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HYDROVOLCANIC EXPLOSIONS II. EVOLUTION OF BASALTIC TUFF RINGS AND TUFF CONES

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ABSTRACT. Eleven basaltic volcanoes from a variety of geologic settings were studied in order to compare vent morphology, deposit stratigraphy, and emplacement mechanisms at tuff rings with those at tuff cones. The tuff rings consist of thinly bedded, poorly indurated, relatively fresh pyroclasts deposited with bedding angles less than 12 degrees. Highly inflated pyroclastic surges are the dominant means of emplacement, as evidenced by the abundance of sandwave bed forms. The tuff cones consist of massive, thickly bedded, highly indurated, and hydrated pyroclasts deposited at bedding angles up to 30 degrees. This massive tuff contains ash-fall layers interspersed with nearly equal volumes of base-surge beds, as a result of intermittent Strombolian and Surtseyan base-surge activity. A complete spectrum of explosive volcanic activity, from phreatic to magmatic, results from the shallow-to-moderate depth interaction of magma with external water sources. The venting phenomena range from a single burst that produces an explosion breccia to a prolonged series of explosions of various energies that produce a complex deposit of interbedded pyroclastic fall and surge beds. Stratigraphic data and models of pyroclastic surge suggest that the massive bedding of tuff cones results from a cool (below 100°C), wet emplacement. In contrast, the thinly-bedded deposits of tuff rings are typically emplaced while hot (above 100°C) and relatively dry. As the volume of water that explosively mixes with magma increases, the amount of steam produced increases, but the level of superheating of that steam decreases. This leads to an increased "wetness" of the resulting surge blasts. With increasing ratios of water to magma, activity changes from lava fountains to dry surges to wet surges. The resulting volcanic landforms are respectively cinder cones, tuff rings, and tuff cones. Accordingly, a dry environment would contain cinder cones; abundant ground water promotes tuff rings; and a shallow body of standing water favors development of tuff cones.

INTRODUCTION

Hydrovolcanic explosions result from the interaction of magma or magmatic heat with surface or near-surface water (Schmincke, 1977; Sheridan and Wohletz, 1981). Hydromagmatic processes are important factors for consideration in geothermal exploration and volcanic hazard

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evaluation. An understanding of one-cycle volcanoes forms a basis for the interpretation of more complex eruption cycles in polygenetic volcanoes. *Tuff rings* and *tuff cones* are small (less than 5 km in diam), monogenetic volcanoes composed of tuff that results from hydrovolcanic (hydromagmatic) explosions. Tuff rings have a low topographic profile and slopes, whereas tuff cones have high profiles with steep slopes. This paper presents results of detailed study of eleven basaltic tuff rings and tuff cones in order to compare vent morphology, stratigraphy, and eruptive phenomena produced in a variety of geologic environments.

The depth of water is important in determining the explosivity of hydrovolcanic eruptions. Heiken (1971) emphasized the importance of explosive interaction between near-surface water and magma for several basaltic tuff rings and tuff cones in southwestern Oregon. He concluded that the depth of burst beneath a shallow lake controlled the formation of tuff rings (shallow explosions) and tuff cones (deep explosions), whereas cinder cones formed at locations above the shoreline. In contrast, deep water promotes non-explosive to weakly explosive interactions of water and magma producing pillow lava, pillow breccia, or hyaloclastite (Honnorez and Kirst, 1975).

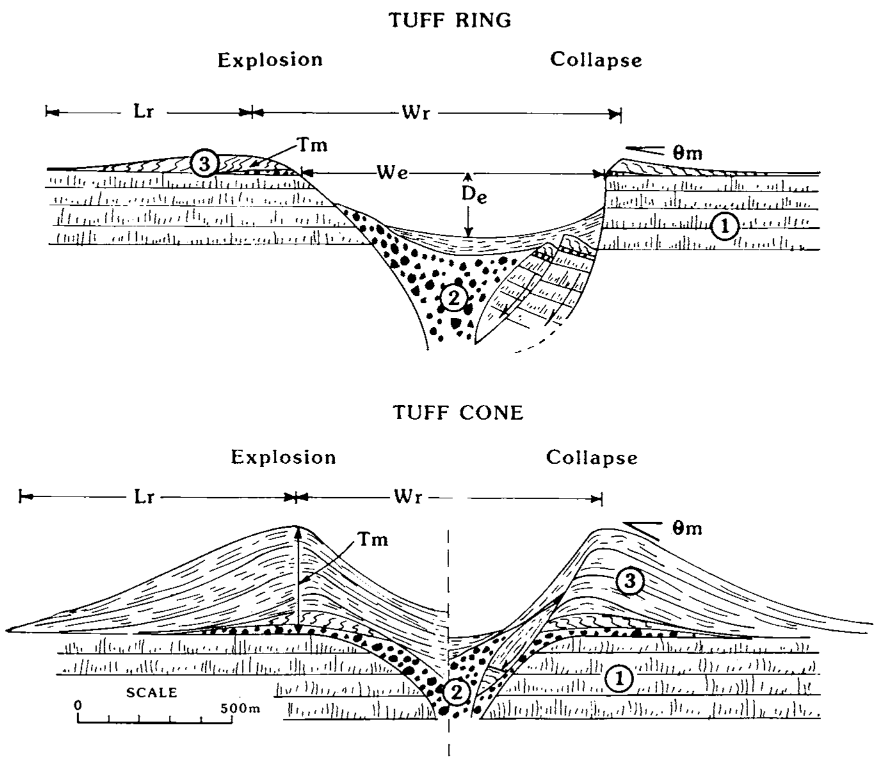


Fig. 1. Schematic cross sections of a tuff ring and a tuff cone. Explosion features are shown on the left side and collapse features on the right side. Explanation: (1) preexisting rocks, (2) explosion breccia, and (3) pyroclastic deposits.

Steam-blast explosions produce distinctive tuff or tuff breccia deposits (Schmincke, 1977; Honnorez and Kirst, 1975; Lorenz, 1974) that in some cases alter to palagonite (Hay and Iijima, 1968). Strong hydrovolcanic explosions generate breccia over-flaps, ballistic showers, and base-surge blasts. The concept of pyroclastic surge (base surge) developed from studies of tuff ring explosions (Moore, 1967; Waters and Fisher, 1971). The interpretation of surge emplacement used in this paper is based on the model presented by Wohletz and Sheridan (1979).

MORPHOLOGY OF TUFF RINGS AND TUFF CONES

Tuff rings and tuff cones (fig. 1) are the most common landforms created by explosive hydromagmatic (phreatomagmatic) volcanism. These small monogenetic volcanoes contain relatively large craters, which extend down to or, in the case of maar craters, below the level of the preexisting ground surface (Ollier, 1967; Lorenz, McBirney, and Williams, 1970). Tuff rings are more commonly associated with maars than tuff cones.

Tuff ring and tuff cone craters generally broaden and deepen as eruptions progress, leading to collapse and slump structures inside their topographic rims. In addition, the vent location may change during an eruption, multiple vents may be active, adjacent vents may vary greatly in production rate, and vent configuration or prevailing winds may cause strongly assymetrical deposits. Crater rims may occur along crests of beds with quaquaversal dips, parallel to collapse scarps, or at intersections of adjacent craters. Therefore, the morphology of a single vent or a group of vents may be difficult to specify.

Thick pyroclastic deposits surrounding hydrovolcanic vents range in morphology from steep-sided cinder cones with small apical craters through tuff cones with moderate slopes and much larger craters to tuff rings with very gentle slopes and large craters which extend below the preexisting topographic surface. In the absence of a standard way of representing crater morphology, we suggest that the maximum deposit thickness at the crater rim (Tm in fig. 1) be considered as the characteristic dimension for comparison of deposits. Additional morphometric parameters useful for deposit characterization (fig. 1) include: rim-to-rim width (Wr), maximum dip (θm), excavation width (We), excavation depth (De), and runout length (Lr). Data for the volcanoes studied are presented in table 1. Tuff rings have thin (less than 50 m) sections of rim beds, small (less than 12°) maximum dips, and most have generally excavated a crater below the existing ground surface. Tuff cones have thick (greater than 100 m) rim deposits, steep (greater than 25°) maximum dips, and crater floors generally above the preexisting surface.

STRATIGRAPHY

The significant difference in deposit thickness (Tm) and slope angles between tuff cones and tuff rings reflects a fundamental difference in the lithology of their deposits. The three principal deposit types (fig. 2), in their stratigraphic order, are: (1) explosion breccia, (2) thinly bedded deposits, and (3) thickly bedded deposits.

Explosion breccia is a descriptive term for coarse-grained, chaotic pyroclastic deposits that surround explosive hydromagmatic vents, near the base of tuff rings and tuff cones. Deposits surrounding small (approx 1 km) explosive maars, like Ukinrek maar (Self, Kienle, and Huot, 1980), are predominantly composed of explosion breccia. The breccia consists of coarse, angular fragments of broken country rock, 2 cm to more than 1 m in diameter, supported in an ash and lapilli matrix (pl. 1). Where average clast size is less than 10 cm, a crude stratification may be evident. Such breccia beds up to several meters in thickness commonly are interbedded with fall deposits and poorly developed surge beds. Breccias are best developed where a vent has pierced coherent, near-surface rock such as a basalt flow, sandstone, or limestone. If the surficial material at the vent is unconsolidated, breccia is missing or poorly developed. Where explosion breccias extend more than several hundred meters from the vent, they generally grade laterally into finer grained fall and surge deposits.

Typical explosion breccia contains a mixture of fragments from the underlying strata. If explosions initiate at sufficient depth, the breccia shows a poorly developed inverted stratigraphy with fragments of deeper strata emplaced above fragments of near-surface strata, similar to the overturned "flap" of large impact craters or those that vent from buried nuclear explosions. The mechanism of emplacement is dominantly ballistic fall, especially for large fragments down to lapilli, but locally the deposit may contain beds of finer particles emplaced by surge.

