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Jean Lajoie

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Facies Models 15. Volcaniclastic Rocks

Jean Lajoie
Département de Géologie
Université de Montréal
Montréal, P.Q. H3C 3J7

Introduction

The realm of volcaniclastic rocks is changing very rapidly due to important work now in progress, but to write on *facies* in volcaniclastites is, to say the least, somewhat ambitious. The subject is in its infancy. There are a few good descriptions of volcaniclastites but in general authors have restricted their work to the petrography, chemistry, and explosive mechanism. Little is known of lateral and vertical variations in these rocks. The study of facies in volcaniclastic sequences is important as it could be a good tool in mineral exploration (Horikoshi, 1969; Sangster, 1972).

In the present paper, I shall try to summarize what we know of lateral and vertical variations and assemblages (facies) in volcaniclastites as seen by a sedimentologist. This will merely whet the appetite of the reader, but I think that to have "summarized" facies in the assemblages that are not well described would have been hazardous, not to say fictitious.

Walker (1976) in his general introduction on facies, suggested that models can be used as frameworks for future observations, as norms and predictors, and as a basis for hydrodynamic interpretation. The volcaniclastic models discussed in the present paper should be seen as general frameworks for future observations. They may be used to initiate hydrodynamic interpretation, but more work needs to be done before they can be considered norms or predictors. Walker (1976) points out that facies models originate from the distillation of many local examples. In some volcaniclastic rock types there is not much to distill.

The paper is not a review, and therefore the reference list is not exhaustive. I have tried to use general, comprehensive studies of the various subjects treated.

Terminology

When one first begins work on volcaniclastic rocks one is struck by the many definitions there commonly are of the same word. I thus find it necessary to introduce the terminology that will be used in this paper.

Volcaniclastic rocks include all fragmental volcanic rocks that result from any mechanism of fragmentation. The classification most commonly used in North America is that of Fisher (1961, 1966). *Epiclastic* fragments result from the weathering of volcanic *rocks. Autoclastic* fragments are formed by the mechanical breakage or gaseous explosion of lava during movement. *Hyaloclastic* fragments, a variety of autoclastic, are produced by quenching of lava that enters water, water-saturated sediments, or ice. *Pyroclastic* fragments are formed by explosion and are projected from volcanic vents. Showers of pyroclastic fragments produce fall deposits. Clasts that are ejected from vents and that are transported *en masse* on land or in water form pyroclastic-flow deposits. Pyroclastic fragments are primary if ejected from a vent, and secondary if they are recycled from *unconsolidated* primary deposits. In ancient deposits the distinction between primary and secondary pyroclastic debris may be very difficult, if not impossible, to make.

Wentworth and Williams (1932) introduced a grain-size classification for pyroclastic fragments, similar to the classification used for other clastic sediments. The classification was adopted by Fisher (1961) and is reproduced in Figure 1.

Volcaniclastic sedimentation is such a vast subject, and has so many variables that it will not be possible to treat all of its aspects. Epiclastic rocks which do not differ except in composition from other clastic rocks will not be treated. In this paper, I shall briefly describe the characteristics of autoclastic and pyroclastic rocks. I shall then discuss the observed and possible variations in time and space of the fundamental characteristics (facies). Due to space limitations, fragment petrography will not be discussed. The reader will find in Ross and Smith (1961), and in Heiken (1972, 1974) good descriptions of the morphology and petrography of volcaniclastic fragments.

Autoclastic Rocks

Flow breccias and hyaloclastites are the two autoclastic types that will be discussed in this paper. Both are formed by the fragmentation of lava by friction, or by rapid cooling as it flows in water or under ice, and are therefore commonly associated. The distinction between these two rock types is primarily based on grain size, the breccias being coarse and the hyaloclastites, fine. Flow breccias occur in both subaerial and subaqueous environments. Hyaloclastites are for some authors synonymous with aquagene tuffs, but this usage of the word tuff has been criticized.

Flow breccias and hyaloclastites are common in basaltic sequences, and relatively rare in acid sections as basic lava flows more readily than acid magmas due to its lower viscosity. In these autoclastic rocks, the clasts are generally monolithologic with most fragments being derived from the same parent magma. Lava may scrape vent walls or rip fragments as it flows, but exotic fragments are rarely reported in descriptions of flow breccias. In basaltic sequences, the breccias commonly consist of complete pillows and (or) pillow fragments set in a matrix of devitrified glass shards and lumps (Carlisle, 1963; Dimroth *et al.*, 1978; Figs. 2, 3 and 4). Pillows are exceptional in acid lava. Acid flow breccias are made up of abundant angular blocks, with coarse and fine sand-size fragments, set in a glassy matrix (Pichler, 1965).

PREDOMINANT GRAIN SIZE (mm)	EPICLASTIC FRAGMENTS	PYROCLASTIC FRAGMENTS	PYROCLASTIC ROCKS
	COBBLE	BLOCK AND BOMB	PYROCLASTIC BRECCIA
64	PEBBLE	LAPILLUS	LAPILLISTONE
2	SAND	COARSE ASH	TUFF
$\frac{1}{16}$	SILT	FINE ASH	

Figure 1
Grade size for epiclastic and pyroclastic fragments, and terms for pyroclastic rocks. From Fisher (1961, 1966).

Figure 2
Flow breccia that consists of pillows and pillow fragments set in a matrix of hyaloclastite. Mont Etna, Sicilia. Photo courtesy of John Ludden.

Figure 3
Basaltic flow breccia in the Archean of Rouyn-Noranda, overlain by graded pyroclastic deposits. The lava flowed from left to right, and the fabric is due to the orientation of the brecciated pillows in shear planes. Photo courtesy of Pierre Trudel.

Facies in flow breccias and hyaloclastites. Due to their mode of origin one would expect *in situ* flow breccias and hyaloclastites to show little or no systematic lateral and vertical variations in clast content, size, and composition. Autoclastic associations are however much more complex.

The vertical variations in a typical flow breccia of basaltic composition are summarized in Figures 5 and 6. The pillowed lava grades upward into an isolated-pillow breccia that is overlain and transitional with a broken-pillow breccia. In the Archean of the Noranda region, similar sequences are exceptionally overlain by fine-grained hyaloclastites. In this model, clast size decreases from base to top. This grain size variation cannot be called graded-bedding; there is no bedding to begin with as there is no true deposition of clasts since they were formed *in situ*. The distinctive characteristics of this type of breccias are the monolithologic composition of the clasts and the transitional contact with the flow. Since the fragmentation is formed by quenching, the shards are not welded (Carlisle, 1963, p. 68).

Flow breccias are commonly associated with subaerial acid lava flows, where they occur underlying and (or) overlying the flow. There is however no modern example of submarine acid flows. It is a rare and poorly known phenomenon in the rock record. Pichler (1965) described acid subaqueous breccias and hyaloclastites exposed on the island of Ponza in Italy. To my knowledge, this is the only description of acid hyaloclastites in the literature. The lateral and vertical associations of facies that he proposed are summarized in Figure 7. The characteristics of the deposit are somewhat similar to those discussed previously, except for the absence of pillows and of large fragments. The coarse fraction is angular, and found near the parent rhyolitic magma. The clasts are unwelded, and since they are formed *in situ*, the volcaniclastite is massive or shows pseudo stratifications that commonly parallel the breccia-lava contact. Figure 7 has no scale, but Pichler (1965, p. 305) gives an example in which facies 3 overlying the dome reaches 5 m in thickness.

