Journal of Volcanology and Geothermal Research, 17 (1983) 65—88
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

IGNIMBRITE TYPES AND IGNIMBRITE PROBLEMS

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(Received August 19, 1982; Revised and accepted February 5, 1983)

ABSTRACT

Walker, G.P.L., 1983. Ignimbrite types and Ignimbrite Problems. In: M. F. Sheridan and F. Barberi (Editors), Explosive Volcanism. J. Volcanol. Geotherm. Res., 17: 65-88.

A spectrum of ignimbrite emplacement types exists, ranging from the "conventional" high-aspect ratio (H.A.R.I.) type, emplaced relatively quietly and passively in valleys, to the low-aspect ratio (L.A.R.I.) type, emplaced cataclysmically. Features of the L.A.R.I., such as a remarkable ability to scale mountains and cross open water and a strong fines-depletion of part of their deposits, stem from a high flow velocity which may result from an extremely high magma discharge rate. Being less rare than large-volume H.A.R.I. eruptions covering the same area, L.A.R.I. eruptions are a much more immediate volcanic hazard. Being thin and inconspicuous, a L.A.R.I. may easily be overlooked when determining the past record of a volcano.

Another ignimbrite spectrum depends on variations in particle viscosity during emplacement and extends from the low-grade (water-cooled?) ignimbrite which is totally non-welded even if >50 m thick, to the high-grade (superheated?) one which is densely welded even if <50 m thick. Problems of air-cooling and water-cooling of ash flows need to be tackled, and it may be necessary to recognize strongly cooled ash flows which were emplaced in part at <100°C.

One problem of ignimbrite eruptions is the origin of the extensive associated ash fall, comparable in volume to the ignimbrite. This ash may be: (a) pre-ignimbrite Plinian pumice; (b) co-ignimbrite ash, containing material lost from both the eruptive column and ash flow; (c) phreatoplinian, due to the entry of significant amounts of water into the vent; (d) phreatoplinian co-ignimbrite, due to explosions at rootless vents where ash flows enter water from land.

Another problem is the origin of associated well-sorted and sometimes wavy-bedded deposits. These deposits may be from: (a) base surges, related to either the collapsing column or entry of water to the vent; (b) base surges, due to explosions at rootless vents where ash flows enter water from land; (c) fines depletion in, and deposition from, the strongly fluidized head of the ash flow; (d) standing waves in a high-velocity ash flow; (e) pyroclastic surges springing from the ash flow; (f) superficial turbulence in the topmost fractions of the ash flow as it comes to rest.

Major problems concern the relationship between pyroclastic surges and flows, the ability of one to change into the other, and the distinction between their deposits. Thus, the May 18th 1980 "directed blast" of Mount St. Helens is widely regarded as a surge, yet produced deposits having many characteristics of a L.A.R.I.. Understanding the behaviour of the fine ash and dust fraction is thought to be critical to the solution of these problems.

INTRODUCTION

The unravelling of the origin of ignimbrites, or ash-flow tuffs as the welded ones are often called, is one of the outstanding success stories of modern volcanology. This work focused attention on features such as the welding and crystallization zonations shown by ignimbrite sheets, and the association of major sheets with major calderas (e.g., Marshall, 1935; Smith, 1960a, 1960b; Ross and Smith, 1960; Boyd, 1961). It was recognized how voluminous some ignimbrite units are and, incidentally, partly resolved the dispute on whether granites can have a magmatic origin. More recent studies are using ignimbrites to explore physico-chemical conditions and magma zonations within magma chambers (e.g., Hildreth, 1979, 1981; Smith, 1979).

An important direction of recent and current research is focusing attention on the emplacement mechanisms of ignimbrites, and it is this direction which is reviewed in the present paper. This approach includes studies on the field relations of young ignimbrites and their response to the pre-existing topography; it also places much reliance on granulometric and component analyses to document features such as fines depletion and crystal concentration in pyroclastic deposits as a means of understanding the physical processes which operate to produce them. These studies have been co-ordinated with fluidization experiments and numerical modelling towards the same end (e.g., Wilson, 1980).

This direction of research is actively being pursued because it is so abundantly clear that there is still much that is not understood. The present article is therefore a progress report, discussing concepts still only partially propounded or not yet fully tested, and serves as a guide to some of the "grey" areas of incomplete knowledge. The research is, inter alia, radically changing the diagnostic criteria for the different pyroclastic types, and is very relevant to volcanic hazards evaluation.

Few words in volcanology have had so chequered a history and been used in so many different ways as "ignimbrite", which is why "ash-flow tuff" was introduced in its place. "Ignimbrite" is, however, a convenient word and here it is defined as a pyroclastic deposit or rock body, made predominantly from pumiceous material, which shows evidence of having been emplaced as a concentrated hot and dry particulate flow. "Ash flow" is here retained to denote the pyroclastic flow when it is moving. As with many definitions in geology, it is difficult to allow for all contingencies by devising an all-embracing definition; thus, as discussed later, there are grounds for including as "ignimbrites" some deposits which may not have been hot when they were emplaced.

Ignimbrites are associated with nearly half of the world's volcanoes. They embrace all but the most mafic compositions. They occur in geological formations of all ages. They range in size over at least five orders of magnitude, and the largest are the greatest eruptive units known, the formation of which would be cataclysmic events on a scale too big to be envisaged clearly by modern man.

HIGH- AND LOW-ASPECT RATIO IGNIMBRITES

A convenient non-genetic means of describing the overall geometry of rock units is by means of the "aspect ratio", applicable, for example, to extrusive lava bodies, pillows as seen in cross-sections of pillow lava, and deformed juvenile clasts (fiamme) in welded tuffs. The aspect ratio is V/H, where V is a vertical dimension (e.g., the average thickness), and H is a horizontal dimension (e.g., the diameter of a circle covering the same areal extent as the rock unit).

It is known that V/H for ignimbrites, as for lava extrusions, covers a wide range in values (Fig. 1); it varies from about 1/400 for the Valley of Ten Thousand Smokes (V.T.T.S.) ignimbrite to about 1/100,000 for the Taupo and Koya ignimbrites (Ui, 1973; Walker et al., 1980a).

