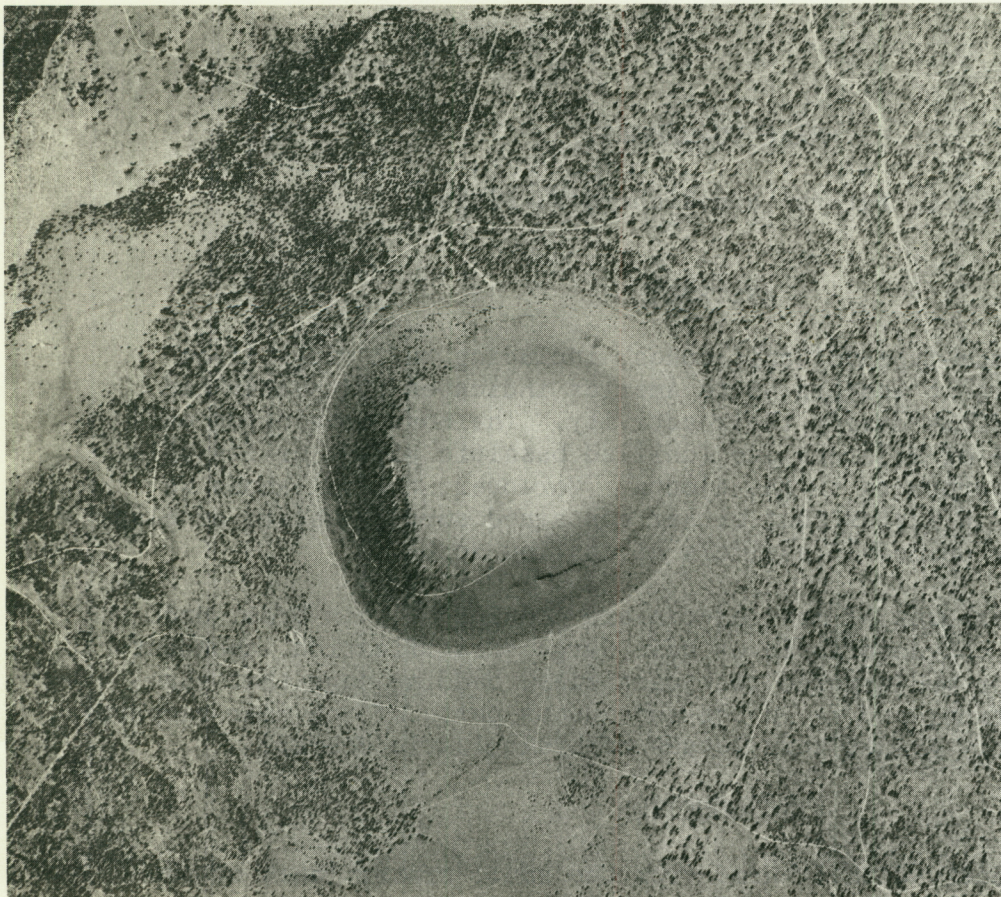
Fig. 1: Hole in the Ground, a maar crater in central Oregon. (Delano photographics, Portland, Oregon.)

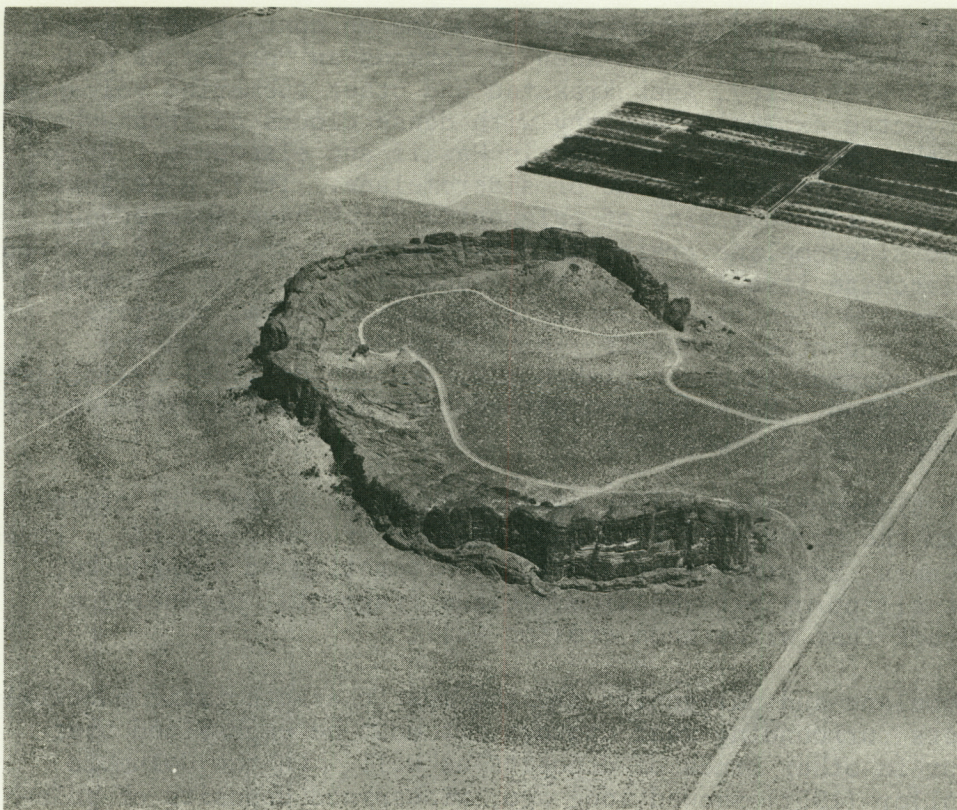Fig. 2: Cerro Colorado, a tuff ring in the Pinacates area, Sonoran desert, Mexico.

