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MODELS FOR PYROCLASTIC SURGES AND PYROCLASTIC FLOWS

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ABSTRACT

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Pyroclastic surges are low-concentration turbulent flows that form in at least three ways: (1) eruption column collapse (*ground surge, base surge*), (2) elutriation from the top of a moving pyroclastic flow (*ash cloud*), and (3) directly from a crater without an accompanying vertical eruption column.* Ground surge deposits occur at the base and ash cloud deposits occur at the top of pyroclastic flow sequences. Ground surges and ash clouds may move independently of their associated pyroclastic flow, and, like flows directly from a crater, their deposits may occur alone or within any part of pyroclastic flow sequence. The presence or absence of surge layers, their position with respect to pyroclastic flow deposits and their physical characteristics have significance with respect to the characteristics or eruption columns and flowage mechanisms of pyroclastic flows.

INTRODUCTION

Pyroclastic surges are turbulent, low-concentration density currents that deposit relatively thin, fine-grained, cross-bedded and wavy and planar laminated sequences. They are distinguished from high-concentration pyroclastic flows that deposit relatively thick, unbedded to poorly bedded, poorly sorted tuff and tuff breccia (see Sparks, 1976). Sparks et al. (1973) recognized a texturally distinct sequence of flow unit deposits emplaced during the passage of a single pyroclastic flow, with pyroclastic surge deposits (ground surge deposit as defined by Sparks and Walker, 1973) present only at the base of a flow-unit sequence. This paper documents the occurrence and origin of pyroclastic surge deposits that occur at the top of pyroclastic flow sequences within the Bandelier Tuff, New Mexico, and accordingly modifies the flow-unit model of Sparks et al. (1973).

*Note added in proof: During the April 17, 1979, eruption of Soufriere, St. Vincent, nuées ardentes were observed to form simultaneously with (and without collapse of) a strong vertical eruption column that attained an altitude of about 20,000 m (Richard Fiske, personal communication).

Sparks and Walker (1973) attribute the origin of ground surges to "ash hurricanes" (Taylor, 1958), although ash hurricanes or their deposits are poorly defined. Taylor's (1958) descriptions of the Mount Lamington eruption suggest that relatively fine-grained, low-concentration flows of pyroclastic material (the ash hurricane type of nuée ardente) develop at about the same time as "ponderous ash flow nuées" (Taylor, 1958, p. 51) in two ways: (1) directly from the crater without a vertical eruption column ("shallow-pocket explosion", Taylor, 1958, pp. 32—35), and (2) from collapsing eruption columns (Taylor, 1958, pp. 35—39). Still another type of pyroclastic surge is the ash cloud that develops from elutriating top of a moving pyroclastic flow (Smith, 1960a, pp. 802—804). Base surges are another type of pyroclastic surge that develop mainly by the collapse of phreatomagmatic eruption columns (Waters and Fisher, 1971).

Three modes of origin for pyroclastic surges therefore are: (1) from collapsing eruption columns, (2) from the tops of moving pyroclastic flows, and (3) directly from a crater. The stratigraphic position of their deposits relative to pyroclastic flow deposits has significant implications with respect to eruption and flow mechanics. The following kinds of pyroclastic surge deposits (the general name for all types of low-concentration pyroclastic flows, named on the basis of origin and/or place in sequence), have been indentified:

(1) Ground surge deposit: occurs immediately below a pyroclastic flow deposit and may originate from a collapsing eruption column or directly from a crater.

(2) Base surge deposit: originates from a collapsing phreatomagmatic eruption column and is not associated with hot pyroclastic flows.

(3) Ash cloud deposit: deposit from an ash cloud that mechanically segregates from the top of a pyroclastic flow and occurs above it, or may become detached and flow independently. Crandell and Mullineaux (1973, p. 6) first used the name ash cloud deposit. Elutriated fines that form towering columns of ash above the pyroclastic flows are deposited later as ash fall (co-ignimbrite ash fall of Sparks and Walker, 1977).

BANDELIER TUFF

Stratigraphy

The Bandelier Tuff, a sequence of pyroclastic flow and airfall deposits, was formed by two eruptive cycles (Ross et al., 1961) dated by Doell et al. (1968), that originated from the Toledo and Valles Calderas, Jemez Mountains, New Mexico (Fig. 1). Seminal works on the origin of calderas and the characteristics and zonation of ash flow tuff (ignimbrite) have originated from studies of the deposits of these caldera complexes (Smith, 1960a, b; Ross and Smith, 1961; Smith and Bailey, 1968).

Several cooling units occur in the Pajarito Plateau region. The contact between cooling units 1 and 2 of the Tshirege Member (Fig. 2) is a flow unit

