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ERUPTION, TRANSPORT AND DEPOSITION OF IGNIMBRITE: A CASE STUDY FROM MEXICO

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ABSTRACT

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The Acatlan ignimbrite covers 150 km² around a vent situated 40 km southwest of Guadalajara, Mexico. The upper and main ignimbrite flow unit is compositionally zoned, and has white or pink rhyolitic pumice in its lower part and black andesite in its upper; these parts are believed to have been erupted continuously from the same magma chamber. This zonation has been important in correlating an extremely coarse, lithic-rich deposit, a co-ignimbrite lag-fall deposit, with this ignimbrite. The co-ignimbrite lag-fall deposit indicates that the flow unit formed by continuous collapse of an explosive eruption column, and enables the source vent to be located. The vertical compositional grading of the flow unit also provides a means of testing the various proposed mechanisms of ignimbrite emplacement (turbulent vs. high-concentration flow). The preservation of compositional zonation and other features in the deposit indicate that flow was not turbulent. Details of the grain-size distribution indicate that laminar flow was important early in the flow history when collapsing material from the eruption column was superimposed in stratigraphical sequence. Initial high gas-flow rates (associated with flow segregation and formation at the site of column collapse) rapidly decayed away from vent and later in its history the flow degassed to a semi-rigid plug overriding a sheared basal layer.

INTRODUCTION

The Quaternary Acatlan ignimbrite covers some 150 km² in the western part of Mexican volcanic belt southwest of the city of Guadalajara (Fig.1). This paper, together with an earlier one (Wright and Walker, 1977a), documents a case study of the eruption, transport mechanism and deposition of one flow unit of this ignimbrite. A flow unit is defined as the deposit of a single pyroclastic flow (Sparks et al., 1973). Like most ignimbrites, the Acatlan ignimbrite is composed of several flow units.

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The ignimbrite occurs in an area with abundant Quaternary volcanoes including the large rhyolite volcano of La Primavera to the north (Mahood, 1977, 1980; Walker et al., 1980). Pumice fall deposits from this volcano occur above the Acatlan ignimbrite at some localities. A basalt lava overlying the ignimbrite 1 km north of Acatlan (Fig.1) is reversely magnetized (Wright, 1979), suggesting that the ignimbrite is older than 690,000 years B.P. (the age of the youngest reversed polarity epoch; see Cox, 1969, and Watkins, 1972).

An important feature of the ignimbrite is that the upper and main flow unit shows an upward zonation from rhyolitic to andesitic pumice. This is believed to result from, the continuous eruption of the two types from the same magma chamber. Upward injection of the hotter, more basic magma into the rhyolitic magma, and the consequent forced convection and mixing, may have triggered the eruption (Sparks et al., 1977).

The compositional zoning found in the Acatlan ignimbrite is an important key in this study for two reasons:

(1) An extremely coarse and lithic-rich deposit can be correlated with the upper main flow unit because it shows the same compositional zoning. Wright and Walker (1977a) interpreted this as a new type of pyroclastic de-

Fig.1. Distribution of the Acatlan ignimbrite (stippled). Star marks probable source vent of Cerro el Chino. Large dots locate exposures of co-ignimbrite lag-fall deposit; larger dot locates the section detailed in Fig.5. Northeast of Cerro el Chino the lag-fall deposit is concealed beneath younger lava flows. Circled numbers locate key sections of the ignimbrite discussed in text. Contour interval: 100 m; diagonal rule: ground higher than 1600 m. Inset shows index map of Mexico; stipple: Mexican volcanic belt (after Gunn and Mooser, 1971); G = Guadalajara.

posit: a co-ignimbrite lag-fall. It indicates the ignimbrite formed by continuous collapse of an explosive eruption column and locates the ignimbrite source vent (Fig.1).

(2) The vertical compositional profile through the upper main flow unit, which reflects the time sequence of magma compositions erupted, provides a means for testing the various proposed mechanisms of ignimbrite emplacement (Wright and Walker, 1977b); flow cannot have been turbulent, otherwise, mixing of the two contrasted pumice types would have taken place and destroyed the compositional zoning.

FIELD RELATIONS

The ignimbrite has a maximum exposed thickness of 100 m and is locally divisible into as many as five flow units. Flow unit boundaries are clearly defined; each unit has a fine-grained basal layer (Sparks et al., 1973; Sparks, 1976). Locally, thin air-fall and pyroclastic surge deposits are found immediately below the ignimbrite, and are thought to be early products of the same eruption.

In the lower flow units of the ignimbrite (Fig.2a), and in the air-fall and surge deposits, the juvenile component is exclusively aphyric white or pink rhyolitic pumice with associated rhyolitic shards. The main and uppermost flow unit has an average thickness of 20 m and is compositionally zoned (Fig.3a). In its lower part the juvenile component is a white or pink rhyolitic pumice and in its upper, an aphyric black andesitic pumice (Table 1). The andesitic pumice also sometimes contains streaks of silky, white rhyolitic pumice. A transition zone about 3 m thick occurs between the lower and upper parts within which pumice of both compositions occurs (Fig.3b); the rhyolitic pumice gradually decreases in amount upward as the andesitic increases. The base of the upper part of the flow unit is marked by a distinct colour change from pink to black (Figs.3a and 3b). There is no evidence of a flow unit boundary within the passage zone or at the colour boundary, despite the fact that the ignimbrite is non-welded in some of the best exposures and conditions are favourable for detecting such a boundary.

Over the western part of the outcrop the upper andesitic part is welded (Fig.2b). Welding continues to the very top of the deposit; no non-welded zone is present or evidence for one found above this surface. Significantly it is the more basic, presumably hotter, part which has welded and the ignimbrite shows an upward increase in the degree of welding (Wright, 1979).

The co-ignimbrite lag-fall deposit has been described by Wright and Walker (1977a) and is exposed over an area of about 4.5 km^2 just north of Bellavista (Fig.1). Where best seen in a barranco head 1.5 km northwest of the town, the deposits are stratified and extremely rich in lithic fragments ranging to more than 50 cm in diameter (Figs.4 and 5). The lag-fall deposit totals 10 m in thickness and lies between earlier rhyolitic flow units of the ignimbrite and coarse welded, andesitic bomb-rich, air-fall deposits produced at a later stage in the same eruption.