The model presents some difficulties, mostly in the ratio of clastics to the size of the rhyolite dome. On extrusion, acid

Figure 4
Brecciated basaltic flow in the Archean of Rouyn-Noranda. Coin is two cm. Photo courtesy of Pierre Trudel.

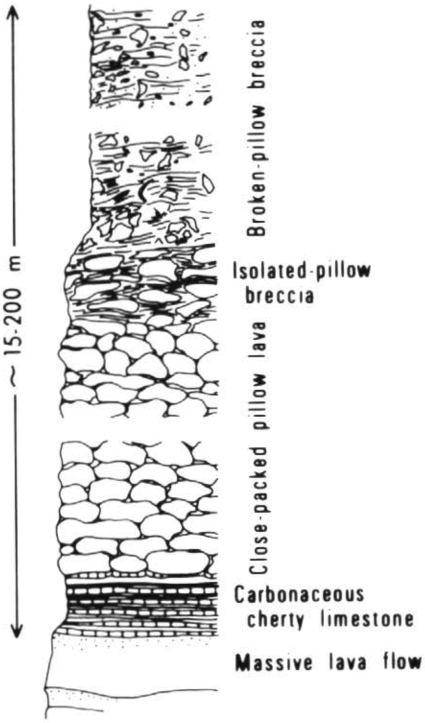


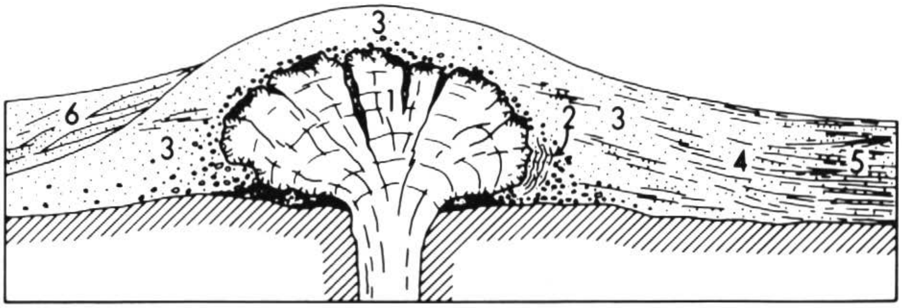
Figure 5
Typical pillow breccia-hyaloclastite sequence in the Triassic of Quadra Island, British Columbia. From Carlisle, 1963.

Figure 6
Hyaloclastite transitional with pillow lava. Rouyn-Noranda region. Photo courtesy of Léopold Gélinas.

lavas form a chill margin under which the temperature rapidly decreases. The margin may be brecciated, as well as parts of the underlying dome, but the volume of clasts produced by such a mechanism should be much less than that implied by Pichler. At Lipari, the flow breccias are found under the rhyolitic flow, and the autoclastics overlying it are very thin, where present (Ludden, pers. commun., 1979). The model is not accepted by all workers, and there is some doubt as to the origin of the fragmentation. Pichler (1965) presents little evidence to support the continuous peeling of the chill margin. The large fragments and tongues of felsic magma that one would expect to find in the deposit, are not present. In the example used by Pichler (1965), Santorini, the volcaniclastites overlying the rhyolitic dome are in shallow-marine waters, and unless there are particular conditions which he does not discuss, the volcaniclastic cover should be much thinner than 5 m.

Autoclastic fragments may be reworked by bottom currents or resedimented from density flows. In certain cases the deposit may show some of the characteristics of pyroclastic rocks. These secondary hyaloclastites may be difficult to distinguish from pyroclastites as both types of fragmentation may form similar textures. However, pumiceous fragments should be more common in pyroclastic deposits. Also, fragments in reworked hyaloclastites should normally

Figure 7
Vertical and lateral associations of rock types in acid hyaloclastites, 1) submarine extruded dome covered by auto-breccias and hyaloclastites. 2) blocky talus with remnants of ancient crust. 3) unstratified, in situ, *sand-size hyaloclastites. 4) "stratified",* in situ *hyaloclastites. 5 and 6) resedimented "hyaloclastites". Modified from Pichler, 1965. For scale, see text.*



be monolithologic, and unwelded whereas pyroclastites are commonly polylithologic, and may be welded. Honnorez and Kirst (1975) have shown that shape can be used to distinguish fragments of hyaloclastic origin from those of pyroclastic.

The model proposed for basaltic flow breccias and hyaloclastites is sufficiently well established, and could be used as a norm, but it is safe to say that for acid hyaloclastites we don't yet have a model.

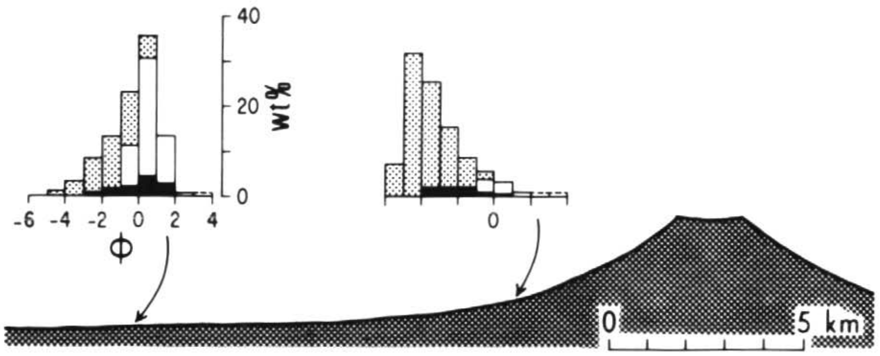


Figure 8
Lateral variations in size and contents of pumice (stippled), crystals (blank), and lithic (black) in a pyroclastic fall deposit in the Azores. Modified from Walker (1971).

Pyroclastic Rocks

Pyroclastic debris (pumice, shards, crystals, and lithics) ejected from vents, fall or flow in air and (or) water under the influence of gravity. The settling velocities are proportional to fragment size, shape, and density. Therefore, the principles that govern the sedimentation of pyroclastic fragments are identical to those responsible for the deposition of other clastic debris.

The lateral extent and the geometry of pyroclastic deposits are influenced in part by magma composition, and the environment in which the eruption takes place. Basaltic subaerial eruptions generally produce cones of scoria and ash of limited areal extent around or down-wind of the cones. Basaltic eruptions that take place in shallow water or where water has access to the vent are more strongly explosive, and produce ash rings and ash layers that may have considerable areal extent. Due to the higher volatile content of the magma, eruptions of acid and intermediate compositions are generally explosive. These eruptions may project very large volumes of pyroclastic debris to heights well in excess of 25 km, and may produce thick fall and flow deposits.

