Plinian Eruptions and Their Products

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ABSTRACT

Plinian eruptions are amongst the most powerful of explosive volcanic events, and the extensive pumice deposits which they produce have an exceptionally wide dispersal because of the great eruptive plume height. Historical data on 12 plinian eruptions, and available quantitative data on the deposits of these and 37 other plinian eruptions are collated in this review to characterise further the plinian eruptive style and its products and to establish the known limits of their variation. The deposit volumes have been recomputed according to a standard procedure to provide a better basis for comparison, and they vary over 4 orders of magnitude to reach a maximum of about 100 km^3. Almost all volcanic magma compositions apart from the most mafic are represented among the juvenile products; rhyolitic and dacitic deposits account for 80% of the total volume and basaltic ones less than 1%. Compositional zoning is very common.

Plinian eruptions are of open vent type and produce deposits which tend to be homogeneous in grain size and constitution through their thickness. Considerable departures from homogeneity often however exist. Finer grained beds which often interrupt the continuity can be produced by a number of different mechanisms, the features of which are summarised. In a significant proportion of plinian deposits the finer beds are the deposits of intraplinian pyroclastic flows, or are related to such flows; pyroclastic flows such as may be attributable to column collapse thus do not form exclusively at the end of the plinian phase.

The most recent work indicates that major phreatoplinian eruptions dominated by the copious inflow of water into the vent can produce deposits quite as widely dispersed and as voluminous as the biggest plinian eruptions, and it appears that the characteristics of the grain size populations of the two types tend to converge in the most powerful eruptions.

INTRODUCTION

Plinian eruptions are among the most powerful of all explosive volcanic events. They release copious amounts of pumice with great rapidity in a sustained open-vent discharge, and with their eruptive plume towering tens of kilometres high they spread coarse ejecta over a wide area. Plinian deposits are among the most clearly defined and distinctive of all the products of explosive volcanism, are found associated with perhaps 40% of the world's polygenetic volcanoes, and embrace all but the most mafic of magma compositions. They make important marker horizons for tephrochronology. The type example, early studied by RITTMANN (1950), is that which buried Pompeii in 79 A.D., and serves as a reminder of the hazard posed by plinian eruptions which makes their study of more than purely academic interest.

Perhaps five to ten plinian eruptions take place per century and only one (Hekla, 1947) has yet been carefully observed by volcanologists (THORARINSSON, 1950, 1954; THORARINSSON and EINARSSON, 1950), and most of what is known about them has perforce been deduced by measuring their deposits. The pioneer studies include those by SAPPER (1905) on Santa Maria, 1902, LARSSON (1935) on Quizapu, (1932, WILLIAMS (1942) and MOORE (1934) on Crater Lake, MINAKAMI (1942) on Asama 1783, THORARINSSON (1944) on Askja 1875, RITTMANN (1950) on Pompeii 79, TSUYA (1955) on Fuji 1707, and THORARINSSON (1954) and EINARSSON (1950) on Hekla 1947. The

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TABLE 1 - Data on 49 plinian deposits.
Abbreviation in the first column is used in the text figures. The figure in brackets after the deposit name is the age in kiloyears.
VOL – Volume in km^3, computed as described in the text.
COMP – Composition of first-erupted part; rhy - rhyolite; rhyod - rhyodacite; dac - dacite; and - andesite; bas - basalt; trach - trachyte; phon - phonolite.
NOTES - IPF - intraplinian pyroclastic flow(s); PPF - post-plinian pyroclastic flow(s).
T – Duration of plinian phase: h - hour, d - day; D – dispersal index, in thousand of km^2
* Unpublished data; ** Isopach map modified by Walker; *** Welded plinian deposit.

	DEPOSIT	REFERENCES	VOL.	COMP.	NOTES	T	D
AZORES	FOA - Fogo A (4.6 ky)	Walker & Croasdale, 1971	5.4	trach	zoned		1.5
	FOE - Fogo 1563	" "	1.3	trach		2d	1.3
	FOB - Fogo B (<4.6 ky)	Booth et al, 1978	1.0	trach			1.3
	SED - Sete D (<4.6 ky)	" "	1.5	trach			0.6
	FAC - Faial C	Walker & Croasdale*	1.3	trach	zoned		2.4
	FAH - Faial H	" "	1.3	trach			0.6
	FAI - Faial I (1.5 ky)	" "	1.0	trach			0.5
TENERIFE	TEG - Granadilla (>32 ky)	Booth, 1973	~45	phon	PPF		
	TEJ - Tenerife J	Booth & Walker*	~30	phon	IPF		
	TEK - Tenerife K	" "	>5	phon			
	TEL - Tenerife L	" "	~10	phon			
CHILE	SPD - San Pedro	Francis et al, 1974	2	and			
SANTORINI	SAN - Minoan (3.4 ky)	Bond & Sparks, 1976	~5	rhyod	PPF		
GUATEMALA	STM - Santa Maria 1902	Williams & Self, 1981	10	dac	zoned	2d	40
ICELAND	ASK - Askja 1875	Sparks et al, 1981	1.0	rhy	mixed	6.5h	23
	HK1 - Hekla 1104	Thorarinsson, 1967	2.0	rhy			
	HK3 - Hekla H3 (2.8 ky)	Thorarinsson et al, 1960	19	rhy	zoned		
	HK4 - Hekla H4 (4 ky)	Larsen & Thorarin., 1977	14	rhy	zoned		
	HK5 - Hekla H5 (6.2 ky)	" "	5	rhy			
	HK47- Hekla 1947	Thorarinsson, 1954	0.4	and		1h	
	HK70- Hekla 1970	Thorarinsson & Sigvald., 1972	0.17	and		2-3h	
ITALY	POM - Pompei 79	Rittmann, 1950; Lirer et al, 1973	6.0	phon	zoned	1d	4
	AVE - Avellino	Lirer et al, 1973	2.5	phon	zoned		3
	MER - Mercado	Walker*	5.5	phon			
JAPAN	OSU - Osumi (13 ky)	Aramaki & Ui, 1966	90	dac			
	ONT - Ontake Pm-1 (50 ky)	Kobayashi et al, 1967	22				
	TAA - Tarumai Ta-a 1739	Soya, 1971	3	and	PPF		
	TAB - Tarumai Ta-b (0.5ky)	" ; Suzuki et al,1973	5.5	and	PPF		
	ASA - Asama 1783	Minakami 1942; Aramaki 1956	0.4	and		2d	
	FUJ - Fuji 1707	Tsuya, 1955	1.6	bas	zoned	4d	
	SHI - Shikotsu fal (20 ky)	Katsui, 1963	100	rhy	PPF		
	USU - Usu Ub (0.4 ky)	Oba & Kondo, 1964	4.0	rhy			
NEW ZEALAND	TAU - Taupo (1.8 ky)	Walker, 1980	24	rhy	PPF, IPF		100
	HAT - Hatepe (1.8 ky)	Walker, 1982	6	rhy			10
	WAI - Waimihia (3.4 ky)	"	29	rhy	PPF, mixed		30
	ROT - Rotorua (13.8 ky)	Nairn, 1980**	3.5	rhy			
	OMA - Omataroa (<40 ky)	Howorth, 1975; Walker*	60	rhy	PPF		
	MAN - Mangaone (<40 ky)	" "	~40	rhy	PPF, IPF		
	TAR - Tarawera 1886	Walker*	1.8	bas		4h	9
MARTINIQUE	PEA - Pelee A (2 ky)	Walker & Booth*	1.4	and			2.3
	PEB - Pelee B (1.2 ky)	" "	1.6	and			2.4
MEXICO	TOL - Toluca Low. (14 ky)	Bloomfield et al, 1977	0.9	and			
	TOU - Toluca Upr.(11.6 ky)	" "	9	and			3.1
	PRB - La Primavera B	Walker et al, 1981c	50	rhy	PPF		36
	PRD - La Primavera D	"	2	rhy			7
	PRE - La Primavera E	"	12	rhy			15
	PRJ - La Primavera J	"	2.6	rhy			
PANTELLERIA	PAN - Pantelleria B	Wright, 1980	***	pant	welded		
PAPUA NEW GUINEA	RAB - Rabaul (1.4 ky)	Walker et al, 1981b	1.7	dac	PPF		4
U.S.A.	CRL - Crater Lake (7 ky)	Williams, 1942; Fisher 1964	~60	dac	zoned, PPF		