Thinly bedded deposits of tuff rings are dominantly composed of pyroclastic surge deposits (pl. 2-A) with subordinate ash-fall beds. Cross stratification is characteristic in surge deposits, which show a wide spectrum of bed forms (including sandwave, massive, and planar) that fit into the facies model of Wohletz and Sheridan (1979). Numerous bedform transitions per vertical meter indicate rapidly changing depositional

TABLE 1

Location, water source, and dimensions of tuff rings and cones studied

Locality	Water Source	Wr, rim to rim width (m)	De, excavation depth (m)	Tm, maximum thickness (m)	θm, maximum dip
Tuff Rings					
1. Crater Elegante, Mexico	ground water	1600	200	50	10-12°
2. Kilbourne Hole, New Mexico	ground water	2500	80	50	4°
3. Peridot Mesa, Arizona	ground water	550	lava filled	18	2-3°
4. Taal, Philippines	island in lake	600	130	25	5-10°
5. Ubehebe, California	ground water	800	200	30	10°
6. Zuni Salt Lake, New Mexico	ground water	1600	30	30	3°
Tuff Cones					
7. Cerro Colorado, Mexico	playa lake	990	10	100	25°
8. Diamond Head, Hawaii	ocean beach	1700	0	207	25°
9. Koko Crater, Hawaii	ocean beach	1000	0	330	30°
10. Pavant Butte, Utah	Pleistocene lake	460	0	235	24°
11. Surtsey, Iceland	shallow marine	500	lava filled	150	30°

characteristics. The color of surge deposits in recent basaltic tuff rings depends upon the ratio of light-colored lithic ash to dark-colored juvenile components. Pyroclastic fall beds, other than explosive breccia, rarely contain abundant (50 percent or greater) lithic material. These thinly bedded deposits generally are poorly indurated, and the glassy ash displays little or no palagonitization. The bedding is nearly horizontal, showing dips that rarely exceed 10 percent. Fragments greater than 2 cm in diameter commonly make up less than 1 percent of surge deposits and occur as pebble stringers in massive surge beds or in pyroclastic-fall beds near the crater rim.

Thickly bedded deposits of tuff cones (not to be confused with massive, pyroclastic-surge beds) show indistinct or poorly developed bedding (pl. 2-B). These deposits commonly are orange-tan or yellow-tan in color and consist of subequal amounts of massive surge beds and poorly bedded fall. Cross stratification is rare. Inversely graded planar surge beds associated with massive beds increase in relative abundance with distance from the vent. Massive beds that average about 1 m in thickness are separated by thin, fissile laminae of fine ash. Indistinct bedding planes characterized by crudely developed pebble stringers occur at intervals of 5 or more cm within massive beds which do not otherwise show any size grading.

These massive deposits, depending on age, generally are strongly indurated due to a high degree of palagonitization. This alteration obscures primary textures, especially where beds are composed of fine ash.

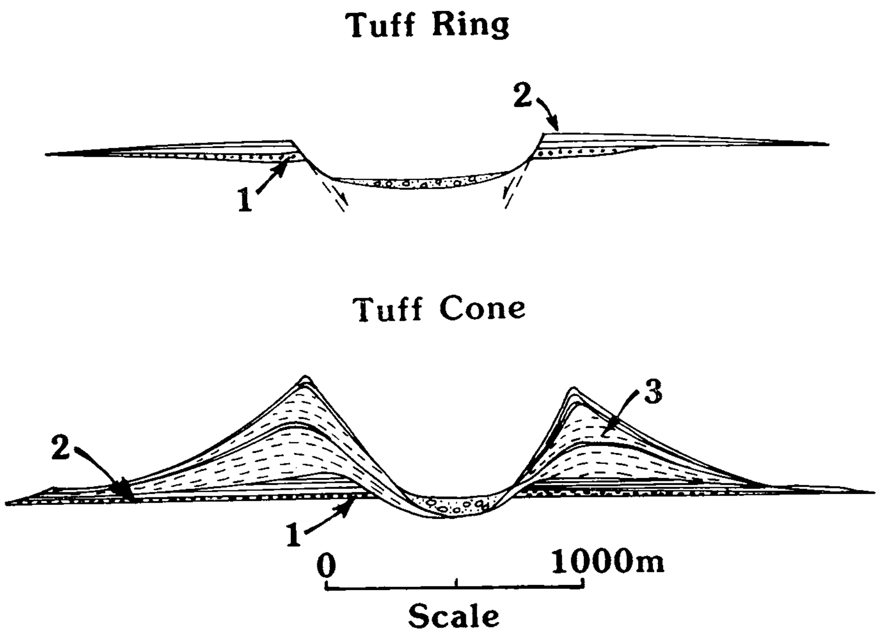


Fig. 2. Schematic cross sections showing principal deposit types: (1) explosion breccia, (2) thinly bedded deposits, and (3) thickly bedded, massive deposits.

PLATE 1

Explosion breccia, at Koko Crater, Hawaii. Note hammer near picture center for scale.

Lithic material constitutes less than 5 percent of these deposits. Fragments larger than 2 cm in diameter may account for as much as 5 to 10 percent of the deposits. Their typically steep bedding that averages 20 to 25 degrees of dip at the rim usually displays quaquaversal dips away from the crater rim.

Figure 3 illustrates the general stratigraphic relationship of the three major deposit types. The basal layer of tuff rings typically is an explosion breccia that pinches out from a maximum thickness of approx 20 m at the crater rim and within a radial distance of several hundred meters. Overlying the breccia are thinly bedded surge deposits that reach a maximum thickness of 50 m and pinch out at a distance that is typically about one crater width beyond the rim. Tuff cones have a similar stratigraphy except that the bulk of the cone is composed of massive deposits that may either unconformably or conformably overlie the thinly bedded tuff ring deposits at the base. Hence, stratigraphy shows that tuff cones start out in eruptive sequence as tuff rings but early in their development change eruptive style so that later cone-building eruptions emplace massive tuff. Thickly bedded, massive tuff deposits commonly reach 100 m in thickness at the crater rim and extend outward no more than one crater diameter. Beds of these deposits can be traced from inside the crater up and over the rim and down to the lower flanks of the cone. Final eruptions at tuff cones characteristically form thinly bedded surge deposits that mantle the earlier-formed tuff cone. Generally, deposits left by these late surges are less than 1 m thick, unconformably overlie the earlier massive sequence, and appear to follow collapse of sections of the crater's inner wall.

Vesiculated tuffs (Lorenz, 1974) merit discussion because of their significance for interpretation of the "wetness" of the emplacement media. These fine-ash beds are so wet on emplacement that the entrapped vapors are unable to escape. The resulting deposit contains smooth-walled voids that record the existence of gas bubbles in the wet tuff. These beds are nearly saturated with water at the time of deposition.

Accretionary lapilli and *armored lapilli* also indicate a wet environment. Accretionary lapilli consist of numerous concentric layers of fine ash formed as the aggregate tumbles during growth, usually proximal to the vent. Armored lapilli consist of a lapilli-sized core of a juvenile or lithic clast that is coated with one or more layers of volcanic dust. Accretionary and armored lapilli generally occur as clasts in fine-grained, massive surge beds that suggest a very wet to saturated emplacement.

DESCRIPTIONS

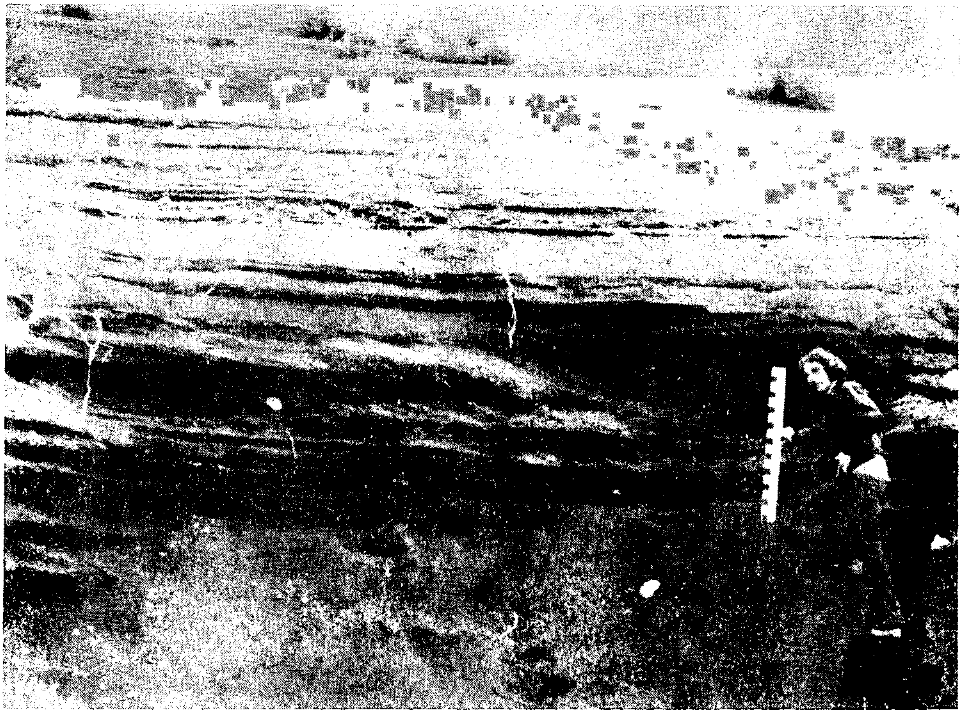
The following descriptions present the distinctive features of the tuff rings and tuff cones studied. These features demonstrate the eruption histories at each vent. The bed-form distribution of pyroclastic fall and surge deposits is interpreted using fluidization-deflation model of surge deposition (Wohletz and Sheridan, 1979). In this model, sandwave, massive, and planar bed forms are deposited respectively from surges of decreasing steam to pyroclast volume ratios (degree of inflation). Fall deposits result from little or no steam generation during eruptions. For this reason, the deposits record the amount of water interaction (explosivity) during eruption. Sandwave beds deposited from highly inflated surges require the greatest amount of explosive water interaction and fall beds the least.