Facies in pyroclastic fall deposits.
The showering of pyroclastic debris is governed by their settling velocities. It follows that size, composition, and thickness should vary with distance from the vent. Figure 8, modified from Walker (1971), is an example of such lateral size and composition variations in an air-fall unit. In this example size decreases for all compositions, and the relative abundance of fragment-type varies in the direction of transport. Due to their low density, pumiceous fragments make poor projectiles and are therefore more abundant near the vent, whereas crystals may travel greater distances. This zonation of textures is common in many air-fall deposits of the world (Walker, 1971; Kuno *et al.*, 1964; Lacroix, 1904). Pumices may be lighter than water and thus float if they fall in it. The deposition of pumiceous fragments may only occur when they are waterlogged. It follows that in such depositis, the distribution of pumices may be very erratic.

Any particular fall deposit becomes finer-grained as the distance from the vent increases. However fine-grained deposits may form near the vent as well as far from it. Fine debris accumulates near the vent when the eruption is weak. Even if coarse-grained fall deposits are reliable indicators of vent proximity, fine-grained deposits do not necessarily indicate distance from the vent.

In fall deposits, the dispersion of the graphic standard deviation (σ_{ϕ}) is considerable near the vent. This results from the differences in settling velocities; small and dense clasts fall at velocities similar to those of larger and lighter clasts. Figure 9 suggest that a high σ_{ϕ} could indicate proximity of an eruptive center.

The downwind decrease in thickness of pyroclastic fall deposits is discussed by Eaton (1964). Some windborne ash may be transported over extensive areas and make excellent marker horizons. Fall deposits may be poorly stratified, as stratification is a result of discontinuity in the volcanic activity; beds and laminations may be crudely defined (Fig. 10, A and B). Walker and Croasdale (1971) gave some characteristics of basaltic fall deposits. According to these authors, ashes from subaqueous eruptions are well stratified, and beds are extremely thin (1 mm). Deposits due to rhythmic ejections of incandescent cinder and lapilli are thicker, rarely less than one cm, and commonly more than five cm. Pyroclastic fragments of acid and intermediate compositions may be ejected in very large volumes, and bed thickness may easily reach 4 m near the vent.

There is little systematic variation in the vertical grain sizes within beds. As settling is a function of size and density, grading may be present in fall deposits, but is best observed in the thicker units. The grading may be normal or reverse (Bond and Sparks, 1976). Reverse density-grading has been documented by Koch and McLean (1975). It results from the progressive evacuation of compositionally stratified magma chamber with increasing intensity of eruption. In subaerial falls, all fragments are heavier than the fluid whereas in subaqueous falls as discussed above, pumices may float and may not be present in the deposit, or may only occur at or near the top of the bed.

Because they are controlled by the eruption intensity, vertical variations of facies are unpredictible in pyroclastic fall deposits.

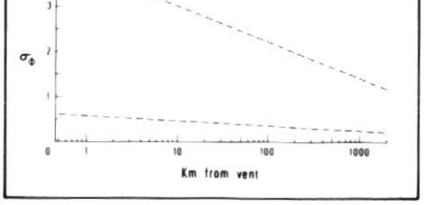
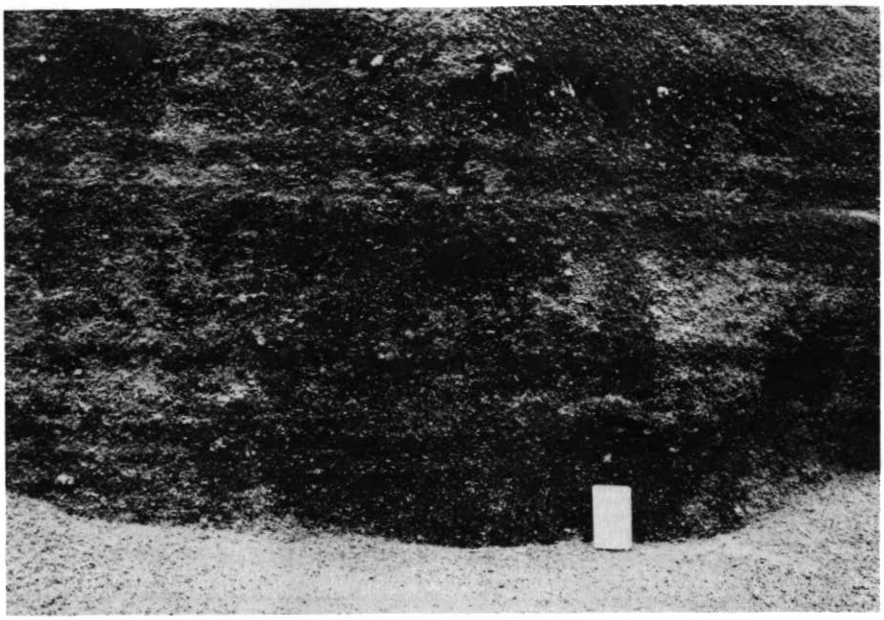


Figure 9
Variation of sorting (σ_{ϕ}) with distance from the vent for pyroclastic fall deposits. From Walker, 1971, Figure 7.



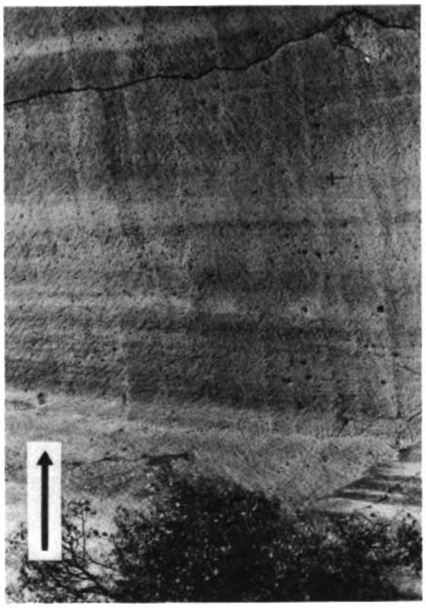


Figure 10
Stratification in air-fall deposits. A: Crude bedding, La Palma, Canary Islands. Notebook is 20 cm long. B: Crude laminations, San Lorenzo de Gran Canaria, Canary Islands. Arrow is 50 cm.

Pyroclastic flow deposits. The characterization and definition of facies in pyroclastic flow deposits is not easy. Most authors have described deposits from flows that are particular to pyroclastites, such as *nuées ardentes,* base surges, ignimbrites, lahars, and others. This terminology of pyroclastic flows is discussed in many standard texts; Macdonald (1972) could be recommended to the neophyte. The major problem in dealing with deposits of these flows is that the criteria used for their definition are not exclusive to pyroclastic rocks. It follows that the characteristics given for some particular facies may also be found in other mass-flow deposits, or the singularities presented for a particular facies of pyroclastic deposit may be found in others. I would like to give two examples to illustrate this particular problem.