past decade has seen a great upsurge of interest in plinian deposits, and has also seen important theoretical studies on the dynamics of plinian eruptions (WILSON, 1976; WILSON *et al.*, 1978; SETTLE, 1978; WILSON *et al.*, 1980).

The four most important attributes of a plinian eruption and its deposits are judged to be a high content of juvenile pumiceous material amongst the ejecta, a high discharge rate leading to a wide dispersal of this pumice, the coarseness of the pumice, and the continuity of the discharge producing a deposit which tends to be homogeneous through its thickness. Perhaps the greatest contributions to the characterization of plinian eruptions and their deposits have been those by Thorarinsson, working on the Icelandic examples.

A compilation of data on dispersal of plinian and other fall deposits was made by EATON (1963; 1964) and on the lateral variations in grain size by FISHER (1964). A classification scheme of plinian deposits was proposed by WALKER (1973), followed by an up-date of dispersal-related features (WALKER, 1980). The present is a general review on all their features based on a compilation of data collected from 49 deposits (Table 1). Only those deposits are included for which an isopach map is available and is accompanied by sufficient grain size data to test if the deposit is a plinian one (on the criteria of WALKER, 1973). Certain deposits of doubtful status have been omitted: the White River ashes (LERBEKMO *et al.*, 1968; 1969; 1975) for example which, though very widely dispersed, seem to be too fine-grained for plinian deposits, and the Oraefajokull 1362 deposit (THORARINSSON, 1958) for which few grain size data are available.

VOLUME

The volumes of plinian deposits as quoted in the literature vary between 0.17 and 28 km^3. Determination of the volume of widely-dispersed fall deposits has however long posed a problem and the values quoted, being determined by widely different methods involving various simplifying assumptions, are not a secure basis for comparison. The volumes have accordingly been recomputed here according to a uniform procedure described below.

A common method for estimating the volume of a fall deposit is to measure the area enclosed by each isopach and then to plot area against thickness on an «area» plot (Fig. 1); integration of the resulting line then yields the volume. There are two uncertainties in this method: how to extrapolate the line at the low-thickness

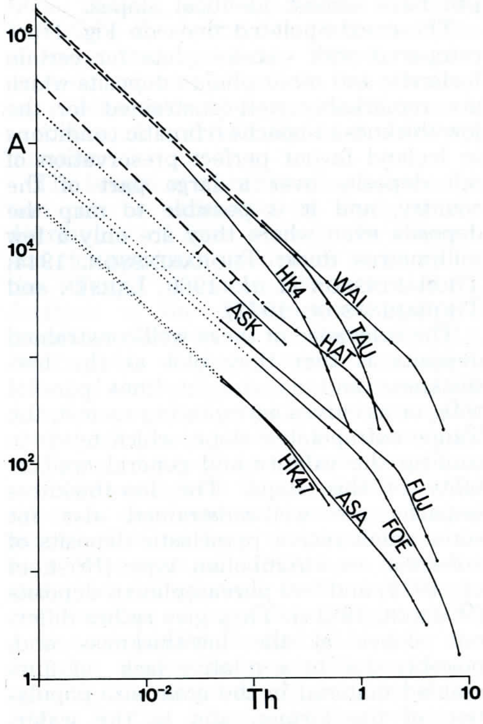

FIG. 1 - «Area» plot, showing area A enclosed by isopachs in km^2 versus thickness «Th» in metres for several pumice deposits the isopachs of which are well constrained at the low-thickness end. Dashed lines = extrapolations required to produce the same volume within the 1 μm isopach as that determined by the crystal concentration method. Dotted lines = extrapolations parallel with the Taupo slope. Pumice deposits in this and subsequent figures identified by the abbreviations in Table 1.

end, and which limiting thickness to take at this end.

To resolve these uncertainties an independent method of deriving the volume has been applied to the Taupo, Waimihia and Hatepe plinian deposits, based on the content of free crystals (WALKER, 1980, 1981*b*); knowing the volume, a straight line extrapolation at the low-thickness end and a limiting thickness value can then be selected on the «area» plot so as to yield by integration the same volume. It is found for the three deposits in question that straight line extrapolations to the same lower limiting thickness value of 1 µm have almost identical slopes.

These extrapolated lines on Fig. 1 are compared with «area» plots for certain Icelandic and other plinian deposits which are remarkably well-constrained for the low-thickness isopachs (climatic conditions in Iceland favour perfect preservation of fall deposits over a large part of the country, and it is possible to map the deposits even where they are only a few millimetres thick: THORARINSSON, 1944; THORARINSSON *et al.*, 1960; LARSEN and THORARINSSON, 1977).

The relevance of these well-constrained deposits is that they plot at the low-thickness end as straight lines parallel with, or as curves asymptoting against, the Taupo extrapolated slope, which tends to confirm the validity and general applicability of this slope. The low-thickness isopachs are well-constrained also for some small recent pyroclastic deposits of vulcanian or strombolian type (ROSE *et al.*, 1973) and two phreatoplinian deposits (WALKER, 1981*a*). They give rather different slopes at the low-thickness end, possibly due to a relative lack of fine-grained material in the grain size population of the former, and to the water-flushed depositional mechanism of the latter.