Fig. 3: Fort Rock, a dissected tuff ring in central Oregon. Waves of a former lake have removed most of the outer slopes and breached one side of the crater. (Delano photographics, Portland, Oregon.)
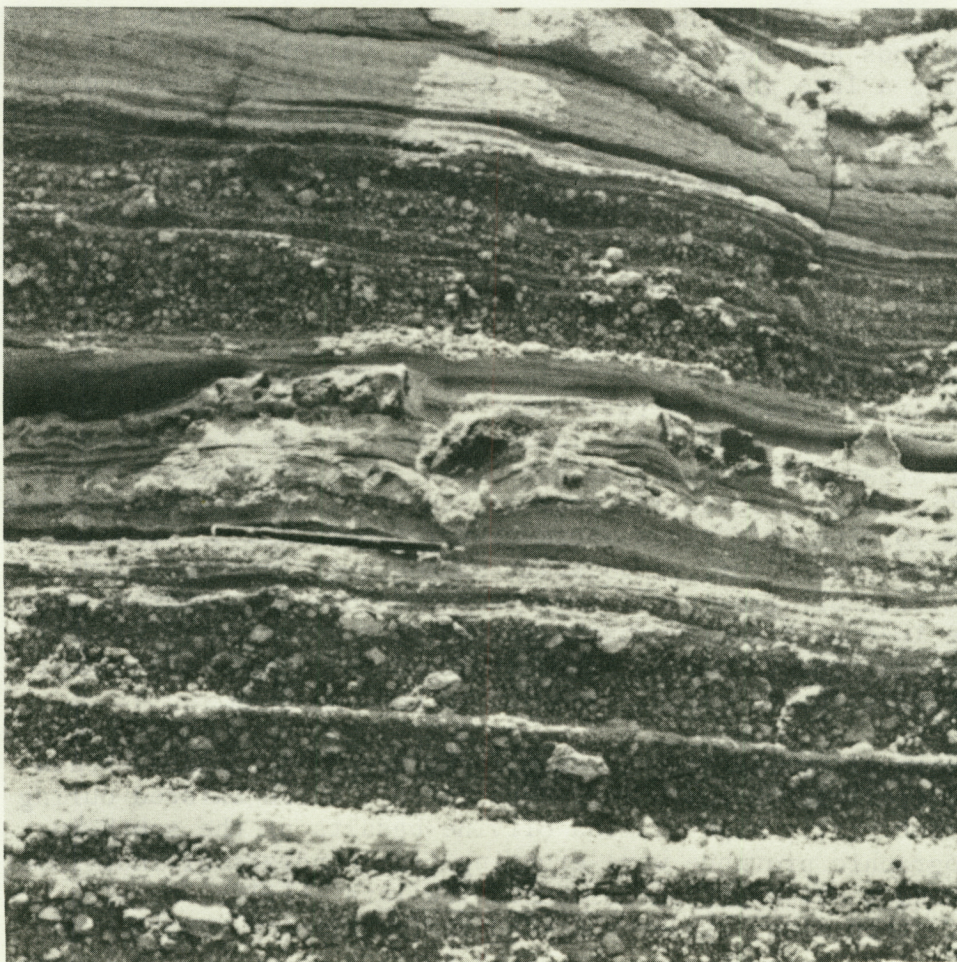

Fig. 4: Alternating ash fall beds (dark, with very thin white laminae), and base surge beds (light colored). Near Macdoel, California.

chilled basaltic glass, formed by granulation of magma on contact with water (Peacock and Fuller, 1928). It has been seen to form as an "explosive projection of black sand" at Surtsey, Anak Krakatau and other submarine volcanoes; also it has been projected explosively along with dense clouds of steam where basalt lava entered the sea during eruptions in Hawaii and elsewhere. Palagonite is a diagenetic alteration product of sideromelane. It is a yellowish rock, characterized by botryoidal rims of palagonite which have swelled out from the edges of the sideromelane grains as these slowly hydrated and changed in composition. Palagonite itself is inherently unstable; in time it breaks down to iron and magnesium rich clays, zeolites, opaline silica, chlorite, celadonite, carbonates and other products. With complete alteration the yellowish brown color changes to a greenish black, and the original hyaloclastic texture is greatly obscured. Such altered palagonites are easily mistaken for black argillites, graywackes or mudstones.