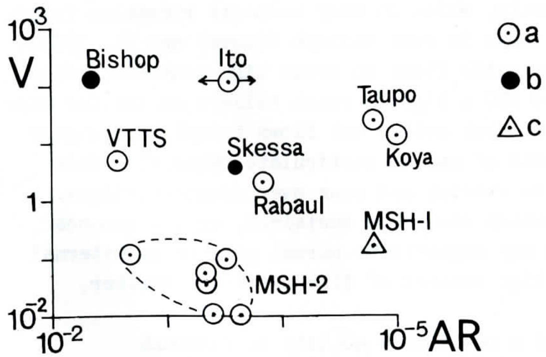

Fig. 1 Plot of volume (V, in km^3) against aspect ratio (AR) for a number of ignimbrites and related deposits. a - mainly non-welded; b - mainly welded; c - relatively poor in pumice; VTTS - Valley of Ten Thousand Smokes; MSH - Mount St. Helens (1 - "directed blast" of May 18, 1980, from Moore and Sisson 1981; 2 - post climactic 1980 flows, from Rowley et al., 1981). The arrows for Ito express uncertainty, whether to take the area known to be occupied by ignimbrite, or the area enclosed by an envelope drawn around the most outlying outcrops.

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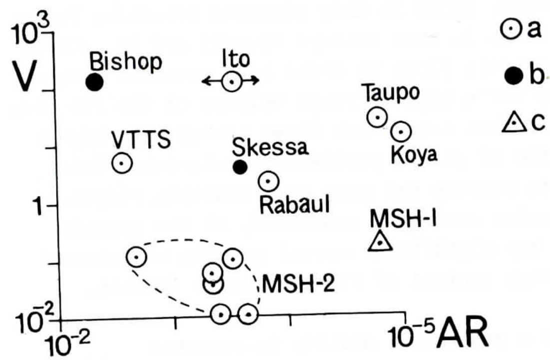

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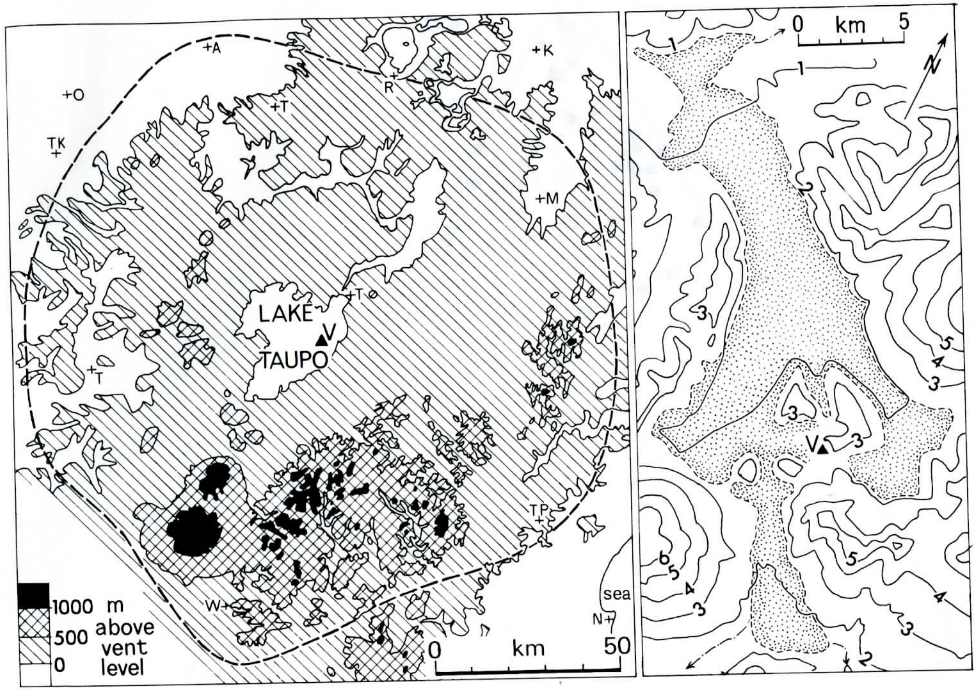

Fig. 2 Contrasted response to the topography of a low-aspect ratio ignimbrite (left) and a high-aspect ratio ignimbrite (right); note the 6-fold difference in scale of the two maps. V - vent.
Left: the Taupo ignimbrite (Walker et al., 1981a); the dashed line is an envelope enclosing all the known outcrops. Shading indicates land higher than the level of Lake Taupo; there is evidence that the vent was near lake level at the time of the eruption.
Right: the Valley of Ten Thousand Smokes ignimbrite (Fenner 1925; Curtis 1968). Contour interval to 300 ft. (= approx 100 m).

immediately before the Taupo ignimbrite. This dispersal also indicates a high energy discharge rate (Wilson et al., 1978; Settle, 1978).

A number of other features of low-aspect ratio ignimbrites may be correlated with the high flow velocity (Fig. 3). One is the conspicuous development of fines-depleted "layer 1" deposits (F.D.I.) underlying normal ignimbrite; attributed to the highly fluidized condition of the flow head resulting from a high gas throughput. Most of this gas was presumably ingested air. The fact that these deposits are best developed where the flow traversed forests suggests that surface roughness promoted air ingestion, and that gases generated by the heating and combustion of ingested macerated vegetation may also have made a

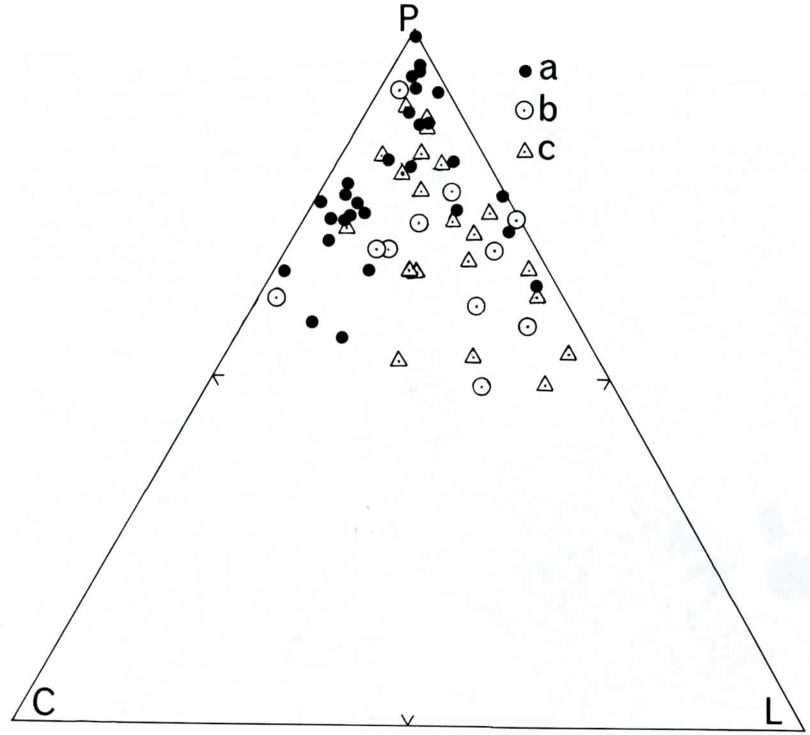

Fig. 3 Composition plot of 62 ignimbrites showing weight of pumice plus shards (P), free crystals (C), and lithics (L), for different petrological types: a - rhyolite; b - dacite, andesite; c - trachyte, phonolite. One sample from each ignimbrite was taken at random, the percentage of components in classes 1/4 mm and coarser was determined, and material finer than 1/4 mm was assumed to consist of pumice. In all samples pumice is the main constituent, but either crystals or lithics can reach about 40%. The content of free crystals is generally significantly higher than the magmatic content.