The volume of each plinian deposit in Table 1 has been recomputed by making a straight-line extrapolation on the «area» plot parallel with the Taupo line and extending it to the same limiting thickness of 1 µm. Table 1 lists the recomputed volume values, which vary from 0.17 km^3 to about 100 km^3. The arithmetic average is 13 km^3 and the median value is 5 km^3; both may be somewhat inflated because of a sampling bias in favour of the larger plinian deposits. The dense rock equivalent volume should be more valid to compare deposits having varied pumice densities and varied lithic or crystal contents, but requires a knowledge of the average bulk deposit density.

When determining bulk density, allowance must be made for the fact that plinian deposits typically increase in bulk density outwards from vent, due in part to the steady pumice density increase (WALKER, 1980), and in part to the crystal content increase (Fig. 2) as the grain size decreases. For example, distal parts of the Taupo pumice (with Md finer than -1 phi) have a bulk density 30 to 60% higher than proximal parts (Fig. 3).

Typical mean bulk density values range from 0.5 to 0.8 g cm^{-3} for rhyolitic deposits to as much as 1.2 g cm^{-3} for basaltic ones. Estimated dense rock equivalent volumes range from 20% to 40% of the actual volumes, and vary between 0.13 and 20 km^3.

Many of the recomputed volumes have a significantly greater value than that previously quoted for the same deposit. For many this is because the volume was

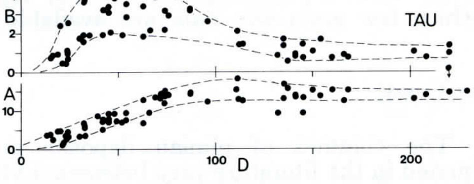

FIG. 2 - Plots showing variations in content of free crystals as it varies with distance D from the source vent in km, A = as weight percentage of sample, B = as mass in g above 1 cm^2 area, for two plinian deposits.

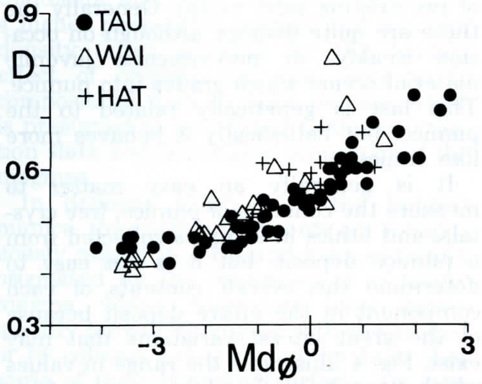

FIG. 3 - Bulk Density D in g cm^{-3} of samples from three New Zealand plinian deposits versus the median diameter in phi units, showing the general increase as the grain size decreases.

previously determined only within a specified isopach: 10 cm for the Toluca Lower pumice, for example (BLOOMFIELD *et al.*, 1977). Note that application of the useful exponential formula $V = 13.08\ a\,b^2$ (where V = volume of deposit, a = its maximum thickness, b = the distance in which the deposit thins to half its value: COLE and STEPHENSON, 1972) assumes a regular exponential thinning from vent; in other words it assumes that the «area» plot can be represented by a single straight line. In practice the «area» plot is invariably curved convex upwards at the high-thickness end, or can be expressed by two straight lines with an inflexion (ROSE *et al.*, 1973).

In some climatic regions as in Italy and Central Mexico having a long annual dry season, conditions are unfavourable for the preservation of fall deposits and few outcrops survive for long outside the 25 cm or even the 50 cm isopach. For deposits on oceanic volcanoes as in the Azores and Tenerife, the islands are often too small to draw many complete isopachs; the outermost that can be drawn for the Granadilla pumice, for example, is the 4 m one (BOOTH, 1973). In such situations the «area» plots are therefore very incomplete, extrapolation is uncertain, and volume estimates are correspondingly uncertain.

ERUPTION DURATION

The main plinian phase of the Hekla 1974 eruption lasted for half an hour. The eruptive column developed very rapidly, expanding laterally as it rose, to reach a height of 27 km within 12 minutes of its first appearance and a peak of nearly 30 km within 21 minutes (THORARINSSON and EINARSSON, 1950; THORARINSSON, 1954, 1968). In the second half hour or so the column height declined to about 10 km and ceased to be plinian. Less tightly constrained limits on the eruption duration are available for 9 other historic eruptions, Table 1, and vary from a few hours to 4 days; the average is 36 hours. Some of these times probably include weaker explosive phases as well as the culminating plinian outburst proper, so 36 hours is probably an overestimate of the average duration.

The length of a prehistoric plinian eruption can be estimated by studying the distribution of finer beds in the deposit, and this approach yields 6 to 17 hours for the Taupo pumice (WALKER, 1980). Analysis of the dynamics of explosive eruptions (WILSON *et al.*, 1978; SETTLE, 1978) yields discharge rates from which, knowing the total discharge, the eruption duration can then be estimated; examples investigated yield times of the same order as those observed in historic eruptions.

Plinian outbursts thus typically last for about a day, and are perhaps seldom shorter than an hour or longer than two days. WILSON *et al.*, (1978) have defined a sustained (as opposed to an instantaneous) eruption as one which is sustained for a time comparable to that needed for the eruption plume to reach its maximum potential height (about 20 mins for Hekla 1947). By this criterion plinian eruptions are sustained events.

DISCHARGE RATES

The nine plinian eruptions for which the duration is known yield average discharge rates of from 3,000 to 120,000 m^3 s^{-1}, with an average of 50,000 m^3 s^{-1} (about 30 × 10^6 kg s^{-1}). These values are based on the recomputed volume values and are averaged for the whole duration of each event; the peak discharge rate was probably appreciably higher. A higher average value, of between 400,000 and 1,000,000 $m^3 s^{-1}$ (200 to 500 × 10^6 kg s^{-1}) is deduced indirectly for the Taupo pumice eruption.

It has been shown (WILSON *et al.*, 1978; SETTLE, 1978) that the eruption column height in sustained explosive eruptions is a function of the energy discharge rate; for magma discharge rates of 2 to 500 × 10^6 kg s^{-1}, the corresponding convective plume heights are about 10 to 40 km. Observed plume heights in explosive eruptions vary up to 50 km or more and in the period 1900 to 1961 some 6 eruptions (not all of them plinian) generated plumes exceeding 15 km high (EATON, 1963; 1964).

CONSTITUTION

The three main components of plinian deposits are pumice (shards), free crystals (phenocrysts liberated from magma in the volcanic explosions) and lithics (fragments of pre-existing solid rocks). Generally the three are quite distinct, although on occasion weakly- or non-vesicular juvenile material occurs which grades into pumice. This last is genetically related to the pumice, but ballistically it behaves more like lithics.