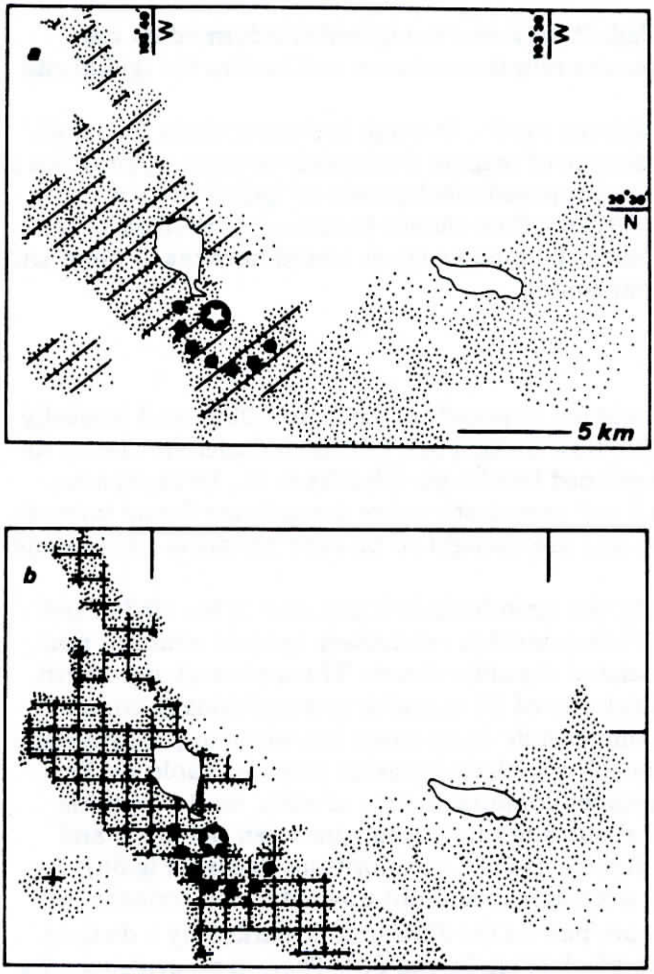

Fig.2. Sketch maps of the Acatlan ignimbrite showing: (a) area where lower rhyolitic flow units are present: diagonal rule; (b) area where upper main flow unit is welded: squared rule. Star: probable source vent of Cerro el Chino; large dots encompass area in which the co-ignimbrite lag-fall deposit is found.

That the lag deposit is of air-fall type is shown by the stratification, marked by a variation in grain size, and expressed quantitatively in Fig.5 by variation in the maximum size of lithic fragments. Some fall units show a distinct normal grading. The absence of fine-grained fall units (ash-grade, < 2mm), and of discrete bedding planes is evidence for rapid accumulation from a continuous vigorous eruption column with only minor variations in intensity.

In the lower part of the lag-fall deposit the pumice is pink or white and rhyolitic, as in the lower flow units and the lower part of the main ignimbrite flow unit. Higher in the deposit, black andesitic pumice enters, as in the upper part of the main ignimbrite flow unit. There is a passage zone about 2 m

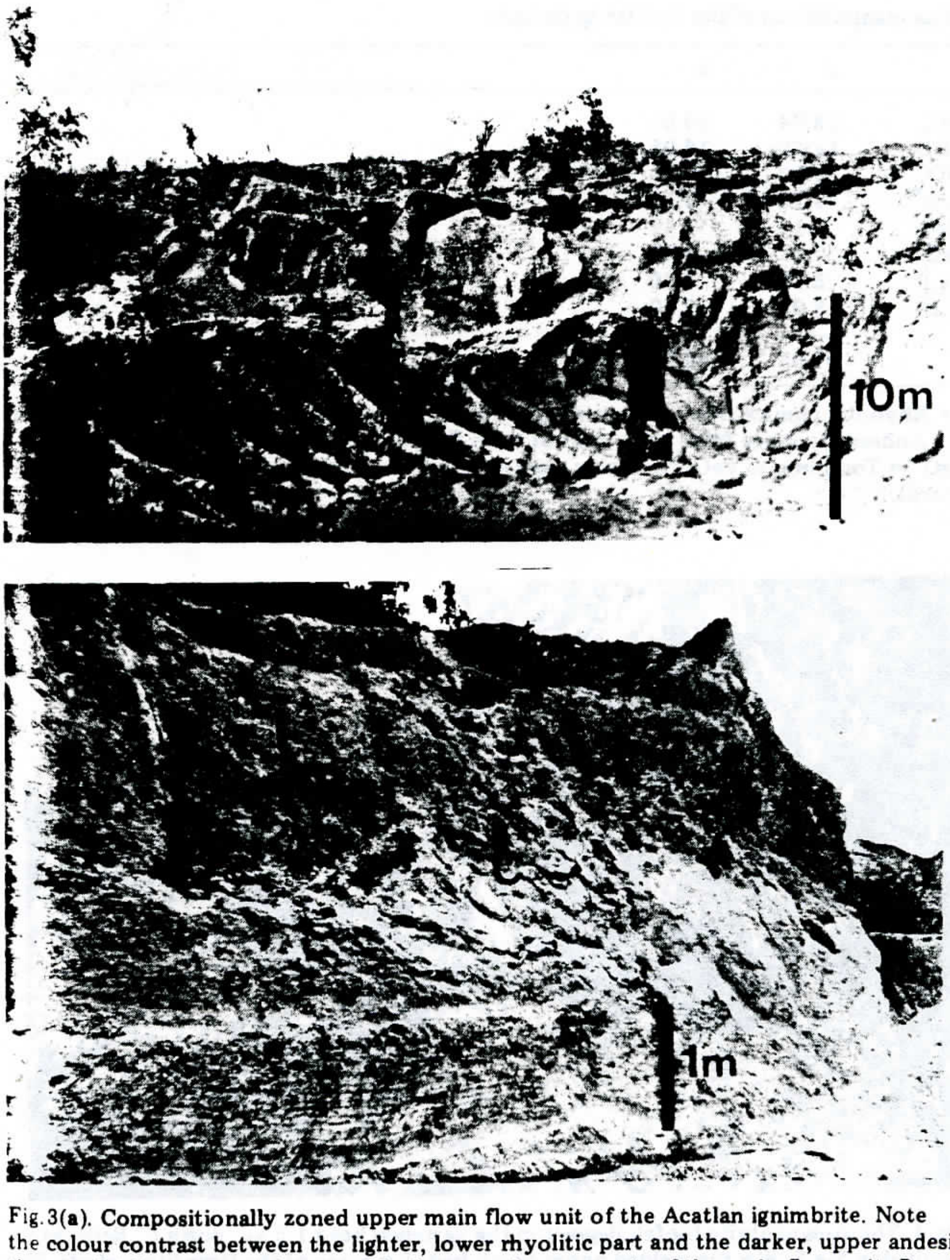

Fig. 3(a). Compositionally zoned upper main flow unit of the Acatlan ignimbrite. Note the colour contrast between the lighter, lower rhyolitic part and the darker, upper andesitic part. (b) Passage zone between the lower and upper parts of the main flow unit. P = passage zone (note the large dark andesitic pumice clasts); C = colour change.