Large-scale cross bedding is commonly used to identify base-surge deposits (Figs. 11 and 13; Schmincke *et al.,* 1973; Sparks, 1976; Bond and Sparks, 1976). But base-surge flow as described by Moore (1967) is similar in many respects to the flow of the *nuées ardentes* that Lacroix (1904) described. The eruptive mechanisms may be somewhat different, but the results are similar: turbulent suspensions that move away from the vent, aided by gravity. The descriptions that Lacroix (1904) gave of the *nuées ardentes* are among the best descriptions of turbidity currents in the literature. Large-scale cross bedding does occur in turbidite sequences as well as many other types of sedimentary sequences. It may also be present in *nuées ardentes* deposits although there is no evidence yet since very few deposits have been described. Large-scale cross bedding is closely associated with the *nuées ardentes* of Pelée. Lacroix (1904, p. 469) shows a splendid photograph of more than 1 km of an exposure which he called *dunes de cendres* in which the dunes may reach amplitudes that are in excess of 1 m. Crowe and Fisher (1973) showed the similarity that exists between the primary structures found in base-surge deposits with those found in other turbulent, density-flow deposits. They point out that the structure-forming variables (rate

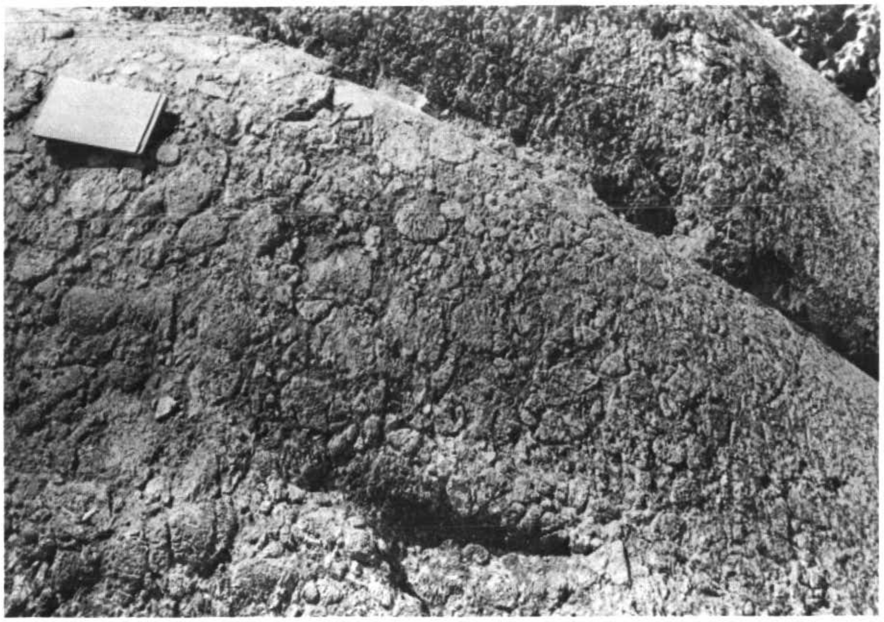
Figure 11
Base-surge deposit, Gran Canari, near La Calderilla. Two sets of trough cross-bedding are present, one to the right of pencil, and a second one underlying it.

of deposition, flow power, and grain size) are the same. The point that I wish to make here is that the primary structures of base-surge deposits characterize the flow rather than the eruption mechanism, and as such they may be found in many other types of pyroclastic facies.

Lahar is a second example of ill-defined rock type. It is defined as any unsorted or poorly sorted deposit of volcanic debris that moved and was deposited as a mass that owed its mobility to water. Schmincke (1967) described lahar deposits in the Ellensburg Formation of Washington which he interpreted as being deposited from "watery viscous suspensions", but the primary structures and structure sequences that are described could be interpreted as the result of other types of flow such as turbulent suspensions. There is little difference between these rocks and others found in many turbidite sequences. The structures characterize the flow, not the environment in which it moves.

Lacroix (1904) showed quite conclusively that gravity controls the movement of pyroclastic flows. It follows that the physics which applies to these flows should be identical to that of other density flows. There is therefore little chance to find *one* model that could characterize subaqueous or subaerial flows. Given similar flow parameters (density, viscosity, velocity, thickness) and grain size, deposits from all types of flow could have similar sedimentary characteristics. It should be clear by now, that in describing pyroclastic flow deposits it was not possible to use the genetic nomenclature that is common in the literature. I may not have much success, but I suggest to workers not to use the genetic ill-characterized pyroclastic-flow terminology.

The deposition of pyroclastic flow ejecta may occur on land or in water. The distinction between subaerial and subaqueous deposits is not always easy because evidence is commonly indirect. According to Fisher and Schmincke (in press) the main problem with subaqueous pyroclastic flows is that the deposits of witnessed *nuées ardentes* that have entered water have not been described. Except for a few occurrences, subaerial flow deposits are not that well described either. Many such deposits are massive (Fig. 13 is an example) probably due, in part, to their relative proximity to the vent.



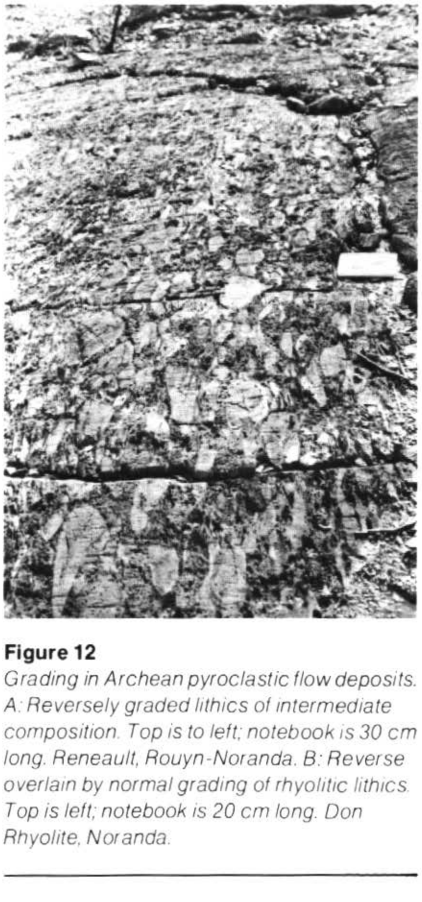


Figure 12

Grading in Archean pyroclastic flow deposits. A: Reversely graded lithics of intermediate composition. Top is to left; notebook is 30 cm long. Reneault, Rouyn-Noranda. B: Reverse overlain by normal grading of rhyolitic lithics. Top is left; notebook is 20 cm long. Don Rhyolite, Noranda.

Some subaerial deposits described in the literature are said to be massive, but the photographs that accompany these descriptions commonly show grading and (or) parallel laminations. Workers must then rely on fossils, the presence of pillows in the sequence, and other indirect evidence in order to distinguish the two types of deposits. The welding of fragments has been used as evidence for subaerial deposition, but there are known occurrences of subaqueous deposits that are welded (Francis and Howells, 1973; Gélinas *et al.*, 1978).

