Explosive volcanic eruptions — a new classification scheme

By GEORGE P. L. WALKER, London *)

With 6 figures and 2 tables

Zusammenfassung

Eine systematische Klassifikation von explosiven vulkanischen Ausbrüchen wird auf Grund verschiedener Messungen ihrer pyroklastischen Ablagerungen vorgeschlagen. Die zwei wichtigen Parameter sind die Größe der Dispersionsfläche (D) und das Maß der Zerkleinerung der Asche (F). Ein empirisches Maß der Dispersion ist die von der 0.01-T_{max}-Isopache umschlossene Fläche (in km²): T_{max} ist die größte Mächtigkeit der jeweiligen Tuffit-Decke. D beträgt weniger als 10 km² für Ausbrüche mit stark kegelbildender Tendenz und über 1000 km² für ausgeprägte schichtbildende Ausbrüche. Der andere Parameter (F) ist der prozentuale Anteil der Asche im Tuffit, der kleiner als 1 mm ist oder, genauer gesehen, an der Stelle wo die 0,1-T_{max}-Isopache die Dispersionsachse überschneidet. Kleine F-Werte (ca. 20) stammen von Aschen, deren Zerkleinerung durch Auseinanderreißen von Magma geschieht, dagegen bedeuten hohe F-Werte (ca. 80) hauptsächlich thermische Zerbrechung beim Abschrecken der Lava in Wasser.

Drei Arten von pyroklastischen Ausbrüchen lassen sich anhand der D- und F-Werte ihrer Ablagerungen unterscheiden: hawaiische/strombolische Tuffitdecken zeigen niedrige D- und niedrige F-Werte; surtseysche zeigen niedriges D und hohes F und plinische hohe D- und niedrige bis mäßige F-Werte. Es wird weiterhin vorgeschlagen, die hawaiischen und strombolischen Typen aufgrund ihrer D-Werte zu unterscheiden, normal- und explosiv-strombolische Eruptionen mit Hilfe ihrer F-Werte zu trennen, und ein neuer Typ — sub-plinisch — sollte einen Zwischencharakter zwischen strombolischen sowie plinischen Typen besitzen. Andere Arten, die noch nicht genau gekennzeichnet sind, liegen wahrscheinlich zwischen den oben erwähnten Typen.

Abstract

A classification scheme is proposed based on measurements made on the resulting pyroclastic fall deposits, the significant parameters being the area of dispersal and degree of fragmentation of the material. An empirical measure of the first is the area enclosed by the 0.01 T_{max} isopach (where T_{max} is the maximum thickness of the deposit), called D, which ranges from less than 10 km² for deposits of strongly cone-building type to more than 1000 km² for deposits of strongly sheet-forming type. An empirical measure of the second is the percentage of material finer than 1 mm in the deposit, or more simply at the point where the 0.1 T_{max} isopach crosses the dispersal axis. The latter value, called F, varies from less than 20 for deposits in which fragmentation was mainly achieved by the tearing apart of magma, to more than 80 where it was largely due to thermal shock resulting from the quenching of lava by water.

Three kinds of pyroclastic fall deposit are characterised on the basis of their D and F values: hawaiian/strombolian, with low D and low F; surtseyan, with low D and high F; and plinian, with high D and low or moderate F. A distinction based on D is proposed between the strombolian and hawaiian types, and one based on F between normal and violent strombolian. A new, sub-plinian, type is proposed intermediate

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*) Author's address: Department of Geology, Imperial College, London SW7 2BP, England.

in character between strombolian and plinian. Others, still to be characterised, are thought to occupy the field outlined by these types.

Résumé

Une classification des éruptions volcaniques explosives est proposée sur la base de différentes mensurations faites sur leurs dépôts pyroclastiques. Les deux paramètres importants sont les dimensions des aires de dispersion (D) et le degré de finesse des cendres (F). Une mesure empirique du premier paramètre est donnée par la surface (exprimée en km^2) limitée par la ligne isopaque de 0.01 T_{max} (T_{max} étant l'épaisseur maximum d'une couche de tuffite). D est inférieur à 10 km^2 pour des éruptions manifestement coniques et dépasse 1000 km^2 pour des éruptions conduisant à la formation d'épandages courants. L'autre paramètre (F) est le pourcentage des cendres dans la tuffite qui est inférieure à 1mm, ou, plus exactement, à l'endroit où l'isopaque de 0.1 T_{max} recoupe l'axe de dispersion. De petites valeurs de F (20 environ) proviennent de cendres dont l'amenuisement résulte de l'étirement du magma; par contre des fortes valeurs de F (environ 80) indiquent principalement une fragmentation thermique par suite de la chute dans l'eau.

Trois types d'éruptions pyroclastiques peuvent être distingués à partir de valeurs de D et de F tirées de leur dépôt: les couches tuffitiques du type « hawaiien-strombolien » montrent des valeurs faibles de D et F: les couches surtseyennes ont des valeurs faibles pour D et fortes pour F. Les couches pliniennes ont des valeurs élevées pour D, et faibles à moyennes pour F. On peut en outre se proposer de distinguer les types hawaiiens et stromboliens sur la base de leurs valeurs de D, de séparer les éruptions stromboliennes normales et explosives à l'aide de leurs valeurs de F. Un type nouveau, « sous-plinien », posséderait un caractère intermédiaire entre les types « stromboliens » et « pliniens ». D'autres types qui n'ont pas encore été suffisamment caractérisés, prennent plase vraisemblablement entre les types mentionnés plus haut.