Freshly erupted sideromelane, unless mixed with large amounts of clayey material derived from the underlying bedrock, is granular and sand-like. It is easily reworked by waves, running water or wind. Alteration to palagonite, however, swells shut all pores between sideromelane fragments, producing a firm non-permeable rock that withstands erosion well.

Although sideromelane and palagonite are the most characteristic materials in the ejecta blankets surrounding maar craters, it must be emphasized that these materials occur in other kinds of deposits as well. On the Columbia River Plateau, as Fuller (1931) showed long ago, widespread deposits of palagonite, pillow breccia, and pillow lava occur where subaerial flows of the Yakima Basalt entered shallow marginal lakes that formed in the crease between the surrounding highlands and the accumulating flows. Fuller pointed out that the lava upon entering a lake granulated into small fragments of sideromelane which were deposited in steeply-dipping foreset beds, forming a delta of hyaloclastic debris over which the lava then advanced as if on dry land, building a horizontal lava topping above the inclined foresets. Such palagonitic accumulations are very different in bedding and structure from the palagonitic rim beds that accumulate around maar craters.

Forms of Maar Volcanoes

One of the most common kinds of maar volcano is a simple explosion pit, filled with a crater lake. These generally have low rims of mixed hyaloclastic and foreign ejecta, and their broad flat floors are well below the surface of the bedrock in which steam blasts quarried the hole. With an increase in the volume of hyaloclastic debris, broad ramparts of sideromelane-rich ejecta rise above the crater rim forming tuff rings whose crater floors are still below the water table. Indeed, many tuff rings start subaqueously on the floors of lakes or seas, and ultimately grow until they project above the water as ring craters. An example is Anak Krakatau which emerged from under water in 1927. Still more ejecta builds stumpy conical forms (tuff cones) that stand conspicuously above the countryside; an example is Diamond Head on Oahu.

In southern Oregon all varieties of these forms are well-exposed within the basins of former Pleistocene lakes (now evaporated), which existed during a time when the characteristic high-alumina olivine basalts of the southern Oregon-Cascade petrographic province were erupting from hundreds of individual centers. On dry ground these eruptions produced low lava shields, or else the classic forms of steep-sided cinder cones built from frothy scoria, and topped by small craters with floors far above the surface on which the cinder cone rests. By contrast, within the Pleistocene lakes, and also near their

Fig. 5: Base surge
deposits; direction
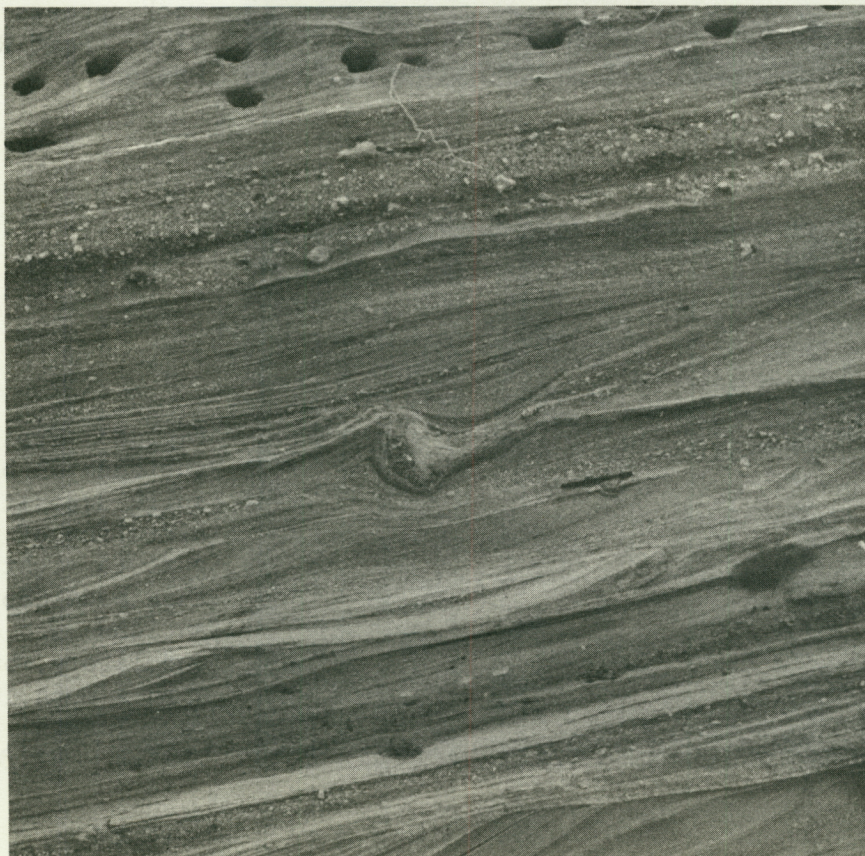of transport to the
right. Near Macdoel,
California.