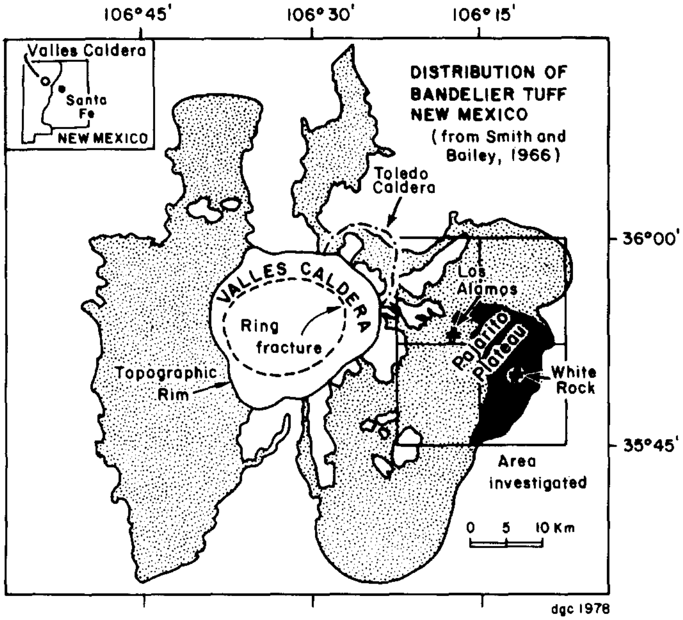

Fig. 1. Location map of Valles Caldera, showing the distribution of the Bandelier Tuff (modified from Smith and Bailey, 1968). The Bandelier Tuff was studied along canyon walls extending radially from Valles Caldera in the area shown (cross hatching).

boundary forming a nearly planar marker horizon in the Pajarito Plateau area (see Fig. 1). Cooling unit 1, emplaced on an irregular erosion surface, has one to five relatively thin (0.5—1 m) pumice-rich layers near its top (pumice swarms of Crowe et al., 1978) characterized by abnormal concentrations of pumice fragments up to 10 cm in diameter. These subsidiary thin flow units are laterally discontinuous, and lack consistent distance vs. maximum pumice size relationships as is shown by thin pumice-rich flow units elsewhere (Sparks, 1975). Thin pyroclastic surge deposits (Crowe et al., 1978) occur at the tops of the pumice layers in many places, but the more persistent layer occurs at the top of unit 1.

Cooling unit 2 consists of three or more flow units. It was deposited on the relatively flat surface of unit 1, averages about 15 m in thickness, but gradually thins away from the source caldera within the field area. The lower flow unit of unit 2 is inversely graded within a 3- to 25-cm-thick zone above unit 1 (basal layer 2a of Sparks et al., 1973) and in many places cuts into the underlying surge and cooling unit.

Ash cloud deposit

Evidence presented in this section indicates that the pyroclastic surge deposits between cooling units 1 and 2 are ash cloud deposits. The main ash cloud layer occurs as discontinuous lenses. Where the lenses first appear several kilometers

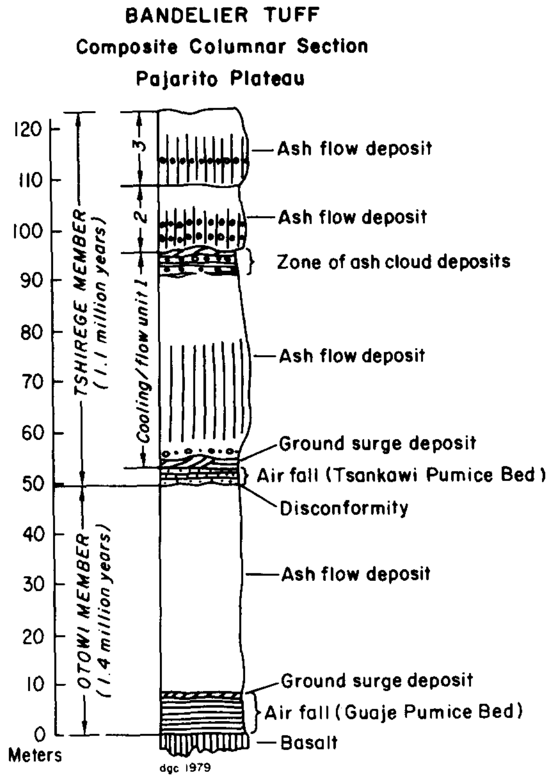

Fig. 2. Composite columnar section of Bandelier Tuff, Pajarito Plateau area (modified from Crowe et al., 1978).

from Valles Caldera, they are < 2 to about 5 cm thick and about 0.5 to 1 m long, but distally become thicker (up to 35 cm) and nearly continuous. Laminations in the lenses are 0.5—3 mm thick, and consist of crystal-rich layers alternating with crystal-poor ash layers of similar thickness. Bed forms are planar to cross-bedded; cross-bedding becomes better developed as lens thickness increases. Maximum thickness of the individual lenses (Fig. 3) systematically increases distally, producing an overall "hill and valley" pattern unrelated to earlier topography. Internal cross-bed laminations have low-angles (~1—15°) (Fig. 4A) and thicken in places to structures that are similar to base surge duneforms (Fisher and Waters, 1970; Crowe and Fisher, 1973).

The above described deposits could be attributed to formation from the passage of a dilute density current that is unrelated to the underlying flow unit. However, several lines of evidence indicate that the deposits are primary and closely associated in time with cooling unit 1, and accordingly are interpreted as ash cloud deposits: (1) small-diameter (≤ 3 cm), crystal-rich, pipe-like gas-escape structures (see Walker, 1972) extend into the laminated ash cloud deposits (Fig. 4B) from cooling unit 1; (2) the main surge horizon locally interfingers