Tuff rings

Crater Elegante has been studied in detail by Gutmann (1976), who interpreted the formation of the maar to collapse of a tuff-breccia cone following evacuation of its near-surface phreatomagmatic eruption chamber. The ejecta blanket that surrounds the maar is composed of thin-bedded tuff breccia. Lava underlying the tuff breccia along the north rim intrudes the tuff. These dikes indicate that the lava was still fluid and emplaced just prior to eruption of the tuff. Gutmann (1979) has shown that Elegante followed the pattern of Strombolian vents in the Pinacate field, which characteristically begin by lava effusion before entering a pyroclastic stage.

The tuff breccia at Elegante is a thinly bedded deposit of dominantly surge origin, which has been studied extensively by Wohletz and Sheridan (1979). Beds range in dip between 4 and 7 degrees away from the crater rim. The tuff is a nonlithified, yellowish tan, poorly sorted,

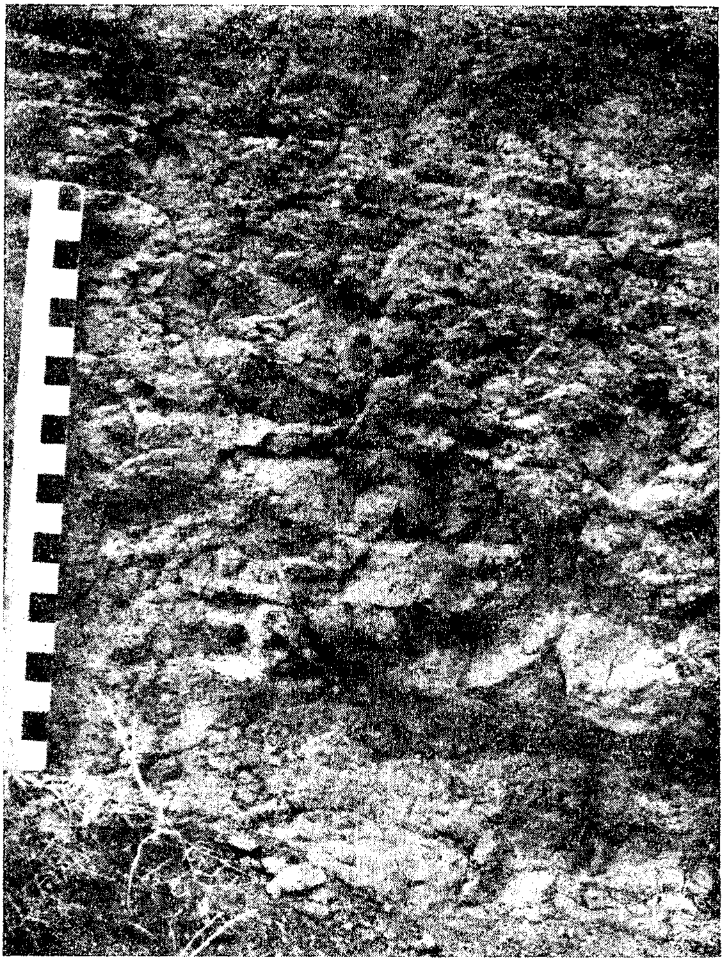
PLATE 2



A. Thinly bedded surge deposits at Pavant Butte, Utah. Note the abundant cross stratification, poor degree of induration, and fresh appearance of this basaltic ash. Meter stick for scale.

gravelly, muddy sand comprised of subequal amounts of juvenile and nonjuvenile (quartzo-feldspathic sand and accessory fragments) materials.

The rim stratigraphy (fig. 4) records three stages of surge producing Surtseyan eruptions, each with a characteristic lateral facies distribution that is evidence of varying eruption energies and vent location (Wohletz and Sheridan, 1975). An interpretation of the section is as follows. Early eruptions in the area produced lava flows. Lava fountaining followed, depositing agglutinated red cinder in some areas followed by Strombolian fall eruptions of gray cinders. The basal contact of surge deposits marks the beginning of explosive interaction with water in saturated alluvial sediments underlying the surface lava flows. The first stage of Surtseyan activity produced mostly pyroclastic-fall beds and planar surge beds. The second stage is marked by wide fluctuation of eruption explosivity producing sandwave, massive and planar surge deposits, and air falls in repeated sequences. A typical sequence of this stage includes eruption of highly inflated surges (depositing sandwave beds) followed by eruption of less inflated surges (massive beds), and then poorly inflated surges (planar beds). Each sequence of Surtseyan explosions is culminated by Strombolian eruption of an ash-fall unit.



B. Massive basaltic tuff at Pavant Butte, Utah, showing high degree of induration. Meter stick for scale.

The third stage of eruptions is wholly Surtseyan, producing dominantly sandwave beds and minor amounts of massive beds.

Zuni Salt Lake is a maar crater in west central New Mexico that is the northernmost of a number of vents. Many of these are tuff rings, aligned along a fracture that extends for over 16 km (Bradbury, ms). The crater is underlain by Precambrian crystalline rocks and Paleozoic to Mesozoic sedimentary rocks. Fragments of these rocks are present in the tuff indicating a deep aquifer (Bradbury, ms).

The tuff is composed dominantly of thinly bedded surge deposits and subordinate amounts of pyroclastic-fall beds, one of which mantles the ring. The maar rim is marked by a series of arcuate, concentric faults which drop blocks of the tuff ring into the crater.

Stratigraphy of the tuff suggests the following eruption history. Hydromagmatic activity began with eruptions that pierced a basalt flow producing a localized explosion breccia on the south rim and an ash-fall deposit that is somewhat thicker than 1 m near the rim. Ensuing Surtseyan activity produced dominantly surges and minor amounts of ash falls. The proportion of ash-fall beds in the tuff increases near the top of the deposits. Culminating activity was both Strombolian and passive, resulting in the construction of three cinder cones within the maar and emplacement of a ring dike along the crater rim. This final magmatic stage of activity shows that flow of water into the vent decreased and finally was cut off prior to cessation of lava extrusion.

Kilbourne Hole in south-central New Mexico has been described by a number of workers including De Hon (1965) and Hoffer (1976) who give detailed descriptions of the stratigraphy. The rim ejecta are divided into three units: a basal explosion breccia and pyroclastic-fall unit, a middle surge unit, and an upper laharic unit. The basal unit is approx 10 to 15 m thick and crops out on the north and east rim of the crater. The explosion breccia consists of angular blocks of basalt up to 1 m in diameter supported in a poorly bedded, pyroclastic-fall deposit. The basalt blocks are fragments of a lava flow pierced by the eruption. The fall beds are approx 5 to 10 cm thick, are normally graded, and are dark gray. Near the top of this breccia unit, dune beds are apparent. The middle unit consists of thinly bedded pyroclastic-surge deposits which attain a thickness of 30 to 40 m on the east rim. These beds are light tan near the base of the unit and become light gray near the top of the unit as the juvenile constituent of the tuff increases in abundance.

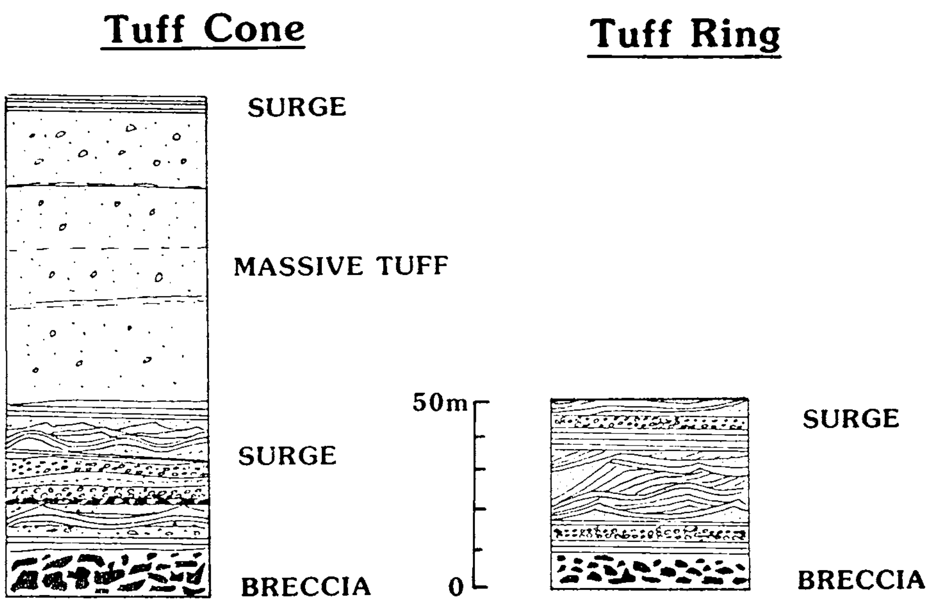


Fig. 3. Schematic stratigraphic sections for a tuff cone and tuff ring.

The surges are dominantly a sandwave facies near the crater and show repeated alterations in bedding from seams of coarse fall lapilli to finely bedded sandwaves to massive beds with abundant accretionary lapilli. The upper unit, 3 to 4 m thick, is light-tan, fine ash showing indistinct bedding and slight palagonitization.

