# The ignimbrite source problem: Significance of a co-ignimbrite lag-fall deposit

John V. Wright
George P. L. Walker
Geology Department
Imperial College
London SW7, England

## ABSTRACT

**A co-ignimbrite lag-fall deposit is one that 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. An example from Mexico is identified as such because it shows the same compositional zoning from rhyolite to andesite as the associated ignimbrite. It indicates that the ignimbrite originated by continuous collapse of the eruptive column and locates the ignimbrite source vent. In this example the vent is located on flat ground, apparently unrelated to any pre-existing volcano, and the ability of the ignimbrite to travel laterally some 20 km must be due to eruptive column height rather than ground slope.**

## INTRODUCTION

Evidence is accumulating that pumice flows result from the gravitational collapse of explosive eruptive columns, either from the interrupted collapse that results when a column already in the air is left unsupported, for instance by closure of the vent, or more likely from continuous collapse. The relationships described here strongly support an origin by continuous collapse; they also contribute to an understanding of the initial stages in the generation of pumice flows and to solving the problem of how to locate ignimbrite source vents. We adopt the convention of referring to the active pyroclastic flow as a pumice flow (consisting predominantly of vesiculated juvenile magma) and calling the resulting rock body an ignimbrite, whether it is welded or not.

At Bellavista, 40 km southwest of Guadalajara in the state of Jalisco, Mexico (Fig. 1), an extremely coarse and lithic-rich deposit found intimately associated with ignimbrite is interpreted as a new type of pyroclastic deposit: a co-ignimbrite lag fall. The deposit is related to the Acatlan Ignimbrite, of probable Quaternary age, which covers some 150 km² and whose exposed thickness is as much as 100 m. It occurs in the western part of the Mexican volcanic belt (Gunn and Mooser, 1971), in an area diversified by numerous small Quaternary volcanoes, including monogenetic cinder cones and lava domes, some younger and some older than the ignimbrite, together with hills of Tertiary volcanic rocks. Basalts, andesites, and rhyolites of the calc-alkalic suite are all represented in the area.

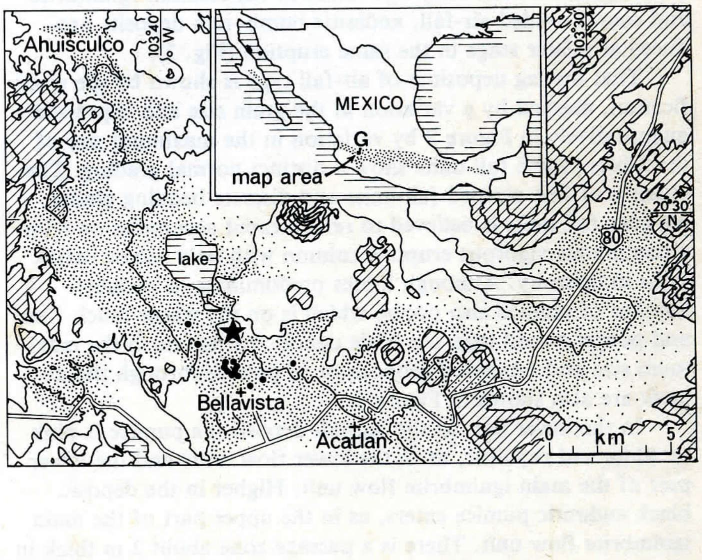

**Figure 1. Sketch map of Acatlan Ignimbrite (stippled). Star marks probable source vent of Cerro el Chino; large dots indicate exposures of lag fall; deposit is concealed beneath younger lava flows northeast of Cerro el Chino. Contour interval = 100 m; diagonal rule = ground higher than 1,600 m. Inset: index map of Mexico, showing Mexican volcanic belt (stippled) and Guadalajara (G).**

Certain specific features of the Acatlan Ignimbrite have a particular bearing on the origin and interpretation of the co-ignimbrite lag-fall deposits. At many exposures the ignimbrite is divisible into flow units; as many as five are found. Flow-unit boundaries are clearly defined; each unit has a fine-grained basal layer (Sparks and others, 1973; Sparks, 1976). The juvenile component of the lower flow units is exclusively an aphyric white or pink rhyolitic pumice ($SiO_2$ = 72.2% when the analysis is recalculated to 100% on a water-free basis) with associated shards. The main and uppermost flow unit, which has an average thickness of 20 m, is compositionally zoned; in its lower part the juvenile component is a white or pink rhyolitic pumice and in its upper part an aphyric black andesitic pumice ($SiO_2$ = 61.9%). A passage zone about 3 m thick occurs between the lower and upper parts within which pumice of both compositions occurs, the rhyolitic pumice gradually decreasing in amount upward as the andesitic pumice increases. No sign of a flow-unit boundary has been seen within this passage zone, despite the fact that because this zone is nonwelded in some of the best exposures, conditions are favorable for detecting such a boundary.