significant contribution (Walker et al., 1980b). The fines-depleted layer 1 deposits include the pumice-rich F.D.I. variant attributed to forward jetting of parts of the flow head (Walker et al., 1981b; Wilson and Walker, 1982), and the more common "heavies-enriched" ground layer variant attributed to sedimentation of heavy particles in the flow head (Walker et al., 1981c). Various segregation features are also well developed including a pronounced upward concentration of light particles which were translated by laminar flowage into a pronounced lateral variation (Walker and Wilson, 1982).

One corollary of the foregoing is that, if ash flows can deposit well-sorted fines-depleted material and produce landscape-mantling veneer deposits, the diagnostic criteria for the various pyroclastic types need to be revised: good sorting and mantle bedding are not attributes of fall deposits alone. Again, it is now known that accretionary lapilli similar to those in rain-flushed ash falls occur in many ignimbrites. Care is also needed when distinguishing between welded tuffs of air fall and flow origin. In consequence, diagnostic criteria must continually be updated as pyroclastic types become better characterized.

Another corollary of the foregoing is that the distance travelled by a low-aspect ratio ash flow is set by the quantity of material in the flow. This is because all the time on its journey outwards from the vent the flow loses material as it deposits layers of fines-depleted and veneer-type material on the ground over which it passes, and as dust escapes to the air. The flow travels outwards until all the material has been used up. A crude analogy may be drawn to a rolled carpet, which, when given a lateral push, unrolls to form a layer on the ground, and continues moving until it is fully unrolled.

A third corollary is that, because parts of a L.A.R.I. represent deposits from an ash flow and do not consist of the ash flow itself in the position where it came to rest, their thickness and grain size at any given point may bear little relationship to the thickness or grain size of the ash-flow when it passed over that point.

The commonly held view of ignimbrite formation envisages the ash flow as coming to rest en masse, so that the thickness and structure of the resulting ignimbrite are similar to those of the ash flow. In these respects, an ignimbrite is thus similar to a lava flow. This view is probably valid for some ignimbrites, but it is manifestly not valid for the L.A.R.I.. Thus, a veneer deposit a few centimeters thick may record the passage of an ash flow many tens of meters deep, and a well-sorted and strongly fines-depleted layer 1 may be deposited from an ash flow which was itself unsorted and carried a high content of fine material.

The volcanological literature has tended to focus attention on the thick ignimbrites at the expense of the thin ones. The idea that a pyroclastic layer only a few centimeters thick (as found in some L.A.R.I. examples) may have an ash flow origin is still a somewhat novel one. Very few examples of ignimbrites under 1 m thick have yet been documented, but such thin flows seem nevertheless to be very common. Thus, upwards of ten separate flows ranging from 0.1 to 1.5 m thick are found toward the top of the Mangaone Plinian pumice deposit in New Zealand. The Vulsini D ignimbrite in Italy (Sparks, 1976) and the Rio Caliente ignimbrite in Mexico (Wright, 1982) are examples of the common multiple type of ignimbrite which is built of an accumulation of many individual, thin flow units.

HAZARDS FROM LOW-ASPECT RATIO IGNIMBRITES

Hazard from eruptions of small-volume L.A.R. flows is more immediate than that from eruptions of large-volume H.A.R. flows of the more "conventional" type which have the same destructive potential. One reason is that eruptions of

L.A.R. flow are much less rare: there have been not less than five in New Zealand, Kyusyu and Rabaul in the past 6000 years. Furthermore, the disastrous eruptions of Mt. Pelée 1902 and Mt. St. Helens 1980 produced some deposits which, though too poor in pumice to be called ignimbrite, are closely akin to L.A.R.I.s. The L.A.R.I., being thin, inconspicuous, and readily eroded, may easily be overlooked when making a stratigraphic study of the past record of a volcano. The study of L.A.R.I.s is still in an early stage and the full capabilities of volcanoes to produce them are not yet established. Eruption of a moderately large-volume L.A.R.I. comparable to deposits at Taupo or Koya would undoubtedly be a major disaster to any country, and because of the large quantity of released ash would have repercussions throughout the hemisphere.

To reiterate, the thickness of a deposit at any point is no guide to the thickness of the ash flow that passed that point and hence to the destructive potential of the flow. This is abundantly clear at Mt. St. Helens and St. Pierre (Martinique) where massive demolition of forest or buildings took place yet where the accumulated thickness of the deposit is only tens of centimeters.

HIGH- AND LOW-GRADE IGNIMBRITES

It is a familiar fact that one ignimbrite may be totally non-welded whereas another having the same thickness may be densely welded more or less from bottom to top. It is convenient to designate as "low-grade" those ignimbrites which are totally non-welded even where they are 50 m or more thick, and as "high-grade" those which are densely welded even where they are less than 5 m thick. The dependence of welding on the viscosity of the non-crystalline juvenile particles at the time of deposition is well established from the numerical modelling of Kono and Osima (1971) and Riehle (1973). What is uncertain is the reason why in some ignimbrites the particle viscosity at that time was more than about 10^{15} poises, whereas in others having a similar composition the viscosity was less than about 10^{10} poises.

A first possible explanation for this variation is that the grade reflects the initial temperature of the magma immediately prior to eruption. It is a fact that many high-grade ignimbrites are aphyric or nearly so, indicating that the magma was near the liquidus temperature. Examples are the Skessa tuff in Iceland (Walker, 1962) and the Walcott tuff in Idaho, both of which have a phenocryst mineralogy indicative of relatively hot and dry magmas. However, exceptions occur: the Cimino ignimbrite in Central Italy has a fairly high grade but carries nearly 50% of crystals. Conversely, some ignimbrites are practically aphyric yet are of low-grade type; an example is the fairly low-grade Rio Caliente ignimbrite in Mexico.