Краткое содержание

Предлагается систематическая классификация взрывных вулканических извержений на основании измерений их пирокластических отложений. Двумя важными параметрами являются величина площади дисперсии (D) и размер измельчения пепла (F). Эмпирическим мерилом досперсии считается охватываемая изопахой 0,01 $Т_{\text{макс.}}$ площадь $\%_0$в км^2 : $Т_{\text{макс.}}$ — это самая большая толщина данного туффитового покрова. (D) составляет менее чем 10 км^2 для извержений с сильно конусообразующей тенденцией, и свыше 1000 км^2 для выраженных пластообрзующих извержений. Другой параметр (F) — это процентная доля пепла в туффите, которая оказывается меньшей, чем 1 мм, или — точнее — на том месте, где изопаха 0,1 $Т_{\text{макс.}}$ пересекает ось дисперсии. Наибольшие значения F (приблизительно 20) принадлежат таким пеплам, размельчение которых осуществляется за счет разрыва магмы, высокей значения F (приблизительно 80), напротив, обозначают главным образом термическое разрушение при быстром охлаждении лавы в воде.

На основании значений D, F и их отложений можно различать три вида пирокластических извержений: гавайские/ стромболианские туффитовые покровы обнаруживают низкие значения D и F; Суртсэйские показывают низкое D и высокое F, а плиниевские — высокое значение D и низкие до массивных знадений F. Далее предлагают различать гавайские с стромболианские типы на основании их значений D : по значениям F подразделять нормальные и взрывные стромболианские извержения. Новый, субплиниевский тип, должен иметь промежуточный характер между стромболианским и плиниевским. Другие, еще точно не охарактеризованные типы, лежат вероятно между выше перечисленными типами.

Introduction

Almost all volcanic eruptions are in some degree explosive, and perhaps half have pyroclastic rocks as their sole eruptive products. The existing nomenclature employs terms such as plinian, strombolian, vesuvian and vulcanian to denote different styles of explosive activity, but these terms are ill-defined (as becomes apparent when definitions in different books are compared) and are inadequate to cover all kinds of explosive eruption. Moreover the definitions are based on the characteristics of the eruption, and few attempts have yet been made to correlate the phenomenon with the resulting pyroclastic deposit.

Explosive eruptions are evanescent phenomena. The presence of a trained observer on the scene is often fortuitous, and conditions are frequently such as to preclude close observation anyway. Fewer than 10% of the explosive eruptions of the present century have been reasonably well documented scientifically, and few volcanologists have the opportunity to observe more than 3 or 4 large explosive eruptions in their lifetime. It is not difficult, however, for one person in a year to measure the deposits of several large eruptions of the past, and the volume of data forthcoming from such measurements is enormously greater than that forthcoming from observations on current activity. This is not in any way to decry the value of visits to erupting volcanoes but merely to emphasize the vast and yet largely untapped source of information available from the products of past eruptions. Rapid progress towards the understanding of explosive eruptions is more likely to be made by studying this source than by observing eruptions, although a combination of both is desirable.

There is a pressing need for a modern classification and terminology which, while based primarily on measurements of the deposits, is also closely linked with the eruptive phenomena as observed or deduced. The classification is needed, for example, as a basis for grouping like deposits together so as to discern other features which they hold in common. Regarding the terminology, either the existing terms can be retained and re-defined, or a completely new terminology devised. On the whole it is perhaps better to re-define the existing terms and introduce new ones when the need arises. Thus a re-definition of "plinian", and a new term "surtseyan", have recently been proposed (Walker & Croasdale, 1971, 1972).

Accepting the need, the problem is then one of identifying the significant features of a pyroclastic deposit and of the eruption responsible for it, and choosing parameters based on them which can be readily measured. This paper examines two parameters which may fulfil this need. The approach is a purely practical and empirical one, necessarily so at this stage.

A broad subdivision of pyroclastic deposits according to their mode of transportation, into pyroclastic fall and pyroclastic flow types, is already well established and attention in the following is confined to the former type.

Obviously important features of an explosive eruption are its magnitude and explosive violence. A measure of the first is given by the volume of ejecta produced, for which Tsuya (1955) has proposed a scale of magnitudes, or by the total energy output which can be derived from it (Yokoyama, 1951), and will not be further considered in this paper.

Explosive violence is more difficult to assess. It is related not only to the rate of expenditure of energy, but also to the way it is expended. Possible practical measures of these two variables are the area of dispersal, and degree of fragmentation, of the ejecta. These two will now be examined with a view to their use as a basis for the proposed new classification scheme.

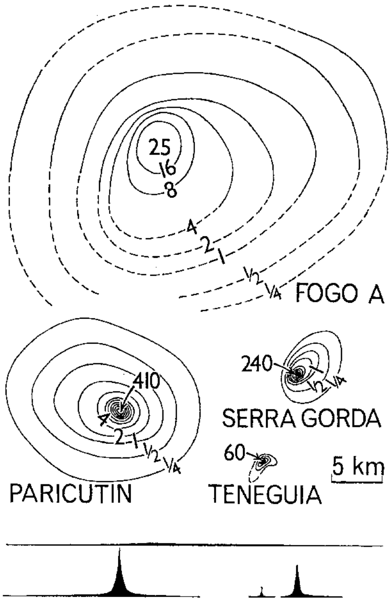

Fig. 1. Comparative isopach maps of one sheet-forming pyroclastic deposit (Fogo A, Azores) and three cone-building deposits (Paricutin, Mexico; Serra Gorda, Azores; Teneguia, La Palma). The same isopachs are drawn for each. Thicknesses are in metres, including the maximum thickness of each deposit. The comparative profiles across the four deposits below are drawn on roughly the same scale, with a large vertical exaggeration.