Facies in pyroclastic flow deposits. Most workers accept that pyroclastic flows move under the influence of gravity along topographic depressions. It follows that the mechanics of pyroclastic flows do not basically differ from those of other types of density flows. Grain-size, density, and shape of the fragments affect the rate of sedimentation. However, since pyroclastic flows are the result of complex interactions of many processes some deposits may have anomalous size and thickness characteristics.

Beds deposited from pyroclastic flows are commonly graded (Fig. 12 A and B) or massive (Fig. 13). Normal grading of *lithic* clasts is a frequent feature of many ancient and recent deposits of the world (Sparks *et al.*, 1973). *Pumice* clasts may be either reversely or normally graded. In many subaerial deposits the pumices are reversely graded, and normal grading of pumices seems rare. In such deposits, the pumice size may increase gradually from base to top (true grading), or the larger pumices may be concentrated in an upper horizon within the bed (Sparks, 1976). The reverse grading of pumices is explained by flotation, the matrix being denser than the fragments. In beds of subaqueous deposits, the

Figure 13
Massive pyroclastic flow deposit. Fortaleza Grande, Gran Canaria. Pipe is roughly 1 m in diameter.

pumices and the lithic fragments may be concentrated in different horizons but both types of fragment commonly show similar grading trends, reverse or normal (Fiske and Matsuda, 1964; Yamada, 1973; Bond, 1973; Tassé *et al.*, 1978). The grading of pumices in pyroclastic flow deposits is not fully understood. It may be that subaqueous flows have lower densities than their subaerial counterparts, but there is little evidence to support this.

Sparks *et al.* (1973) proposed a "standard" vertical bedding sequence in subaerial pyroclastic flow deposits (Fig. 14, I), derived from observations made in the Azores, Canary Islands, Italy, Greece, Japan, and the West Indies. This model subdivides the "flow unit" (bed?) in two transitional "layers" (2a and 2b). Layer 2a is relatively fine-grained and reversely graded. In layer 2b, which makes up more than 90 per cent of the bed, the size of the pumiceous fragments increases upward and reaches a maximum at the top, whereas the lithics are concentrated near the base of the bed. This standard sequence contrasts with many sequences observed in subaqueous deposits (Fig. 14, II) described by Fiske and Matsuda (1964), Fiske (1969), Bond (1973) and Tassé *et al.*, (1978), where the entire accumulation is normally graded, by size and (or) density. As already mentioned, reverse grading does occur in subaqueous deposits, but pumices and lithics commonly have similar grain-size variations. The deposits described by Fiske and Matsuda (1964) consist of a lower graded or massive division, overlain and transitional with a stratified division (b, in Fig. 14, II), in which the grading is continuous from the underlying division (a). The authors interpreted the strata in division b as beds. Deposits with similar structures have been described by Tassé *et al.* (1978), in the Archean of Noranda, and by Yamada (1973) in Pleistocene rocks of Japan. They proposed that, since the grading was continuous from the graded division into stratified division, the accumulation was the result of *one event*, that produced *one bed*. The stratifications (Fig. 15) were therefore interpreted as parallel laminations. These proposed standard beds should not be taken as invariable models. The characteristics of the deposit will vary with the flow conditions. Velocity, density, and viscosity of the flow could change such that the characteristics observed in a given bed close to the vent may be very different from those observed in more distal sections. Tassé *et al.*, (1978) have shown that beds of pyroclastic flows in the Noranda region could not be characterized by one standard model.

There is little known on lateral and vertical variations in pyroclastic flow deposits. Grain size and bed thickness may either decrease or increase downflow. There are many examples of increasing bed thickness with distance of transport, particularly close to vent. Schmincke and Swanson (1967) suggested that this was probably due to the relative high velocity and low viscosity of the flow near the vent. Grain size generally decreases with distance of transport, but in the Precambrian rocks of Noranda grain size both increases and decreases with distance from vent (Tassé *et al.*, 1978). In deposits of turbulent low-density flows the size decreases, but in relatively higher density flows, size may increase before it decreases in the direction of transport. Analogous situations have been described in turbidites.

Primary structures that are controlled both by flow parameters and grain size are perhaps the best tool to establish facies in pyroclastic flow deposits.

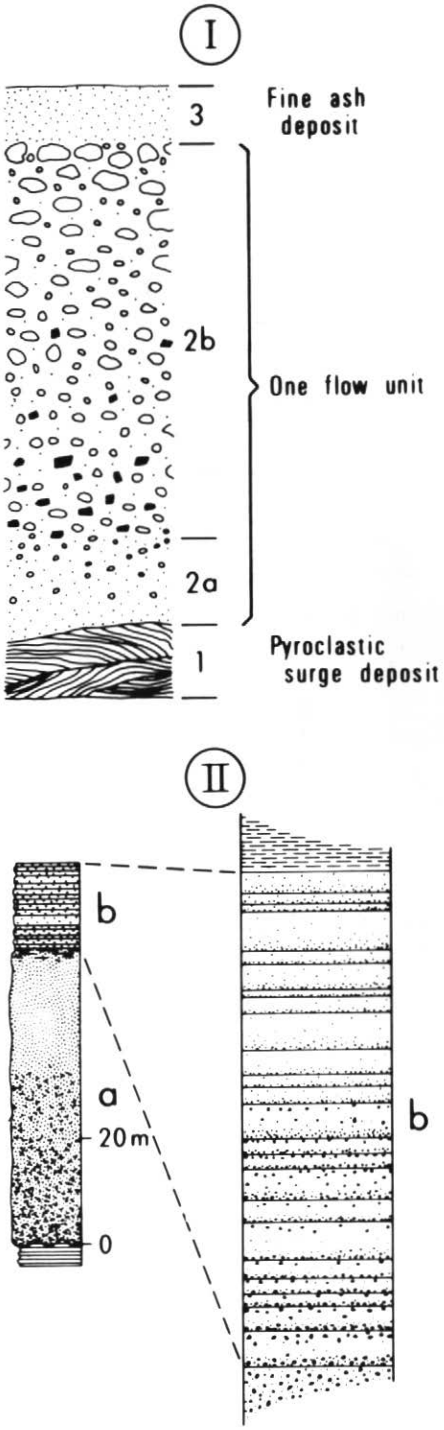


Figure 14
Vertical sequence of primary structures commonly present in subaerial (I) and subaqueous (II) pyroclastic flow deposits. From Sparks et al. *(1973), and Fiske and Matsuda (1964). In Sparks* et al. *(1973), the model has no scale; the thickness of layer 2a varies from a few cms to more than 1 m.*

Figure 15
Parallel stratifications in a Precambrian pyroclastic flow deposit. Noranda, Quebec.

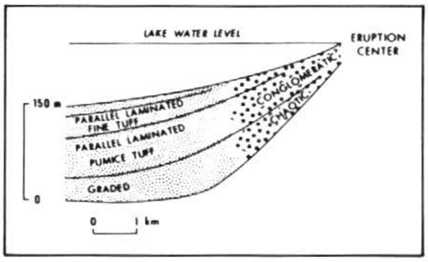


Figure 16
Lateral variations of size and primary structures in a Pleistocene pyroclastic flow deposit in Japan. Modified from Yamada (1973).