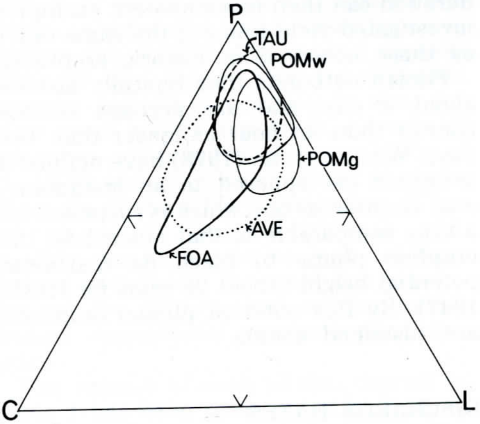

FIG. 4 - triangular plot of weight percentages of pumice + shards (P), free crystals (C), and lithics (L), showing fields occupied by samples from four plinian deposits. POMw = white pumice lower part of deposit, POMg = grey pumice upper part of deposit.

It is generally an easy matter to measure the contents of pumice, free crystals, and lithics in samples collected from a pumice deposit, but it is not easy to determine the overall contents of each component in the entire deposit because of the great lateral variations that may exist. Fig. 4 illustrates the range in values which have been found in samples from several typical plinian deposits.

The juvenile pumice varies in composition from rhyolitic to basaltic, and from pantelleritic and trachytic to highly alkalic, (Fig. 5). Half of the deposits listed in Table 1 are rhyolitic or dacitic, and they account for 80% of the total volume; in contrast, basaltic plinian deposits make up only 0.5% of the total volume.

Leaving aside the darker colour of the more mafic examples, all deposits show a remarkable general similarity in field appearance irrespective of their composition, suggesting that the physical properties and gas content of the magma are more important than the chemical composition *per se* in determining the eruptive characteristics. There is a tendency for

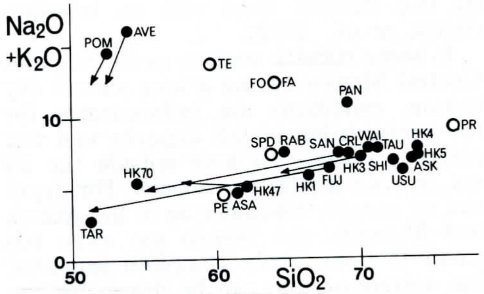

FIG. 5 - Chemical composition of juvenile pumice in plinian deposits. For compositionally zoned deposits the arrow indicates the trend upwards in the deposits, with the arrow head marking the most mafic composition. Open circles: estimated composition.

the dacitic and more mafic pumice to have a higher phenocryst content and a higher density (after allowing for the loading effect of crystals and the more mafic composition) than rhyolitic pumice, which is presumed to be related to the vesiculation state and rheological properties of the magmas.

In deposits which have the lightest pumice, the pumice fragments are conspicuously ragged in form and have evidently originated by the tearing-apart of foamy magma. Many fragments have subsequently broken by impact with the ground or by collapse along cooling joints so that some of their bounding surfaces are now near-planar in form. In deposits which contain the denser pumice, the fragments are bounded much more frequently by near-planar surfaces, suggestive of a rather different fragmentation mechanism.

DISPERSAL

Plinian deposits cover a wide range in dispersal area, and there is a need for comparing deposits. The actual area cannot be measured since the thickness decays exponentially away from source, and the area enclosed by any one specific isopach is not suitable since it is volume-dependent. A normalised «dispersal index» (D) was accordingly proposed by WALKER (1973), being the area enclosed by the 0.01 Tmax isopach (where Tmax is the maximum thickness of the deposit, obtained by extrapolation from a log thickness/distance plot). Values of D are given on Table 1. The lower threshold separating plinian deposits from subplinian was arbitrarily chosen to be D = 500 km² and the upper limit 50,000 km², threshold value for the proposed ultraplinian type, one example of this type (Taupo) having been documented to date (WALKER, 1980).

Other measures of dispersal are the areas enclosed by isopleths of median grain size (Md), maximum pumice size (MP), or maximum lithic size (ML) (Fig. 6). The order of ranking of deposits is rather similar on D, MP, ML or Md as is shown by Fig. 7. In practice it is easier to determine the areas enclosed by ML or MP isopleths than D, the value of which is sensitive to the value of Tmax chosen,

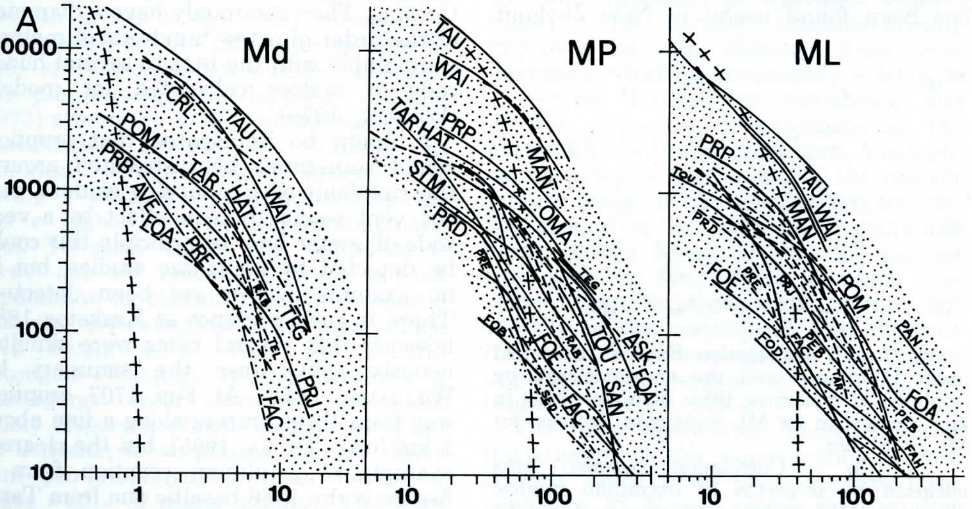

FIG. 6 - Areas A in km² enclosed by isopleths of median deposit grain size (Md), maximum pumice diameter (MP), and maximum lithic diameter (ML), in mm. The stippled field is that of plinian deposits. Crossed line = plot of the Rotoehu G phreatoplinian deposit; the Oruanui phreatoplinian deposit is nearly identical.

and it is proposed that when deciding if a particular deposit comes into the plinian category or not, more reliance should be placed on whether the ML, MP, Md values plot in the plinian field of Fig. 6 than on the D value.