Dispersal

A very important distinction must be made at the outset between an explosive eruption which produces an extensive and widely dispersed pyroclastic sheet, and one which produces a steep-sided pyroclastic cone localised on the vent. These two types are illustrated by Fig. 1. It is perhaps surprising that this distinction, between what might loosely be described as sheet-forming and cone-building explosive eruptions, has seldom been made hitherto, but it seems to the writer to be of fundamental importance.

The pyroclasts thrown or carried into the air by an explosive eruption settle to the ground around or down-wind of the vent, and are dispersed over an area the size of which is largely a function of the height reached by the eruptive column: the greater the height the wider the dispersal. The strength of the wind determines the shape of the dispersal fan but it probably has little effect on the extent of the area of dispersal except for the finer-grained pyroclasts.

It is believed that a sheet-forming eruption is one with a very high eruptive column of the order of ten to several tens of kilometres high, while a cone-building eruption is one with a low column, generally less than one kilometre high. A complete gradation exists between the most extreme examples of each type. Sheet-forming eruptions may take place at the rate of several tens per century, to judge from the figures compiled by Eaton (1964). Cone-building eruptions take place much more commonly, one of the most recent being that of Teneguia in October-November 1971 (Figs. 1 and 4) on the island of La Palma.

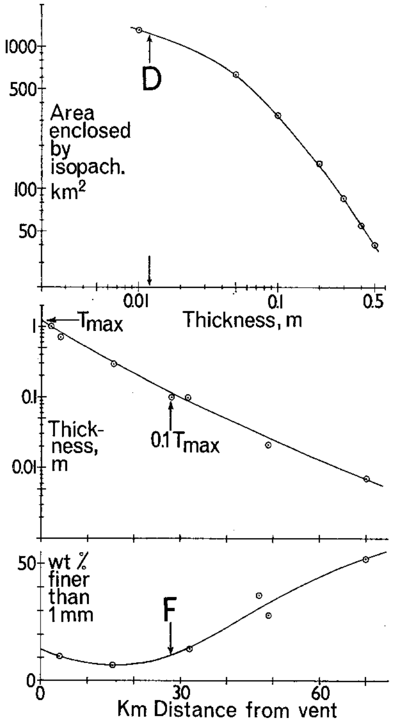

Fig. 2

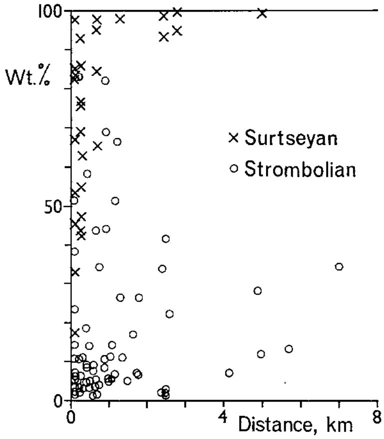

Fig. 3

Fig. 2. Graphs drawn for the Hekla 1947 pumice deposit (data from Thorarinsson, 1954) to facilitate the determination of D and F values. The middle graph plots the thickness along the dispersal axis as a function of distance from the vent, and T_{max} can be obtained by extrapolation. The upper graph plots the area enclosed by isopachs against the thickness and, knowing T_{max}, enables D to be read. The lower graph plots the weight percentage finer than 1 mm of samples collected along the dispersal axis against distance from the vent, and enables F to be read.

Fig. 3. Plot of the weight percentage finer than 1mm against distance from the vent centre for samples of basaltic ashes of surtseyan and strombolian types, showing the generally much finer-grained nature of the former.

There are many possible kinds of numerical value for the area of dispersal. One is the distance from the source at which a specified thickness of the deposit is found, but it is unsatisfactory since it depends also on the absolute magnitude

Table 1. Data from selected pyroclastic deposits. D — area enclosed by 0.01 T_{max} isopach; T_{max} — maximum thickness of deposit; A — weight percentage finer than 1 mm for the whole deposit inside the 0.01 T_{max} isopach; B — weight percentage finer than 1mm for the whole deposit inside the farthest-out mappable isopach; B′ — the farthest-out mappable isopach; F — weight percentage finer than 1 mm on the axis of dispersal at the 0.1 T_{max} isopach.