TABLE 1

Glass compositions of the Acatlan ignimbrite

	a	b
SiO_2	73.34	59.61
Al_2O_3	14.66	16.05
TiO_2	0.13	0.98
FeO^*	1.15	4.55
MgO	0.11	1.47
CaO	0.57	3.85
Na_2O	3.16	4.40
K_2O	3.93	2.40
	97.05	93.31

a = Rhyolitic pumice from lower part of the upper main flow unit (average of 4 analyses).
b = Andesitic pumice from upper part of main flow unit (average of 3 analyses).
FeO^* = Total iron as FeO. (Analyses were made on the electron microprobe by R.S.J. Sparks.)

Fig.4. The co-ignimbrite lag-fall deposit in the barranco head 1.5 km north of Bellavista detailed in Fig.5. *W* = the welded upper bomb bed; *L* = some of the large lithic clasts. The deposits are stratified but there is an absence of discrete bedding planes.

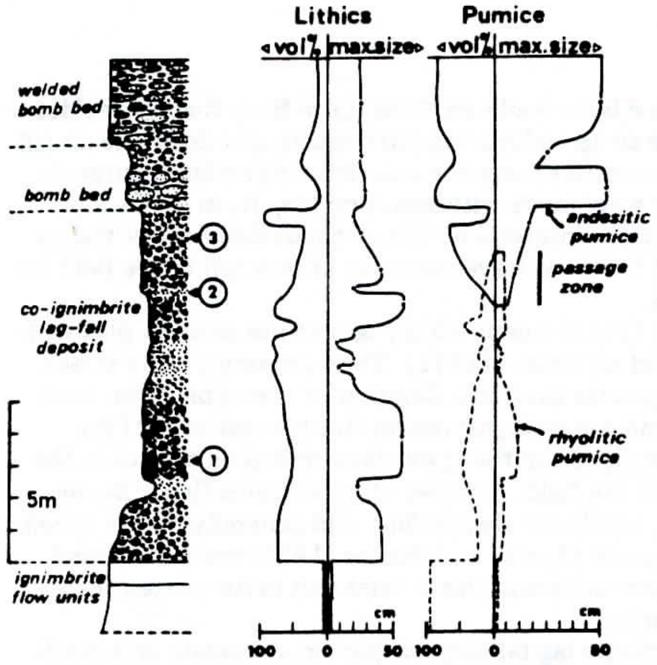

Fig.5. Generalized section through the co-ignimbrite lag-fall deposit in barranco head 1.5 km north of Bellavista (see Fig.1, and Wright and Walker, 1977a, for grid reference). Volume percentages of lithics and pumice are visual estimates made in the field. Lithics are as large as 2 m in other exposures. Circled numbers refer to position of samples used for grain-size analysis, detailed in Fig.10.

thick in which both pumice types occur, and andesitic pumice increases in amount upward at the expense of rhyolitic pumice. At the top of the section the deposit rather abruptly changes character with the influx of large andesitic pumice bombs, as much as 1 m in size, and a decrease in the proportion of lithic fragments. The bombs are concentrated in two horizons, of which the upper is the thicker and poorer in lithic material. The upper, and in places also the lower bed and intervening fall unit are welded, and are clearly welded tuffs of air-fall type (Sparks and Wright, 1979).

The compositional zoning found in the lag-fall deposit and bomb horizons parallels that found in the ignimbrite. It is the key to the interpretation because it shows that the lag-fall deposit accumulated synchronously with the formation of the ignimbrite, and is indeed correlated with main upper, compositionally zoned, ignimbrite flow unit (Wright and Walker, 1977a).

The source vent of the Acatlan ignimbrite is believed to lie in the area encompassed by the lag-fall deposit. A likely position is marked by the younger rhyolite extrusive dome of Cerro el Chino (Fig.1). This dome is located on flat ground, within a volcanic region but not associated with any pre-existing volcano.

GRAIN-SIZE STUDIES

Mechanical analyses have been made on 41 samples from the non-welded ignimbrite, three from the co-ignimbrite lag-fall deposit, one from the air-fall underlying the ignimbrite and five from the associated pyroclastic surge deposits. Grain-size analyses were made with sieves ranging from −5 to 4 phi (32 mm−1/16 mm) with 1-phi intervals by the methods detailed by Walker (1971) and supplemented by linear traverses made at outcrop in the field for clasts coarser than 64 mm.

On an Md_ϕ/σ_ϕ diagram (Fig.6) nearly all the ignimbrite samples plot within the pyroclastic flow field of Walker (1971). They are very poorly sorted and all have σ_ϕ values of greater than 2.0. Samples of the upper main compositionally zoned flow unit are well grouped in the coarsest part of the pyroclastic flow field. Samples from the lower flow unit tend to plot in the finer, more central parts of the field. Samples of basal layers (layer 2a, terminology of Sparks et al., 1973) are always finer and generally better sorted. A co-ignimbrite ashfall deposit (Sparks and Walker, 1977) has been found interbedded with lower flow units and this is finer and better sorted than other layers in the ignimbrite.

Samples of the co-ignimbrite lag-fall deposit plot in a separate and much coarser field. Although they are poorly sorted ($\sigma_\phi > 2.0$) analyses are very similar to other very coarse near-vent pyroclastic fall deposits (see Walker and Croasdale, 1971; Bond and Sparks, 1976).