Fig. 6: Base surge
deposits; direction
of transport to the
left. Note tailing
out of fine material
from 4-inch fragment
at center.

Fig. 7: Sub-aqueously deposited sideromelane, now partly palagonitized. Weathering brings out the lenses and tongues of coarse material at the base of each subtly graded thin bed. Freshly broken rock appears massive. Fort Rock, Oregon.

Fig. 8: Typical antidune in base surge deposits. Direction of transport to right. The thin beds above the antidune are also undulatory, but with a much longer wave length. Ubehebe Crater, California.

borders where abundant ground water was available, tuff rings (Fig. 3), tuff cones, and simple explosion pits (Fig. 1) take the place of the subaerial shields and cinder cones. The presence of water in the eruptive environment changes not only the nature of the ejecta -- replacing lava flows and scoria accumulations of lapilli and bombs with chilled and shattered fragments of sideromelane -- but it also alters the external morphology of the volcano, profoundly affects the mode of dispersal of the ejecta, and notably increases the stickiness and plastic behavior of the newly deposited debris.

General Structural Features

Unlike the lobe and tongue-like deposits found in normal volcanic cones, the deposits that make up nearly all maar ramparts are characterized by unusually thin and continuous bedding (Figs. 4, 5, 6, 10). In palagonitized rocks the stratification may appear deceptively massive, but weathering generally brings out the mixture of subtle vertical gradations alternating with abrupt changes in grain size that is peculiarly distinctive of maar deposits (Fig. 7). Because of the thin and continuous stratification, most authors have described the beds of maar ramparts as air-fall tuffs, but the presence of low-angle crossbedding in many thin layers, and of a rhythmic wave-form undulation in many cross-bedded sequences which is not shared by beds above and below these sequences, makes an air fall origin untenable for many thin beds (Figs. 5, 6, 8). Moreover, other thin beds occur in repeated graded sequences that suggest deposition from underwater turbidity currents. Extensive plane-parallel beds also occur; some of these drape over underlying irregularities with a uniform thickness, and are undoubtedly air fall layers. Others, however, fill and obliterate the hollows in the underlying surface, spreading evenly as a uniform flat-topped sheet which masks the hollows and ridges below (Fig. 5, 6).

On a much larger scale, all of these beds show primary dips. A cross section taken radially through a maar rampart resembles the cross section of an anticline, but the beds are not folded -- dips in both outward and craterward flanks are primary. In many maars the basement rocks below such anticline-like ramparts are flat-lying alluvial deposits or other undeformed sediments.

The bedding sags (Figs. 9, 10) produced by the impingement of air fall blocks into freshly deposited maar volcano strata also testify to initial dips. Such blocks arrive on ballistic trajectories, traveling radially from the nearby crater. The direction and angle at which they impinge is recorded in the asymmetry of the sag beneath the block, and the geometry of the sag can also be used to document the fact that the beds were dipping at the time the block arrived.

We have studied the sedimentary features found in rim deposits of maar volcanoes from more than forty localities in western North America. Our conclusions are that air fall layers alternating with base surge deposits constitute most of the maar ramparts that were built subaerially, and that the eruption clouds from which they formed contained such great quantities of both water vapor and liquid water that the newly deposited material -- at least near the vent -- was wet, sticky and plastic. In deposits that accumulated subaqueously, however, these two kinds of deposits are replaced chiefly by thin normally graded beds formed by underwater mudflows and soupy slurry floods which spread outward from the underwater vent as thin turbidity flows. In places such turbidity sequences alternate with air fall debris that was projected upward through the water surface, and then rained down into the water, falling vertically through it onto the turbidity deposits below.

We turn now to brief descriptions of the nature of each of these kinds of volcaniclastic strata as exposed in the ramparts of the maar volcanoes that we have investigated.