	D km^2	T_{max} m	A %	B %	B′	F %
Serra Gorda, S. Miguel (strombolian basaltic)	3.0	240	2	7	12.5 cm	2
Monti Rossi, 1669, Etna (strombolian basaltic)	4.0	180	6	12	12.5 cm	7
Teneguia 1971, La Palma (strombolian basaltic)	0.9	60	5	7 *)	1 cm	4
Capelinhos 1957—8, Faial (surtseyan basaltic)	7 *)	200	70*	88 *)	5 cm	85
Fogo A, S. Miguel (plinian trachytic)	1500	20	15	—	—	20
Fogo 1563, S. Miguel (plinian trachytic)	500	20	9	—	—	7
Furnas I, S. Miguel (sub-plinian trachytic)	80	7	11	—	—	10

*) for the part on land, Fig. 4.

of the eruption and the strength of the wind. A more suitable one, which is more or less independent of the magnitude and wind strength, is the area enclosed by an isopach which bears a fixed ratio to the maximum thickness (T_{max}) of the deposit. The 0.01 T_{max} isopach has been arbitrarily chosen, and called D. It ranges in known pyroclastic deposits from less than 0.1 to more than 1000 km^2. Values of D are given in Table 1.

It is not always feasible to measure T_{max} directly, and Fig. 2 shows how it may be determined by extrapolation on a graph (the middle graph of the three shown). An acceptable value can only be derived thus, however if thickness measurements of the deposit are available to within a few kilometres of the vent.

Fragmentation

The significance of the degree of fragmentation is less clear. Perhaps its importance was qualitatively included in the distinction between strombolian and vulcanian eruptions, the former with a white eruptive cloud (mostly vapour), and the latter with a dark cloud (loaded with fine ash). Its possible importance first became apparent to the writer when a comparative study was made recently of samples of basaltic pyroclastic deposits of strombolian/hawaiian and surtseyan types (Walker & Croasdale, 1972). The former, collected from scoria cones and associated ash beds produced by mildly explosive activity or fire-fountaining on land, are relatively coarse-grained and 102 out of 109 samples from the Azores, Canary Islands, Iceland and Sicily were found to have a median diameter coarser than 1 mm.

The latter, collected from ash rings and associated ash beds produced by the much more explosive activity when basaltic eruptions take place in water, are relatively fine-grained and 70 out of 88 samples from the Azores and Iceland were found to have a median diameter finer than 1 mm. The difference between the two types is shown clearly by the plot of these sieve analyses on Fig. 3 and the maps of Fig. 4.

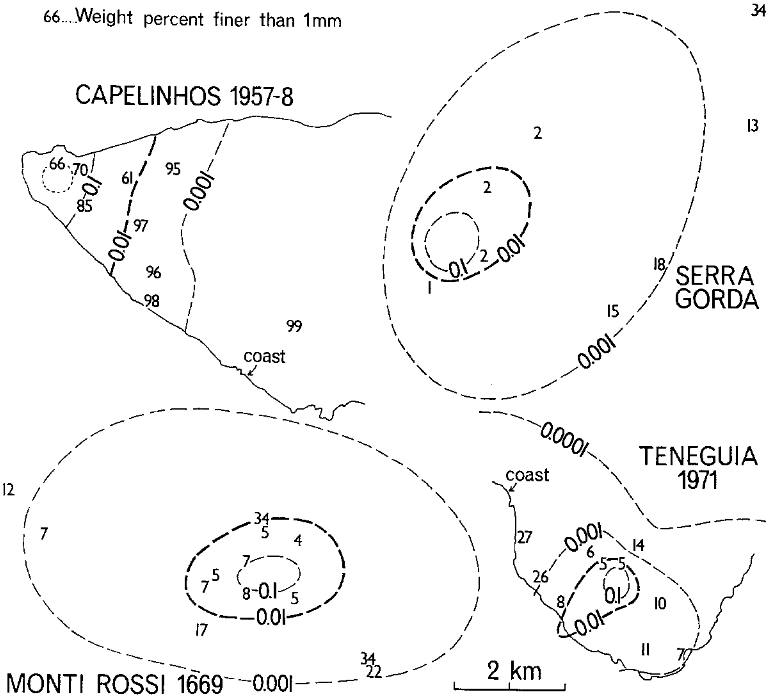

Fig. 4. Comparative maps of four basaltic pyroclastic deposits, one (Capelinhos) of surtseyan, and the other three of strombolian type. The 0.1, 0.01 and 0.001 T_{max} isopachs are drawn for each, and the smaller figures give the percentages of material finer than 1 mm in sieved samples.

Fragmentation to produce a strombolian/hawaiian deposit is mainly due to the tearing apart of relatively fluid lava which results from the movement, expansion and escape of gas bubbles. The fragments are for the most part solidified lava spray. Much of the fragmentation to produce a surtseyan deposit on the other hand can be attributed to thermal shock when lava spray is quenched in water.

The particles have shapes which are related to their origin. In strombolian/hawaiian deposits they are often ragged and are in part bounded by smooth or rounded surfaces moulded by surface tension (the term "achnelith" has been proposed for such particles, *loc. cit.*), whereas in surtseyan deposits they are bounded only by fracture surfaces and the inner walls of broken vesicles.

The possible importance of the degree of fragmentation later became apparent also when the various trachytic pyroclastic fall deposits in the Azores were compared. Some, believed to result from eruptions of plinian type and exemplified by the Fogo A deposit on São Miguel (WALKER & CROASDALE, 1971), are relatively coarse-grained and the pumice fragments in them have a ragged shape consistent with their formation by the tearing apart of viscous magma. Others, exemplified by the Caldeira Secca ash on the same island (BOOTH et al., 1973), are very much finer-grained and are interpreted as resulting from eruptions in water as the trachytic analogues of surtseyan eruptions. The majority lie between the Fogo A and Caldeira Secca types in keeping with the rather aqueous environment in which their eruptions have taken place.