Yamada (1973) proposed a model (Fig. 16) for lateral variations of primary structures for a subaqueous deposit of Pleistocene age, but the only complete study of lateral variations of facies is that of Tassé *et al.* (1978) for Archean flows of Noranda; Figure 17 is a simplified version of the model that they proposed. The rocks that were studied are intermediate in composition and not welded. The studied sections show two distinct bed types that have different mean-thickness, grain size, and primary structures. The two types are therefore treated in two different assemblages (A and B, Fig. 17). Type A beds (Fig. 12, A), are thicker than type B (Fig. 18) and mean bed thickness increases with distance of transport in type A, whereas it decreases in type B. In both bed types, primary structure *sequences* vary systematically away from the vent, but the sequences are somewhat different in the two types. In type A beds, the most abundant structure is grading, and parallel laminations are relatively rare. The proximal section has a high proportion of massive or reversely graded beds whereas the distal section is characterized by normal grading, and a higher number of beds that show parallel laminations. The two intermediate sections suggest a gradation from the proximal to the distal facies. Grading is also very common in type B beds, and is generally normal. Traction structures, such as parallel and oblique laminations (dunes and ripples) are more abundant than in type A, and their proportion increases with distance of transport.

Tassé *et al.*, (1978) interpreted the lateral variation of facies by analogy with sedimentary density flows. Type B beds most probably result from the accumulation of decelerating turbulent suspensions of low density such as turbidity currents. Most of the flows responsible for type A beds appear to have been turbulent in the distal regions, but almost half (45%) of the deposit in the more proximal section probably accumulated from laminar suspensions such as debris flows, as suggested by the reverse grading and massive beds. It follows that different transporting mechanisms acted at different stages of the flows. This may be caused by an increase in flow velocity due to gravity, coupled with a decrease in viscosity.

In the subaqueous deposits of Noranda, the ratio between lithics and pumices decreases with distance from the vent. This relationship has also been observed in some Japanese deposits (Kuno *et al.*, 1964), and is opposite to the pumice-lithic ratio commonly found in pyroclastic fall deposits. This is due to the lower density of the pumice which settle at lower velocities, and are therefore found further down flow.

In ancient pyroclastic flow deposits, grain orientation may be used to help locate vents. The technique could be used with other lateral variations such as size, bed-thickness, and (or) primary-structure sequences. It is described by Elston and Smith (1970), and has been successfully applied in Archean pyroclastic rocks of northwestern Ontario (Teal, 1979).

It is not possible at this stage to use the Noranda model proposed by Tassé *et al.* (1978) as a norm or a predictor for subaqueous pyroclastic flow deposits. To my knowledge it is the only study of lateral facies variations, other than grain size and bed thickness, done in this type of deposit, future observations shall have to verify it, and thus make it norm.

Subaerial flow deposits may show facies that are similar to those of subaqueous flows, but because of the higher temperature of the mass and, in certain cases the higher viscosities, they may exhibit different characteristics. Rhyolitic flows have fragments that are commonly deformed, stretched, and welded. The eutaxitic "texture", that results from the parallel arrangement and alternation of layers of different textures or composition may be common in these rocks. The structures are found in deposits that accumulated from laminar suspensions (Schmincke and Swanson, 1967) but they also occur in turbulent flow deposits (Lock, 1972).

Little is known of vertical variations of facies in pyroclastic flow deposits. Most workers have focused their attention on eruptive cycles. Aramaki and Yamasaki (1963), and Sparks *et al.* (1973) are examples. The only published systematic work on vertical variations of texture and bed thickness in flow deposits was done in the Archean of Rouyn-Noranda (Tassé *et al.*, 1978; Gélinas *et al.*, 1978). Because pyroclastic flows move under the influence of gravity, they are partly or completely controlled by topographic depressions when the flow is very thick. The channel fills could therefore have characteristics that are similar to those of fills described in other sedimentary sequences, where grain size and bed thickness decrease up-section. We have shown with the Archean examples that these vertical variations are also present in channel fills of pyroclastic flows, and channels have been identified by mapping vertical variations of size and thickness.

Distinction between pyroclastic flow and fall. Workers have been interested for quite sometime in finding parameters or characteristics to distinguish pyroclastic flows from falls. Much work has been done on statistical parameters of grain size distribution with some apparent success (Walker, 1971; Sheridan, 1971, Fig. 19). Sheridan (1971) grouped, on Figure 19, rhyolitic base-surge dunes and lunar fines in Field I, and rhyolitic ash flows in Field II. His Field III is said to be composed mostly of air fall deposits. This technique is not infallible and there