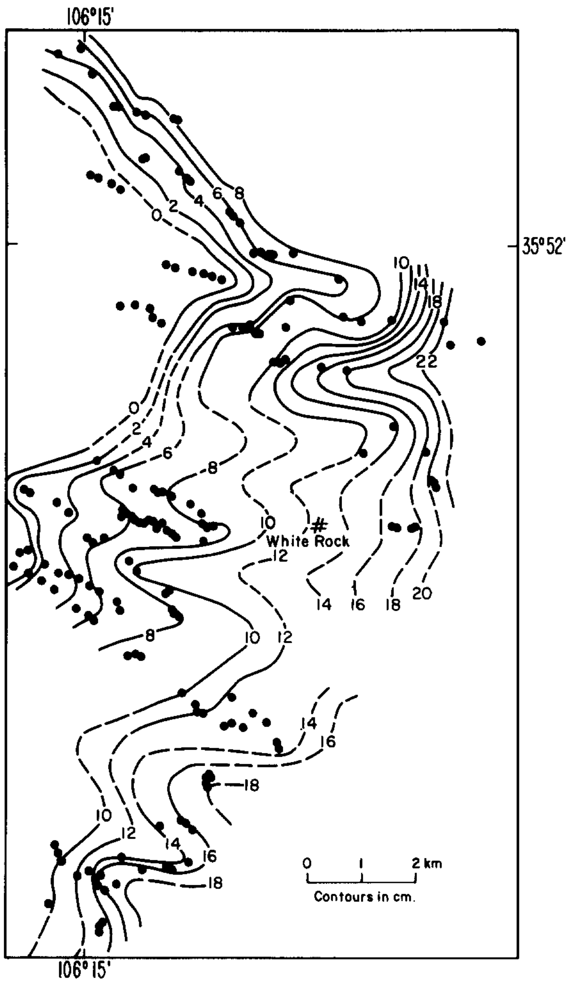

Fig. 3. Average maximum thickness of individual ash cloud lenses at top of cooling unit 1, Tshirege Member (see Fig. 2). Area of contours shown by cross hatching in Fig. 1. The map was constructed by the method of moving averages because maximum thickness changes are irregular and sampling was random. Dots are localities where sections were measured.

and is texturally gradational with cooling unit 1; and (3) subsidiary surge lenses occur beneath the main surge horizon in several places. The subsidiary surge lenses are laterally discontinuous and occur entirely within massive deposits of unit 1 or else lie above thin pumice swarms or flows within its upper part.

Origin of ash cloud and pumice swarm deposits

Witnessed accounts of nuées ardentes have noted that the flows segregate into two main parts (Smith, 1960a), a ground-hugging pyroclastic flow