Air-Fall Deposits

A well-known characteristic of air-fall layers is that they drape with nearly uniform thickness over surface irregularities. Moreover, widespread air-fall ash beds are generally thin (rarely exceeding a few inches), and nearly all are normally graded. These criteria, however, fail as air-fall layers are traced closer to the vent. In a basaltic cinder cone, for example, coarse lapilli and bombs are deposited at the angle of repose, and most bedding surfaces are either slip surfaces in unconsolidated debris, or rolling-talus surfaces, perhaps emphasized by infiltration of fine ash falls. Moreover, reversed (Fig. 12) and normal grading are both common -- probably reflecting changes of turbulence in the eruption cloud or changes in eruptive energy instead of merely the more rapid settling of coarse materials. In and near the vent, furthermore, ungraded coarse pyroclastic materials may accumulate in chaotic unstratified deposits tens of feet in thickness.
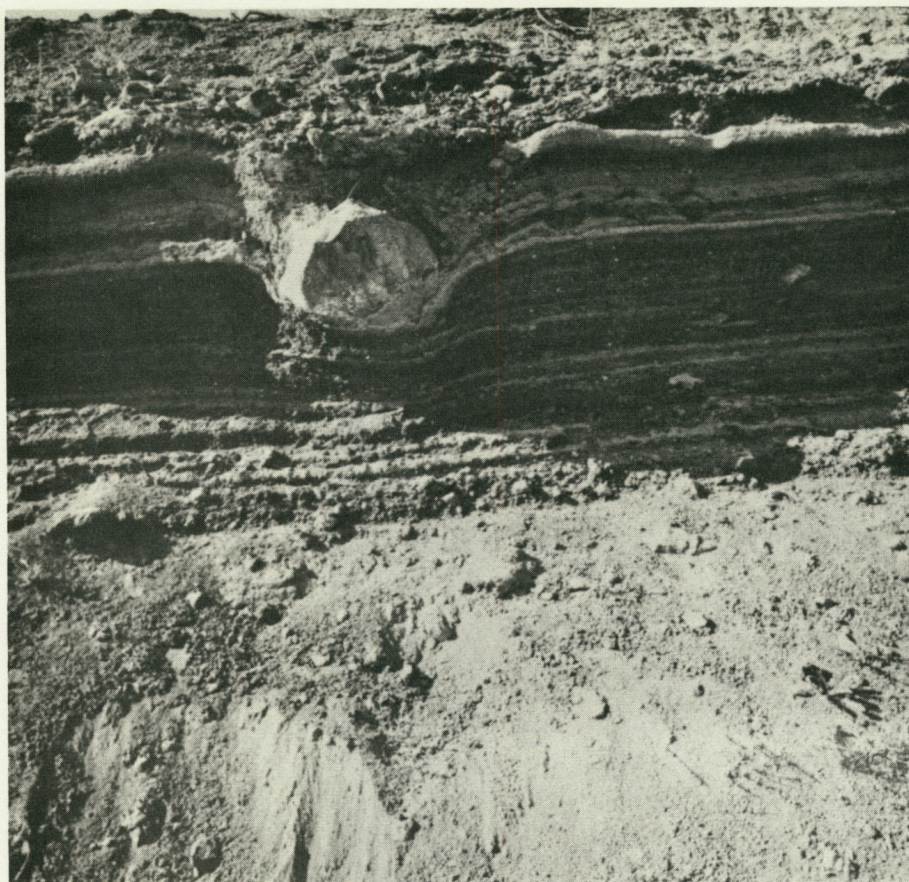
In the ramparts of maar volcanoes air-fall deposits are abundant, but their stratification and other features are modified from those of essentially "dry" air-fall deposits in a number of significant ways:

Accretionary Lapilli -- The water content of eruption clouds from maar volcanoes varies significantly from that of normal volcanoes. Great clouds of steam boil upward from the magma-water interface, and liquid water containing suspended mud and silt is sprayed upward in quantity along with the rock fragments. The eruption cloud is a heavy, turbulent mixture of gases, liquids and solids. It is not surprising, therefore, that many air-fall layers of maar volcanoes are rich in accretionary lapilli (Figs. 11, 12). The accretionary lapilli are in part the typical spheres, from two to ten millimeters in diameter composed of many concentric shells built from fragments of varying size. Moore and Peck (1962) state that in normal air-fall tuffs such accretionary lapilli are formed when raindrops fall through eruption clouds of dry material and collect successive shells of slightly different grain size while the droplet is buffeted about in the turbulent eruption cloud. In maar-deposited lapilli the greater range in grain size of the crescentic layers and their poorer sorting suggest that water droplets sprayed upward by the eruption can readily build such coatings without the necessity of rain falling through dry solids.

A different variety of accretionary lapilli, however, is more common in the deposits of maar volcanoes. It consists of a solid core of sideromelane or a fragment of bedrock mantled by a hardened layer of mud or silt-sized material (Fig. 12). Some of these cored lapilli are coated by only one layer, others show many concentric shells. The rock fragment that forms the core is, as a rule, sharply angular. Similar thin coatings of mud and silt-sized debris may even mantle rock fragments several centimeters in diameter (Fig. 12). Some strata are composed almost entirely of one kind of lapilli; in others the two kinds are mixed together indiscriminately along with other kinds of volcaniclastic debris.