A second possible explanation is that low-grade ignimbrites suffered appreciable cooling during eruption. An example is the Rabaul ignimbrite which had a high magmatic temperature when quenched (Heming, 1974; Heming and Carmichael, 1973), yet is of fairly low-grade type. The eruptive column is one place where cooling might occur, mainly by thermal exchange with indrawn air.

Sparks and Wilson (1976) found that ignimbrites preceded by a Plinian phase tend to be less welded than those not preceded, and suggested that the former resulted by collapse from a high column and were more cooled. Cooling by as much as 300°C could occur in the collapsing column (Sparks et al., 1978).

Another place where heat loss could occur is from the head of the ash flow. Boyd (1961) calculated that heat loss from the active flow is small, but loss could be considerable in strongly fluidized examples where there is a high throughput of ingested air in the head. Any surface water would also contribute to the cooling, but ingested vegetation might act in the opposite direction and contribute some heat if sufficient oxygen for combustion could gain access to it. The informally named "Morrinsville ignimbrite" in New Zealand (Walker and Wilson, 1982) shows some evidence for having been cooler at its far distal end after travelling 200 km than it was nearer source, but the author does not know of any well documented example of an ignimbrite that markedly changes grade laterally.

The view could be taken that these various kinds of heat loss are inadequate to account for the observed variations in grade, and recourse then be taken to more drastic solutions: the high-grade ignimbrites stem from superheated magma, and low-grade ignimbrites develop where the magma has been water-cooled. Consider the second. Phreatomagmatic eruptions are those in which sufficient water (either surface water or groundwater) enters the vent to modify significantly the character of the eruption and the nature of the resulting ash deposit (see Sheridan and Wohltez, this volume). It is not the absolute flux of water into the vent that is important: it is the ratio of the water to magma flux. Thus, Plinian eruptions produce coarse pumice deposits and are generally regarded as characterizing dry vents. There may, however, be a considerable influx of water into the vent, but the Plinian charcter is preserved if the water flux is small in comparison with the magma flux. A phreatomagmatic eruption is one in which the water flux is sufficiently large relative to the magma flux to have a significant effect on the eruption.

Some low-grade ignimbrites may have come from an eruption column in which significant water-cooling of the juvenile material occurred at a water flux which was insufficient to generate a phreatoplinian column. One gram of water heated to steam at 100°C can cool 10 g of rhyolitic magma by 250°C, sufficient to increase the magma viscosity by more than three orders of magnitude and produce a significant decrease in grade of the resulting ignimbrite. The Oruanui ignimbrite in New Zealand is a possible example (Self, this volume). It lacks the usual field evidence for a high temperature (e.g., welding or the presence of carbonized plant remains), and its association with a particularly widespread phreatoplinian ash (Self and Sparks, 1978) testifies to the involvement of water in the eruption.

Generally the larger pumice clasts in ignimbrite lack jointing, and in this respect they contrast with pumice-fall deposits in which each of the larger pumice clasts readily breaks along its own system of cooling joints. The explanation is that the pumice clasts in ignimbrite were enclosed in a hot

matrix and cooled slowly together with the matrix, whereas in a fall deposit each pumice clast cooled more or less independently of the others in the air.

In some ignimbrites there is clear evidence that the larger clasts were much hotter than the matrix. Thus in the 1883 ignimbrite of Krakatau, the larger pumice show a pink thermal coloration, contrasting with the uniformly white or grey color of the matrix, and each pumice lump has its own system of cooling joints showing that it cooled by loss of heat into the matrix. Breadcrust blocks, such as occur in part of the Rio Caliente Ignimbrite (Walker et al., 1981c) and in several New Zealand ignimbrites, carry a similar connotation: the breadcrusted structure was caused by cooling due to a loss of heat into a cooler matrix. Whether the matrix in the Krakatau example was water-cooled is speculative, but the possibility that it was so cooled clearly exists.

Many high-grade ignimbrites show rheomorphic structures, normally confined to the basal part of rather thick units. Rheomorphism results when the ash particles coalesce to form a reconstituted lava body which then flows downslope. The finest rheomorphic structures in thin eruptive units are shown not by ignimbrites, but by welded tuffs of fall origin, exemplified by those of Pantelleria (Wright, 1980; Wolff and Wright, 1981); and the reason for this is clear. For an ash flow to be generated at the site of column collapse, the magma viscosity must be sufficiently high that the particles do not stick together, otherwise a welded ash-fall tuff forms around the vent. If indeed the particle viscosity is sufficiently low, the whole mass flows away from the vent as a lava flow, as often happens at the base of lava fountains in Hawaii. The point is that if the ash particles had been sufficiently fluid to flow as a thin rheoignimbrite, it is unlikely that an ash flow would have formed in the first place. Basaltic ignimbrites are scarce for the same reason: basaltic magma in general, is too fluid to permit ash flows to form.

THE LAHAR-IGNIMBRITE BOUNDARY

There is a semantic problem attached to certain particulate flows which lack evidence for having been hot when emplaced. Conventionally, these would be termed lahars or mudflows although it is possible that their mobility was due to fluidization by gas. An example is the Morrinsville ignimbrite which in some distal outcrops shows the pink thermal coloration common to many non-welded ignimbrites but in the most distal outcrops lacks this feature. This ignimbrite shows a gradual and progressive change in characteristics out to these distal parts and there is no reason to suspect that the continuous phase was anything but gas, albeit more or less cold (Walker and Wilson, 1982).

It is here proposed that usage of the terms "ash flow" and "ignimbrite" should logically be extended to embrace all examples in which there is reason to believe that the continuous phase was gas, the kind of evidence in favor of gas being the common presence of gas elutriation pipes and fines-depleted layer 1 deposits. "Lahar" and "mudflow" should be restricted to examples where there is reason to believe that the continuous phase was liquid water, the kind of evidence being the capacity of lahars (because of their strength) to carry coarse lithic debris, the inverse coarse-tail grading sometimes shown by this debris, and the common presence of vesicles in the muddy matrix.