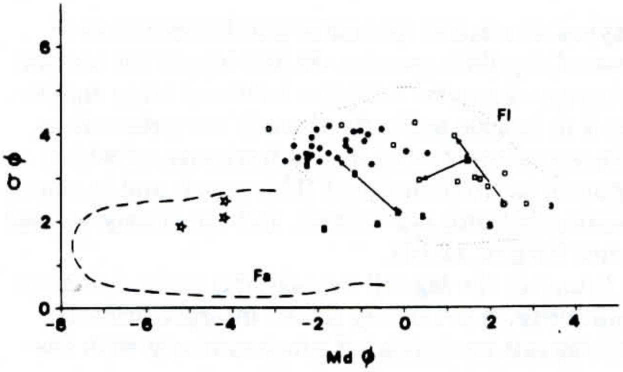

Fig.6. Md_ϕ/σ_ϕ plot of the Acatlan ignimbrite. Closed circles: compositionally zoned upper main flow unit; open squares: lower rhyolitic flow units; *b* = basal layer (layer 2a) connected to the lower-most sample in layer 2b (terminology of Sparks et al., 1973); *3* = co-ignimbrite ash-fall deposit found interbedded with lower flow units; stars: co-ignimbrite lag-fall deposit; *a* and *s* are, respectively, air-fall and pyroclastic surge deposits associated with the eruption of the ignimbrite. Dotted line is the 1% contour for field of pyroclastic flow (*Fl*) deposits and dashed line is modified 1% contour for field of pyroclastic fall (*Fa*) deposits by Sparks and Wright (1979), after Walker (1971).

For comparison, analyses of the air-fall and pyroclastic surge deposits underlying the ignimbrite are also given in Fig.6. The fall deposit is much better sorted ($\sigma_\phi < 2.0$). Surge deposits show a wide variation in grain size between samples taken from different laminae but are generally better sorted than the ignimbrite.

Grain-size variations of the compositionally zoned upper main flow unit and co-ignimbrite lag-fall are now detailed; these deposits represent the products of a single episode of eruption column collapse and pyroclastic flow formation.

Upper main flow unit

Grain-size variations within a flow unit must place important controls on any model of pyroclastic flow. In this study the upper main flow unit of the Acatlan ignimbrite has been measured and sampled at three widely spaced sections covering the lateral extent of the ignimbrite. Compositional zoning provides the means for correlating this single flow unit, and moreover, preservation of this zonation places restrictions on interpreting the transport mechanism. Fig.7 shows there is little lateral variation in the average grain-size distribution of the flow unit. The ignimbrite is relatively coarse-grained (Fig.6) for the flow unit contains less than 50% ash (Fig.7), and therefore, it is worth noting that the term "ash-flow tuff" should not be used to describe the deposit.

Md_ϕ and σ_ϕ parameters do not change significantly with height through the flow unit (Fig.8), and there is little evidence of vertical grading of larger clasts. In its upper part there is a small increase in Md_ϕ and an increase in sorting due to the larger average size of andesitic pumice clasts (Table 2) which cause the size distribution to be positively skewed (see Fig.9). Maximum clast sizes show there is a general lack of vertical and lateral grading (Fig.8, and see Wright and Walker, 1977, fig.3) although the largest andesitic pumice clasts commonly occur in the passage zone.

The size distribution of the flow unit has been examined in greater detail in section 2 (Fig.7), where samples have been separated into their components (Fig.9). In the passage zone Md_ϕ of andesitic pumice shows a sharp increase because only the largest clasts occur there. This suggests a gravitational effect; only the large clasts had sufficient settling velocities (Sparks, 1976) to move downwards into the lower rhyolitic part of the flow. Some of these largest juvenile andesitic clasts are poorly vesiculated and have a measured density of up to 1.6 g cm^{-3}, so there was a considerable density contrast between them and the matrix of the flow (Table 3). Above the colour change small amounts of finer grained rhyolitic pumice are found which show a sharp decrease in Md_ϕ vertically upwards through the upper part of the flow unit. This component is interpreted as having been moved upwards out of lower rhyolitic parts of the flow unit by gas. Although there is no variation in their abundance, lithic fragments show a general increase in Md_ϕ through