A numerical value for the degree of fragmentation could be given by the percentage finer than a given arbitrary grain-size (say 1 mm) in the entire assemblage of fragments thrown out by the eruption. No attempt has however ever been made to determine this, nor is it normally likely to be determinable except by making measurements during and immediately after the eruption. The next best measure, determinable for many pyroclastic deposits, is the percentage in the whole deposit lying within a selected isopach. This has now been determined on seven separate deposits for the 0.01 T_{max} isopach (column A, Table 1). It has also been done for the farthest-out complete or near-complete isopach which can be mapped (column B, Table 1). Fig. 4, on which the percentages finer than 1 mm in sieved samples are superimposed on a form of isopach map, illustrates the basis for such a determination.

Many samples must be sieved to obtain A or B (50 samples of the Fogo A deposit, for example), and for general use a more easily obtained measure is required, preferably one based on samples collected from a single station. That adopted here and called F is the percentage finer than 1 mm at the point where the 0.1 T_{max} isopach crosses the axis of dispersal. This isopach was chosen rather than 0.01 T_{max} because for the examples given in Table 1 its value lies closer to A and B. Fig. 2 shows how F can be obtained graphically from sieve analyses of a few samples collected along the dispersal axis.

The characterisation of three types of pyroclastic deposit

F, which might be called the fragmentation index of the deposit, is plotted against D on Fig. 5 for a number of pyroclastic deposits including those listed in Table 1. Practically all are of three types, namely normal strombolian/hawaiian, surtseyan and plinian, these being at present the three most well-defined types. On Fig. 5 they cluster in three well separated areas.

In normal strombolian/hawaiian activity the mildly explosive disruption and ejection of relatively fluid basaltic or near-basaltic lava typically produces a scoria (cinder) or spatter cone usually with an ash bed of limited areal extent around or down-wind of it. The writer has visited more than 150 such cones, and they constitute a very distinctive type. Some, like Stromboli and the Northeast Crater of Etna, are the sites of activity persisting over decades or longer. Others, like Teneguía 1971 or Kilauea Iki 1959, are monogenic cones generally between 20 and 200 m high produced by eruptions lasting typically a few weeks to a few years.

The eruptive column in normal strombolian/hawaiian eruptions is generally not more than about 300 m high, although higher columns also occur at times, for example 600 m at Kilauea Iki in 1959 (Richter et al., 1970) and 500 m at Askja in 1961 (Thorarinsson & Sigvaldason, 1962). The dispersal area is correspondingly limited (Fig. 1 and 4). The degree of fragmentation is also small (Fig. 4): indeed many cones are too coarse-grained to yield manageable sieve samples, and many contain welded spatter in large amount.

Both isopach and grain-size data are available for the following deposits, the numbers corresponding with those on Fig. 5:

S 1 Serra Gorda, São Miguel, Azores (Booth et al., 1973)
S 2 Un-named cone E of Fogo, São Miguel, Azores (Booth et al., 1973)

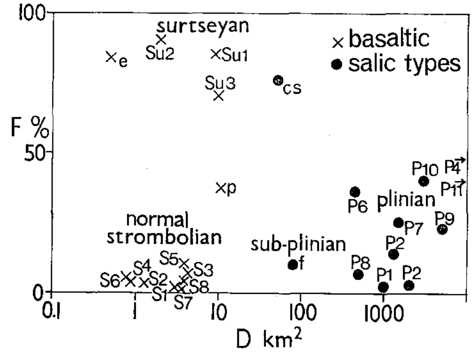

Fig. 5. Plot of F (percentage finer than 1mm on the axis of dispersal where it is crossed by the 0.1 T_{max} isopach) against D (the area enclosed by the 0.01 T_{max} isopach) for a number of pyroclastic deposits of strombolian (S 1 to S 8), plinian (P 1 to P 11) and surtseyan (Su1 to Su 3) types, as listed in the text. Also represented is one sub-plinian (f — Furnas I) and one violent strombolian (p — Paricutin) deposit, and one (cs — Caldeira Secca) which is the salic analogue of a surtseyan deposit. e is the ash from the 1971 explosion crater on the eastern side of Etna.

S 3 Monti Rossi 1669, Etna (unpublished data by Walker)
S 4 Teneguia 1971, La Palma (unpublished data by Walker)
S 5 Guimar, Tenerife (limited amount of unpublished data by Walker)
S 6 Fasnia 1705, Tenerife (unpublished data by Walker)
S 7 Carvão, São Miguel, Azores (unpublished data by Walker)
S 8 Galiarte, Terceira, Azores (unpublished data by Self & Walker).

The eight deposits listed here are believed to be representative of all but about 10% of the 150 visited (the 10% anomalous ones are appreciably finer grained than normal, and are discussed in the next section).

Surtseyan activity, which results when a basaltic eruption takes place in the sea or a lake, is more explosive than strombolian and produces an ash ring (soon lithified by palagonitisation and converted into a tuff ring) and ash beds around and down-wind of it. The eruption column may reach several kilometres in height, as in the Surtsey 1963—4 (Thorarinsson et al., 1964) and Capelinhos 1957—8 (Machado et al., 1962) eruptions, and dispersal is probably generally greater than for strombolian/hawaiian activity. Little is however known of the extent of the dispersal area because most of it normally lies at sea. For the three examples plotted on Fig. 5 a value for D is arrived at only by assuming that the isopachs are concentric circles. These examples are as follows, the numbers corresponding with those on Fig. 5:

Su 1 Capelinhos 1957—8, Faial, Azores (Campos et al., 1962; unpublished data by Walker) (Fig. 4)
Su 2 Karl, Reykjanes, Iceland (unpublished data by Walker)
Su 3 Monte Brasil, Terceira, Azores (unpublished data by Self & Walker).