The upward zonation from rhyolitic to andesitic pumice is believed to result from the successive eruption of the two magma types from the same magma chamber. The fact that the two types have become superposed within the same ignimbrite flow unit implies transport of the pumice flow by laminar flow. If the flow were turbulent, then mixing of the two contrasted pumice types would have destroyed the zonation within the single flow unit. The full evidence for and implications of this flow mechanism will be presented elsewhere.

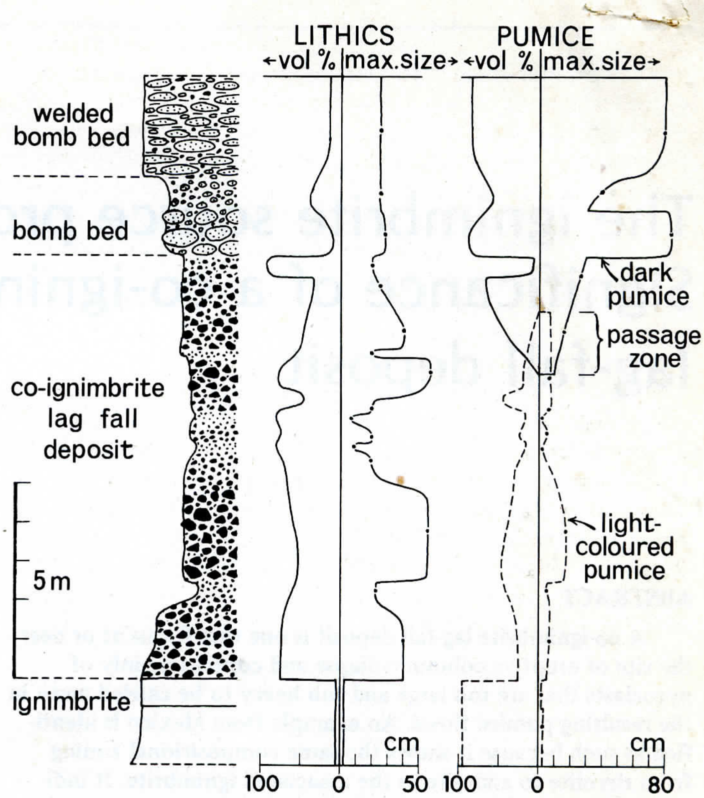

Figure 2. Generalized section through lag-fall deposit and associated rock units in barranco head 1.5 km northwest of Bellavista (CETENAL topographic map sheet F-13-D-74; scale 1:50,000; grid reference to 100 m 6416E, 2 2611N). Volume percentages of lithics and pumice are based on visual estimates made in field. In other exposures lithic blocks as large as 2 m are seen.

## FIELD RELATIONS

The co-ignimbrite lag-fall deposits are exposed over about 4.5 km² 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 as large as 50 cm and more in diameter. The deposits total 10 m thick and are sandwiched between early flow units of the Acatlan Ignimbrite and coarse welded air-fall, andesitic-bomb–rich deposits produced at a later stage in the same eruption (Fig. 2).

That the lag deposit is of air-fall type is shown by the stratification, marked by a variation in the grain size and expressed quantitatively in Figure 2 by variation in the maximum size of the lithics. Some fall units show a distinct normal grading. The absence of fine-grained fall units and discrete bedding planes between fall units is believed to reflect rapid accumulation from a continuous vigorous eruptive column with only minor variations in intensity. Although lithics predominate, a variable amount of pumice also occurs which is on the whole much finer and poorer sorted than the lithic debris. Variations in the maximum size and estimated proportion of pumice through the deposit are also shown in Figure 2.

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 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 because of the influx of large andesitic pumice bombs as much as 1 m in size and a decrease in the proportion of lithics. The bombs are concentrated in two horizons, of which the upper is the thicker and poorer in lithics. The upper and in places the lower bed and intervening fall unit are welded, and are clearly welded tuffs of air-fall type. It is believed that welding has taken place partly because of the heat retained by the large bombs and partly because of a high accumulation rate; therefore, the time available for convective and radiative cooling of each bomb while on the ground before burial was short.