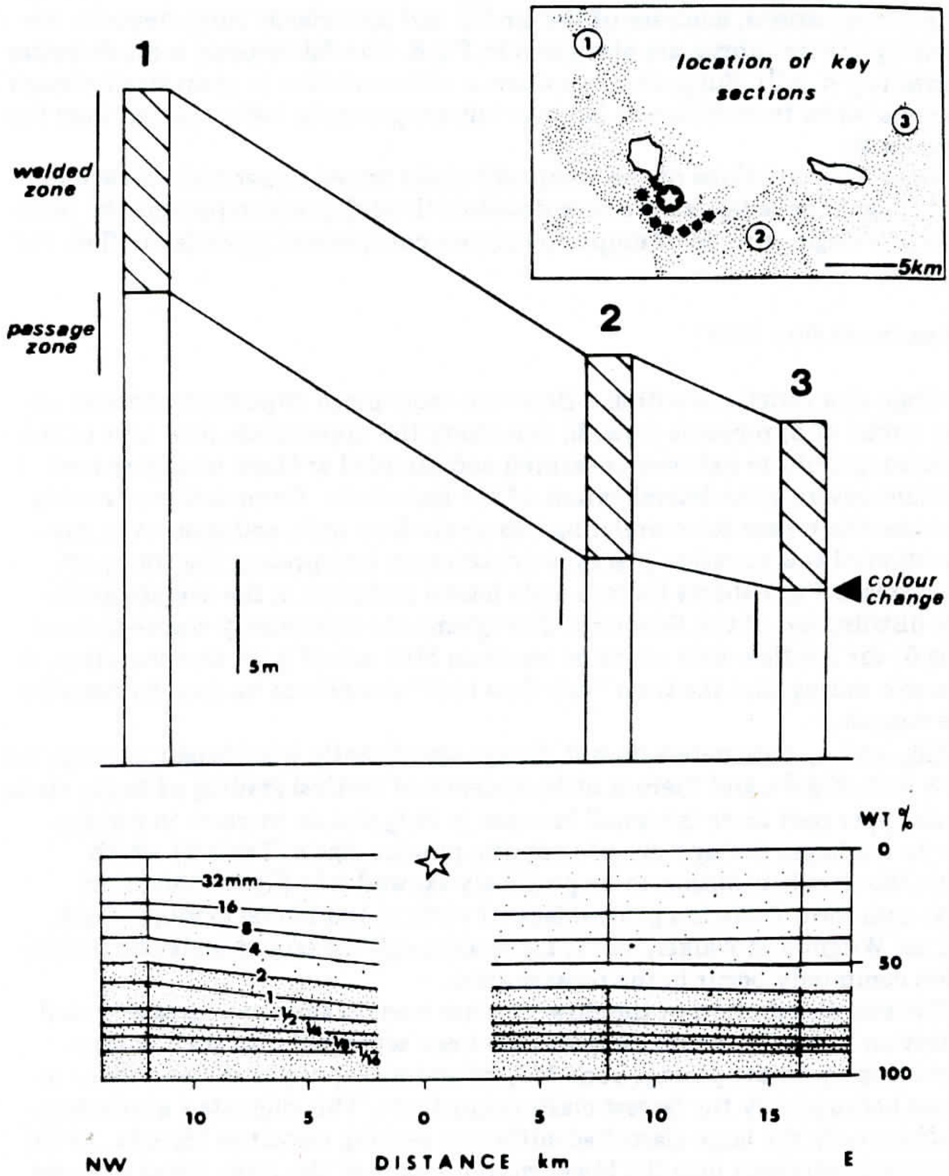

Fig.7. Average grain-size distribution of the upper main flow unit of the Acatlan ignimbrite. Less than 2 mm (close stipple) = ash. Star marks source position; unornamented is area in which co-ignimbrite lag-fall deposit occurs. Inset locates the three key sections; star marks probable source vent of Cerro el Chino and large dots encompass area in which the lag-fall deposit is found. Key section 3 is also shown in Fig.3a.

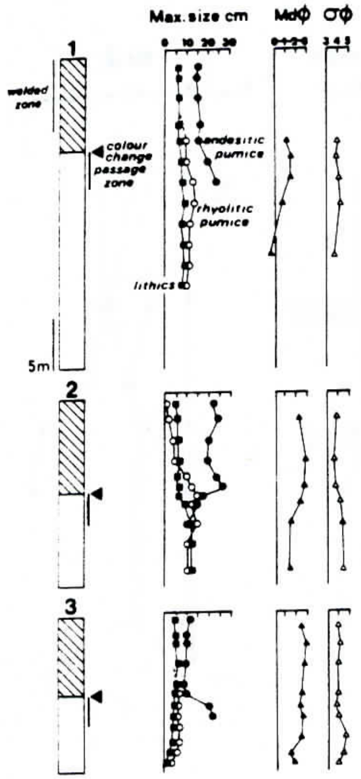

Fig.8. Variation in maximum clast size (average of the five largest clasts, pumice and lithics), Md_ϕ and σ_ϕ for the three key sections of the upper main flow unit shown in Fig.7.

TABLE 2

Average* maximum diameter (cm) of pumice clasts in the Acatlan ignimbrite

	Rhyolitic pumice	Andesitic pumice
Lag-fall	12	79
Ignimbrite	17	47

*Average of the five largest clasts measured.

the flow unit. This change must reflect original variations in the eruptive column and not dynamics of the transport mechanism, because the largest lithic fragments which are more visibly controlled by flow dynamics, occur towards the base of this section (Fig.8).

Fluidization is commonly believed to play an important part in the transport of pyroclastic flows (Sparks, 1976; Wilson, 1980). The gas flow processes involved in fluidization produce their own grading and sorting in the finer-

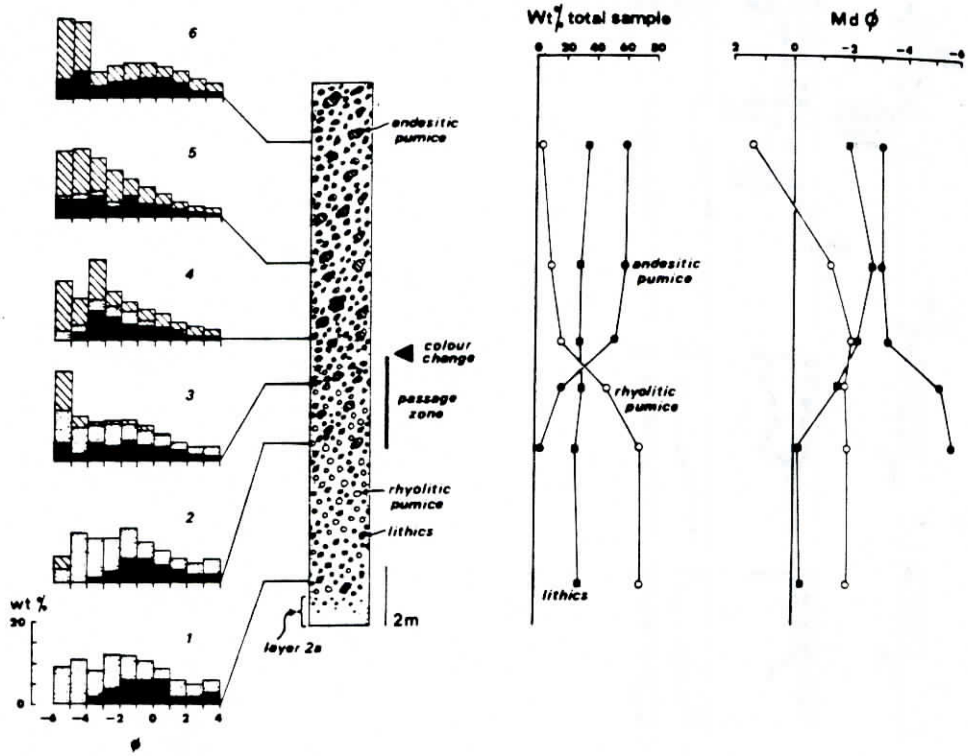

Fig. 9. Details of the grain-size distribution in key section 2 of the upper main flow unit in the Acatlan ignimbrite (located in Fig. 7). In histograms, the weight percentages retained by each sieve are plotted against the sieve aperture in phi. Weight percentages of the components are also plotted for each size fraction. Stipple: rhyolitic pumice; diagonal rule: andesitic pumice; black: lithics.