This stratigraphy suggests that opening eruptions were dominantly low energy Strombolian ones that distributed fragments of the capping basalt flow and juvenile material toward the north and east. Subsequent eruptions became Surtseyan and ejected dominantly reworked alluvial

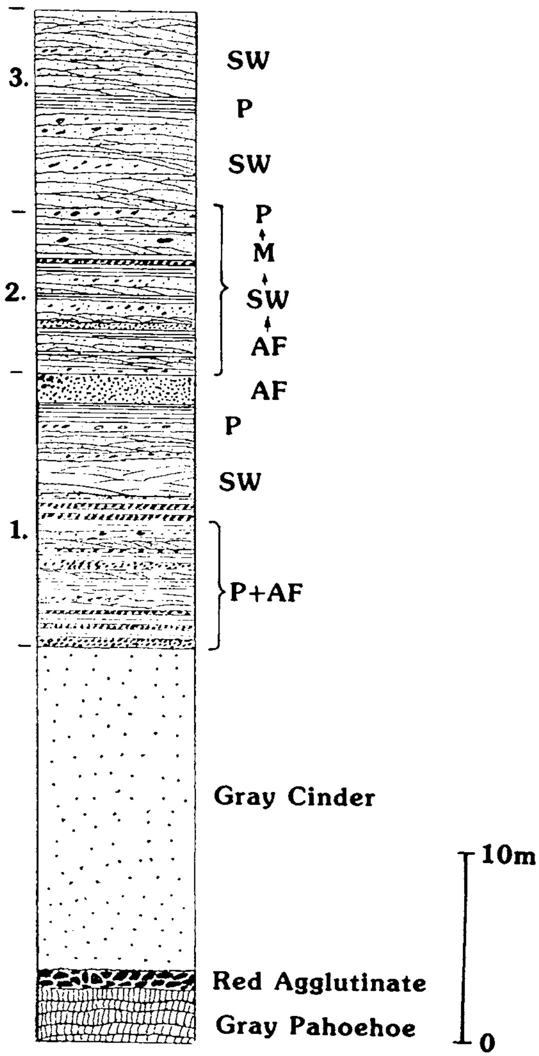


Fig. 4. Stratigraphic section measured at the south rim of Crater Elegante, Sonora, Mexico. Numbers indicate the three eruption stages. P = planar beds, M = massive beds, SW = sandwave beds, and AF = air-fall beds.

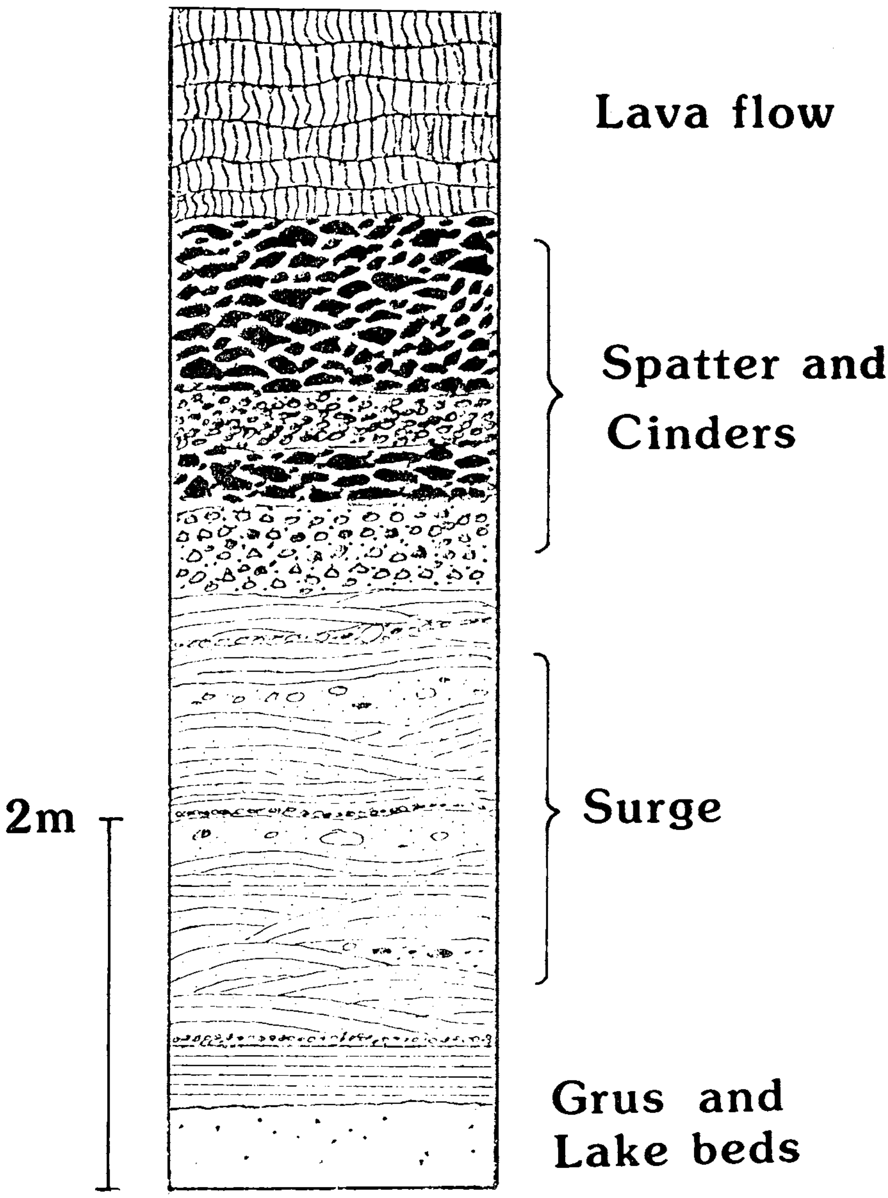


Fig. 5. Stratigraphic section near the rim at Peridot Mesa, Arizona.

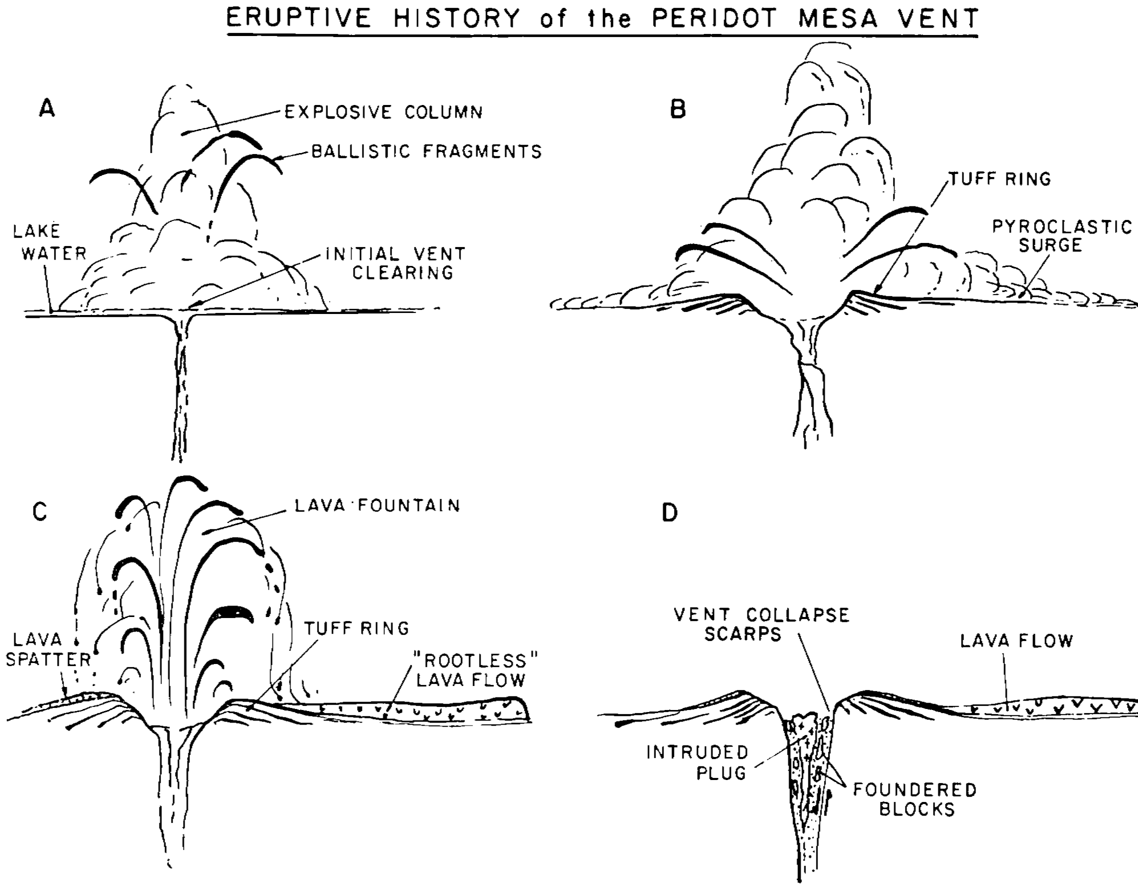


Fig. 6. Illustration of the four eruption stages at Peridot Mesa, Arizona. The rim-to-rim diameter is 550 m. (A) Explosion of magmatic volatiles initiate surface venting. (B) Hydromagmatic explosions produce surges, widen the vent, and deposit tuff-ring beds. (C) Lava fountaining produces cinders, spatter, and a rootless lava flow. (D) Cessation of lava extrusion results in collapse of the inner vent walls.

material from the underlying Santa Fe group in highly inflated surges. These opening Surtseyan eruptions cleared the vent and excavated the large crater. As eruptions progressed, the proportion of juvenile material in them increased. Final eruptions were weakly Surtseyan, producing wet, massive beds of ash that moved downslope as lahars.