VENT POSITION AND FORM

For the smaller plinian deposits good exposures are often available right up to the vent area, and the thickness and grain size increase exponentially as the vent is approached. For the larger plinian deposits exposures are commonly lacking in the vent area, due partly to deep burial by younger deposits and partly to volcano subsidence. The vent position is then best determined by mapping the distribution of maximum lithic or pumice size. The isopleths for the larger, ballistic, lithic 3 fragments (those large enough that their distribution is negligibly affected by the wind) are particularly useful since they tend to be circles concentric about the vent. Experience shows that ballistic lithics exceeding about 100 or 200 mm in size typically extend out to 2 to 5 km from the vent (BOOTH *et al.*, 1978) which has been found useful in New Zealand examples where exposures in the vent area are lacking.

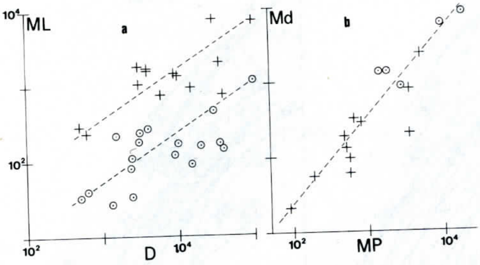

FIG. 7 (a) - Correlation between dispersal index D in km^2 and the area enclosed by isopleths of maximum lithic diameter (ML) in km^2; circles: m for ML = 64 mm; crosses: for ML = 8 mm.

(b) - Correlation between area enclosed by isopleths of maximum pumice diameter (MP) in km^2 and area enclosed by isopleths of deposit median grain size (Md) in km^2. Crosses: Md = −3 phi (8 mm), MP = 64 mm; circles: Md = −1 phi (2 mm), MP = 16 mm.

It has always tacitly been assumed that plinian deposits are thickest at the vent, and the isopachs invariably close around the vent, but it has been demonstrated for the Taupo deposit that the maximum thickness isopach closes around an area downwind from vent, and for the Waimihia deposit extends some tens of kilometres downwind from vent; for the products of unusually powerful eruptions such as these the isopach map alone is thus not a reliable vent position indicator.

Little is known from direct observation about the form and dimensions of plinian eruptive vents. In general the bigger the eruption, the greater the probability that the vent will be concealed because of subsidence or burial. The Taupo and Askja vents for example are both concealed beneath lakes resulting from subsidence, and the La Primavera B vent is concealed beneath thick ignimbrite and lava extrusions. When modelling explosive eruptions, it is convenient to regard the vent as being of cylindrical form with a circular cross-section, and explosive vents approximating this form are often revealed by erosion in older volcanic terrains. They commonly have a diameter of the order of a few hundreds of metres, comparable with the tens to several hundreds of metres calculated for models (WILSON, 1976).

It might be anticipated that eruption would sometimes be distributed around the ring-fault of a collapsing caldera, and the vent would then in effect be a very wide-diameter one. In principle this could be detected by grain size studies, but in no example has it yet been detected. There is good evidence at Krakatoa 1883 however that several vents were simultaneously active (see the summary by WILLIAMS, 1941). At Fuji 1707 eruption was from three craters along a line about 1 km long (TSUYA, 1955), but the clearest example of a plinian eruption from a fissure is the 1886 basaltic one from Tarawera, the fissure in that instance being 7 km long, locally now having basaltic dykes exposed along it (COLE and HUNT, 1968). It is interesting to note that beyond about

3 or 4 km out from the fissure the thickness and grain size distribution patterns are indistinguishable from those that would be given by eruption from a single-point vent.

WHOLE-DEPOSIT GRAIN SIZE POPULATIONS

The characteristics of whole-deposit grain size populations have been estimated for five plinian deposits (Tarumai Ta-b, SUZUKI *et al.,* 1973; Askja 1875, SPARKS *et al.,* 1981; Taupo, Waimihia and Hatepe, WALKER, 1980, 1981*b*). They yield somewhat conflicting results: the Tarumai and Askja populations are distinctly coarser than the New Zealand ones (WALKER, 1981*c*). The content of fine material in the five deposits in question cannot be measured directly, and depends on an indirect estimate being made of the total deposit volume. Two possible interpretations of the conflicting results exist: first that the difference is real, and the high degree of fragmentation in the New Zealand examples is the result of the greater power of their eruptions; and second that the difference is an artifice of the method used to arrive at the total volume.

Impressed by the difference in appearance of coarse plinian pumice falls and fine phreatomagmatic deposits, WALKER (1973) attempted to incorporate this into a classification scheme by defining an empirical «fragmentation index» (F), having a low value for plinian deposits and a high value for phreatomagmatic ones. To some extent this difference is borne out by estimated whole-deposit populations of plinian deposits compared with the phreatoplinian ashes of Askja 1875 (SPARKS *et al.,* 1980), Hatepe and Rotongaio (WALKER, 1981*a*). However, a convergence occurs between the most widely dispersed plinian and phreatoplinian deposits; these plinian deposits differ from phreatoplinian only in having a larger «tail» of coarse pumice. The very different appearance of the respective deposits may well merely reflect a different depositional mechanism (such as water-flushing) for the latter.

The subject of the magma fragmentation mechanisms which operate in explosive eruptions and are responsible for the characteristics of grain size populations is a little-understood one at present, and clearly more work needs to be done to clarify these grain size relationships.

SORTING AND FRACTIONATION

It is convenient to distinguish between «sorting» and «fractionation»: the former here refers to the range of particles coexisting in the same sample, and the latter refers to the variations in grain size, particle fall velocities, and constitution which are found in the same bed as it is traced laterally away from source.

Plinian deposits are characteristically less well sorted than the best sorted sediments because sorting takes place during a single act of explosive eruption and fall to earth, whereas for sediments it may result from an act repeated many times (*e.g.* the repeated breaking of waves on a beach). Because the particles often have greatly differing densities, sorting on grain size is less good than sorting on fall velocity (an expression of hydraulic equivalence). The sorting characteristically improves as the distance from vent increases, which is presumably related to a general decrease in turbulence and greater uniformity of conditions as the plume travels farther from vent. A complicating factor is that much of the coarser pumice breaks in the air or on impact with the ground or by subsequent crumbling along cooling joints, so that the pumice now seen in the deposit is much less coarse than is appropriate to the fall velocity of the material at that distance from vent. This breakage has the effect of improving the sorting by reducing the range of particle sizes.

The most noteworthy consequence of fractionation is the concentration of free crystals which takes place outward from vent (Fig. 2). It stems from the fact that the assemblage of crystals covers a limited size range, and crystals are concentrated at a distance from vent where the fall velocity of the crystals equals the fall velocity of the deposits. The peak, expressed as a percentage of the deposit sample, is reached 17 km from the vent in Fogo A, an average plinian deposit not appreciably dispersed by the wind, and 100 to 150 km in the strongly wind-dispersed deposit of the much more powerful Taupo eruption. The Askja 1875 deposit contains some dark pumice, the proportion of which increases with distance from vent because this magma fraction was more finely fragmented than the part which gave rise to the white pumice.