CO-IGNIMBRITE AND RELATED ASH-FALLS

Recent studies of young pyroclastic deposits have shown that major ignimbrites are characteristically associated with ash-fall deposits of comparable volume to the ignimbrite. Examples are the Campanian Tuff (Italy), the Toba Tuff (Sumatra), the Bishop Tuff (California), the Ito and Koya ignimbrites (Japan), the Los Chocoyos ignimbrite (Guatemala), and the Rotoiti and Oruanui ignimbrites (New Zealand), all of which have ignimbrite and associated ash-fall volumes of tens of hundreds of cubic kilometers. The ash-fall deposits are characteristically widely dispersed, examples being the Toba Ash found to 2500 km west of Sumatra (Ninkovich et al., 1978), and deep sea ashes found 2000 km east of New Zealand (Ninkovich, 1968) which are probably related to major Quaternary ignimbrites in the Taupo Zone.

Impressed with the evidence for crystal enrichment in ignimbrites (Hay, 1959; Lipman, 1963; Walker, 1971) which could be accounted for by the selective loss of vitric ash, Sparks and Walker (1977) proposed that the "lost" vitric material resided in the associated widely dispersed ash-fall beds, and that these ashes of "co-ignimbrite" type were thus complementary to ignimbrite. From more recent work it has appeared that, while this interpretation may be valid in some instances, there is another way to account for crystal enrichment in ignimbrite, and there are several possible alternative origins for the ash-fall.

First, an alternative way of accounting for the "lost" vitric ash, demonstrated at Taupo (Walker and Wilson, 1982), is that it was removed from the proximal ignimbrite (to produce the strong crystal enrichment observed there), and is contained in the predominantly very fine and crystal-poor distal ignimbrite. The mechanism is a simple one: light vitric material is preferentially concentrated towards the top of the moving ash flow, and by laminar flowage this top part came to travel farther and was translated to the distal part of the ignimbrite. It is not known how common this mechanism is, but the distal part being in general thin and less likely to be welded, tends to have a lower survival potential than the relatively crystal-rich main part of an ignimbrite and may thus be lost or escape notice. The distal part of the Morrinsville ignimbrite is so fine and lacking in evidence for having been hot that it could easily fail even to be identified as ignimbrite.

Second, one alternative origin for the extensive ash-fall is that it is the fine distal part of a pre-ignimbrite Plinian pumice fall. Most studies of Plinian pumice deposits (with the notable exception of some Icelandic studies, Thorarinsson, 1954, 1981; Thorarinsson et al., 1959; Larsen and Thorarinsson, 1977; Persson, 1966a, 1966b, 1967) have concentrated on the well preserved and impressively coarse near-vent parts. Mass budget studies from crystal contents have revealed that Plinian deposits may be much more voluminous and may include

a much more extensive fine distal part than was generally thought (Walker, 1980, 1981b). The ash fall associated with the Bishop Tuff (W. Hildreth, pers. comm.) and one lobe of the ash associated with the Los Chocoyos ignimbrite (W. I. Rose, pers. comm.) agree more closely in chemical composition with the pre-ignimbrite Plinian pumice than with the ignimbrite itself.

Another alternative origin for the ash-fall is that it is of phreatoplinian type. There is evidence that the Oruanui and Rotoehu ashes are of this type, and their remarkably wide dispersal shows that the phreatomagmatic explosions were of quite exceptionally great power. The former are regarded as originating at the primary vent (Self and Sparks, 1978), and the latter at rootless vents where pyroclastic flows entered water from land (Walker, 1979). The rate of decay in thickness and grain size of both ashes is so low as to make location of the vent position extremely imprecise and hence identification of the origin uncertain. The presumed position of the Oruanui primary vent is submerged beneath Lake Taupo, and of the Rotoehu is deeply buried beneath younger volcanic rocks.

The origin of the great paroxysmal explosions of Krakatau in 1883 is still in doubt. It is known that each major explosion coincided with the formation of an ignimbrite flow unit (Williams, 1941; Self and Rampino, 1981). One possibility is that the explosions resulted from the entry of ash flows from land into the sea, as was postulated for the Rotoehu Ash.

It may be significant that most of the major ignimbrites which are associated with a widespread ash-fall deposit occur near the sea or a large lake and have calderas now flooded by the sea or lake, examples being Krakatau, Aira (source of the Ito ignimbrite), Kikai (source of the Koya Tuff), and Taupo (source of the Oruanui Ash). All of these are situations where the extensive ash fall could result from the interaction of magma with water.

HAZARDS FROM EXTENSIVE ASH-FALL

The extensive ash fall generated in a major ignimbrite eruption might cause more disruption than the ignimbrite itself because of the great area encompassed. In known examples the ash-fall exceeds 10 cm thick over 10^5 to 10^6 km^2. For example, the Oruanui ash (Self and Sparks, 1978) covered half of New Zealand to this thickness, and the Akaroa ash (Machida and Arai, 1978) covered half of Japan. Such an ash fall would ruin crops and deprive grazing animals of their food and drink over an enormous area.

The occurrence of accretionary lapili in such ashes indicates that they commonly fall in a damp or wet condition. Being cohesive and having a density when wet typically of 1500 $kg\text{-}m^{-3}$, a modest ash thickness might cause the collapse of most buildings and endanger the lives of those sheltering inside. Herein lies the main hazard to life unless people take positive steps to remove the ash while it accumulates. Note that civil defense authorities tend to recommend people to seek shelter in times of ash fall which may be unsound advice. Ash falling in a damp and hence cohesive condition would also bring down telephone and electric power lines and make roads temporarily impassable, thereby causing a complete breakdown of communications.

ABILITY TO CROSS OPEN WATER?

The 1883 ignimbrite of Krakatau is several meters thick on Sertung, an island 20 km from the presumed vent position. How the ignimbrite reached Sertung is uncertain. The sea is shallow and possibly the ignimbrite formed a temporary "causeway" to the island. Alternatively, a fast-moving flow might have been able to displace the water or flow over the sea floor.

Evidence is not lacking that some ash flows were able to cross significantly wider and deeper stretches of open sea. One, the 6000-year old Koya flow (Ui, 1973), which is widely spread in southern Kyusyu, originated in the Kikai islands 40 km offshore (Tadahide Ui, pers. comm.). Two of the Aso 4 flows (Watanabe, 1978), which originated at Aso caldera, crop out on offshore islands or extend to Honsyu, implying an ability to cross more than 40 km of sea.

The entry of ash flows from land into water thus appears, in different situations, to have followed three quite different courses: the ash-flow plunged into water to generate a pyroturbidite (e.g., the Roseau Ash: Carey and Sigurdsson, 1980), exploded to generate extensive phreatoplinian ash-falls (Walker, 1979), or traversed the water to deposit ignimbrite on land beyond. Conditions which favour these courses have not yet been explored.