Bedding Sags -- Many air-fall layers in maar volcanoes are initiated by a violent eruptive burst which showers the maar rampart with shattered blocks of all sizes. If these fall directly upon newly deposited wet sediments -- of either air-fall or base surge origin -- they impinge deeply into the sticky bedded deposits, producing spectacular bedding sags (Figs. 9, 10). Soft sedi-

Fig. 9: Bedding Sag. The block, about 14 inches in diameter, is part of the ash fall deposit at the top of the picture. It penetrated 1 foot of base surge deposits, and bowed the underlying dark ash flow layers. Trajectory was toward the observer. Near Macdoel, California.
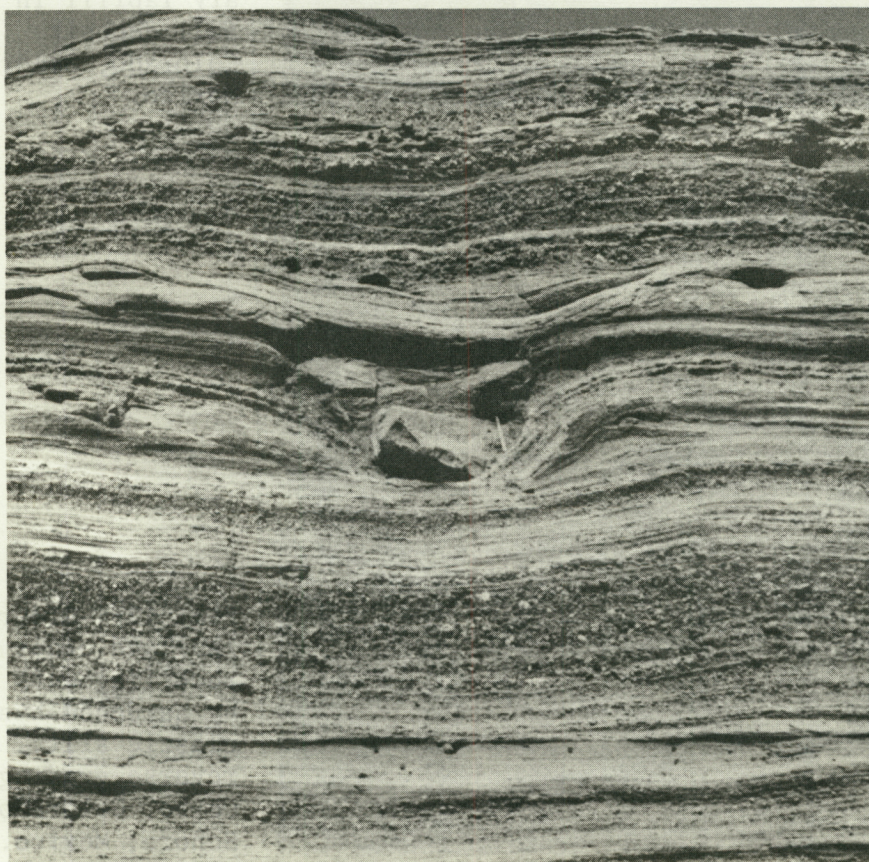

Fig. 10: Bedding sag in base surge deposits. Trajectory of fall indicates a source to the left and behind the cut, which agrees with directional structures in the underlying and overlying deposits. Large block is 11 inches long. Near Macdoel, California.

Fig. 11: Accretion-
ary lapilli in air
fall deposit. Cerro,
Colorado, Sonora,
Mexico.

Fig. 12: Sideromel-
lane and other small
rock fragments armored
by hardened hyalo-
clastic silt. Note
reverse grading.
Cerro, Colorado,
Sonora, Mexico.

ment deformation by both plastic flow and by faulting is shown in the distorted stratification beneath these blocks, and as noted earlier, the geometry of the deformed bedding gives information on both the location of the crater and on the initial dip of the sediments penetrated.

Disruption of bedding also results when blocks fall from a normal volcanic eruption into dry lapilli or fine ash -- but the effects are different. The dry material splashes out radially from the hole in rays and tongues. Bedding beneath the projectile is broken and obliterated by intergrain movement for an inch or two from the block, but the bedding does not bend and fault into the spectacular cohesive forms which testify to the wet sticky condition of the maar deposits.

Base Surge Deposits

Base surges are horizontally-directed density currents which spread outward at hurricane velocities from the base of vertically ejected eruption clouds. They have been observed to emerge from the base of phreatic volcanic eruption columns -- for example, at Taal in the Philippines, Capelinhos in the Azores, and Surtsey in Iceland. They are prominent in explosion clouds raised by detonation of shallowly buried nuclear explosives. Doubtless they also develop during high-velocity meteorite impact.

The significance of volcanic base-surge processes for interpretation of the puzzling low-angle cross bedding and the undulatory wave forms of thin bedded strata in many ancient maar ramparts was clarified by Moore's observations of base-surge processes and deposits during the 1965 phreatomagmatic eruptions from Taal Volcano (Moore and others, 1966; Moore, 1967). The explosions at Taal rose from a vent partly submerged beneath the waters of a lake. Base surges consisting of a mixture of steam, lake-bottom muds, and newly chilled and granulated volcanic glass spread laterally from the vent at velocities up to 100 miles per hour. They carried blocks up to a meter across, removed all trees within 0.5 kilometers of the crater, and sand blasted trees and other objects to distances of 6 kilometers. Sticky, wet deposits of mud and volcanic debris were plastered over steep surfaces, adhering even to the vertical sides of buildings and trees. In places near their source these surges eroded, but a little farther out poorly sorted debris was strewn along the direction of transport in a nearly uniform but slightly undulating sheet. About 3 kilometers out, where the surge was rapidly losing velocity, the bed load accumulated in low dune-like forms with their long axes oriented at right angles to the direction of transport -- forming a crescentic wave-like pattern surrounding the crater. The wave lengths of these undulations and dunes decreased from 19 meters near the vent to 4 meters at 2.5 kilometers from the source. Most were less than a meter in amplitude.