The compositional zoning found in the lag-fall deposit and bomb horizons parallels that found in the ignimbrite, and it is the key to the interpretation because it shows that the lag-fall deposit accumulated synchronously with the formation of the ignimbrite.

## ORIGIN

Sparks and Walker (1977) have summarized a model for the generation of pumice flows at the place where eruptive column collapse is actively taking place. The collapsing material is a relatively dilute mixture of juvenile particles, lithics, and gas (including both volcanic gas and entrapped air), in which gas occupies by far the greatest volume. A pumice flow with high particle concentration rapidly forms, consisting mainly of particles that are too dense or too large to remain suspended in gas. Some fines are at the same time trapped in the flow and help keep it fluidized, while others remain in dilute particulate suspension and are lost from the pumice flow in an upper turbulent cloud.

An extension of this model can now be proposed in which the largest lithics, those too heavy to be supported or transported by the pumice flow, sink rapidly to the bottom and remain at or near the site of column collapse when the pumice flow moves away. We propose the term "lag-fall deposit" because the accumulation of lithics is a residuum left behind by the pumice flow: a kind of lag deposit. It is an air-fall deposit of a sort also, but one from which most of the finer and lighter material has drained out, leaving only a little trapped in the interstices. We call it a "co-ignimbrite" deposit because it is a product of the same eruptive episode as the ignimbrite itself and in this respect resembles "co-ignimbrite ash-fall deposits" (Sparks and Walker, 1977) that result when the fine ash settles out from the dilute ash-gas mixture above the eruptive column and the pumice flow.

We do not know if co-ignimbrite lag-fall deposits are developed at all ignimbrite vents, and we can envisage conditions where they are not so developed—for instance, when the eruptive column lacks large lithic fragments or when (because the discharge rate is very high or the ground slope very steep) the pumice flows can carry away even the largest lithic blocks. For any given situation there should be a cut-off size; lithic fragments larger than this size would not be transported away from the vent area by the pumice flows. A lag-fall deposit should form whenever this cut-off size is smaller than the maximum lithic ejecta size.

The entire Bellavista lag-fall deposit is tentatively correlated with one ignimbrite flow unit: the main upper one. Values of the average maximum diameter of lithics measured at various places in the lag-fall deposit plot in a separate and much coarser field than those in the main ignimbrite flow unit (Fig. 3), indicating a lithic cut-off size; however this cut-off is apparent rather than real because the values plotted are maximum sizes. An actual cut-off size does, however, exist: very few lithics in the ignimbrite exceed about 3 cm in size, and the greater part of the lithic fraction in the lag-fall deposit is coarser than 3 cm. Rhyolitic pumice shows no evidence of the existence of a cut-off (Fig. 3). This results from the limited size of the rhyolitic pumice and its uniform density (Table 1); it occurs in the lag-fall deposit trapped in the interstices.

It is not known which level in the lag-fall deposit corresponds to the end of the ignimbrite-forming part of the eruption. The andesitic bombs in the bomb horizons are larger than the largest andesitic pumice fragments found in the ignimbrite (Fig. 3), so it is possible that the bomb beds are also co-ignimbrite lag-fall deposits. Moreover, the density of the bombs is twice that of large juvenile andesitic clasts in the ignimbrite (Table 1). Whether the density contrast was sufficient for the bombs to have remained in the lag deposit because of their weight alone is not known. Alternatively, because of their relatively high temperature and low viscosity, the bombs stuck together on impact and were unable to enter the pumice flow because of their cohesion. Although it is uncertain whether or not the bomb horizons represent a lag deposit, they belong to the same eruption and maintain the compositional sequence.

The reason the lag-fall deposit rests on early flow units of the same ignimbrite could be that lag-fall deposits for these early flow units are confined to an area nearer source which is not exposed, or it may reflect a scarcity of large lithics during the early parts of the eruption.

TABLE 1. COMPARISON OF AVERAGE DENSITIES OF COMPONENTS OF LAG FALL AND MAIN IGNIMBRITE FLOW UNIT OF ACATLAN IGNIMBRITE

| | Rhyolitic pumice | Andesitic pumice | Lithics |
|---|---|---|---|
| Lag fall | 0.7 | 1.5 | 2.75 |
| Ignimbrite | 0.7 | 0.8 | |

*Note*: Measurements were made using clasts in the size range 2 to 25 cm; densities in grams per cubic centimetre.