TABLE 3

Comparison of the average density (g cm^{-3}) of pumice and matrix in the main flow unit of the Acatlan ignimbrite

	Pumice	Matrix
Andesitic	0.78	0.96
Rhyolitic	0.69	1.12

Note. Pumice densities were measured using clasts in the size range 2—25 cm. Matrix is here taken as the size fraction less than 2 mm.

grained fractions. A method of grain-size analysis is presented here (after C.J.N. Wilson, unpublished data) to study the grading and sorting induced in flow units by gas flow processes. If the intraflow gas sources are dominant and are due to release of gas from juvenile clasts by diffusion (Sparks, 1978) or breakage and attrition (Wilson, 1980), the gas flow will increase systema-

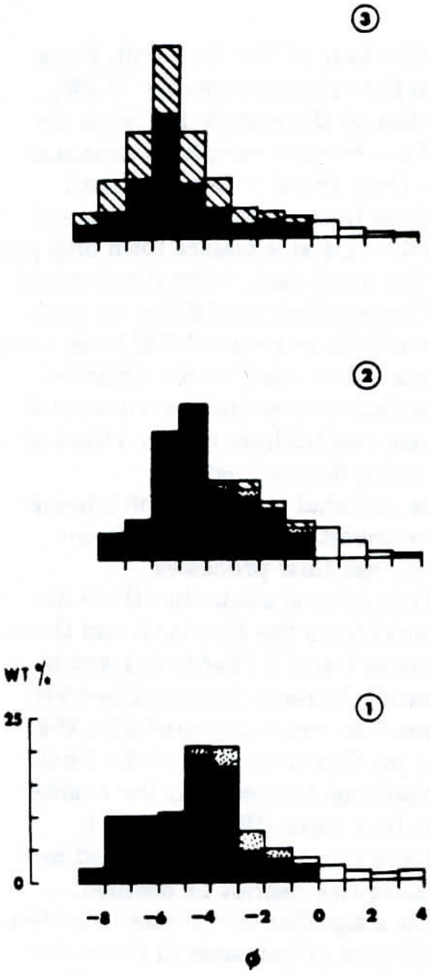

Fig. 10. Size-distribution histograms for three samples of the Bellavista co-ignimbrite lag-fall deposit positioned in Fig. 5. Black: lithics; stipple: rhyolitic pumice; diagonal rule: andesitic pumice. Note that the 6-ϕ (64 mm) and larger size classes are expressed as volume rather than weight percentages.

tically with height through the thickness of the flow. Other gas sources, such as entrapment of air at the flow front (MacTaggart, 1960) will not vary systematically with height but will affect the whole thickness uniformly (Wilson, 1980).

Gas grading is examined in detail where a number of samples have been taken at various heights in a flow unit at a single site. The assumption is made that the lowermost sample in the layer 2b of a flow unit is least affected by gas flow processes, and will therefore be closest in grain-size distribution and component proportions to the original material supplied to the flow from vent. This sample is termed the reference sample. If no separate layer 2a is recognized, the reference sample is taken at the base of the flow unit. For a given size class* each sample is normalised to the reference sample: W_1/W_2, where W_1 is the weight percentage in a size class of the sample and W_2 is the weight percentage in the same size class of the reference sample. Normalised values are then placed in a *whole-rock* array. Only the $\leqslant -2\text{-}\phi$ ($\leqslant$ 4 mm) fractions are considered as it is probably only in these sizes that evidence of gas grading and sorting will be found. If the $\leqslant -2\text{-}\phi$ size classes form only part of the total grain-size distribution, which is the usual case, normalized values must be corrected for the diluting effects of larger clasts controlled by gravitational processes. The $\leqslant -2\text{-}\phi$ fractions are therefore recalculated to be 100% thus eliminating the effects of the larger clasts. When samples are separated into their components, arrays can be constructed to examine the movement of the constituent particles. No corrections are needed here for the effect of larger clasts as in these cases only ratios are being determined.

These methods can be used to: deduce the material lost from the moving pyroclastic flow by gas flow processes, and to investigate the grading and sorting of components within the flow unit by gas flow processes.

The whole-rock grain-size arrays (Table 4) in general show that there has been very little removal of fine-grained material from the flow unit and therefore gas flow rates must have been low. Sections 1 and 2 (Table 4, a and b) show significant systematic removal of material (decrease in normalised values) only in the $\leqslant 3\text{-}\phi$ ($\leqslant$ 1/8-mm) size classes. The neutral graded size, that is the size which is not detectably graded by gas flow processes at the finer end of the grain-size distribution or by gravitational processes at the coarser end, is 2 ϕ (1/4 mm) which indicates low gas flow rates (Wilson, 1980). Section 3 (Table 4, c) shows no evidence of any removal of fine-grained material by gas flow processes and a neutral graded size cannot be defined.

In section 2 the 1-ϕ to 3-ϕ size classes show a significant increase in material at the top of the flow unit and there is evidence of increases in these size classes also in section 3. Other fluctuations in the whole-rock arrays of the three sections can be correlated, for example, in the 1-ϕ to 3-ϕ size classes just above the compositional boundary. These types of fluctuations and the compositional zonation indicate the presence of an internal stratigraphy which is preserved laterally.

A rhyolitic/andesitic pumice array (Table 5) has been constructed for the upper part of the flow unit, above the colour change, to study the movement of rhyolitic pumice. This plots the ratio: $(P_{r1}/P_{a1})/(P_{r2}/P_{a2})$, where P_{r1} and P_{a1} are the weight percentages of rhyolitic pumice and andesitic pumice, respectively, in a size class of the sample, and P_{r2} and P_{a2} are the weight percentages of rhyolitic pumice and andesitic pumice, respectively, in the same size class of the reference sample. The array shows that rhyolitic pumice has been moved upward but only in the $\leqslant 2\text{-}\phi$ size classes, suggesting that gas flow processes are responsible. The presence of fine-grained rhyolitic pumice

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*A size class is the weight percentage retained by a sieve of particular aperture.

TABLE 4

Grain size arrays of the main flow unit of the Acatlan ignimbrite

a. Whole rock array key section 1.

LAYER	SAMPLE	GRAIN SIZE Ø -2	-1	0	1	2	3	4	<4
	5	1.09	1.22	1.37	1.33	1.12	0.75	0.49	0.79
C—	4	1.60	1.39	1.33	1.21	0.90	0.59	0.45	0.73
2b	3	1.55	1.08	1.23	1.21	0.96	0.66	0.60	0.85
	2	1.16	1.07	1.17	1.18	0.98	0.67	0.88	0.92
	RS1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
						▲ NGS			

b. Whole rock array key section 2.