The base surge created by the Sedan nuclear test of July 6, 1962 raced outward at initial velocities of more than 50 meters per second, and deposited concentrically oriented dune-like forms with 3-meter wave lengths around the explosion crater (Roberts and Carlson, 1962).

Base surge dunes are strictly accretionary forms -- a product of the frictional interaction between the surface and the rapidly moving density current passing overhead. Much of the stratification is therefore in continuous thin sheets. Thin beds and laminae pass over the dune-form without notable change in thickness, although changes in velocity of the current do cause erosion of beds in the apical part of the dune, and a thickening of the strata on the lee slope, as the dune axis migrates outward in the direction of transport (Figs.

8, 5). Cross bedding in the dunes is invariably low angle -- most beds dip less than 10°, and dips are always far less than the angle of repose. The dunes have a wave-form; they never show the steep slip-faces of wind-blown dunes, nor the steep foresets like those developed at delta fronts and in torrential stream deposits.

Typical features of base surge deposits in maar ramparts are shown in Figures 4, 5, 6, 8 and 10. The fluid mechanics of base surge transport and deposition is not well understood, and direct experimental duplication is impossible. In other papers (Fisher and Waters: Science, 1969; American Journal of Science, 1970) we have brought together the descriptive and qualitative evidence regarding base surge deposits, and compared them with the dune-like forms developed by high regime flow in controlled alluvial channels. Although one is intuitively aware of the marked differences between rapidly flowing debris-laden water and the hurricane drive of a base surge density current, the similarity in base surge bed forms with those developed in streams during high-flow regimes suggests that the mechanisms of dynamic interaction between bed materials and a current passing overhead are fundamentally the same. Simons and Richardson (1966) discuss the variables for alluvial channels and show the predictable changes in bed forms that develop. With other factors held constant, an increase in velocity (or shear stress on the bed) produces bed forms in a definite order: ripples, dunes, plane-bed forms, and antidunes. Using their terminology, the dune-like forms in base surge deposits are antidunes. Plane-bed forms are also found in the base surge deposits from maar volcanoes (Figs. 5, 6, 8). Some may be difficult to tell from air-fall strata, but in most the continuous gradation into antidunes, the subtle large scale undulations in plane-bed sequences combined with the minor antidune cross-bedding of much shorter wave length within interstratified thin beds, the evidence of rotation of coarse clasts in thin plane parallel beds (Figs. 4, 5, 6), and the streaming out to leeward of fine material whisked around the coarse fragments (Fig. 6) testify clearly that these beds were deposited by flow, not by fall.

Coarse fragments at or near the bottom of a base surge bed generally rest upon the surface of the underlying bed as if on a table (Fig. 4). In rare instances scratches, skid marks, and faint load casts were observed where fragments had impinged on the bed below -- a strong contrast to the marked bedding sags beneath air-fall blocks (Figs. 9, 10).

From a practical field point of view, one of the most useful features of base surge stratification is the evidence it gives on direction of transport. Most base surge layers are continuous over crater rims, and the cross bedding and other directional features leave no doubt that most of the surges boiled laterally uphill out of the crater and then down its outer slopes, depositing a continuous sheet of debris over the maar rampart.

Base surge deposits are not found in the deposits of all maar volcanoes, but they are so common as to force the conclusion that the sticky, water-rich nature of maar eruption clouds serves as a dense, difficultly-liftable "cork" in the volcano orifice which favors the escape of the powerful steam eruptions as lateral base surges from beneath the heavy cloud. Base surge deposits are most prominent in the low tuff rings with broad and shallow craters; the steeper sided tuff cones contain mostly air fall debris. Underwater accumulations show still a different kind of flow deposit -- formed essentially by sideromelane-laden turbidity currents.

Subaqueous Turbidity Flows and Slides

Deposits in the ramparts of many maars came to rest under subaqueous conditions. In the former lake basins of Bonneville, Utah; Christmas Lake and Fort Rock valleys in Oregon; and the Tulelake-Klamath Lake areas of California-Oregon; are several well-exposed tuff rings whose deposits are easily examined. Moreover, the depth of water in which they formed can be ascertained from nearby former shorelines. These deposits consist mostly of sideromelane; in some of them palagonitization has proceeded far enough to close the intergrain pores and form rocks that are quite resistant to erosion (Fig. 3). Others consist of friable, sand to granule sized black glass.