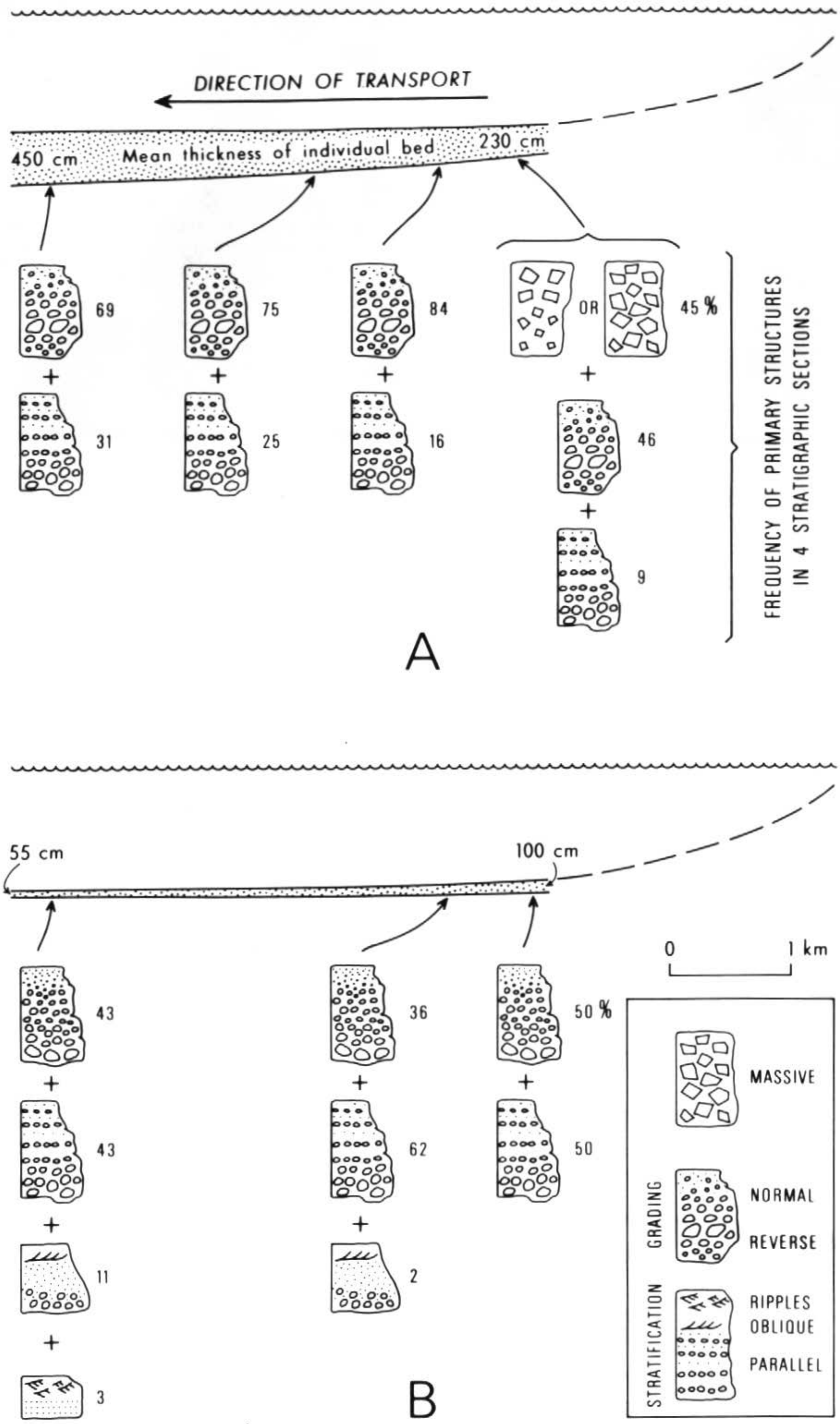


Figure 17
Lateral variations of mean bed thickness and primary structure sequences with distance of transport, in an Archean subaqueous pyroclastic flow deposit, for two different types of accumulation (A and B). The frequency distributions of structure sequences are in percentages, and total 100% for each section. Modified from Tassé et al., *(1978).*

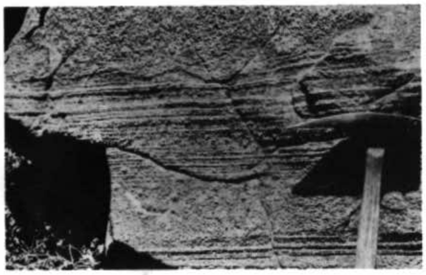


Figure 18
Primary-structure sequence in a type B bed, Rouyn-Noranda. From Tassé et al. *(1978).*

are many exceptions. For example air falls plot with "base-surge flat beds", and "Surtsey base surges". I would also use primary structures and their sequences to distinguish flow from fall. Our work has shown that flows leave imprints that are different from falls.

Summary

The purpose of this article has been to present what is known of facies relationships in some autoclastic rocks, and in pyroclastic fall and flow deposits. Autoclastic fragments, that are formed *in situ* are monolithologic and not welded. The clastites may be transitional with the parent magma, and have the same composition. The internal structures of these deposits indicate the absence or near absence of transport.

Pyroclastic fall deposits are very well stratified. They commonly show a systematic lateral decrease in grain size and bed thickness. In such deposits, sorting is least close to source due to settling of fragments of different densities. In fall deposits the vertical variations are controlled by eruption intensity, and are therefore unpredictible.

In flow deposits, bed thickness and grain size commonly decrease down flow, but close to vent the variations are not systematic. Beds deposited from flows are commonly graded. In subaqueous deposits the grading of all fragments is generally normal but in many subaerial flow, pumices are commonly reversely graded. The primary structure sequences vary systematically down-flow, and depict the changing flow conditions (density, viscosity, velocity) and the grain size that is transported. Vertical variations of size and thickness are poorly known in these deposits but where they have been studied they are characteristic of channel fills.

Statistical parameters of grain size have been used extensively to distinguish pyroclastic flows from falls. Primary structure sequences are also a powerful tool that could help make this distinction.

The reader must by now be aware that much work remains to be done on volcaniclastic rocks. I hope that this paper has been stimulating.

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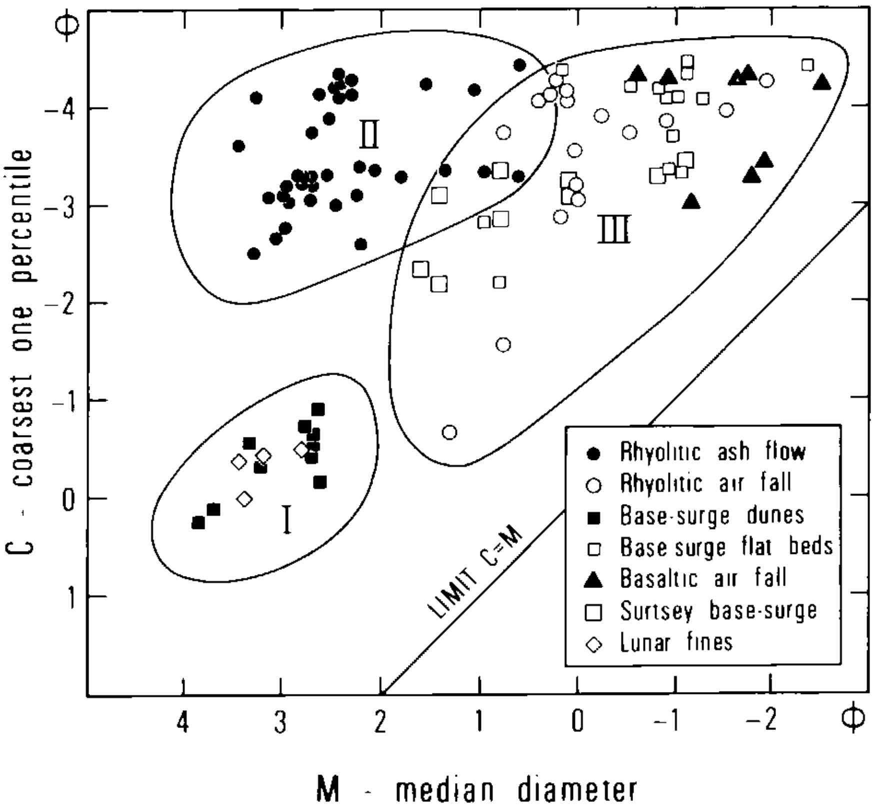

Figure 19
C-M diagram for pyroclastic falls and flows From Sheridan, 1971.

References

General

Heiken, G.H., 1972, Morphology and petrography of volcanic ashes Geol Soc. Amer Bull., v 83, p. 1961-1988

Heiken, G.H., 1974, An atlas of volcanic ash. Smithsonian Contr. Earth Sci., v 12, 101 p

Macdonald, G.A., 1972, Volcanoes Prentice-Hall Inc., Englewood Cliffs, N J., 510 p
A good introduction on the subject of volcanoes.

Ross, C.S., and R L. Smith, 1961, Ash-flow tuffs: their origin, geologic relations and identification: U S Geol Surv. Prof Paper 366, 81 p.
A good text with abundant photographs. Excellent review of the literature Excellent descriptions

Nomenclature and Classification

Fisher, R V., 1961, Proposed classification of volcaniclastic sediments and rocks Geol Soc Amer Bull., v 72, p. 1409-1414.