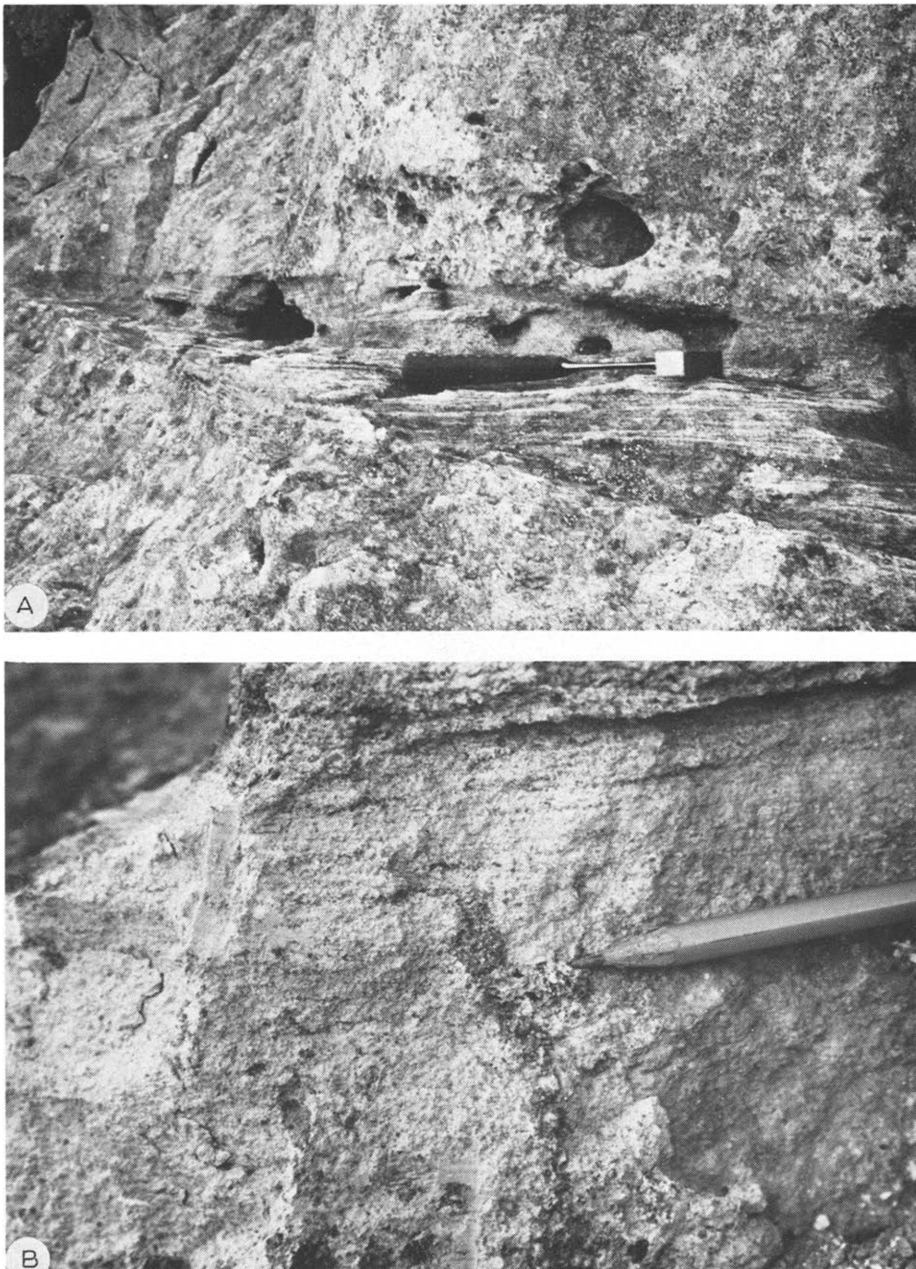

Fig. 4.A. Cross-bedding in distal ash cloud deposit near White Rock. Current is from left to right. Note trough in surge layer to left of hammer. Hammer is near crest. Fine-grained basal layer of unit 2 above surge deposit is poorly developed at this locality. Large dark fragment (5 cm diameter) is pumice. B. Crystal- and lithic-rich gas-escape structure, 1—2 cm wide, extends from top of cooling unit 1 into laminated surge deposits and ends or extends into a crystal-rich lamination of the surge deposit.

("glowing avalanche") and an overriding ash cloud ("glowing cloud"). The ash cloud apparently segregates from the top of the flow during movement and may become detached and flow independently. Ash cloud deposits (Crandell and Mullineaux, 1973, pp. 19—20) at Mount St. Helens, Washington, are massive, planar-bedded or have foreset bedding. They thicken and increase in elevation outward from valley-fill pyroclastic flow assemblages, are finer-grained (sand-size ash) than the air-fall or flow deposits, and consist mostly of non-vesicular material.

The distribution and thickness of the ash cloud deposit on top of cooling unit 1 (Fig. 2) and the inhomogeneities within the top of unit 1 (pumice swarms and surges) are interpreted to be caused by two main factors: (1) discontinuities in concentration in a transitional zone near the top of the partially fluidized pyroclastic flow and the overriding low-concentration ash cloud, and (2) a lobe-and-cleft configuration highly characteristic of advancing density currents (Fisher, 1977, pp. 1295—1296). Fig. 5, based upon field measurements in cooling units of the Bandelier Tuff, illustrates the gradual separation of the ash cloud from the flow. The surge begins to form after the flow has moved some distance, increases in thickness at intermediate distances from the source or from the margins of flow lobes, and pinches out at the distal edge of flow units.

A lobe-and-cleft configuration of pyroclastic flows (Fig. 6) gives evidence of internal vortices extending behind an advancing front. This contention is supported by observations of Taylor (1958, p. 41) at Mount Lamington that "both topographic obstacles and *unrelated turbulence* (emphasis mine) produced local changes in direction." Movements not related to topography "were apparently due to the nuées tendency to expand laterally in vortex-like forms . . . " (Taylor, 1958, p. 41). Because increasing concentration damps out turbulence (Fisher, 1971), vortex activity should become increasingly important as concentration decreases upward in a flow. Field relations in the Bandelier Tuff described above may be explained as follows: as the main, high-concentration debris flow-like body of the pyroclastic flow (Sparks, 1976) decelerates, turbulent vortex cells develop in a zone at its top (and in the ash cloud) and continue to shear across the top and deposit discontinuous thin flow-unit lenses or pumice swarms. The vortices expand and cross over one another, and each crudely developed flow unit tends to segregate into high-concentration basal zones with overriding low-concentration

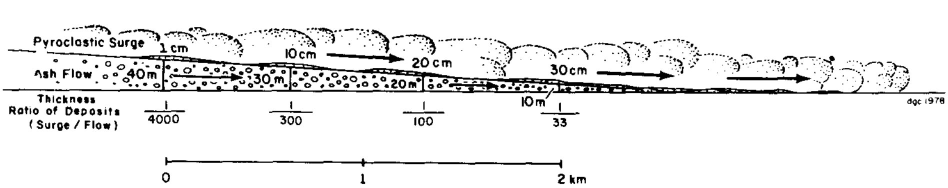

Fig. 5. Diagramatic model of development of cooling/flow unit 1, Tshirege Member, based upon supposition of cleft-and-lobe configuration of advancing flow.