THE PYROCLASTIC FLOW-PYROCLASTIC SURGE PROBLEM

One of the unresolved problems of volcanology concerns the exact relationship between pyroclastic flows and pyroclastic surges, and how to distinguish reliably between their deposits. The following explores these problems, starting with the premise that pyroclastic flows are concentrated particulate systems in which the continuous phase (gas) is volumetrically equal or subordinate to particulate material, and pyroclastic surges are dilute and turbulent particulate systems in which gas greatly predominates. The character of the resulting deposits reflects these differences. Thus, the high particle concentration in pyroclastic flows inhibits sorting or the loss of fine particles, whereas the low particle concentration in pyroclastic surges may allow sorting and the ready escape of the fine particles so that the resulting deposits are strongly fines-depleted (Fig. 4).

Base surges commonly develop in explosive eruptions in which the convective plume is not sufficiently powerful to carry aloft a major proportion of the pyroclasts. Column collapse therefore occurs. They often develop in phreatomagmatic eruptions where much of the thermal energy that might contribute to a convective plume is dissipated by converting water to steam, and also in phreatic or Vulcanian eruptions where a major proportion of the ejecta are cold and have no thermal energy to contribute. Not all base surges are caused by eruptive column collapse. Others may be caused by very shallow and strongly

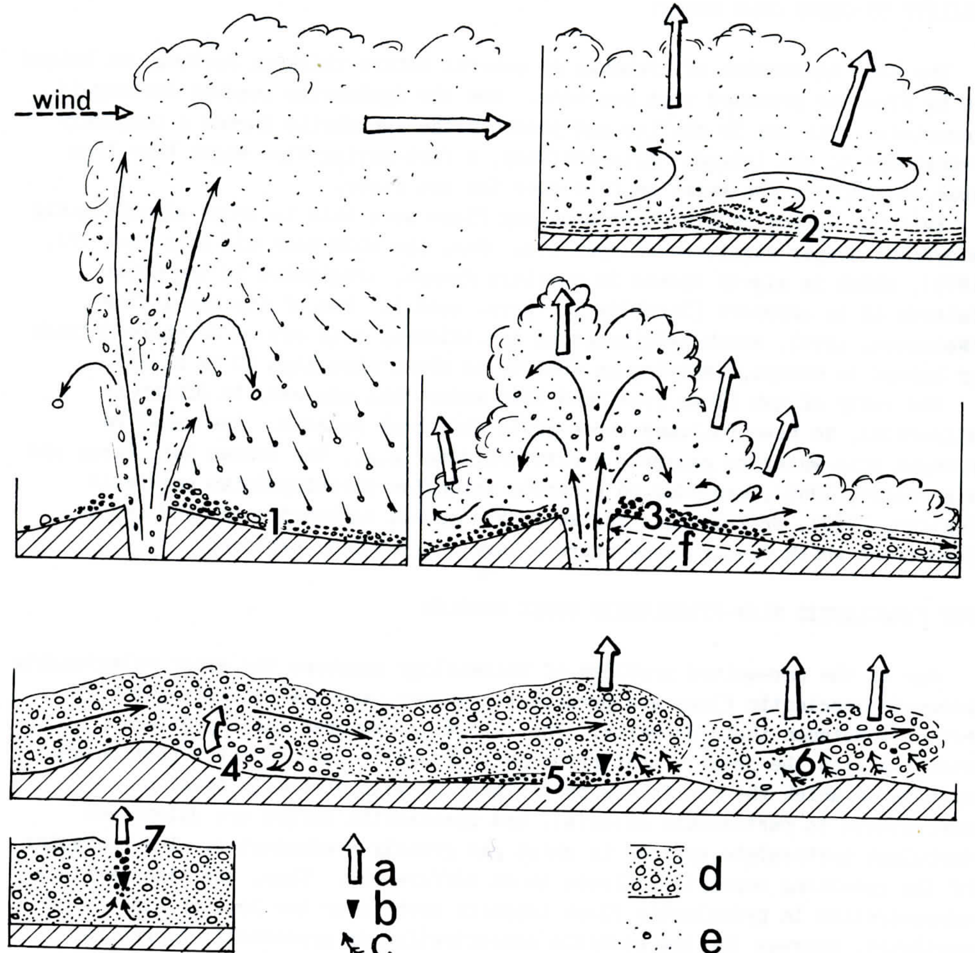

Fig. 4 Schematic views showing seven situations which produce fines depletion and good sorting of pyroclastic deposits. 1 - pyroclastic fall; 2 - pyroclastic surge; 3 - lithic lag breccia (co-ignimbrite lag-fall deposit); 4 - coarse pumice lee-side lens; 5 - ground layer forming at flow head; 6 - fines-depleted ignimbrite formed by forward jetting from flow head; 7 - elutriation pipe; a - loss of fines; b - sinking of dense particles; c - strong ingestion of air; d - high-particle concentration flow (i.e., pyroclastic flow); e - low particle concentration flow; f - deflation interval (the interval required to deflate a dilute turbulent flow to a high-particle concentration pyroclastic flow).

divergent, in part outwardly-directed, explosions. Perhaps the eruptive column in some is diverted laterally by the "stoppering" effect of a heavy load of debris already aloft above the vent.

It became realized following the 1965 eruption of Taal volcano that the deposits of base surges commonly show dunes and wavy bedforms (Moore et al., 1966; Moore, 1967) and dune-type bedding found in pyroclastic deposits (e.g., Fisher and Waters, 1970; Waters and Fisher, 1971; Crowe and Fisher, 1973) has since come to be regarded as diagnostic of a base-surge origin. This prompts three cautionary comments. One, lenticular or wavy bedforms and a form of cross-bedding can be generated by other processes operating in ash flows. Two, similar bedforms can be generated by wind or running water in non-volcanic sedimentary processes, and could indeed be primary bedforms if a strong wind is blowing during ash deposition. Three, not all base-surge deposits are wavy bedded: some are planar bedded (Sheridan and Updike, 1975; Wohletz and Sheridan, 1979).

Lenticular and wavy bedforms in ash flows develop in fast-moving flows, either downflow from topographic elevations where the flow, due to its momentum, leaps over the ground (Fig. 5), or where standing waves develop in a flow travelling at a very high velocity over a planar surface (Walker et al., 1980c). These are situations where a local low particle concentration exists in vortices in or below the flow, and a strongly fines-depleted pumice deposit accumulates there. The resulting coarse pumice lee-side lenses are quite distinct in their grain-size characteristics from base-surge deposits.