LAYER	SAMPLE	GRAIN SIZE Ø -2	-1	0	1	2	3	4	<4
	6	0.85	0.95	1.05	1.22	1.41	1.32	0.74	0.84
	5	1.33	1.16	0.95	0.94	0.87	0.77	0.53	0.88
	4	1.30	1.07	0.98	1.03	0.98	0.89	0.63	0.89
C—	3	1.04	1.10	1.08	1.00	0.93	0.91	0.76	0.98
2b	2	0.93	1.07	0.99	0.97	0.96	0.97	0.93	1.08
	RS1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
						▲ NGS			

c. Whole rock array key section 3

LAYER	SAMPLE	GRAIN SIZE Ø -2	-1	0	1	2	3	4	<4
	10	1.04	0.88	1.01	1.08	1.21	1.13	1.03	0.95
	9	1.18	1.01	0.99	0.97	0.98	0.87	0.89	0.90
	8	1.09	0.98	1.10	1.08	1.14	1.01	0.91	0.75
	7	0.98	0.90	1.01	1.14	1.25	1.09	0.94	0.92
C—	6	1.20	0.95	0.99	0.98	0.95	0.98	1.05	0.88
2b	5	1.20	1.00	0.97	0.98	0.91	0.96	1.08	0.86
	4	1.09	0.82	0.81	0.78	0.88	0.98	1.48	1.32
	3	0.78	0.97	0.97	0.96	0.95	1.05	1.62	1.21
	RS2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2a	1	0.66	0.89	1.62	1.58	1.31	1.06	0.91	0.51

NGS is the neutral graded size; RS is the reference sample; C is the colour change between the lower rhyolitic and upper andesitic parts of the flow unit. Stipple: gas flow grading; unornamented: sizes not detectably graded (note no systematic gravitational grading, increases or decreases in material, can be recognized in the whole rock array in sizes coarser than the NGS or in key section 3). Boxes enclose grain size fluctuations which can be correlated in the different sections and are referred to in the text. Samples 1 to 6 are as numbered in Fig.9.

in the upper andesitic part of the flow unit is therefore attributed to movement by gas processes from the lower rhyolitic part and not to flow turbulence.

Whole-rock grain-size arrays also give an insight into processes occurring in the basal layer. The basal layer in section 3 (Table 4, c) shows substantial increases in finer-grained material (0 ϕ to 3 ϕ), and this may be due to the attrition of larger pumice fragments. However, there has been a preferential loss from the basal layer of the finest ash ($< 4\ \phi$, $< 1/16$ mm) either at the flow

TABLE 5

Rhyolitic/andesitic pumice array for key section 2

Sample	Grain size (ϕ)							
	−2	−1	0	1	2	3	4	<4
6	0.15	0.05	0.12	0.19	0.38	0.35	0.34	0.35
5	0.18	0.22	0.42	0.63	1.25	0.74	0.61	0.82
RS4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Annotation is as in Table 4.

front or through the body of the flow. In the > 0-ϕ (> 1 mm) size classes material has been removed, firstly, by attrition of pumice and, secondly, by grain dispersive forces, shown by an observed upward increase in the maximum size of clasts in the basal layer in the field.

Co-ignimbrite lag-fall

In Fig.11, grain-size histograms are given for three samples taken from the section of the co-ignimbrite lag-fall deposit detailed in Fig.5. All the histograms are unimodal, unlike those of the ignimbrite which are bimodal or positively skewed (Fig.9). The lag-fall deposits are strongly enriched in lithic fragments, compared to the ignimbrite (Fig.11).

It is estimated that the lag-fall deposit (excluding the welded bomb beds) has a volume of 0.3 km³, compared with 3 km³ for the main flow unit of the

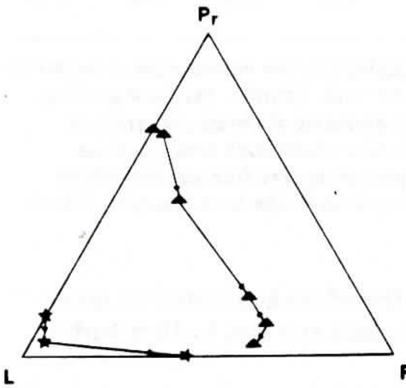

Fig.11. Variation in the proportion of lithics (L) and pumice (P_r = rhyolitic pumice and P_a = andesitic pumice) in the co-ignimbrite lag-fall deposit and upper main ignimbrite flow unit. Stars: co-ignimbrite lag-fall deposit from section detailed in Fig.5; triangles: ignimbrite from key section 2 (see Fig.10). Arrows indicate increasing stratigraphic height of samples. The diagram demonstrates that the lag-fall deposits are lithic-enriched and that the compositional zonation in the main flow unit parallels that in the lag-fall.

ignimbrite (Wright and Walker, 1977a). The lag-fall thus contains a small but significant proportion of the erupted material. The lithics contained in the lag-fall amount to approximately 25% by weight of the lithics present in the main flow unit of the ignimbrite.

DISCUSSION

(1) The co-ignimbrite lag-fall deposit is clearly a fall deposit. We conclude that the ignimbrite was also generated by the fall of debris from the eruption column. In the theoretical models envisaged by Sparks and Wilson (1976) and Sparks et al. (1978) for the generation of ignimbrite, column collapse is continuous. In the example described here collapse must likewise have been continuous. Although the eruption vigour fluctuated, as is evident from its stratified nature, the lag-fall deposit shows no evidence of any temporary cessation of activity.

The upper compositionally zoned flow of the Acatlan ignimbrite extends some 20 km from source, over more or less flat country and has climbed more than 100 m to reach some of the easternmost exposures. This dispersal cannot have been aided by a pre-existing volcanic slope and is best accounted for by the collapse of a high eruption column. A vent muzzle velocity of the order of 300 m s^{-1} is indicated by the ~3-km radius in which metre-sized lithic blocks occur (Wilson, 1972), and this suggests a column collapse height of 1–3 km depending on the vent radius (Sparks et al., 1978). A collapse height of more than 2 km could adequately account for the apparent mobility of the pumice flow (see Sparks, 1976, fig.21).

Sparks and Walker (1977) and Sparks et al. (1978) presented a model for the formation of pyroclastic flows at the place where eruptive column collapse is actively taking place. An extension of this model was proposed by Wright and Walker (1977a) to include the formation of a co-ignimbrite lag-fall deposit. Such a deposit forms at or near the site of eruptive column collapse and consists mainly of pyroclasts that are too large and too heavy to be carried away in the resulting pumice flows.