The bedding in these rocks is subtle and easily overlooked; it may be still further obscured by palagonitization. It is made by countless thin lenses and tongues of slightly coarser fragments graded upward into thin layers of sand-sized sideromelane. The coarse lenses are thin -- some consist of a sheet of coarse fragments with disrupted framework and only one or two fragments in thickness. The lenses and tongues are discontinuous, elongated in the direction of transport, and they overlap complexly with one another (Fig. 7). The gradation upward to smaller sized particles may be very gradual, but in other beds coarse particles are scattered in the base of a much finer matrix which is well graded. In general, both the coarse lenses and the finer grained components are much cleaner and better sorted than in the base surge deposits and air fall tuffs of maar volcanoes.

Occasional coarser, thicker, and more massive layers interrupt the well-graded sequence, as do also some chaotic and poorly sorted layers -- probably air falls into the water from more powerful eruption clouds which broke upward through the water-air interface. Moreover, the continuity of these graded beds is broken -- especially on the inner walls of the crater -- by numerous landslide terraces and tongues, debris flows, and other features that give evidence of crater enlargement by spalling and slumping. Such down slope accumulations dip inward steeply, about at the angle of repose.

The origin of the thin graded beds seems best explained by more or less rhythmic boiling over, from within a submerged vent, of a turbulently agitated slurry of hot water and hyaloclastic particles. Much like the action of a geyser, we can picture the water in the crater throat heating up on contact with the magma, acquiring turbulent motions which throw the finer sideromelane granules into suspension, and finally getting so hot that the lowest parts of the water column flash violently into steam, thus heaving the rest of the turbulent mixture upward and spilling parts of it over the crater rim. Once over the crest of the tuff ring, the material flows down the slope as a typical underwater turbidity current, adding still another lens or tongue with graded bedding to the many already accumulated. The steam pressure now relieved, water pours back into the volcano throat and the whole process is repeated. Such violent rhythmic disturbances have been observed above the underwater volcano at Myojin Reef -- indeed a ship that ventured too close was pulled below the surface into the turbulent maelstrom and broken to pieces. Similar agitation was noted above Surtsey before its tuff ring built above the surface. The activity then changed to more continuous pouring forth of a column of steam accompanied by "explosive projection of black sand" and by base surges.

After an underwater tuff ring builds above the water surface, air fall and base surge deposits add to its height. Eventually enough hyaloclastic material may accumulate around the vent, so that water is excluded. Then lava flows and normal scoria lapilli may appear, as is now happening at Surtsey. At Table

Rock in Oregon, and at the tuff ring complex called The Peninsula near Tulelake, California, drying out of the vents and dropping of the water level in the widespread lakes combined to bring on a final stage of lava flows, and of cinder cones.

CONCLUSIONS

To recapitulate, our examination of more than 40 different areas containing typical maar craters, tuff rings, or tuff cones -- all of which are built by the maar type of eruptions -- has produced indubitable evidence that water had access to the volcanic orifices during most of the time that these features were forming. Water in the environment is the common factor that explains the peculiarities of maar volcanoes.

The most convincing evidence is the universal presence in the ejecta of large amounts of sideromelane or its palagonitic decomposition products, plus the physical evidence of base surge stratification in the deposits composing the maar ramparts, abundance of two kinds of accretionary lapilli, bedding sags which show complicated soft-sediment deformation, and great piles of subtly graded thin sideromelane beds. Each of these testifies to the presence of water in the environment at the time of the eruptions which produced it.

REFERENCES

Fisher, R. V., and Waters, A. C., 1969, Bed forms in base surge deposits: Lunar implications: Science, v. 165, p. 1349-1352.

Fisher, R. V., and Waters, A. C., 1970, Base Surge bed forms in maar volcanoes: Am. Jour. Sci., v. 268, p. 157-180.

Fuller, R. E., 1931, The aqueous chilling of basaltic lava on the Columbia River Plateau: Am. Jour. Sci.(5), v. 21, p. 281-300.

Moore, J. G., 1967, Base surge in recent volcanic eruptions: Bull. Volc., v. 30, p. 337-363.

Moore, J. G., and Peck, D. L., 1962, Accretionary lapilli in volcanic rocks of the western Continental United States: Jour. Geology, v. 70, p. 182-194.

Moore, J. G., Nakamura, K., and Alcaraz, A., 1966, The 1965 eruption of Taal Volcano: Science, v. 151, p. 955-960.

Peacock, M. A., and Fuller, R. E., 1928, Chlorophaeite, sideromelane, and palagonite from the Columbia River Plateau: Am. Mineralogist, v. 13, p. 360-383.

Roberts, W. A., and Carlson, R. H., 1962, Ejecta studies, Project Sedan: Univ. Calif., Lawrence Radiation Lab., PNE-217p, 62 p.

Simons, D. B., and Richardson, E. V., 1966, Resistance to flow in alluvial channels: U. S. Geol. Survey Prof. Paper 422-j, p. j1 - j61.