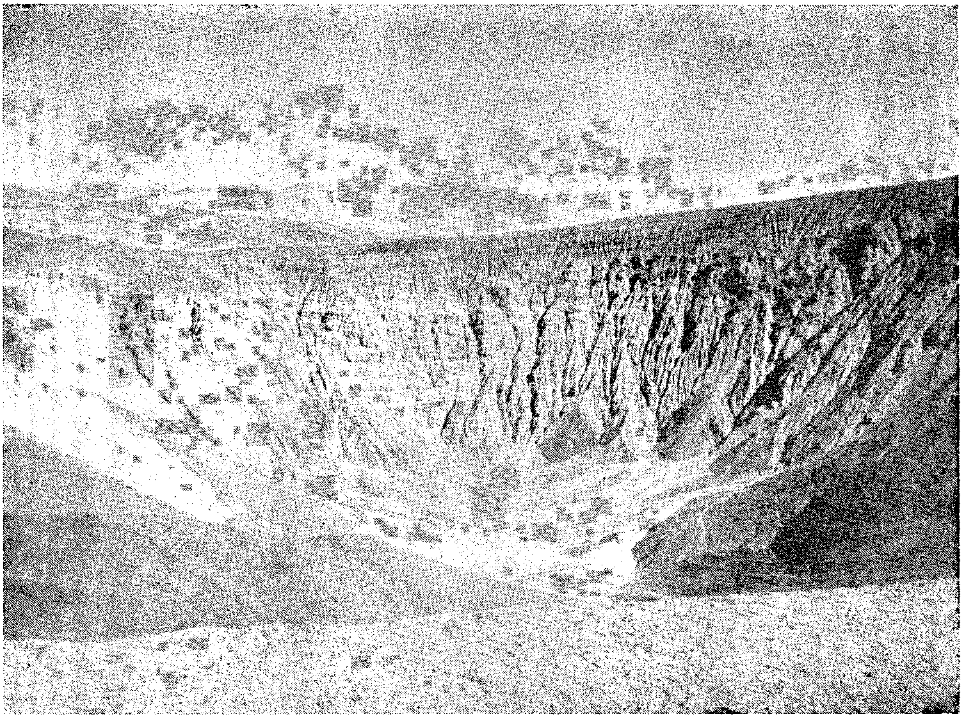
Peridot Mesa in central Arizona is one of several tuff rings in the San Carlos volcanic field. These vents erupted basaltic magma adjacent to a shallow lake, as evidenced by interstratification of the tuffs with Pliocene lake beds. The Peridot Mesa vent, however, is located on a topographic high of granite bedrock and not in the lake beds. The short description which follows is taken from Wohletz (1978), and rim stratigraphy is shown in figure 5. Four stages of eruption are envisioned (fig. 6). Early eruptions produced steam-rich surges that deposited a tuff ring of dominantly sandwave beds. Less than 10 percent of the tuff ring is ash-fall material with horizons of palagonitized accretionary lapilli. Late-stage eruptions deposited basalt cinders and abundant spatter. These must also have produced a lava fountain, because the lava flow originates neither from within or beneath the tuff ring but on the outer slopes of the ring. These eruptions mark the cessation of water-magma interaction.

Several lines of evidence suggest that eruptions were both hydromagmatic and magmatic. Production of both cinders and spatter of similar size is interesting in that cinders were chilled before emplacement and spatter was not, as evidenced by its subsequent agglutination or welding. Cinders interbedded with surge deposits suggest that water interacting with the magma formed and chilled these pyroclasts, whereas exsolving magmatic gases formed spatter. Alkaline affinity of the lavas, abundance of large mantle nodules, and emplacement of vent plugs (Holloway and Cross, 1978; Wohletz, 1978) are strong evidence that these vents are diatremes similar in structure to eroded remnants on the Colorado Plateau. McGetchin (1968) and McGetchin and Ullrich (1973) have demonstrated that eruption of diatremes is characterized by exsolution of supercritical gases from the magma. The presence of dissolved magmatic gases would explain a lava-fountaining stage of eruption, an uncommon feature in purely hydromagmatic eruptions.

Taal Volcano is located in the Philippine Islands near the center of Lake Taal. More than 25 eruptions have occurred since 1572. These generally have been hydromagmatic due to access of lake water to the vents. The eruption cycle began in 1965 as Strombolian eruptions (Moore, Nakamura, and Alcaraz, 1966). The eruptions produced an elongate tuff ring, as a radial trough was cut into Volcano Island with the vent below the elevation of the lake. The geology of the 1965 Taal eruptions have been described by Moore, Nakamura, and Alcaraz (1966), Moore (1967), and Waters and Fisher (1971).

Taal volcano continues its intermittent activity to date with new outbreaks approximately yearly. The 1965 eruption was among the most violent. Subsequent activity has become progressively more magmatic in character as the access of lake water to the vent has been reduced. By

PLATE 3



Photograph of the rim of Ubehebe Crater, Calif. Bowl-shaped excavation crater (De = 200 m) with crater rim surge deposits (Tm = 50 m). Light and dark ejecta bands show at least seven eruptive episodes.

September of 1976, activity was Strombolian with construction of a steep-sided cinder cone with avalanched-controlled flanks.

Stratigraphy of the ash deposit near the crater reveals the following eruption sequence, which corresponds to accounts of witnessed activity (Moore, Nakamura, and Alcaraz, 1966). Early eruptions deposited juvenile fall materials, including basaltic spatter and lapilli. These deposits resulted from a dominantly vertical eruption cloud containing incandescent material. The major explosive phase that followed produced surge deposits characterized by dune formation and sandblasting effects. This explosive phase was marked by the repeated eruption of base surges of dominantly lithic material and coincided with lake water gaining access to the vent. Cohesive layers of ash plastered on the vertical faces of tree trunks and walls of houses suggest a wet emplacement as do layers of accretionary lapilli in the vicinity of the vent (Moore, 1967).

The initial 1965 explosions of Taal deposited a near-vent explosion breccia that is a chaotic mixture of fragments from silt size to 50 cm in diameter. This deposit displays only crude stratification with minor intercalated sandwave beds. As the eruption evolved, thin sandwave beds become prominent, yielding to massive beds with accretionary lapilli toward the top of the section. Eruptions at Taal subsequently have decreased in explosive intensity, and deposition by ash-fall has become more frequent. The 1976 phase was dominated by construction of a cinder cone within the tuff ring. Hydrovolcanic explosions now are infrequent.

Ubehebe Crater in California is an explosion crater surrounded by a tuff ring. Its geology and base-surge deposits are very well exposed and have been studied in detail by Crowe and Fisher (1973) and Wohletz and Sheridan (1979). Ubehebe is the largest of several interconnected craters that developed along a north-trending fault that cuts a thick fanglomerate unit. The deposit surrounding the crater is thinly bedded

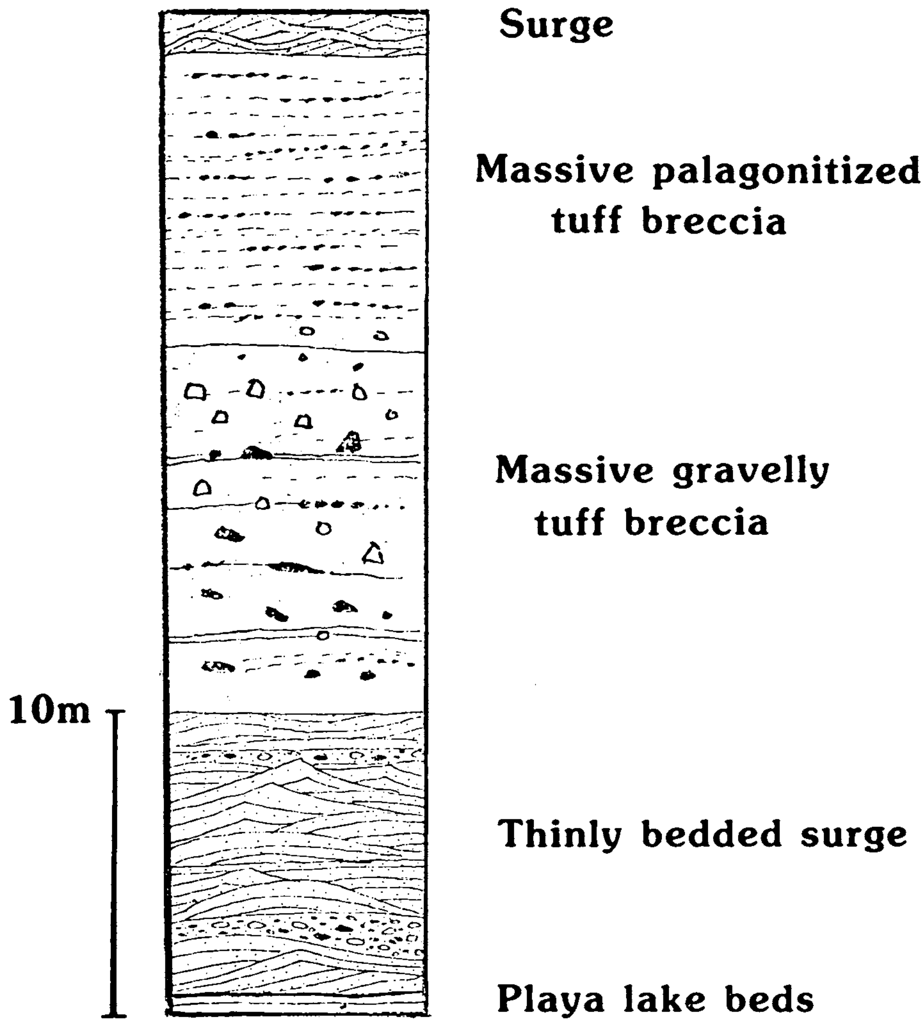


Fig. 7. Stratigraphic section of the east rim of Cerro Colorado.

and consists dominantly of surge deposits showing well developed antidune structures (Crowe and Fisher, 1973) and subordinate fall deposits.

The crater-rim deposits (pl. 3) include an explosion breccia and seven sequences of tephra distinguished as dark and light bands on the crater rim. These tephra bands record eruptions controlled by the interaction of upwelling basalts with ground water in the fanglomerate. Each eruption began with lithic-rich surges (light colored deposits) followed by surges and falls of tephra richer in juvenile material.