A high degree of fragmentation is typical of surtseyan eruptions. Sieved samples from ten all give high average values for the content finer than 1 mm, as summarised in Table 2. Since these samples were collected from the ash rings themselves, the F values should therefore be appreciably higher, probably around 90%.

The third well-defined type is the plinian. The rate of release of energy in a plinian eruption is exceptionally high, resulting in an extreme dispersal, but F is rather low which suggests that only a small proportion of this energy is expended in fragmenting the magma. Much data are available in the literature for this type because plinian deposits are so impressive, so amenable for study, and so useful in tephrochronology. Both isopach and grain-size data are available for the following deposits, the numbers corresponding with those on Fig. 5:

P 1 Hekla c. B.C. 870, Iceland (Thorarinsson et al., 1959; Persson, 1966; unpublished data by Walker)
P 2 Hekla 1104 (Thorarinsson, 1967; unpublished data by Walker)
P 3 Hekla 1947 (Thorarinsson, 1954)
P 4 Askja 1875, Iceland (Thorarinsson, 1944; Persson, 1966; unpublished data by Walker)
P 5 Crater Lake, Oregon (Williams, 1942; Moore, 1937)
P 6 Asama 1783, Japan (Minakami, 1942; Aramaki, 1956; Murai, 1961)
P 7 Fogo A, São Miguel, Azores (Walker & Croasdale, 1971)
P 8 Fogo 1563, São Miguel, Azores (Walker & Croasdale, 1971)
P 9 Somma-Vesuvius 79 (Lirer et al., 1973)
P 10 Somma-Vesuvius c. B.C. 1300 (Lirer et al., 1973)
P 11 Granadilla pumice, Tenerife (Booth, 1973).

The following definition was recently proposed of plinian, namely "an exceptionally violent* continuous gas blast eruption which ejects pumice copiously" (Walker & Croasdale, 1971; *powerful would be a better word than violent). This is more or less the sense in which the term was used by Escher (1933), and also by Thorarinsson (1968) who has done much to characterise

Table 2. Average weight percentage of material finer than 1 mm in samples collected from various basaltic ash rings of surtseyan type.

Karl, Iceland	67%	(11 samples)
Capelinhos 1957—8, Faial	66%	(11 samples)
Ditto, pre-1957 ash ring	89%	(3 samples)
Monte Guia, Faial	66%	(7 samples)
Morro Grande, San Jorge, Azores	80%	(6 samples)
Monte Brasil, Terceira	65%	(8 samples)
São Roque, S. Miguel	51%	(6 samples)
Capellas, S. Miguel	59%	(7 samples)
Villa Franca Island, S. Miguel	74%	(5 samples)
Surtsey 1963—4 (Sheridan, 1971)	~ 55%	(9 samples)

such eruptions and their deposits. This definition accounts for the main features of a plinian deposit, as outlined below.

Firstly the exceptional power means a very high velocity of ejection from the vent, a great height reached by the eruptive column (27 km in the Hekla 1947 eruption, Thorarinsson, 1950), and a very high rate of discharge of pumice (12,000 m^3 s^{-1} dense rock equivalent averaged over one hour, Hekla 1947, and 17,000 m^3 s^{-3} over $8^1/_2$ hours, Askja 1875, Thorarinsson, 1968). A wide dispersal and a high D value is thereby guaranteed. Moreover even coarse ejecta are carried to a great height and are widely dispersed: the deposit is coarse-grained over an exceptionally large area.

Secondly, the continuous nature of the gas blast results in a near-homogeneous deposit with little internal stratification. Some stratification can, however, result from interruptions due for instance to vent wall collapse, and nuées ardentes can produce deposits locally interstratified with the air-fall pumice. A slight but distinct reverse grading is normal and is best interpreted as due to a progressive increase in vigour of the gas blast with time as progressively deeper levels of the magma chamber are tapped. A continuous gas blast of exceptional power probably cannot be sustained for long. Typical durations are 1 hour for Hekla 1947, $8^1/_2$ hours for Askja 1875, and probably 24 hours for Somma-Vesuvius 79. The Fogo 1563 eruption lasted longer, for about two days, but interruptions in its continuity are evidenced by the internal stratification which it shows.

Thirdly, all the plinian deposits listed above are predominantly made of juvenile material: pumice, glass shards and (when the pumice is porphyritic) loose crystals. Lithics, such as might be derived from the walls of the vent, are on the whole subordinate although they may make up a fairly high proportion of certain parts of the deposits. These features are in keeping with the nature of the eruptions in which a powerful gas blast comes from and operates within a body of magma.