(2) The transport mechanism of the compositionally zoned flow unit is now discussed. Details of the grain-size distribution show that gas flow rates were relatively low (Table 4) and account for the general lack of vertical or lateral gravitational grading (Fig.8). A corollary is that the flow must have been a high particle-concentration dispersion with a relatively high yield strength (Wilson, 1980).

When sections of the compositionally zoned flow unit are examined in detail it is apparent that the topmost part shows an enrichment in 1-ϕ to 3-ϕ material, while below the top metre the 1-ϕ to 3-ϕ sizes show evidence of gas grading. All the field evidence suggests that this topmost fine "capping" must have been emplaced contiguously with the main body of the flow, and hence gas grading in the 1-ϕ to 3-ϕ sizes must have occurred within a very short interval between formation of the majority of the flow unit and the topmost capping. This capping may represent a fines-rich "tail-end" of the collapsing column. Gas processes could only have moved 1-ϕ to 3-ϕ sizes for a short period of time, so the time span of higher gas flow rates must have been very short. Certainly, these high transient gas flow rates were associated with flow segregation and formation at the site of column collapse. After superposition of the finer grained capping the residual gas flow rates (due to diffusion of gas from juvenile clasts, Sparks, 1978) were only capable of moving $\leqslant$ 4-ϕ sizes.

Preservation of the compositional boundary, described by Wright and Walker (1977b) as a means of testing the proposed mechanisms of ignimbrite emplacement, and other features of a remnant internal stratigraphy indicate vertical mixing of the flow by turbulence was absent. In accordance with evidence from analogous sedimentary flows with a high concentration of debris (Johnson, 1970; Hampton, 1972; Middleton and Hampton, 1973), movement was laminar and/or plug flow. Superposition of portions of the flow in time sequence requires laminar shear. In addition, the grain-size data indicate that this happened in a very short period of time during column collapse and flow formation.

The lack of reverse grading of larger clasts further from the source indicates that in the later stages of flow emplacement the shear rates within layer 2b were low, being insufficient to cause grading by grain dispersive forces

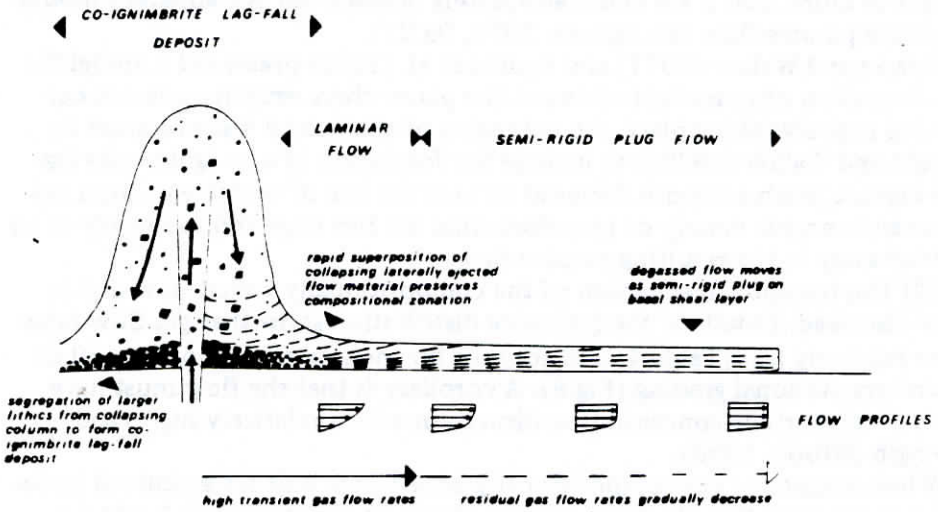

Fig.12. Schematic model (not to scale) for the eruption and flow history of the upper main flow unit of the Acatlan ignimbrite. High initial transient gas flow rates are derived from the "condensation" of the more dilute eruption column and trapped air. Residual gas flow rates are controlled by gas released from juvenile clasts by diffusion (Sparks, 1978). Theoretical models indicate that turbulent flow must occur in the collapsing eruption column (Sparks et al., 1978; R.S.J. Sparks, personal communication), but in spite of this the time sequence of erupted magma was not destroyed. Dashed lines represent genralized instantaneous flow lines.

(Bagnold, 1954, 1956). This suggests that residual gases in the flow were insufficient to cause fluidization, and in its later part the flow must have degassed to form a flow in which a semi-rigid plug (layer 2b) moved over a sheared basal layer (eventually to be layer 2a). A schematic model for the eruption and flow history is given in Fig.12. While theoretical models indicate that collapsing eruption columns should be turbulent (Sparks et al., 1978; R.S.J. Sparks, personal communication), evidence from the Acatlan ignimbrite indicates that, in spite of this, the time sequence of erupted magma was not destroyed.

It is worth commenting that the viscosity of the pyroclastic flow has not been determined in this study (for method, see Sparks, 1976). This is because such estimates can only represent near-source viscosities, during laminar conditions and superposition of portions of the flow, whereas, for most of its history, the flow moved as a semi-rigid plug with considerably higher effective viscosities than are calculated by the method.

CONCLUSIONS

A case study of the eruption and transport of a single flow unit of an ignimbrite has been presented. The upper main flow unit of the Acatlan ignimbrite is compositionally zoned and this has provided a key to identifying a co-ignimbrite lag-fall deposit, and to provide details of the flow mechanism.

A co-ignimbrite lag-fall deposit is important because it indicates that the pumice flow formed by continuous collapse of an explosive eruption column. With regard to the flow mechanism, vertical changes in composition in other ignimbrites have been invoked as evidence of layer by layer deposition from turbulent, low particle-concentration pyroclastic flows analogous to deposition from turbidity currents (Fisher, 1966; Lock, 1978). However, all the evidence presented here indicates that the flow was a high particle-concentration dispersion, and that deposition was more or less instantaneous, as is believed to be the case for mud flows. Preservation of the compositional zonation and other features of a remnant internal stratigraphy indicate that turbulent flow did not occur. Laminar flow was important early in the flow history when collapsing material was superimposed in stratigraphic sequence. Initial high gas flow rates rapidly decayed away from vent, and later in its travel the flow degassed to a semi-rigid plug overriding a sheared basal layer.

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