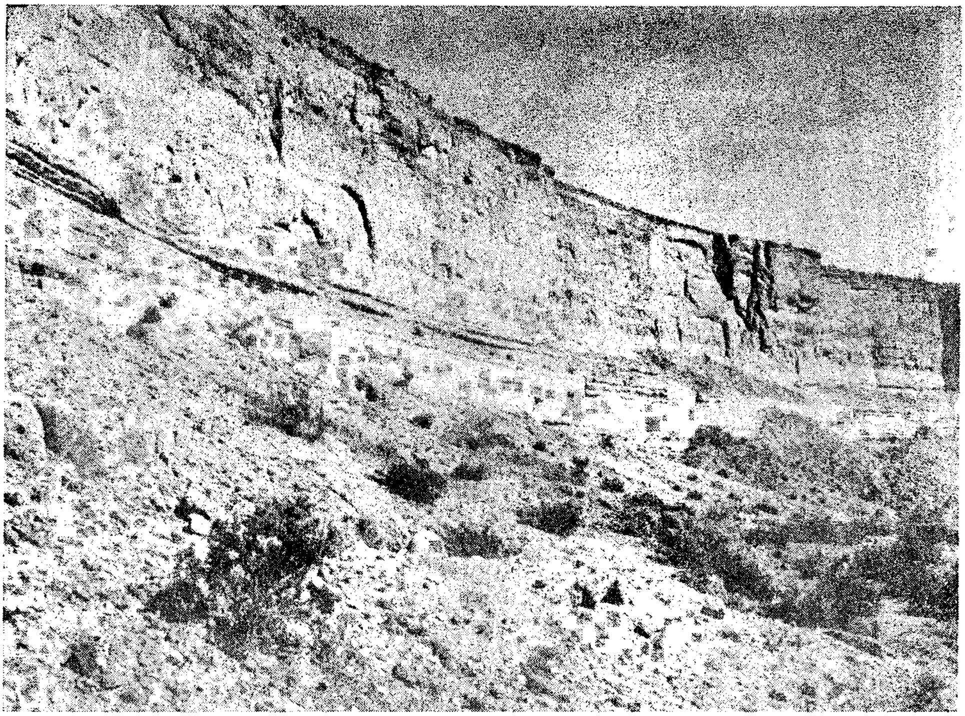
Tuff cones

Cerro Colorado is a tuff cone located in the Pinacate volcanic field, Mexico, approx 20 km from Crater Elegante. Published work on the crater includes description by Jahns (1959), Wood (1974), and Gutmann and Sheridan (1978). The cone lies on the eastern boundary of the volcanic field on the margin of a playa and is underlain by a basalt flow, playa sediment, and alluvium in descending order.

The stratigraphic section (fig. 7) illustrates a typical tuff cone stratigraphy. A basal explosion breccia was not observed and probably never formed since no competent rocks were directly above the vent. The lowest unit, 10 m thick, is a light, pinkish-orange, thinly layered ash. Abundant sandwaves are present, and the ash has a large contribution of lithic material from near surface strata. The upper unit is composed of two parts: a gray, thickly bedded tuff, 10 to 15 m thick, with abundant lithic fragments derived from alluvial gravels, and an overlying palagonitized, poorly bedded, massive tuff, 10 to 20 m thick, yellow-brown in color. This unit shows regular plain-parallel bedding that is indistinct and poorly defined compared to the underlying unit. Bed forms are planar reversely graded beds, massive beds showing pebble stringers, and normally graded planar beds of pyroclastic fall tephra. In massive beds crude stratification is marked by alignment of lithic clasts. The crater-rim section is pictured in plate 4. A third unit less than 2 m in thickness crops out mostly within the crater. Late stage eruptions occurring after collapse produced energetic surges that traveled up the steep crater walls and out onto the flanks of the cone. The deposits are dark colored and show abundant sandwave bed forms despite the high angle of deposition (approx 30 degrees).

Cerro Colorado differs in morphology, stratigraphy, and nature of tephra deposits from Crater Elegante. The most apparent explanation for their differences is that Cerro Colorado erupted in wetter surface conditions. Evidence includes: (1) lower elevation of Cerro Colorado compared with Elegante; (2) existence of playa lake deposits and occurrence of desert floods (Ives, 1936) at Cerro Colorado; (3) location of Colorado on the edge of a recent playa lake; (4) tuffs of Colorado are deposited on slopes up to 25 degrees as opposed to 12 to 15 degrees for Elegante, suggesting wetter, more cohesive surges at Colorado; and (5) high degree of palagonitization at Colorado but relatively less hydration at Elegante.

PLATE 4



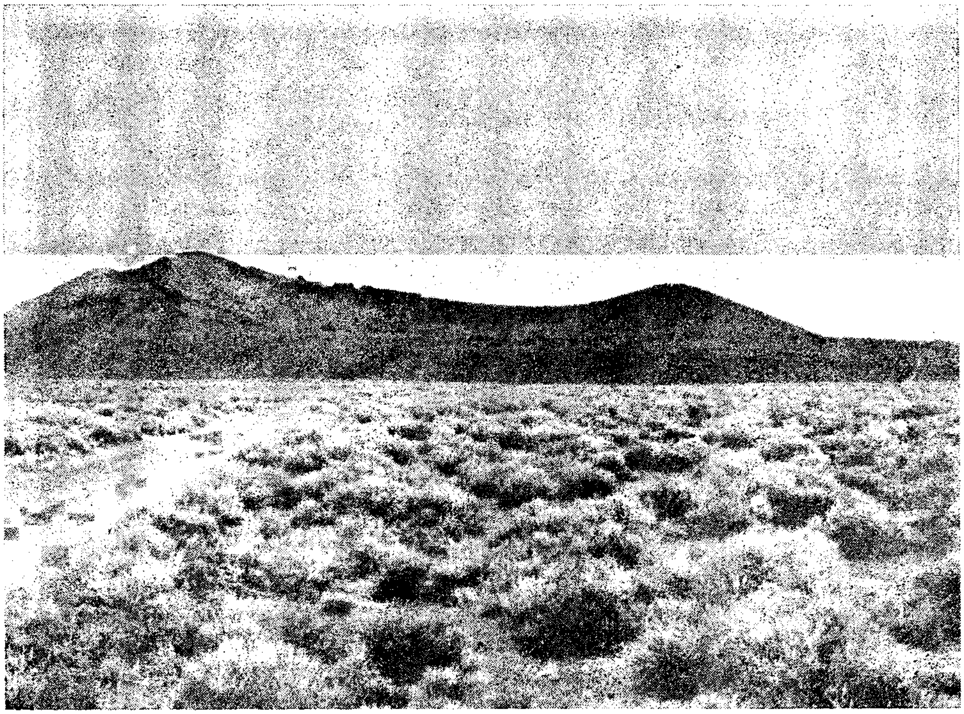
Photograph of the northeast rim of Cerro Colorado, Sonora, Mexico. The base of the section is a light-colored surge deposit consisting of abundant sandwave beds. The upper portion of the section is a darker colored, palagonitized tuff. This good exposure, typical of collapse scarps, is approx 30 m thick.

Pavant Butte in west-central Utah erupted into shallow Pleistocene Lake Bonneville (Gilbert, 1890). The cone consists of two parts (pl. 5). The lower part, topped by a wave-cut platform, consists of nearly flat-lying, thinly bedded, fresh basaltic ash. The upper unit forms the cone built upon this platform. The cone consists of steeply dipping (20 to 24 degrees), massive palagonitic tuff.

The lower unit is at least 75 m thick and covers 5 km^2. It is dominantly of pyroclastic surge origin with subordinate amounts of pyroclastic fall beds and water-reworked ash. The deposit is black, unconsolidated, and shows ubiquitous cross stratification, plane beds 1 to 5 cm in thickness, lens-shaped massive beds up to 1 m thick, and internal disconformities. The freshness of the deposit is striking. Alteration due to palagonitization, movement of ground water, or weathering of the ash appears to be entirely absent.

The upper unit rests with local disconformity over the lower. It reaches a maximum thickness of 180 m and crops out over an area less than 1 km^2. This unit is buff brown and massive-appearing with poorly developed bedding evident upon closer inspection. The surface of the unit is often dark brown in color, presumably due to weathering, and

PLATE 5



Photograph of Pavant Butte, Utah. The basal platform of surge deposits is dark, and the overlying cone-forming massive deposits are light. The rim-to-rim diameter of the cone is 460 m.

in some areas it is blanketed by dark lapilli fall. Dips are quaquaversal along the cone crest and increase from approx 10 degrees near its base to 20 to 24 degrees near the top of the cone. Bedding, where developed, is dominantly planar, but massive beds often show gentle undulations of pebble stringers. The deposit is consolidated and highly altered to palagonite. Near its base, lenses of fresher material occur but are of minor extent. Large blocks and bombs up to 1 m in diameter are common and are often concentrated in the same stratigraphic horizon.

As at Cerro Colorado, minor crater collapse occurred. This formed steep inner crater scarps, some of which have been buried by later deposits. Late-stage eruptions produced surges that climbed out of the crater depositing dark colored beds similar to those at Cerro Colorado.

Surtsey is probably the best known tuff cone in the world due to the excellent documentation of its hydromagmatic eruptions that began in November 1963 and continued into the summer of 1965 (Thorarinsson, 1966). Eruptions were "Surtseyan," Strombolian, and quiet effusion of lava, the former being characteristic of early activity and the latter of late eruptions.

The topography of the deposits resembles that of Pavant Butte in that the cone is sitting on a broad platform of pyroclastics covered by lava flows. The main cone, Surtur II, comprises thousands of pyroclastic fall beds interstratified with planar and massive surge beds. The massive beds contain significantly more large clasts (2 to 10 cm) than do the fall and surge beds. Dips of the beds are variable, nearly horizontal at the base and becoming steeper near the top. Jakobsson (1978) has studied the consolidation and palagonitization of the Surtsey tuffs. He found that shortly after eruption the tuffs were largely unconsolidated (82 to 88 percent by volume were unaltered sideromelane). Consolidation and palagonitization increased with time over several years, apparently concurrent with a rise of temperatures within the tuff.

Recent drilling at Surtsey has revealed a stratigraphy similar to that found at Heimaey (Tomasson, 1967). Pillow lavas at depth are overlain by hyaloclastites and, in turn, by tuffs and breccias. Allen (1979) noted the similarity of the stratigraphy to typical Moberg stratigraphy. The occurrence of explosive hyaloclastites typically is limited to depths less than 100 to 200 m below the water surface.

Diamond Head and Koko Crater are tuff cones that erupted in Quaternary times as determined by stands of sealevel (Stearns, 1961). They belong to the Honolulu group which records at least 30 eruptions of silica undersaturated basalt. They represent late-stage, post-erosional activity typical of the Hawaiian Island chain. Hay and Iijima (1968) have studied the origin of the palagonitization of the tuff deposits described by Wentworth (1926), Wentworth and Winchell (1947), and Winchell (1947). Fisher (1977) studied stratigraphic relationships among surge deposits from Koko Crater and other craters in the vicinity.