DEPARTURES FROM HOMOGENEITY

Plinian deposits tend to be homogeneous in grain size and constitution through their thickness, and although probably no deposit is completely homogeneous, some closely approach this state. Departures from homogeneity include the intercalation of finer beds to produce «interrupted plinian» deposits, rhythmic fluctuations in grain size, an overall reverse or (less commonly) normal size grading, a concentration of lithic fragments at certain levels, varied thermal effects, and a compositional zonation of the pumice. Some of these are discussed below.

Finer Beds

Finer beds found intercalated with the coarse pumice can be produced in a number of different ways. The following list is not intended to be comprehensive, but points to a variety of mechanisms which can produce fine beds, and gives some features which help to identify these mechanisms.

One kind of bed results from a temporary reduction of eruption power as might result from a partial vent closure. An example is a thin ash in the lower part of the Granadilla pumice (BOOTH, 1973) having a median grain size 0.1 times that of bracketing pumice. The overlying deposit is enriched in lithic fragments, which could result from explosive expulsion of debris following vent wall collapse. The deposit higher up becomes coarser and poorer in lithics, suggesting an achievement of vent wall stability after an initial period of instability.

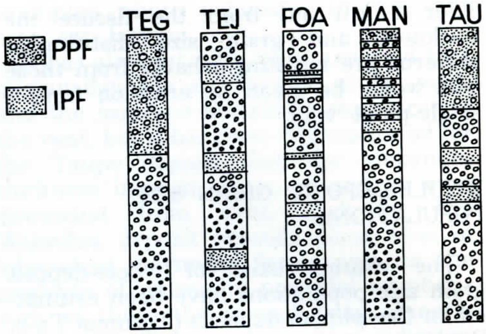

FIG. 8 - Schematic profiles across several plinian deposits showing relationship between the plinian pumice fall, intra-plinian flows (IPF) and post-plinian flows (PPF).

A second kind of fine bed is that deposited from a particulate density flow, this being either a pyroclastic flow proper or a pyroclastic surge. Several such beds occur in the Fogo A deposit (WALKER and CROASDALE, 1971). Evidence for their flow origin is given by the rather rapid lateral variations in thickness, and occasionally by the low-angle internal cross bedding, that they show. Similar intraplinian flow deposits have since been recognised in about 10% of plinian deposits (examples are given in Fig. 8); perhaps the actual percentage is appreciably grater since the flow deposits tend to be thin and inconspicuous and lacking in distinctive characters. Thin pyroclastic flows, veneer deposits left behind by the passage of pyroclastic flows, and the deposits of pyroclastic surges, converge in appearance when they are less than about 10 cm thick, and it may be speculated that only in thicker deposits does a clear distinction exist between them. More research on this topic needs, however, to be done.

A third kind of fine bed, having a bimodal grain size distribution, results when fine ash is flushed out by rain together with the coarser pumice, as in the latest major plinian deposit of Rabaul volcano (WALKER *et al.*, 1981*a*). Indicators of water flushing include accretionary lapilli and water-splash laminations. Fine beds in the Fogo 1563 and Granadilla deposits which appear to have been flushed out by rain lack coarse material, and it is apparent that the rainshower must have coincided with a reduction in the power of the eruption.

A fourth kind of fine bed results when there is a marked change in style of the eruption. An example is the phreatoplinian Hatepe and Rotongaio ashes which were formed during an interval of unknown length between two plinian phases of an eruption that produced the Hatepe and Taupo pumice deposits (WALKER, 1981*a*). The two ashes are believed to have formed after detumescence (resulting from the Hatepe plinian phase) permitted an incursion of water from Lake Taupo into the vent.

Beds having a grain size about half that of the bracketing pumice occurring in the Taupo pumice appear to correlate with small intraplinian pyroclastic flows found nearer the vent, and are interpreted to represent fall-out during episodes of reduced plume height at the times of partial column collapse during which the pyroclastic flow formed.

A fifth kind of fine bed having a bimodal size distribution results when fine ash falls from a different immediate source than the coarse pumice. In an example in the Tenerife J deposit (BOOTH and WALKER, in prepn.), the fine ash can be correlated with small intraplinian ignimbrites and came from ash-flows passing nearby.

A different kind of dual-source deposit occurs at Tarawera. The 1886 plinian eruption there was from a fissure, and while coarse scoria was erupting from the part of the fissure crossing Tarawera Mountain, phreatic to phreatomagmatic activity was proceeding from the part crossing the lowlands S.W. of Tarawera Mtn. Fine ash and mud from the latter were incorporated into the scoria fall over a part of its dispersal fan, both as mud pellets (probably rain-flushed) and as a coating to some of the scoria lumps (WALKER *et al.*, in prepn.). This fine material occurs preferentially in the upper part of the scoria deposit although not as discrete beds.

Grading and Rhythmic Grain Size Fluctuations

Many plinian deposits show an overall reverse grading in which the grain size increases upwards in the deposit, for example Avellino and Pompeii (LIRER *et al.*, 1973). A mechanism which accounts for this feature is a progressive widening of the vent during the course of the eruption. Note that if the dispersal axis shifts direction during the eruption, as happened in the Waimihia, a lack of grading or even a local normal grading may be seen in some exposures even though the deposit as a whole is reversely graded.

The Tenerife J deposit includes intraplinian ignimbrites at two or three levels, and the plinian pumice is divisible into several reversely-graded units which are coarsest immediately beneath each ignimbrite (Fig. 8). Other plinian deposits, for example La Primavera B and Rotorua, show rhythmic fluctuations in grain size which represent rhythmic fluctuations in column height. Variations of these kinds could be produced by the effect of large blocks partially obstructing the vent (WILSON *et al.*, 1980).

Thermal Effects

A general thermal darkening to a grey, brown or black colour of part of a salic pumice deposit often results when the accumulation rate is high, so that the individual pumice lumps which are still hot when they fall do not have time to cool significantly before being buried. Care is needed when interpreting a dark colour – it need not indicate a more mafic composition. A dark colour in pyroclastic deposits is usually attributed to the crystallisation of finely-disseminated microcrystals of iron (or manganese) oxide minerals such as magnetite. A pink thermal colouration of the inside of individual pumice lumps produced by oxidation of the iron, indicating that they were hot when they fell, has been observed to a distance of 35 km from vent in some of the New Zealand pumice fall deposits, but a general thermal darkening of the deposit is known only to within a few kilometres of the vent.