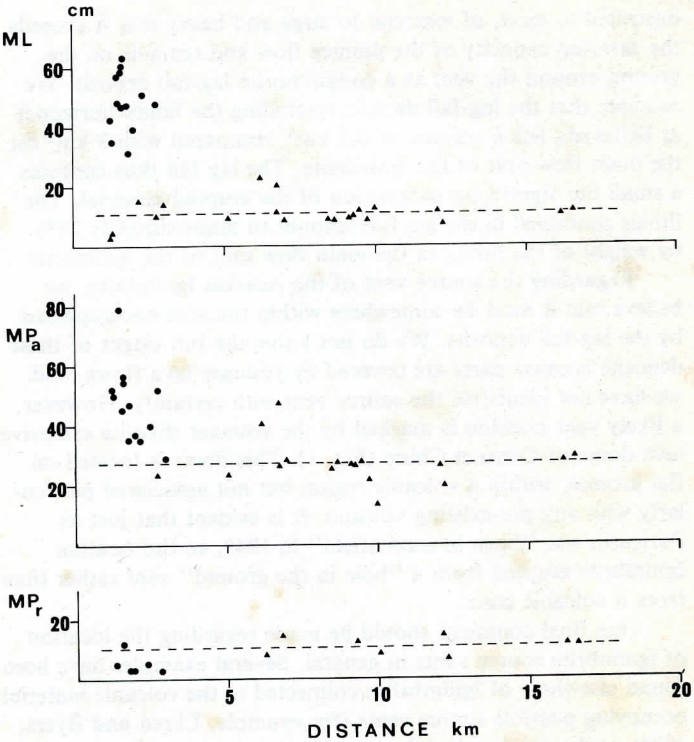

Figure 3. Average maximum diameter of five largest clasts plotted against distance from Cerro el Chino for main ignimbrite flow unit and lag-fall deposit; ML = lithics, MP = pumice (a = andesitic, r = rhyolitic); dots = measured in lag-fall deposit; triangles = measured in ignimbrite. Dashed lines are visual best-fit lines for ignimbrite and indicate lack of lateral grading.

## CONCLUSIONS

A co-ignimbrite lag-fall deposit is significant for three reasons: (1) it has a bearing on the mechanism of formation of pumice flows, (2) it indicates the existence of a cut-off for material too large and heavy to be transported by the pumice flows, and (3) it narrows down the notoriously difficult search for the position of the ignimbrite source vent.

Regarding the mechanism of formation, the lag deposit is clearly a fall deposit, and it is difficult to avoid the conclusion that the ignimbrite was also generated as a result of the fall of debris from the eruptive column. The collapse must, moreover, have been continuous; although the eruption vigor evidently fluctuated slightly with time, the lag deposit shows no evidence of any temporary cessation of activity. The wide dispersal of the Acatlan Ignimbrite—it extends some 20 km from source over more or less flat country and, indeed, has climbed more than 100 m to reach some of the easternmost exposures—cannot have been aided by any pre-existing volcanic slope and is best accounted for by the collapse of a high eruptive column. A high column is consistent with the relatively high vent-muzzle velocity (of the order of 300 m s$^{-1}$) indicated by the ~3-km area of metre-sized lithic blocks (Wilson, 1972).

Regarding the cut-off, it has been known for some time that ignimbrite does not contain all of the erupted material, because of the loss of vitric dust—material having a fall velocity so low that it remains in the dilute particle-gas mixture above the eruptive column and pumice flow (Hay, 1959; Lipman, 1967; Walker, 1972; Sparks and Walker, 1977). A second cut-off is now demonstrated to exist, of material so large and heavy that it exceeds the carrying capacity of the pumice flow and remains on the ground around the vent as a co-ignimbrite lag-fall deposit. We estimate that the lag-fall deposit (excluding the bomb horizons) at Bellavista has a volume of 0.3 km$^3$, compared with 3 km$^3$ for the main flow unit of the ignimbrite. 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 in the main flow unit of the ignimbrite.

Regarding the source vent of the Acatlan Ignimbrite, we believe that it must lie somewhere within the area encompassed by the lag-fall deposits. We do not know the full extent of these deposits because parts are covered by younger lava flows, and we have not identified the source vent with certainty. However, a likely vent position is marked by the younger rhyolite extrusive lava dome of Cerro el Chino (Fig. 1). This dome is located on flat ground, within a volcanic region but not associated particularly with any pre-existing volcano. It is evident that just as Paricutín was "born in a cornfield" in 1943, so the Acatlan Ignimbrite erupted from a "hole in the ground" vent rather than from a volcanic cone.