Diamond Head tuffs show quaquaversal dips of 20 to 25 degrees along the crater rim. Its deposits can be divided into two units (fig. 8). A buff white, basalt unit exposed along the south side of the cone is composed dominantly of reworked coral sands. This represents initial eruptions while the vent was below sealevel in the littoral zone. The numerous beds of this unit, which dip 10 to 15 degrees away from the crater, are of pyroclastic surge origin and show dominantly massive and inversely graded planar bedding with subordinate sandwave bedding.

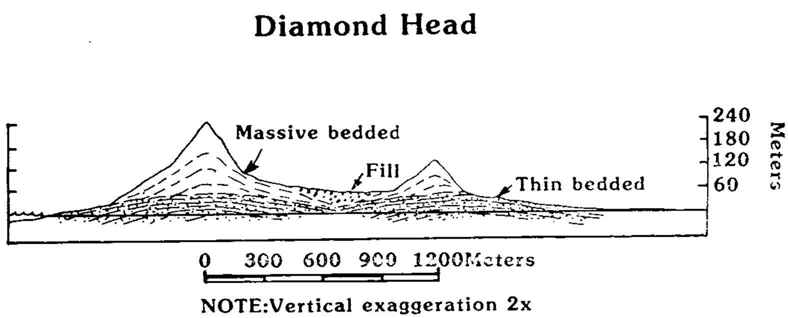


Fig. 8. Cross section of Diamond Head, Hawaii. The basal, thinly bedded tuff is overlain by massive tuff which builds a steep-sided cone.

The base of this unit is not exposed but probably is not more than 10 m thick. Near its base, bed forms are dominantly planar and massive, but sandwaves increase in frequency near the top. Juvenile material is rare in this unit. This lower section appears to be a tuff-ring structure upon which rests the upper unit, consisting of more steeply dipping beds that construct the cone.

The upper unit is a massive, poorly bedded tuff, medium brown to light olive gray in color at its base and moderate yellowish brown near its top. It is a vesicular tuff that is well-lithified due to palagonitization. The massive appearance of this unit is locally due to alteration which has obscured many centimeter-thick beds that show reverse grading. In other places, bedding is poorly developed and only indicated by pebble stringers.

Exposure at Koko Crater is much better than at Diamond Head. However, the stratigraphy is complicated by onlapping deposits from Koko Head and Kahauloa Craters about 1 km to the southeast. As at Diamond Head, beds near the base of the cone dip gently away from the crater at 5 to 10 degrees, whereas beds on the cone dip 20 to 30 degrees. Koko crater tuffs can be divided into three units: a basal breccia and lapilli fall, a tuff ring sequence of thinly bedded surge beds, and the cone-building unit composed of highly altered, poorly stratified massive beds.

The lower unit exposed on the east side of the cone is medium to dark brown. It consists of an explosion breccia, the base of which is not exposed, and 1 to 2 m of lapilli fall. The maximum exposed thickness of the unit is approx 3 m. The breccia is composed of angular fragments of basalt 5 to 10 cm in diameter. Very little fine material exists between larger fragments which form an open, grain-supported framework. Lapilli-fall beds 20 to 60 cm in thickness show poorly developed, normal grading. Massive beds of surge origin composed of finer grained material occur near the top of the unit interbedded with ash-fall beds.

The middle unit is composed of thinly bedded surge material. It is 3 to 5 m thick and best exposed on the south and southeast sides of the crater. The color ranges from medium gray, where it is unaltered and unconsolidated, to medium brown or orange brown where alteration has lithified the tuff. It contains abundant fragments of coral and generally is unconsolidated except in areas where ground water has caused extensive alteration (Hay and Iijima, 1968). U-shaped channels (Fisher, 1977) and sandwave bed forms are common in this unit. Distribution of the middle unit suggests that it formed a tuff ring that was subsequently covered by the cone-building tuffs of the upper unit. Both massive and planar surge facies are exposed on the south side of the crater, the latter forming wave-cut terraces along the present shore.

The upper unit, which is 160 to 190 m thick and forms the bulk of the cone, is orange brown in color and characterized by extensive zeolitization which masks the textures of the tuff. The tuff appears massive, but poorly developed bedding is evident as concentrations of angular lapilli. Much of the unit shows no stratification and contains many large fragments 10 to 25 cm in diameter. These beds are interpreted as planar surge and lapilli-fall beds. As at Diamond Head, dips of beds at the crest are approx coincident with topography (quaquaversal). A 1 to 2 m thick carapace of dark tuff mantles the cone and is eroded away in many places. This carapace is a zone of tuff that has been more strongly lithified by ground-water induced, opal cementation (Hay and Iijima, 1968). This carapace could also be the result of a late-stage surge deposit similar to those at Cerro Colorado and at Pavant Butte. An important point, well-illustrated at Koko Crater by Hay and Iijima (1968), is that palagonite can mask the primarily volcanic textures making interpretation of exposures difficult.

DISCUSSION

Comparison of the deposits of six tuff rings with those of five tuff cones (table 2) suggests that a basic difference between the two deposits is that tephra of the tuff cones were emplaced in a wetter condition than those of tuff rings. The degree of palagonitization of glassy clasts offers the strongest argument for interstitial water (Moore, 1966; Hay and Iijima, 1968). In some cases, such as Surtsey, alteration of glass is caused by steam moving through the deposit due to mild hydrothermal activity at the vent (Sigvaldason, 1968; Jakobsson, 1978). However, the uniform degree of induration by palagonitization throughout most massive deposits coupled with the lack of alteration in the underlying thinly bedded deposits requires another explanation. Palagonitization occurring in the massive deposits is likely due to abundant hot water trapped within the tephra upon emplacement.

Another argument for wet emplacement is maximum angle of deposition. This angle, a measure of cohesiveness, is much greater for the thickly bedded, massive deposits of tuff cones than the thinly bedded deposits of tuff rings. Waters and Fisher (1971) proposed that the cohesive nature of hydromagmatic tuff is a function of wetness. Therefore, the steep bedding of tuff cones reflects wetter emplacement conditions than low angle deposit bedding of tuff rings. In support of this conclusion is the fact that the tuff cones studied erupted beneath shallow

TABLE 2

Comparison of deposits of the tuff rings and tuff cones studied

Tuff rings	Tuff cones
Low bedding angles, 0-10 degrees	High bedding angle, 20 to 25 degrees
Poorly indurated	Highly indurated
Little or no palagonitization	Highly palagonitized
Vents in terrestrial areas of shallow ground water	Vents beneath standing bodies of shallow water
Beds 1 to 5 cm in average thickness and well developed	Bedding is indistinct or at approx 10 cm to 1 m intervals
Dominantly surge bed forms, sand-waves are common	Subequal amounts of ballistic fall and massive surge bed forms

bodies of surface water and tuff rings in areas where only ground water accessed the vent.

A major consideration in comparison of thinly bedded deposits with massive deposits is that the accumulation of bedded tuff in a vertical sequence records variations in depositional process with time. According to the model of Wohletz and Sheridan (1979), thinly bedded deposits of surge origin represent eruption of surge clouds which rapidly fluctuate in degree of inflation with time (unsteady flow). Sandwave, massive, and planar surge bed forms indicate that the volume ratio of pyroclast to vapor (solid fraction, G) in emplacement clouds varies up to a few orders of magnitude from 0.40 down to less than 0.01 (Sheridan and Updike, 1975; Wohletz and Sheridan, 1979). In contrast, thickly bedded, massive tuffs show little bed form variation vertically through the deposit, and the emplacement G varies only in the range of 0.25 to 0.40. Hence, massive tuff is thought to be emplaced by relatively steady flow compared to thinly bedded tuff. This reasoning suggests that a more continuous supply of water to the vents of tuff cones produces moderate vapor explosions of uniform strength. A varying supply of water at vents for tuff rings results in sporadic eruptions of more variable strength.

The following discussion offers an explanation as to why thinly bedded deposits of tuff rings are generally emplaced drier, less cohesive, and with less palagonitization than the thickly bedded, massive deposits of tuff cones. Thinly bedded deposits show characteristics of emplacement in highly inflated surge clouds that deflate (increase in concentration of clasts relative to vapor) as they move away from the vent. During deflation, steam initially trapped in the surge separates from the tephra before it condenses, yielding drier tephra. Thickly bedded deposits show bed forms characteristic of poorly inflated surge transport. These surges only travel a short distance from the vent before coming to rest. Steam remains trapped in the surge and condenses on the tephra yielding wet cohesive ash.

Observations of the eruption of Surtsey (Thorarinsson and others, 1964) document the delayed condensation of steam in erupted surges. Steam was not apparent in surges until several seconds after their initiation. During condensation, initially black clouds of tephra turn grayish white. This and observations by Nairn (1976) and Livshits and Bolkhoritinov (1977) support the hypothesis that, indeed, steam produced in hydromagmatic eruptions often can be highly superheated. However, Thorarinsson and others (1964) also observed eruptions in which so much liquid water was emplaced with tephra that mudflows were produced on the slopes of the cone.