Fisher, R V 1966, Rocks composed of volcanic fragments and their classification: Earth Sci. Rev., v 1, p. 287-298

Wentworth, C.K and H Williams, 1932, The classification and terminology of the pyroclastic rocks Rept Comm Sed., Bull Natl Research Council, v 89, p 19-53

Autoclastic Rocks

Carlisle, D., 1963, Pillow breccias and their aquagene tuffs, Quadra Island, British Columbia: Jour Geol., v 71, p 48-71
A classic study on basaltic flow breccias.

Dimroth, E., P Cousineau, M Leduc, and Y. Sanschagrin, 1978, Structure and organization of Archean subaqueous basalt flows, Rouyn-Noranda, Québec, Canada: Can Jour Earth Sci., v 15, p 902 918

Honnorez, J., and P Kirst, 1975, Submarine basaltic volcanism: morphometric parameters for discriminating hyaloclastites from hyalotuffs: Bull. volcanologique, v 34, p 1-25
A good review of the literature, origin, and characteristics of hyaloclastites

Pichler, H., 1965, Acid hyaloclastites. Bull. volcanologique, v 28, p 293-311
One of the rare descriptions of acid autoclastic rocks

Pyroclastic Fall and Flow

Bond, A., and R S J Sparks, 1976, The Minoan eruption of Santorini, Greece: Jour. Geol Soc., v 132, p 1-16.

Crowe, B M., and R V Fisher 1973 Sedimentary structures in base-surge deposits with special references to cross-bedding, Ubehebe craters, Death Valley, California: Geol

Soc. Amer Bull., v 84, p. 663-682.
An excellent description of base-surge deposits

Elston, W.E., and E.-I. Smith, 1970, Determination of flow direction of rhyolitic ash flow tuffs from fluidal textures: Geol. Soc. Amer Bull., v 81, p 3393-3406
Grain-orientation measurements are described and used for determination of flow direction.

Fisher, R.V., and H.-U. Schmincke, in press, Subaqueous pyroclastic flow deposits. Unpublished manuscript.
An excellent review of the subject: to be published in 1980 as part of a textbook on pyroclastic rocks.

Fiske, R.S., 1969, Recognition and significance of pumice in marine pyroclastic rocks. Geol Soc Amer. Bull., v 80, p 1-8

Fiske, R S , and T. Matsuda, 1964, Submarine equivalents of ash flows in the Tokiwa Formation, Japan. Amer Jour. Sci., v. 262, p. 76-106
One of the rare good descriptions of subaqueous flow deposit.

Gélinas, L., J. Lajoie, M. Bouchard, A. Simard, P. Verpaelst, et R. Sansfaçon, 1978, Les complexes rhyolitiques de la région de Rouyn-Noranda: Min. des Richesses naturelles du Québec. Rapport DPV- 583, 49 p
One of the rare studies on vertical variation of size and thickness in channelized deposits.

Kuno, H , T. Ishikawa, K. Yagi, M. Yamasaki, and S Taneta, 1964, Sorting of pumice and lithic fragments as a key to eruptive and emplacement mechanism: Japan Jour. of Geol. and Geography, v 35, p. 223-238

Lacroix, A , 1904, La montagne pelée et ses éruptions: Masson et Cie, Paris, France, 662 p.
Anyone seriously involved with pyroclastic flows should have read this reference twice!

Schmincke, H -U , and D A. Swanson, 1967, Laminar viscous flowage structures in ash-flow tuffs from Gran Canaria, Canary Islands Jour Geol , v. 75, p 641-664
Good descriptions of textures and structures

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 , S Self, and G P.L Walker, 1973, Products of ignimbrite eruptions: Geology, v 1, p 115-122

Tassé, N , J Lajoie, and E Dimroth, 1978, The anatomy and interpretation of an Archean volcaniclastic sequence, Noranda region, Quebec Can Jour Earth Sci , v. 15, p. 874-888
Perhaps the only published analysis of lateral variations in subaqueous pyroclastic flow deposits

Teal, P R , 1979, Stratigraphy, Sedimentology, Volcanology and Development of the Archean Manitou Group, Northwestern Ontario, Canada: McMaster University, Unpubl. Ph.D. Thesis, 291 p

Walker, G P L , and R Croasdale, 1971, Characteristics of some basaltic pyroclastics. Bull. volcanologique, v 35, p. 303-317.
A relatively good description of fall deposits

Yamada, E , 1973, Subaqueous pumice flow deposits in the Onikobe Caldera, Miyagi Perfecture, Japan Jour Geol Soc. Japan, v. 79, p 585-597

Distinction Between Pyroclastic Flow and Fall

Sheridan, M F , 1971, Particle-size characteristics of pyroclastic tuffs: Jour. Geophys Res , v 76, p. 5627-5634

Walker, G.P.L , 1971, Grain-size characteristics of pyroclastic deposits: Jour Geol , v 79, p. 696-714
An excellent review of size characteristics of more than 1000 samples of flow and fall deposits

Other References Cited

Aramaki, S., and M. Yamasaki, 1963. Pyroclastic flows in Japan: Bull volcanologique, v. 26, p 89-99

Bond, G.A., 1973 A late Paleozoic volcanic arc in the Eastern Alaska Range, Alaska: Jour. Geol , v. 81, p. 557-575

Eaton, G.P., 1964 Windborne volcanic ash a possible index to polar wandering Jour Geol., v 72 p 1-35.

Francis, E.H., and M F Howells, 1973 Transgressive welded ash-flow tuffs among Ordovician sediments of N E Snowdonia, N Wales Jour Geol. Soc , v 129, p 621-641

Horikoski, E , 1969 Volcanic activity related to the formation of the Kuroko-type deposits in the Kasaka District, Japan: Mineral. Deposita, v 4, p. 321-345.

Koch, A.J., and H. McLean, 1975 Pleistocene tephra and ash-flow deposits in the volcanic highlands of Guatemala: Geol. Soc Amer. Bull., v. 86, p. 529-541.

Lock, B E , 1972 A lower Paleozoic rheo-ignimbrite from White Bay, Newfoundland: Can. Jour Earth Sci., v. 9, p 1495-1503

Moore, J.G., 1967 Base surge in recent volcanic eruptions: Bull. volcanologique, v 30, p 337-363.

Sangster, D F , 1972, Precambrian volcanogenic massive sulphide deposits in Canada, a review: Geol Surv Canada, Paper 72-22, 44 p

Schmincke, H.-U., 1967, Graded lahars in the type sections of the Ellensburg Formation, South-Central Washington: Jour. Sed. Petrol., v 37, p 438-448

Schmincke, H -U , R V Fisher, and A.C. Waters, 1973, Antidune and chute and pool structures in the base-surge deposits of the Laacher Sea Area, Germany: Sedimentology, v 20, p. 553-574.

Walker, R G , 1976 Facies models: general introduction. Geosci. Canada, v. 3, p 21-24.

MS received May 11, 1979.