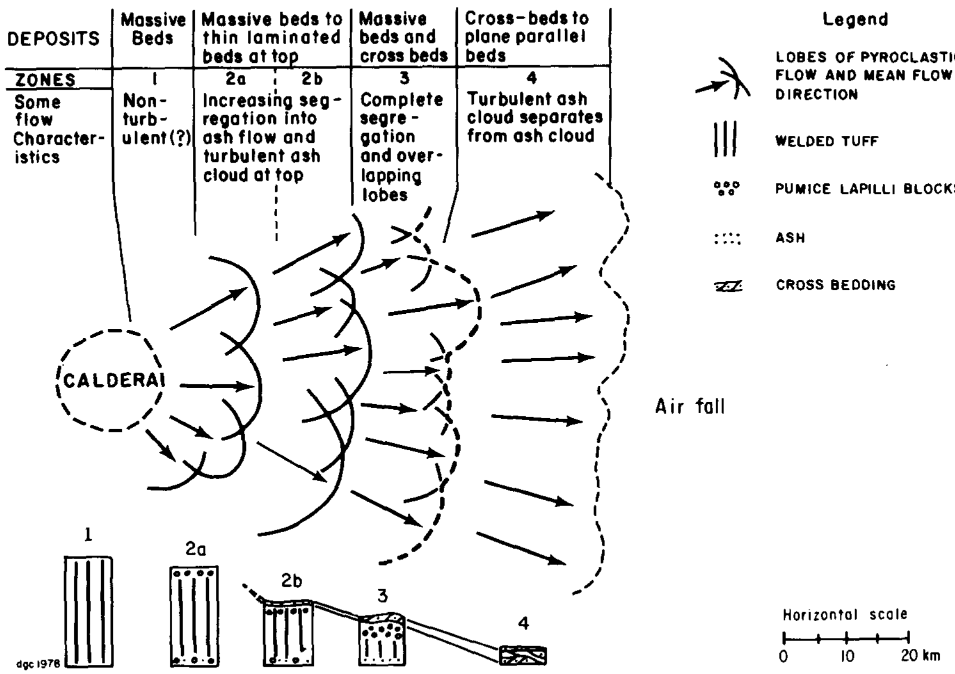

Fig. 6. Emplacement of ash cloud developed from top of pyroclastic flow (cooling unit 1) and relative approximate thickness from field measurements and map relations.

zones as the individual cells deflate. Kuno (1941, p. 147), Ross and Smith (1961, p. 21) and Self (1971) have touched upon this process. Large pumice blocks in the pumice swarms may be "inherited" from blocks that float to the top of the ash flow due to buoyancy effects as it moves. The lobe-like thickening and thinning of the surge deposit shown in Fig. 3 may be explained by greater vortex activity resulting from lower concentration of the surge.

The density separation of a moving pyroclastic flow may be compared to a fluidization spectrum (Leva, 1959, fig. 2-3). The main flow body is likened to the dense phase (high concentration) with minimum "voidage". Particle support modes of the dense phase may correspond to parts of the Middleton and Hampton (1976) model for sediment-gravity flows (Fig. 7). However, within the fluidization spectrum, there is a narrow "critical zone" transitional between the dense phase and dilute phase where voidage increases sharply (concentration drops over a narrow range of gas velocity) and textural discontinuities develop. This is also shown by Wen and Galli (1971, figs. 16.2 and 16.3) for horizontal solid/gas transport in pipes, where dune- to slug-flow develops. Slug flow, however, may not have a counterpart in the solids/water systems described by Middleton and Hampton (1976). Segregation of large-particle pumice and ash to develop pumice swarms might be a type of slugging, although slug flow sensu stricto may not develop in unconfined flows. The

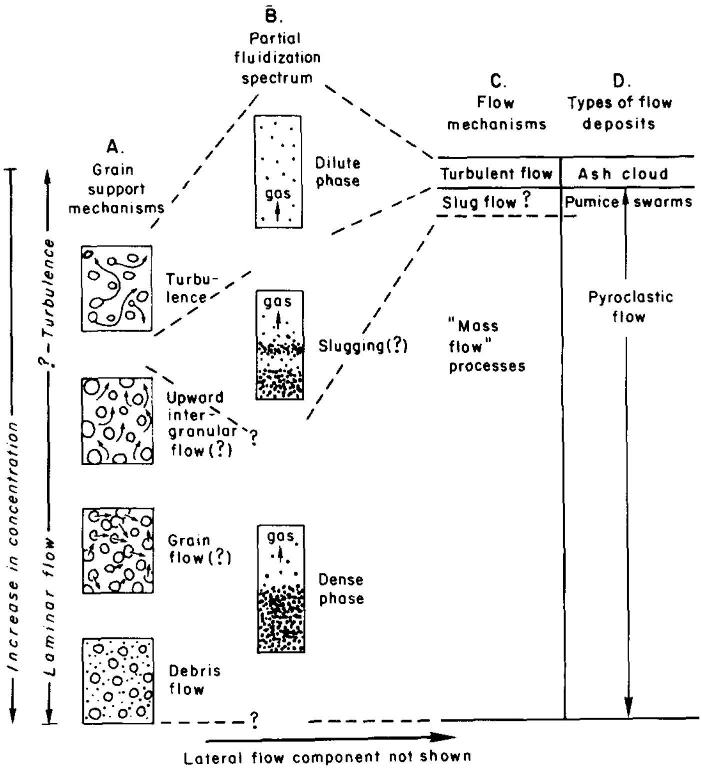

Fig. 7. Possible relationship of grain support mechanism model proposed by Middleton and Hampton (1976), A, with fluidization spectrum, B, and relationship to flow mechanisms, C, and resulting deposits, D.

dilute phase, with maximum voidage (low concentration), is likened to the pyroclastic surge at the top (see Fig. 7). The facies relationships of pyroclastic surge deposits (Wohletz, 1977) indicates that systematic changes in grain support mechanisms occur laterally as a moving flow deflates.

DEVELOPMENT OF PYROCLASTIC SURGE DEPOSITS

A model of flow-unit zones formed by the passage of a single pyroclastic flow should take into account the different ways that pyroclastic surges develop and the fact that they may occur at the top as well as the base of a flow unit. However, the reason why ground surge deposits may occur at the base of pyroclastic flow layers requires further explanation. The following hypothesis is based upon the eruption column collapse model for the origin of pyroclastic flows (Hay, 1959; Sparks and Wilson, 1976; Sparks et al., 1978).

Model for ground surge deposits

If an eruption column is heavier than air and does not become turbulently mixed with it, collapse occurs. This depends upon water (vapor) content, CO_2 content, vent radius and the particle concentration (solids/gas ratio) (Wilson, 1976). Although particle concentration and distribution of particles within eruption columns cannot be studied directly, these factors are very important, because particle concentration influences the behavior of an eruption column, and the distribution of particles may be inherited from the column and reflected in the deposits of flows formed by column collapse.