Some other types of pyroclastic deposit

Like many basaltic provinces the Azores and Canary Islands contain large numbers — many hundreds — of scattered basaltic cones. The majority are composed of relatively coarse scoria with an F value of 10% or less. Some however, perhaps 10% of the total, are ash cones built of finer-grained material and reflect an increased explosive violence. The 1677 cone of San Antonio at the southern end of the island of La Palma is an example. No numerical data are yet available for such cones, but Paricutin (Mexico) for which an isopach map and grain-size data are available (Segerstrom, 1950) seems to be of the same type. Paricutin is about 400 m high (Fig. 1). Of the 24 sieved samples collected inside or on the 0.01 T_{max} isopach, 18 contain more than 50% of material finer than 1 mm, and two channel samples from the upper part of the deposit within this isopach contain more than 90% of such material.

It is desirable to separate such cones from the normal strombolian ones, and this can be done by designating them "violent strombolian" as for example by Macdonald (1972). Their increased explosive violence may be due to a more viscous magma being involved, repeated clogging of the vent, or the access of groundwater (although not on the same copious scale as in surtseyan activity). It is thought that the products of violent strombolian activity bridge the gap between normal strombolian and surtseyan deposits. It should be noted in passing that the explosions in a surtseyan eruption are not particularly violent because, although a great volume of gas participates, it is mostly generated at a high level.

Another type of departure from normal strombolian activity results in an increase in D while F remains more or less unchanged. It is believed to be exemplified by the opening explosive phase of the Hekla 1970 eruption, ash from which fell in northern Iceland 200 km from the vent. The resulting deposit is 6 cm thick at a distance of 18 km and has only 4% finer than 1 mm there. Another example is the deposit believed to result from the 1906 eruption of Vesuvius which at Terzigno (6.5 km from the vent) has 5%, and at Salerno (34 km from the vent) has 30% finer than 1 mm.

These two basaltic or near-basaltic deposits closely resemble strombolian ashes in the field but are much more widely dispersed and are clearly more of sheet-forming than cone-building type. Isopach maps are not yet available but these deposits probably occupy the space between normal strombolian and plinian. Some of the trachytic pumice deposits in the Azores undoubtedly do occupy this space and one, the Furnas I pumice (Booth et al., 1973) is plotted on Fig. 5 and listed in Table 1. It is appropriate to call such deposits "sub-plinian", because they resemble plinian in all respects but their smaller dispersal area, and D limits for the type could arbitrarily be set at 5 and 500 km^2, coupled with a low F value.

More data are required before the salic analogue of the surtseyan deposit, exemplified by the Caldeira Secca ash, can be characterised and the plot of Caldeira Secca on Fig. 5 is itself tentative pending the availability of more data. A very high degree of fragmentation coupled with a D value greater than for a surtseyan deposit appears however to be characteristic. Most of the trachytic pyroclastic deposits of the Azores occupy the field lying between the plinian/sub-plinian and Caldeira Secca types. This is believed to be due to the location of their vents generally on low ground in an aqueous environment near, but not in, caldeira lakes.

While the plot of Fig. 5 appears to be successful in that it groups together like deposits and separates unlike, there are several obvious shortcomings. One arises when ash is prematurely flushed from an ash cloud by rain to produce a deposit which is finer-grained near the source than it otherwise would be. Another is exemplified by the ash which accumulated in May-June 1971 around the new crater high on the eastern slopes of Etna (Booth & Walker, 1973), in which the degree of fragmentation is high partly because much of the material thrown out was derived from pre-existing pyroclastic deposits, fragmented during earlier explosive activity, which slid into the new crater during the eruption. Moreover the explosions were so weak that little coarse debris succeeded in clearing the crater rim. The 1963—5 eruption of Irazu (Murata et al., 1966) is another example.

The distinction between hawaiian and normal strombolian types

Regarding the distinction between hawaiian and normal strombolian activity, most authorities offer little objective guidance beyond describing the former as predominantly effusive and the most weakly explosive style of activity and the latter as being more explosive, intermittent, and characteristic of a more viscous magma. They usually then go on to describe the former as the type characteristic of activity on Hawaii, but this is not very satisfactory since a range of different levels of explosivity is encountered in Hawaii. Thus in the 1959/60 activity of Kilauea the lava fountains varied from 10 to 600 m high and cauliflower-like eruptive clouds at times rose several thousand feet into the air (RICHTER et al., 1970).

The distinction drawn by MACDONALD (1972) is more objective: in strombolian activity the ejecta are fluid when they leave the vent but, unlike hawaiian, are solid when they reach the ground, and form loose scoria instead of spatter. It is implied that this is because the magma is more viscous.

While viscosity is obviously important, other factors (such as the participation of groundwater) are also involved and any factor which even slightly increases the explosivity will in general strongly favour the formation of loose scoria instead of spatter. This is because with increased explosivity the fragments are thrown or carried higher into the air, and because fragmentation of the lava is increased. The effect of the latter is to produce smaller fragments which cool more rapidly, reach a greater height (because they are smaller), and have a lower fall velocity than larger fragments. A rough calculation shows that a halving of the diameter of ejecta from 64 to 32 mm will increase the loss of heat per unit volume by a factor of about 8 between the time of ejection from the vent and the time of arrival on the ground.

There is one circumstance in which increased explosivity does not favour the formation of scoria: when the rate of discharge of lava from the vent is extremely high, as it was at times in the 1959 Kilauea Iki lava fountains (maximum rate, 400 $m^3 s^{-1}$). Each lava fragment in the fountain then travels in a hot environment, with other hot fragments near it, so that air cooling is minimal. Moreover the welding together or coalescence of the fragments when they land is strongly favoured by a high rate of accumulation. A very high rate of discharge and accumulation can account for the remarkable beds of welded tuff found plastered around some of the diatreme-like basaltic vents (such as Nipukollur and Eldgja) in Iceland which, although they show evidence for a high degree of fragmentation and have been dispersed over a relatively wide area, are thoroughly welded into a dense lava-like rock.