A primary welding of the pumice to a dense welded tuff is shown by some plinian deposits and is favoured by a high accumulation rate. Good examples occur at Askja and Santorini (SPARKS and WRIGHT, 1978), Pantelleria (WRIGHT, 1980), and Tenerife (BOOTH and WALKER, unpub. data). SPARKS and WRIGHT (1978) have shown that the accumulation rate for the Askja 1875 welded rhyolitic tuff was about 20 cm min^{-1}, and a similar figure holds for the Tarawera 1886 basaltic scoria (WALKER *et al.,* in prepn.). In known examples welding occurs out to a maximum distance of 1 to 7 km from the probable source vent position, whereas ignimbrites are often welded to a distance of 50 km or more from source.

Among the criteria for the distinction between welded airfall tuffs and ignimbrites, those judged to be the most reliable are the lateral or vertical passage into non-welded ash (recognisable by grain size analysis to be of air-fall type), abrupt changes in grain size and lithic content found through the thickness (reflecting original internal stratification) in the former, and the characteristic topography-mantling form of the airfall deposits (SPARKS and WRIGHT, 1978; WRIGHT, 1980). However the existence of a topography-mantling ignimbrite facies has recently been recognised (WALKER *et al.,* 1981*b*).

Compositional Zoning

A notable composition variation producing a change in colour of the pumice, exemplified by the Pompei and at least two of the earlier pumice deposits of Vesuvius (RITTMANN, 1950; LIRER *et al.,* 1973), is visible in about 20% of plinian deposits. From known examples, the trend is invariably towards a darker and more mafic pumice upwards in the deposit.

The boundary between compositional zones is sometimes fairly abrupt, and sometimes gradational. It is commonly not marked by any grain size discontinuity, showing that the discharge of magma was steady while the composition of erupting magma was changing. Streaky-mix pumice generally occurs and indicates that some measure of mechanical mixing of the chemically-contrasted magma fractions had taken place prior to eruption. Mix-magma pumice occurs at Askja 1875 even though the deposit lacks compositional zoning (SPARKS *et al.,* 1980).

In Fogo A the appearance of more mafic magma coincided with a change from a sustained plinian outburst to a fluctuating subplinian one, reflecting a significant change in viscosity or magmatic gas content. In the Pompei pumice the main colour change took place roughly midway through the plinian stage, and a change in eruptive style was postponed until a still more mafic magma was discharged.

In the Faial C, Waimihia and Hekla H4 deposits the dispersal fans of the two pumice compositions are different, indicating a wind direction change during the plinian phase; for Hekla this was used to deduce the approximate eruption duration (LARSEN and THORARINSSON, 1977).

Compositional zoning is in general best displayed by the smaller-volume plinian deposits, presumably those which issued from the smaller magma chambers, though it may strictly be more a function of chamber shape than size: the processes which promote variation may proceed best, and the processes which tend to produce homogenisation are most inhibited, in a narrow fissure-like chamber extending over a considerable vertical height.

OPENING STAGES OF PLINIAN ERUPTIONS

The nature of the opening and closing stages of a plinian eruption is important both in understanding the development of the eruption and in guiding the reaction of civil defence authorities. There is clearly much variation in pattern: At Hekla in 1947 and probably also in 1970 the plinian column developed within minutes of the commencement of the eruption, at Tarawera in 1886 the eruption apparently proceeded on a modest scale for about one hour before becoming plinian, and at Krakatoa 1883 the plinian phase was preceded by some weeks of activity on a lesser scale.

For prehistoric eruptions it is possible to deduce the way in which eruptions have developed by studying the erupted products, and these studies likewise indicate a wide variation. In about 25% of plinian eruptions, including Fogo A and most of the La Primavera deposits, coarse pumice begins right at the base of the deposit and indicates a very rapid development of plinian conditions. The Avellino pumice shows a steady upward increase in grain size indicating a progressive increase in power of the eruption to the climax. In many other examples, fine and stratified ashes occur instead at the base of a plinian deposit.

Fine basal ashes may often represent a weaker opening phase of the eruption. At Askja 1875 (SPARKS *et al.*, 1981) and perhaps also the fine water-flushed ashes locally rich in accretionary lapilli which occur at the base of some Tenerife plinian deposits, the fine ashes result from an opening phreatomagmatic phase resulting from when eruption began in a lake or when the vent penetrated groundwater-rich surface rocks; development of the plinian phase later became possible when water was excluded or when the magma discharge rate came to surpass the water influx rate into the vent.

Finer basal beds in the Granadilla (BOOTH, 1973), Tenerife J and Mangaone deposits have a high concentration of lithic fragments, suggesting that achievement of a stable plinian column was delayed by vent-wall instability; the rapidity with which plinian conditions are achieved may thus depend on the mechanical strength of the rocks through which the vent is drilled.

CLOSING STAGES OF PLINIAN ERUPTIONS

Regarding the closing stages of plinian eruptions, studies of the deposits show that in more than half of examples the eruption decreased steadily or abruptly in power and changed character from a plinian to an interrupted subplinian or other type. Such a reduction could be explained by exhaustion of the relatively gas-rich magma fraction at the top of the magma chamber. It is not uncommon for the uppermost parts of the plinian deposit to be significantly enriched in lithic fragments, and this is taken to be symptomatic of vent-wall instability accompanying the decrease in power of the eruption. This instability may then cause closure of the vent and terminate the eruption.

In about 30% of plinian pumice occurrences, the pumice is immediately overlain by an ignimbrite with no evidence for any significant time interval between their formation, examples being Crater Lake, Granadilla and Taupo (SPARKS *et al.*, 1973). The commonness of this eruption sequence has stimulated theoretical modelling of explosive eruption, in which formation of the ignimbrite has been attributed to eruption column collapse consequent on a widening of the vent beyond a certain critical radius, or alternatively a decrease in magmatic gas content (SPARKS and WILSON, 1976; SPARKS *et al.*, 1980). It should be emphasised however that not all ignimbrites are preceded by a plinian pumice.

The ignimbrites associated with the Waimihia, Minoan and Rabaul plinian pumice deposits are separated from the pumice by bedded ashes, showing that the onset of ignimbrite-forming conditions did not follow on immediately after the plinian phase. These bedded ashes in the Minoan and Rabaul examples are regarded as phreatomagmatic, formed as a result of an ingress of water into the vent perhaps in the early stages of caldera collapse. At Santorini they include conspicuously cross-bedded base surge deposits.

Sometimes, as in the Mangaone and Tarumai deposits, the resulting ignimbrite has a volume small in comparison with the plinian pumice, but more often the ignimbrite exceeds the plinian deposit in volume, examples being Crater Lake (WILLIAMS, 1942), Shikotsu (KATSUI, 1959), and the Bandelier Tuff (SMITH and BAILEY, 1966). Formation of ignimbrite seems to be strongly favoured in the bigger-volume eruptions, where the plinian deposit exceeds 20 km^3, such eruptions presumably being fed from the larger magma chambers.