Friction between the walls of a volcanic pipe and the rising particulate mass will cause velocity and shear gradients across the pipe and lead to size grading. Geological evidence (Bhattacharji and Smith, 1964; Wilshire, 1961; Coe, 1966; Peterson, 1968; Fisher and Mattinson, 1968) as well as experimental evidence (Bhattacharji, 1967) and theoretical considerations (McBirney, 1963; Komar, 1972) suggest that large fragments in confined pipes and fractures tend to migrate away from solid boundaries. In volcanic pipes, and possibly in the lower parts of vertical eruption columns, this migration is toward the center of the conduit where velocities are higher and shear gradients lower than at the walls of a conduit. Complete mixing could occur if the system became turbulent shortly before or immediately upon emergence where pressure decreases and velocities increase (McBirney, 1963). However, collapse requires relatively high particle concentrations which would inhibit full turbulence until fallback occurred and flow commenced, although even then, full turbulence may not develop. The model requires that a finer-grained sheath around the eruption column becomes partly mixed with air shortly before or as flow commences to produce a low-concentration flow. Continued collapse of the column proceeds from the outer, finer-grained margin toward the interior. Thus, a relatively small-volume, low-concentration turbulent flow precedes a coarser-grained and more voluminous flow representing the interior parts of the eruption column. This model is diagrammatically shown in Fig. 8.

There is photographic evidence to support a model of progressive column collapse. Photographs of the base surge from the Bikini nuclear explosion (Brinkley et al., 1950, fig. 2.43) which was an aerosol of water droplets and gases, show that the surge was forming and the outer margin of the explosion column to be collapsing in downward falling, non-turbulent jets about 11 seconds after the column formed. The downward falling jets are the outward signs that the column has started its descent, the important point being the absence of any indication of marginal turbulence. Collapsing eruption columns at Capelinhos, Azores (Fig. 9), where their exterior sheath of steam has been stripped away by strong winds, show downward falling non-turbulent jets as the base surge develops, very similar to the downfalling jets formed by the subsiding, non-particulate, Bikini explosion column. Fig. 9 also shows that the interior of the column is simultaneously rising within the region where velocities are expected to be the highest. Thus, column collapse com-

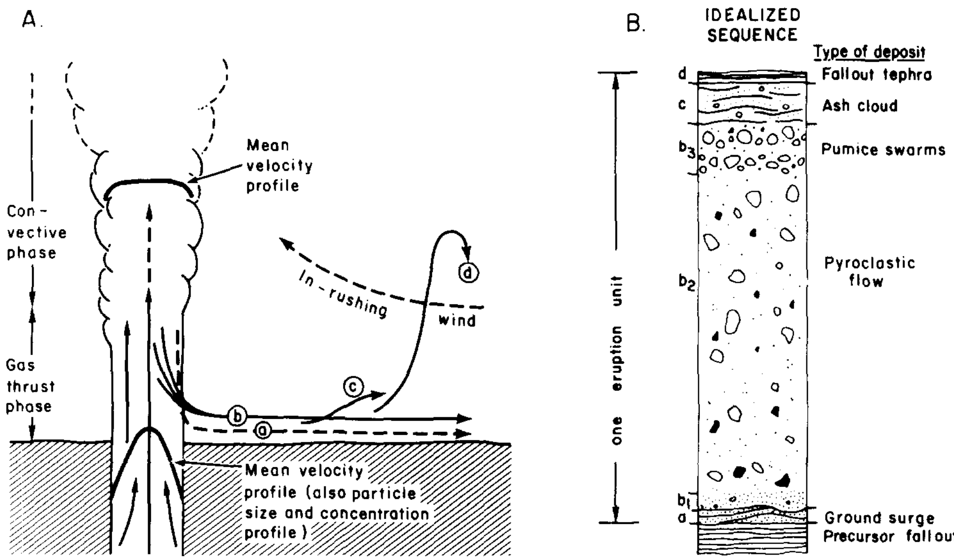

Fig. 8. Eruption column collapse related to idealized eruption unit. Letters *a*–*d* in Fig. 8A correspond to those in Fig. 8B. A. Outer part of column collapses to form a pyroclastic surge (*a*); followed by (*b*) progressive collapse of interior parts to give voluminous, high-concentration pyroclastic flow. Pyroclastic material segregates from surface of flow (dilute phase) to form an ash cloud (*c*). Finest-grained material continues to be elutriated into atmosphere from dilute phase flow (*d*). It falls back on flow deposits or is swept back to join main eruption column by inward rushing atmospheric winds. B. Idealized depositional sequence of one eruption unit showing ground surge deposit (*a*), fine-grained basal layer of pyroclastic flow developed by flowage processes (b_1), main body of the pyroclastic flow representing the main bulk of the collapsed eruption column (b_2), a zone of pumice swarms segregated at the top of the ash flow (b_3), an ash cloud deposit elutriated from the top of the moving pyroclastic flow (*c*) and a thin fallout deposit (*d*).

mences within a short time span, is progressive from its outer margin inward, and appears to occur without significant turbulent mixing with the ambient atmosphere.

Deposits that record column collapse are thin, fine-grained and cross-bedded ground surge deposits followed upward by massive, thick, coarse-grained deposits depicted in the Sparks et al. (1973) model. There is always the possibility, however, that the ground surge is an independently formed pyroclastic surge unrelated to the origin of the pyroclastic flow that lies above it.