An outstanding problem concerns the nature of the nuee ardente. It is well established that the deposits of the nuee ardente include true pyroclastic flows. Commonly the resulting flow deposits are very coarse and consist of dense material, which implies that these particular flows owed their mobility to the height and steepness of the volcano slope, and that grain flow may have been a more important flow mechanism than fluidization. These pyroclastic flows tend to be channelled by valleys, often stand on moderate slopes of 5° or more and at their fartherest extension have steep flow fronts of lobate form. A seared zone often extends a short distance beyond and on either side of such flows and may result from an accompanying pyroclastic surge. The deposits in these seared zones, being thin and rapidly eroded, have seldom been described. One view is that the searing is due to an ash-cloud surge -- a hot ash-cloud fed from, riding over, becoming detached from, and extending beyond the pyroclastic flow (Fisher, 1979). Another view is that searing is due to surges emitted from the flow margin (Rose et al., 1976).

In major "directed blast" eruptions, as at Mt. Pelée on May 8th and 20th, 1902, and Mt. St. Helens on May 18th, 1980, thin deposits which may include a fines-depleted lower part are spread widely as a blanketing layer over the landscape. These deposits have generally been attributed to powerful pyroclastic surges (Fisher et al., 1980; Hoblitt et al., 1981; Moore and Sisson, 1981; Smith and Roobal, 1982). For the following reasons this interpretation is here questioned. One, internal bedding is absent from or is very ill-defined in

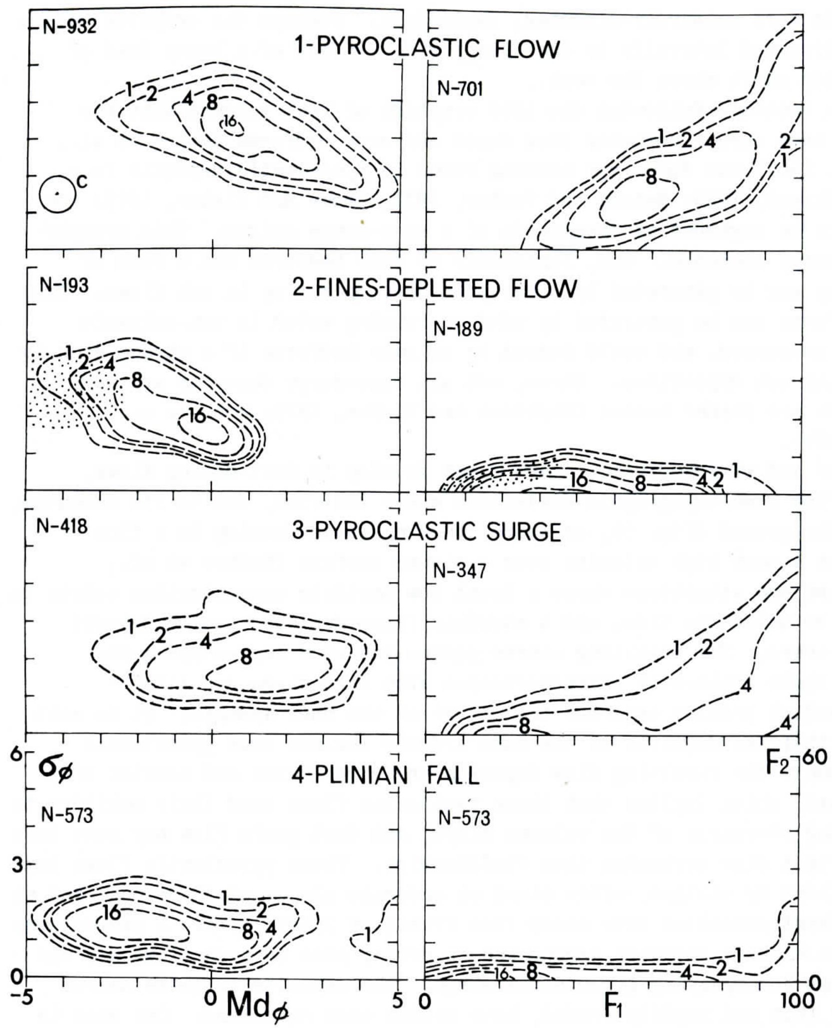

Fig. 5 Contoured fields (left) of σ_ϕ - graphic standard deviation against Md_ϕ - median size, and (right) of F_2 - wt.% finer than 1.6 mm, against F_1 - wt.% finer than 1 mm, for pyroclastic flows and three kinds of fines-depleted pyroclastic deposits. The contours are based on the percentage of samples at any point contained by a circle of size C centered on that point. N - number of samples. Plot number 2 includes various kinds of fines depleted flow deposits associated with ignimbrite: ground layers, fines-depleted ignimbrite, and elutriation gas pipes. The dotted area contains lithic lag breccias (co-ignimbrite lag falls) not included in the contoured field. Note that 2, 3 and 4 overlap, showing that grain size parameters alone are not good criteria of origin.

the relatively coarse basal fines-depleted layer (layer A1 of Waitt, 1981). Two, there are many places where the main layer of the deposit (layer A2 of Waitt, 1981) is found both in valley pond situations and on gently sloping valley sides. Three, although layer 2 at Mount St. Helens elsewhere often shows a dune type bedding, this bedding is faint and the variance between co-existing beds is much less than in the deposits of a powerful surge. The author's opinion is that the distance of travel (nearly 30 km from vent at Mount St. Helens) is unduly great for a low-concentration cloud moving against air resistance and depending on internal turbulence to maintain particles in suspension. Sparks et al. (1978) have demonstrated how rapidly particles settle out from such a cloud.

In its landscape-mantling form and fines-depletion shown by some layers, the directed-blast deposit closely resembles a L.A.R.I., suggesting that the "blast" was a high-velocity ash flow. Having a high velocity, ingestion of air in the flow head (aided at both Mt. Pelee and Mt. St. Helens by the dense vegetation) caused strong fines depletion of head (layer 1) deposits, and dune bedding was caused by local turbulence. The narrow marginal seared zone may however result from a pyroclastic surge. The outer margin of this zone shows evidence at Mount St. Helens for the rising of the "blast cloud" as, with loss of particulate material and heating of entrapped air, its density fell below ambient, and it is easy to envisage this happening to a fast-moving ash flow at the stage when the material is largely used up and is all contained in the head.

It seems possible to recognize a spectrum of pyroclastic flows in nuees ardente and "directed blasts" analogous with the spectrum of ignimbrite types (Fig. 6), ranging from the weakly-emplaced, stubby and lobate flow of ill-sorted material exemplified by Ngauruhoe, 1975 (Nairn and Self, 1978) to the violently emplaced low-aspect ratio flow exemplified by Mt. Pelee 1902 and Mount St. Helens 1980.