OTHER KINDS OF WIDELY DISPERSED PYROCLASTIC DEPOSITS

There are other styles of explosive eruptions which may produce a dispersal as wide as a plinian. One type is a phreatoplinian eruption, and attention is here directed at two of the largest and most widely dispersed of this type, namely the Oruanui and parts of the Rotoehu ash in New Zealand. Both deposits yield D values of the order of 10^5 km^2. Although predominantly fine grained, the coarsest particles are dispersed over an area comparable to that in plinian eruptions, but a distinctive feature is that areas enclosed by isopleths of MP, ML and Md plot on Fig. 6 with much steeper slopes than plinian plots. Two different mechanisms have been proposed for these phreatoplinian deposits: phreatomagmatic explosions at the primary vent situated in a lake (Oruanui: SELF and SPARKS, 1978), and littoral explosions at rootless vents where ash-flows entered water from land (Rotoehu: WALKER, 1979).

VOLCANIC HAZARD

Hazard from plinian eruptions arises from burial, impact by falling clasts, and fire caused by the fall of hot ejecta, of which the first is judged to be the most important. A 25 cm fall, representing a load of the order of 100 to 200 kg m^{-2}, might cause the collapse of many buildings having flat or low-pitched roofs, destroy or severely damage most of the vegetation, and deprive grazing animals of their food. In a big-magnitude event, such a thickness could affect 20,000 km^2 of country extending to as far as 200 km downwind from the vent (Fig. 9). Impact by falling ejecta and fire caused by hot ejecta are less hazardous, but at Taupo 5 cm diameter lithic fragments and 15 cm pumice fell as far as 35 km from source, and in another New Zealand eruption pumice that was probably red-hot inside fell at the same distance.

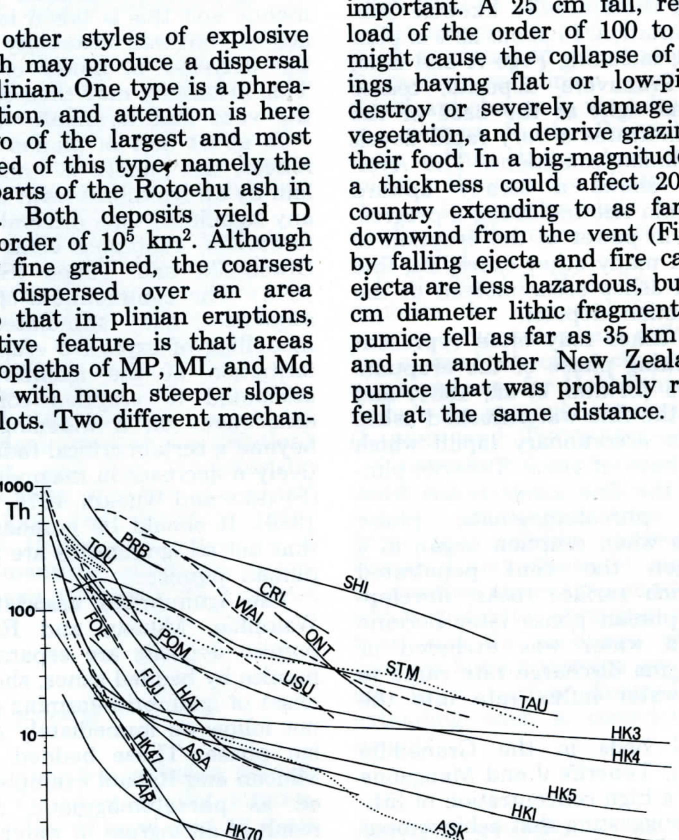

FIG. 9 - Plot of the thickness (Th) in centimetres as it varies with distance from vent (D) in km along the dispersal axis. Note that the slope depends on the wind velocity at the time of eruption as well as the power of the eruption.

In many ways the fall of a comparable thickness of fine ash would be more disruptive; if it fell in a wet condition it might represent a load of 300 kg m^{-2}, and being more cohesive would have the potential to cause the collapse even of steep-roofed buildings and bring power and telephone lines down. Being less permeable, it would be more liable to erosion by high-intensity rainfall, with all the problems of clogging of water-courses and flooding that would follow. Ash-falls of this type commonly accompany plinian eruptions, as at Rabaul and Santorini for example, and extensive co-ignimbrite ash-falls may accompany the generation of post-plinian ignimbrites (SPARKS and WALKER, 1977).

Pyroclastic flows constitute a serious hazard. Intraplinian flows tend to have a small volume and seldom travel farther than about 10 km, although some on the steep cone of Tenerife travelled more than 20 km; the post-plinian pyroclastic flows which are generated in about 30% of plinian events are much more to be feared, and that which followed the Taupo eruption overwhelmed 20,000 km^2 of country out to a radius of 85 km from the source vent. In the circumstances it is fortunate that such plinian eruptions are so infrequent.

CONCLUSIONS

The sample of 49 plinian eruptions for which data are collected here varied greatly in magnitude (as expressed by the volume of ejecta generated) and produced deposits which show a considerable diversity of petrological, compositional and structural characters, but all give evidence for a sustained eruptive blast of very great power. The suddenness with which many plinian eruptions develop, often following a lengthy period of quiescence on the volcano, may indicate that the gradual accumulation over a long time of magmatic gases is an essential prelude to the event; alternatively magma mixing may serve as an important eruption trigger to cause or permit the escale to the surface of magma lying motionless within the crust. Discussion of this aspect is outside the scope of this review, but there is good evidence for magma mixing in many cases.

This review concentrates attention on the deposits of plinian eruptions since the eruptions happen at such a low frequency, and tend to happen so unexpectedly and develop so rapidly, that few volcanologists have ever had the opportunity to witness one; in the event that volcanologists were close by when one happened, the direct observations that they could make in safety might in any case be quite limited in scope. Information on plinian eruptions has thus necessarily been derived mostly from indirect studies made on their deposits.

While much can be learned using this indirect approach, the answers to many questions remain unanswered, and in particular remarkably little is yet known about the nature of the premonitory symptoms of a major plinian event. Two scenarios might be envisaged. One is where the gradual rise of a large magma diapir takes place, causing visible bulging at the surface and giving rather obvious warning of impending danger. The other is where a body of salic magma lies quietly below the surface. The injection of a small batch of mafic magma (which in itself would produce relatively minor geophysical or surface effects) might within a short time span trigger a powerful eruption of the salic magma. In this second scenario the warning of the outburst might well be minimal. More research is clearly needed on such aspects of volcanology.

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