A corrollary is that progressive column collapse, with replenishment to the column from progressively deeper parts of a magma chamber, may explain systematic vertical compositional changes in ash deposits (Wright, 1979). Evidence suggests that pyroclastic flows are high-concentration dispersions that move in laminar fashion similar to debris flows (Sparks, 1976) rather than turbulently (Fisher, 1966), and deposition is by "freezing" rather than "grain-by-grain" as in the turbulent flow model. Systematic compositional changes in pyroclastic flows therefore reflect eruption column dynamics in addition to flow dynamics.

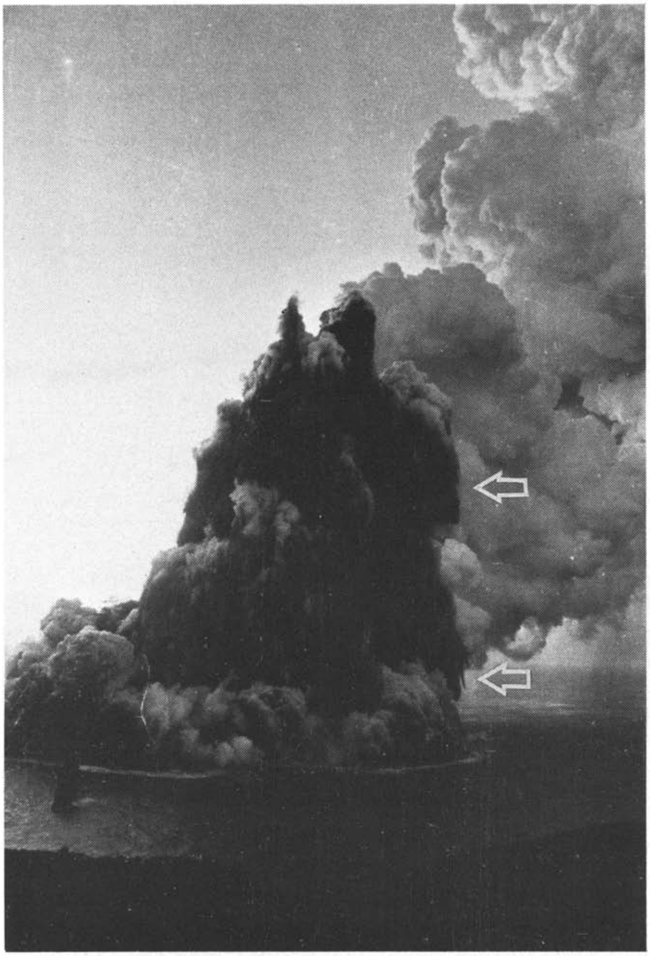

Fig. 9. Capelinhos, Azores, one of its many phreatomagmatic eruptive phases, September, 1957. Steam envelope has been stripped from eruption column by strong winds. Falling jets at right-side edge of eruption column designated by arrows, indicate that the outer margin of the column is subsiding as base surge is developing, while central part of column is rising. Some of the jets, however, could result from large blocks that create a wake of ash and steam behind them. Eruption column is about 400 n high. Photograph by Mr. Othon R. Silveira, Horta, Azores.

MODIFIED IDEAL FLOW-UNIT MODEL

The depositional flow-unit model (Fig. 8) is modified from Sparks et al. (1973) to include (1) minor flow discontinuities at the top of the ash flow (layer b_3), (2) and ash cloud deposit (layer *c*) at the top of the ash flow, followed by (3) fallout tephra at the top (layer *d*). All of the units (except layer *d*) are present in cooling unit 1 (Tshirege Member, Fig. 2) a condition rarely met in single eruption units.

Although only some implications for the presence of pyroclastic surge deposits within pyroclastic flow sequences have been explored herein, their absence, or the presence of one kind but not the other, may be of equal importance in attempts to decipher physical processes that take place within vents, eruption columns and pyroclastic flows.

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REFERENCES

Bhattacharji, S., 1967. Mechanics of flow differentiation in ultramafic and mafic sills. J. Geol., 75: 101—112.
Bhattacharji, S. and Smith, C.H., 1964. Flowage differentiation. Science, 145: 150—153.
Brinkley, S.R., Jr., Kirkwood, J.G., Lampson, C.W., Revelle, R. and Smith, S.B., 1950. Shock from underwater and underground blasts. In: The Effects of Atomic Weapons. Los Alamos Scientific Laboratories, Los Alamos, N.M., pp. 83—113.
Coe, K., 1966. Intrusive tuffs of west Cork, Ireland. Q. J. Geol. Soc. London, 122: 1—28.
Crandell, D.R. and Mullineaux, D.R., 1973. Pine Creek volcanic assemblage at Mount St. Helens, Washington. U.S. Geol. Surv. Bull., 1383-A: 1—23.
Crowe, B.M. and Fisher, R.V., 1973. Sedimentary structures in base-surge deposits with special reference to crossbedding, Ubehebe Craters, Death Valley, California. Geol. Soc. Am. Bull., 84: 663—682.
Crowe, B.M., Linn, G.W., Heiken, G. and Bevier, M.L., 1978. Stratigraphy of the Bandelier Tuff in the Pajarito Plateau; applications to waste management. Los Alamos Sci. Lab., N.M., Informal Rep., LA-7225-MS: 1—57.
Doell, R.R., Dalrymple, G.B., Smith, R.L. and Bailey, R.A., 1968. Paleomagnetism, potassium-argon ages, and geology of the rhyolites and associated rocks of the Valles Caldera, New Mexico. Geol. Soc. Am. Mem. 116: 211—248.
Fisher, R.V., 1966. Mechanism of deposition from pyroclastic flows. Am. J. Sci., 264: 350—363.
Fisher, R.V., 1971. Features of coarse-grained, high-concentration fluids and their deposits. J. Sediment. Petrol., 41: 916—927.
Fisher, R.V., 1977. Erosion by volcanic base-surge density currents: U-shaped channels. Geol. Soc. Am. Bull., 88: 1287—1297.
Fisher, R.V. and Mattinson, J.M., 1968. Wheeler Gorge turbidite-conglomerate series; inverse grading. J. Sediment. Petrol., 38: 1013—1023.
Fisher, R.V. and Waters, A.C., 1970. Base surge bed forms in maar volcanoes. Am. J. Sci., 268: 157—180.
Hay, R.L., 1959. Formation of the crystal-rich glowing avalanche deposits of St. Vincent, B.W.I. J. Geol., 67: 540—562.
Komar, P.D., 1972. Flow differentiation in igneous dikes and sills: profiles of velocity and phenocryst concentration. Geol. Soc. Am. Bull., 83: 3443—3448.