The conclusion is that, while the formation of spatter instead of loose scoria is strongly favoured by a very low viscosity, other factors which may not be viscosity-dependent can also be important.

Hawaiian and strombolian pyroclastics have seldon been quantitatively described (grain-size data are rare, isopach maps rarer) so that there is little factual basis for comparison. The following proposal, based on the author's own field experience, is therefore a very tentative one. It is that hawaiian activity should be defined as effusive basaltic actively so weakly (if at all) explosive that any pyroclastic deposit which results has a D value of less than 0.05 km^2 (that is, the 0.01 T_{max} isopach extends on average less than 126 m from the vent), while strombolian activity produces a pyroclastic deposit with D more than 0.05 km^2. Both give a low F value, are predominantly made of juvenile material, and contain achneliths, while hawaiian activity produces a relatively high proportion of spatter. This proposal is believed to be fairly consistent with MACDONALD,S distinction in that most spatter accumulations have a very low D value and most scoria deposits have a much higher D value. The explosivity index (the percentage of erupted material which forms pyroclastic deposits) is very low in eruptions of hawaiian type, and is on the whole higher for strombolian eruptions, although it shows a wide range and in examples in the Azores varies from under 20% to 100%.

The terms hawaiian and strombolian are here used solely to denote *styles* of activity, without any geographic connotation. Thus the hawaiian style may be shown by volcanoes outside Hawaii, for example in Iceland and the Canary Islands, while strombolian may develop in some eruptions on Hawaii. On this definition both the Kilauea Iki 1959 and Kapoho 1960 cones of Hawaii are strombolian in type, giving D values of roughly 0.7 and 5 km^2 respectively, although the activity at both vents varied with time from strombolian to hawaiian.

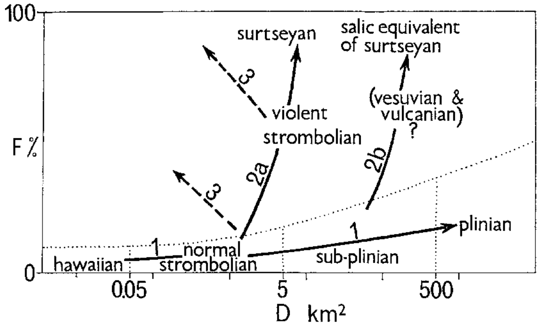

Fig. 6. The same field as Fig. 5, extended to the left, showing the areas occupied by the pyroclastic deposits resulting from different styles of explosive eruption. As explained in the text, trend-line 1 links deposits from eruptions the characters of which are determined by the inherent characteristics of the magmas, least affected by external influences. The arrow gives the direction of increasingly powerful gas blasts. Trend-line 2a marks increased explosive violence in basaltic eruptions, in part at least due to the access of extraneous water to the vent. Trend-line 2 b is the corresponding one for salic magmas. Trend-line 3 is for deposits resulting from explosions which are so weak or taking place in a crater so deep that only the finer-grained ejecta succeed in clearing the crater rim.

Conclusions

The prospect of classifying styles of explosive eruption by means of two parameters measured on the resulting pyroclastic deposits seems to be good. Attention in this paper has been concentrated on what are probably the three most well defined types, and more data are now needed to complete the coverage of all styles of explosive activity and test this scheme of classification fully; in particular, data on which the vulcanian, ultravulcanian and vesuvian styles can be objectively characterised.

Certain broad relationships seem to be discernable, as summarised by Fig. 6. The first is that explosive eruptions the style of which depends primarily on the inherent characteristics of the magma and is least affected by external influences, produce pyroclastic deposits which lie along or near the base of the rectangle. They are linked by the trend-line 1, namely hawaiian — normal strombolian — sub-plinian — plinian. These eruptions are believed to be characterised by an open vent communicating directly and more or less freely with the magma chamber, and there is a continuous uprise and discharge of magma and gases which leave the vent with a vigour which depends probably mainly on the ease with which gas bubbles can escape from the magma (which depends in turn on the viscosity of the magma). The progression from left to right along trend-line 1 is taken to reflect mainly an increased viscosity. It could however also reflect an increased content of dissolved gases and a correspondingly increased depth at which gas bubbles begin to form, and this was favoured by, for example, NAKAMURA (1964) to account for differences in the area of dispersal of various scoria fall deposits on Oshima.

The second broad relationship is that an increased violence of explosions (which is quite distinct from an increased power of the gas blast along trend-line 1) results in a higher degree of fragmentation, which displaces the resulting pyroclastic deposits in a direction shown by the trend-lines 2 a and 2 b (2 a for basaltic pyroclastics, and 2 b for salic). This increased explosivity can be caused by the participation of groundwater in the eruption, the maximum degree of fragmentation being achieved when there is a copious supply of water, as in a surtseyan eruption or its salic analogue. It can also be due to other causes, such as clogging of the vent.

A third relationship is that when the explosions are so weak, or the crater is so deep, that only the finer-grained debris clears the crater rim, the resulting deposits are displaced in the general direction of the trend-line 3.

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