One final comment should be made regarding the location of ignimbrite source vents in general. Several examples have been found elsewhere of ignimbrites connected to the volcanic material occupying possible source vents (for example, Ekren and Byers, 1976), and many workers have no doubt sought such connections. However, in general, it is likely that such connections seldom exist. It is perhaps more realistic to seek a pyroclastic fall deposit formed during the same eruption as a marker of the source region and to locate the vent by drawing isopach and grain-size isopleth maps of the fall deposit, as was done by Curtis (1968) for the Valley of Ten Thousand Smokes ignimbrite. A lag-fall deposit is a better interpretation than a normal pyroclastic fall deposit because it undoubtedly comes from the same vent as the ignimbrite. The lag-fall deposit described here, however, is recognizable as such because of the unusual circumstance that both it and the associated ignimbrite are compositionally zoned. The diagnosis of such deposits in general may, unfortunately, not always be feasible. Criteria for recognizing lag-fall deposits are their coarse grain size, richness in lithics or dense juvenile material, stratification, and lateral correlation with ignimbrite. The Kamewarizaka breccia, found on the eastern rim of the Aira caldera and related to the Ito Ignimbrite (Aramaki, 1969; Yokoyama, 1974) may be a co-ignimbrite lag fall, and we have found another example related to one of the ignimbrites of La Primavera volcano north of Bellavista. Also, the typical thick intracaldera ignimbrite deposits within calderas of the western United States invariably are much more lithic rich than the equivalent outflow deposit and represent lag concentrations, less efficient but on a much larger scale (P. W. Lipman, 1977, personal commun.).

## REFERENCES CITED

Aramaki, S., 1969, Geology and pyroclastic flow deposits of the Kokubu area, Kagoshima Prefecture: Geol. Soc. Japan Jour., v. 75, p. 425-442.

Curtis, G. H., 1968, The stratigraphy of the ejecta from the 1912 eruption of Mount Katmai and Novarupta, Alaska, *in* Coats, R. R., Hay, R. L., and Anderson, C. A., eds., Studies in volcanology (Howell volume): Geol. Soc. America Mem. 116, p. 153-210.

Ekren, E. B., and Byers, F. M., 1976, Ash-flow fissure vent in west-central Nevada: Geology, v. 4, p. 247-251.

Gunn, B. M., and Mooser, F., 1971, Geochemistry of the volcanics of central Mexico: Bull. Volcanol., v. 34, p. 577-616.

Hay, R. L., 1959, Formation of the crystal-rich glowing avalanche deposits of St. Vincent, British West Indies: Jour. Geology, v. 67, p. 540-562.

Lipman, P. W., 1967, Mineral and chemical variations within an ash-flow sheet from Aso caldera, southwestern Japan: Contr. Mineralogy and Petrology, v. 16, p. 300-327.

Sparks, R.S.J., 1976, Grain size variations in ignimbrites and implications for the transport of pyroclastic flows: Sedimentology, v. 23, p. 147-188.

Sparks, R.S.J., and Walker, G.P.L., 1977, The significance of vitric-enriched air-fall ashes associated with crystal-enriched ignimbrites: Volcanol. Geotherm. Research Jour., v. 2 (in press).

Sparks, R.S.J., Self, S., and Walker, G.P.L., 1973, Products of ignimbrite eruptions: Geology, v. 1, p. 115-118.

Walker, G.P.L., 1972, Crystal concentration in ignimbrites: Contr. Mineralogy and Petrology, v. 36, p. 135-146.

Wilson, L., 1972, Explosive volcanic eruptions—II. The atmospheric trajectories of pyroclasts: Royal Astron. Soc. Geophys. Jour., v. 30, p. 381-392.

Yokoyama, S., 1974, Flow and emplacement mechanism of the Ito pyroclastic flow from Aira caldera, Japan: Tokyo Kyoiku Daigaku Sci. Rept., sec. C, v. 12, p. 1-62.

## ACKNOWLEDGMENTS

Reviewed by R.S.J. Sparks. Field work was funded by the British Natural Environment Research Council and the Instituto de Geología, University of Mexico. Wright holds a Natural Environment Research Council postgraduate studentship. Chemical analyses by G. Bullen.

MANUSCRIPT RECEIVED JUNE 14, 1977
MANUSCRIPT ACCEPTED SEPTEMBER 27, 1977