Kuno, H., 1941. Characteristics of deposits formed by pumice flows and those by ejected pumice. Tokyo Univ. Earthq. Res. Bull., 19: 144—149.
Leva, M., 1959. Fluidization. McGraw-Hill, New York, N.Y., 327 pp.
McBirney, A., 1963. Breccia pipe near Cameron, Arizona: discussion. Geol. Soc. Am. Bull., 74: 227—232.
Middleton, G.V. and Hampton, M.A., 1976. Subaqueous sediment transport and deposition by sediment gravity flows. In: D.J. Stanley and D.J.P. Swift (Editors), Marine Sediment Transport and Environmental Management. John Wiley and Sons, New York, N.Y., pp. 197—218.
Peterson, G.L., 1968. Flow structure in sandstone dikes. Sediment. Geol., 2: 177—190.
Ross, C.S. and Smith, R.L., 1961. Ash-flow tuffs; their origin, geologic relations and identification. U.S. Geol. Surv. Prof. Paper, 336: 1—77.
Ross, C.S., Smith, R.L. and Bailey, R.A., 1961. Outline of the geology of the Jemez Mountains, New Mexico. N.M. Geol. Soc. 12th Field Conf., Albuquerque Country.
Self, S., 1971. The Lajes ignimbrite, Ilha Teceira, Azores. Comun. Serv. Geol. Port., LV: 165—180.
Smith, R.L., 1960a. Ash flows. Geol. Soc. Am. Bull., 71: 795—842.
Smith, R.L., 1960b. Zones and zonal variations in welded ash flows. U.S. Geol. Surv. Prof. Paper, 354-F: 149—159.
Smith, R.L. and Bailey, R.A., 1968. Resurgent cauldrons. Geol. Soc. Am. Mem., 116: 613—662.
Sparks, R.S.J., 1975. Stratigraphy and geology of the ignimbrites of Vulsini volcano, Central Italy. Geol. Rundsch., 64: 497—523.
Sparks, R.S.J., 1976. Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. Sedimentology, 23: 147—188.
Sparks, R.S.J. and Wilson, L., 1976. A model for the formation of ignimbrite by gravitational column collapse. J. Geol. Soc. London, 132: 441—451.
Sparks, R.S.J. and Walker, G.P.L., 1973. The ground surge deposit: a third type of pyroclastic rock. Nature, Phys. Sci., 241: 62—64.
Sparks, R.S.J. and Walker, G.P.L., 1977. The significance of vitric enriched air-fall ashes associated with crystal-enriched ignimbrites. J. Volcanol. Geotherm. Res., 2: 329—341.
Sparks, R.S.J., Self, S. and Walker, G.P.L., 1973. Products of ignimbrite eruptions. Geology, 1: 115—118.
Sparks, R.S.J., Wilson, L. and Hulme, G., 1978. Theoretical modeling of the generation, movement, and emplacement of pyroclastic flows by column collapse. J. Geophys. Res., 83: 1727—1739.
Taylor, G.A., 1958. The 1951 eruption of Mount Lamington, Papua. Aust. Bur. Miner. Resour. Geol. Geophys. Bull., 38: 1—117.
Walker, G.P.L., 1972. Crystal concentration in ignimbrites. Contrib. Mineral. Petrol., 36: 135—146.
Waters, A.C. and Fisher, R.V., 1971. Base surges and their deposits: Capelinhos and Taal volcanoes. J. Geophys. Res., 76: 5596—5614.
Wen, C.Y. and Galli, A.F., 1971. Dilute phase systems (Chapter 16). In: J.F. Davidson and D. Harrison (Editors), Fluidization. Academic Press, London and New York, N.Y., pp. 677—710.
Wilshire, H.G., 1961. Layered diatremes near Sydney, New South Wales. J. Geol., 69: 473—484.
Wilson, L., 1976. Explosive volcanic eruptions, III. Plinian eruption columns. Geophys. J. R. Astron. Soc., 45: 543—556.
Wohletz, K.H., 1977. A model of pyroclastic surge. M.S. Dissertation, Arizona University, 175 pp.
Wright, J.V., 1979. Formation, transport and deposition of ignimbrites and welded tuffs. Ph.D. Dissertation, Imperial College, London, 451 pp.