The more highly superheated the steam, the less likely are tephra to be emplaced very wet. Highly superheated steam results from a large amount of thermal energy being imparted from magma to water very rapidly. High heat transfer allows for a much greater degree of vapor expansion (cloud inflation) and more energetic explosions. A highly inflated surge cloud depositing relatively dry, thinly bedded pyroclastics

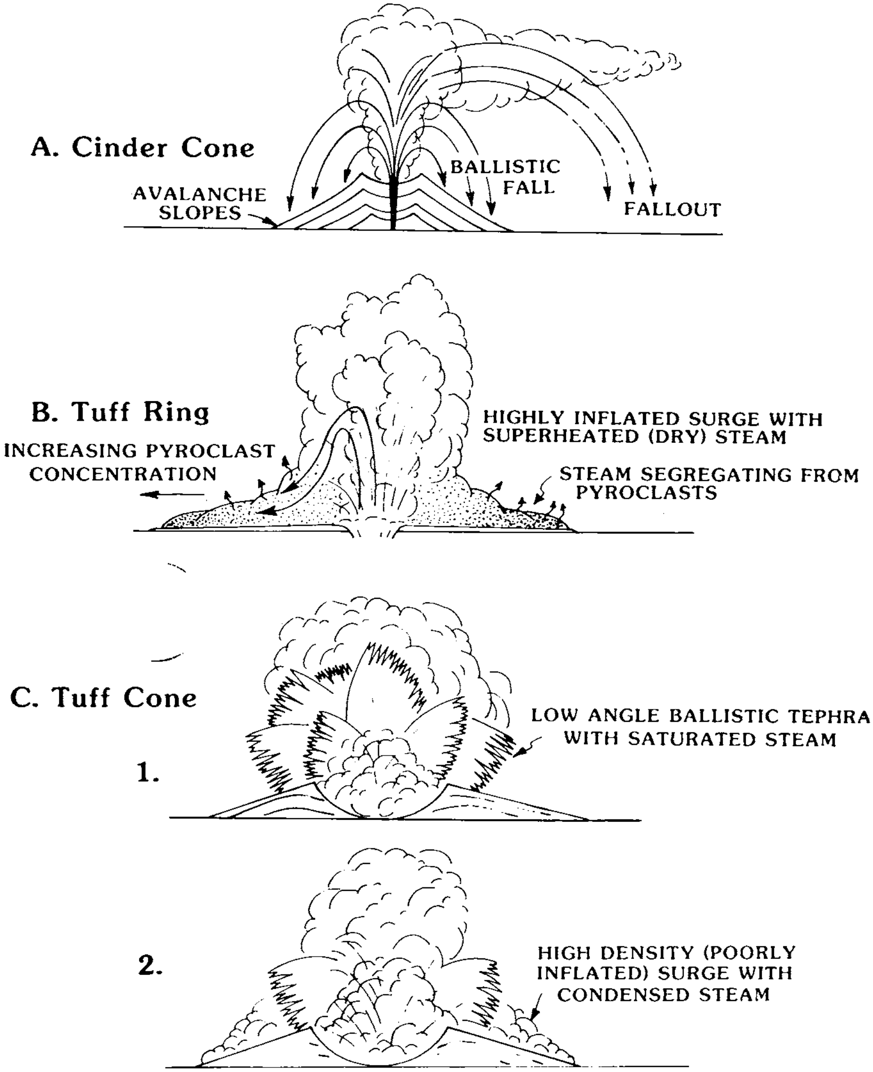


Fig. 9. Eruption phenomena. (A) Cinder cones result when there is a negligible amount of water-melt interaction. Ejection is dominantly ballistic with a small component formed by fallout of elutriated ash. (B) Tuff rings are produced when maximally efficient melt/water interaction is responsible for the explosions. Highly inflated surge clouds dominate the transport phenomena; the ballistic component is minor. (C) Tuff cones result excessive amounts of water interacts with the melt during eruption. Particles following initial ballistic paths are incorporated into low-energy, wet surge clouds.

probably results from a higher degree of steam superheating than does a poorly inflated cloud that deposits wet, cohesive, massive deposits.

Figure 9 illustrates the preceding discussion and is based upon published photographs of hydromagmatic explosions. Tuff cones become relatively steep-sided, because pyroclasts emplaced by poorly inflated, wet surges travel only a short distance from the vent before coming to rest. On the other hand, pyroclasts transported farther from the vent by dry, highly inflated surges result in tuff rings. Why tuff cones generally start out as tuff rings is unknown. However, we believe that the transition to "wetter" eruptions begins only after the vent has evolved sufficiently to allow large quantities of water to come into contact with the magma prior to each explosive vaporization. Perhaps the tuff cones formed as the vent became enlarged to the point where the water flux was sufficient to produce the less energetic wet surges. Early eruptions are "dry" because only a limited amount of water gains access to the vent.

The generalized eruptive histories of the eleven vents are summarized in figure 10. Because explosive energy and degree of melt fragmentation have a high covariance due to their mutual feed-back relationship, they are plotted together as one coordinate on the graph. Explosive energy (and melt fragmentation) reaches a maximum value for a water/melt mass ratio of about 0.3 for basaltic compositions (Sheridan and Wohletz, 1981).

Elegante, Kilbourne Hole, and Diamond Head show a large-scale, progressive increase in inferred water/melt ratio with time. This is probably due to an increase in vent size that allows more contact area with water in the eruptive zone. Other vents show a general decrease in

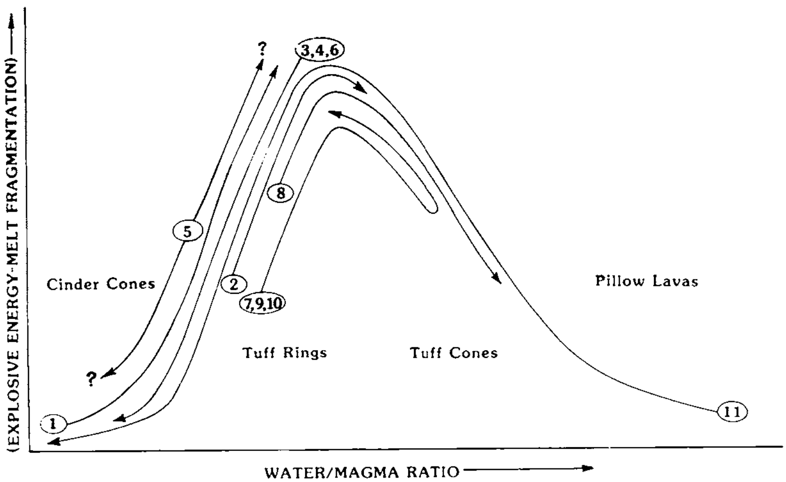


Fig. 10. Schematic diagram of eruptive histories of the studied units. The numbers correspond to the localities in table 1. At Ubehebe Crater (5), cinders are interbedded with surge deposits and the eruption oscillates between surge eruptions and Strombolian explosions.

water/melt ratio with time. This could be explained by rapid drawdown of the water table near the Zuni Salt Lake and Peridot Mesa vents. On the other hand, at Taal and Surtsey it could represent isolation of the vent from a standing body of shallow water due to growth of the volcanic edifice.

Some vents show a more complex history. Cerro Colorado, Koko Crater, and Pavant Butte record an increase in water/melt ratio through their eruptive history with a late-stage reversal of this trend. This trend could reflect prolonged excavation of the crater followed by a late stage depletion of the water supply owing to drawdown or cone growth before the eruption ceased. The alternating episodes of dry surge and air fall at Ubehebe may be due to a complex interaction of tectonic effects on the aquifer level and pulsations in magma production. Detailed study of rim-bed stratigraphy at tuff rings and tuff cones allows semi-quantitative interpretation of variations in water/melt ratios and mechanical energy of explosions throughout their eruptive histories (Sheridan and others, 1981).

CONCLUSIONS

The major conclusions of this study concur with those of Heiken (1971) and point out the main differences between tuff cones and tuff rings, which allow further understanding of hydromagmatic volcanism. These conclusions apply only to monogenetic hydromagmatic volcanoes:

1. Tuff cones and tuff rings are distinctive landforms that result from slightly different types of explosive hydromagmatic volcanism. They generally occur in areas where lava is erupted non-explosively to form both lava flows and cinder cones as part of the same eruption cycle.

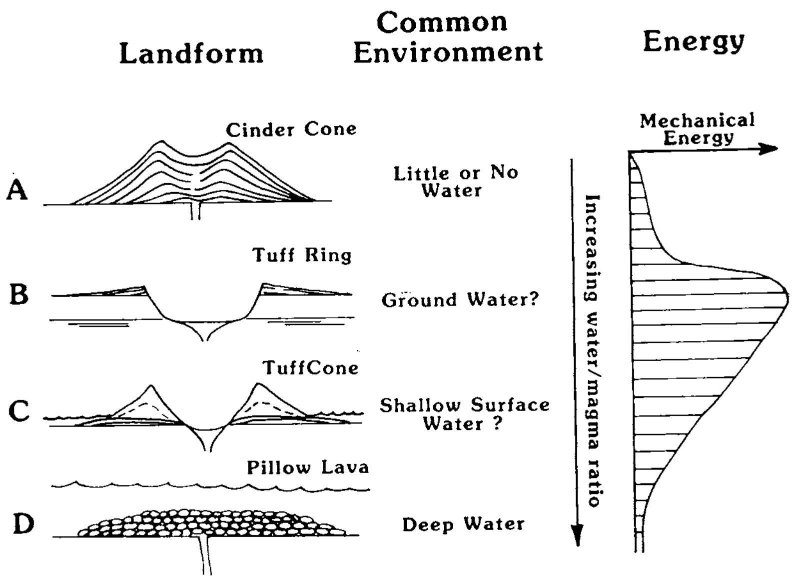


Fig. 11. Relationships of hydromagmatic landform to environment and mechanical energy for basaltic volcanism.

2. Tuff rings produce first explosion breccia and then thinly bedded deposits transported by highly inflated surges.

3. Tuff cones follow the same initial eruptive pattern as tuff rings but continue into a third stage characterized by pyroclast emplacement by poorly inflated surges and pyroclastic falls. This stage forms a massive, crudely bedded tuff which constructs the major portion of the volcanic edifice.

4. Tuff cones of Quaternary age erupted in areas where surface water (lake or shallow marine) was located above the vent.

5. Tuff rings of Quaternary age however, typically formed in areas where the vent was on dry land, but abundant ground water or surface water could enter the vent.

6. Usually the massive deposits of tuff cones are highly indurated, palagonitized, and show bedding angles of 20 to 25 degrees near crater rim crests.

7. Thinly bedded deposits of tuff rings are usually poorly indurated, show little palagonitization, and have maximum bedding angles of less than 10 degrees near rim crests.

8. Deposits surrounding hydromagmatic vents commonly result from a range of explosive phenomena reflecting various degrees of water-magma interaction.

These conclusions support a model that relates the type of volcanic edifice produced by hydromagmatic volcanism to the ratio of water to magma interacting at the vent (fig. 11). This model is in agreement with unpublished data from pyroclast size analysis, SEM grain surface analysis, and experimental work (Wohletz and McQueen, 1981) that will be presented in the near future.

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