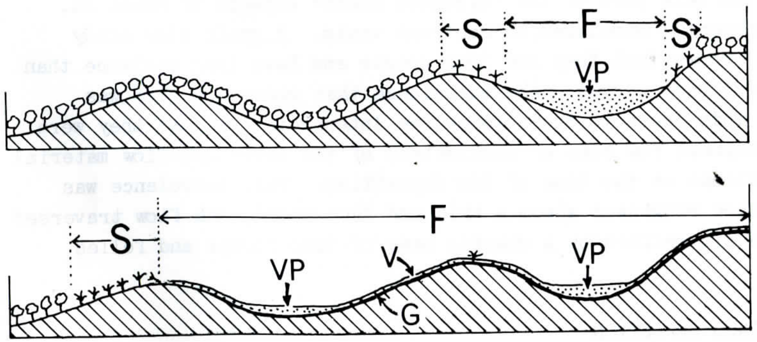

Fig. 6 Schematic view contrasting a high-aspect ratio pyroclastic flow or nuée ardente deposit (above) with a low-aspect ratio flow or nuée ardente deposit (below). F - extent of pyroclastic flow deposits; S - seared zone: pyroclastic surge; VP - valley pond deposit; V - veneer deposit; G - fines-depleted deposits underlying normal flow material.

Returning now to ignimbrites, Sparks et al. (1973), impressed by the frequent occurrence of a particular sequence of erupted layers among the products of many ignimbrite eruptions, proposed a standard sequence including a layer 1 or "ground surge" deposit underlying the ignimbrite.

Layer 1 was loosely defined, and it is now apparent that it embraced a variety of different kinds of deposits. At Taupo the layer 1 deposits are strongly fines-depleted and include "fines-depleted ignimbrite" and also a ground layer. Both are interpreted as deposits from the pyroclastic flow head, their abrupt and near-planar upper boundary against normal ignimbrite being due to shearing as they were over-ridden by the main mass of the flow. There are other possible origins for layer 1 deposits and each deposit must be assessed separately on each ignimbrite by applying the appropriate tests. On present knowledge, a ground layer as found at Taupo is particularly common among layer 1 deposits, and there is merit in restricting the designation "layer 1" to deposits such as these which are an integral part of the ignimbrite.

Some ignimbrites are overlain by wavy-bedded deposits, and there are several ways in which such deposits may have formed. In one proposed mechanism the bedded material resulted from an ash-cloud surge (Fisher, 1979) which emanated from the top of the pyroclastic flow. That it did not originate independently at the main ignimbrite vent may be shown by its outwardly increasing thickness. The thickness alone may, however, not be a reliable indicator since it may be slope-dependent. In another mechanism, the bedded material is of base-surge origin formed as a result of secondary explosions at rootless vents where the ignimbrite entered water. A feature of May 18, 1980 Mount St. Helens flow deposits is the considerable number of rootless vents that developed on them, and the large size of the secondary explosions some of which generated base surges.

Dune-like bedforms interpreted to result from the pyroclastic surge mechanism are seen also in the main part of the "directed blast" deposit of Mount St. Helens and are apparently unrelated to rootless vents. A grain size study (Walker, in prep.) shows that they are less coarse and have less variance than deposits of powerful base surges: the turbulence that generated them was relatively weak. This leads to the alternative interpretation that they were developed in the topmost few tens of centimeters of the loose ash-flow material during minor turbulence at the time of its deposition. This turbulence was caused by the surface roughness where a thin and fast-moving ash flow traversed a mountainous area diversified by a chaotic mass of tree stumps and felled trees.

SIGNIFICANCE OF FINES DEPLETION

A critical element in current discussions about the relationship between pyroclastic surges and pyroclastic flows is whether deflation of a surge is capable of generating a flow. The problem is seen to be one of retaining, or generating, enough of the fine dust on which fluidization of the flow depends.

A highly turbulent environment like that of a violent pyroclastic surge exists at the site of column collapse (Sparks et al., 1978), and as the expanded particle/gas mixture moves outwards from there, deflation to generate a high-particle-concentration mix occurs as gasses escape. Coarse lithic-rich lag breccias which accumulate within the deflation interval, consisting of debris too heavy to be carried far, are strongly fines depleted.

The gasses which escape while deflation proceeds inevitably carry off much fine ash and dust, and the crucial factor determining whether or not a pyroclastic flow then forms is whether there is a sufficient quantity of fines in the resulting high-cencentration mix. Factors which favour the retention or generation of fines favour the formation of pyroclastic flows: a high discharge rate and particle concentration, a low gas content in the column, and hot magmatic eruptive conditions in which fines are rapidly replenished by the continual bursting of vesicles as well as being generated by attrition during flow. Sparks et al. (1978) express the view that continual fines generation is essential, and the author concurs except where column collapse takes place on a steep cone and this requirement is relaxed as grain-flow then becomes a significant mobilising mechanism.

Factors which favour the loss of fines favour the formation of pyroclastic surges instead of flows: a low discharge rate, a high gas content, and a high content of more or less cold pyroclasts with a limited capacity to replenish lost fines. Note that pyroclastic surges are particularly common in eruptions that are dominated by copious amounts of non-magmatic steam, and where a major proportion of the pyroclasts are quenched or consist of reworked cold debris.

The highly expanded environment of pyroclastic surges is regarded as one in which deflation to produce a high particle-concentration basal ash flow is very unlikely because of the strong fines depletion that accompanies deflation. On the other hand, there are no such constraints inhibiting the reverse process: the addition of sufficient gas to a pyroclastic flow may very readily convert it to a pyroclastic surge. Such surges stemming from pyroclastic flows are judged to be responsible for the seared zone that often margins a flow.

CONCLUSIONS

Recent progress in the study of the emplacement and related features of ignimbrites has enabled a facies model to be developed, and is beginning to sort out the inter-related factors of discharge rate, eruptive column height, gas content, flow volume, vesiculation and fluidization state, and effects of ground roughness, which determine whether or not ash flows are generated in eruptions, and (if they are generated) then control the overall structure of ignimbrite sheets. This research has also defined a number of problems for which solutions are needed, such as the nature of interactions between ash flows and water, and the reliable distinction between the products of ash flows and the products of pyroclastic surges.

This article takes stock of what is known, and also of what needs to be known before ignimbrites are well understood. Hawaii Institute of Geophysics contribution No. 1321.

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