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The 1973 Heimaey Strombolian Scoria deposit, Iceland

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Summary. The 1973 eruption on Heimaey, Iceland, presented the opportunity to study the interaction of the principal factors that control the formation of pyroclastic fall deposits. The grain size characteristics and the dispersal of some of the scoria fall units within the Eldfell Scoria deposit are described and related to observations made on the wind speed and direction, the height of the eruption column, the 'muzzle' velocity and the various styles of activity during the first month of the eruption.

1. Introduction

The 1973 volcanic eruption of Eldfell on Heimaey, Iceland (Thorarinsson *et al.* 1973) began with a fissure eruption which discharged incandescent lava fountains from up to 20 vents along its 1.5 km length. Within the first 24 h these vents became centralized at the northern end of the fissure, where the rapid accumulation of scoria from a cluster of 3 vigorous fountains quickly built up a cone. The continuation of strombolian type activity during the first month produced the 200 m high scoria cone of Eldfell and deposited a thick mantle of air fall scoria over the northern half of the island, causing extensive damage to the nearby town. At the same time lava flowed continuously from the cone northwards and eastwards into the sea to produce a continually expanding lava delta.

This paper records studies of the scoria falls of the period 24 January to 19 February. During this time there was more or less continuous strombolian activity from Eldfell. The first two authors observed the eruption from 31 January to 1 February and the second two from 15 to 20 February. During this four-week period winds blew from the cone towards the town (from directions 90–160°) for 160 out of a total of 672 h (Fig. 1). Grain size studies of five main scoria falls on the town during this period are denoted I–V on Figure 1.

The dispersal and grain size characteristics of pyroclastic fall deposits are dependent on, for example, wind strength and direction, the height of the eruptive column, the style of activity and the degree of fragmentation of the magma. For most strombolian deposits no information is available on wind speed, however, wind speeds and directions during the Eldfell eruption were measured by the Icelandic Meteorological Service at the Storhofdi Lighthouse weather station at the southern end of Heimaey. Measurements of average wind speeds and directions were taken over 3 h periods. For the Eldfell scoria deposits it is therefore possible to distinguish between the dual effects of wind and eruptive vigour, thereby permitting similar deposits from other volcanoes to be calibrated.

2. Grain size distribution

Thirty-one samples were collected for mechanical analysis: 5 from Scoria Fall I, 15 from Fall II, 3 from Fall III, 6 from Fall IV and 2 from Fall V. The samples were sieved following the procedure of Walker & Croasdale (1971). Cumulative curves were drawn on probability paper and from these the parameters Md_ϕ (the median diameter $=\phi_{50}$) and σ_ϕ (the graphic standard deviation $=\frac{1}{2}(\phi_{84}-\phi_{16})$) were derived. Little difference in these parameters was found between samples from the individual scoria falls. The overall grain size distribution for Scoria Fall II of Heimaey is given (Fig. 2*a*), and may be regarded as typical.

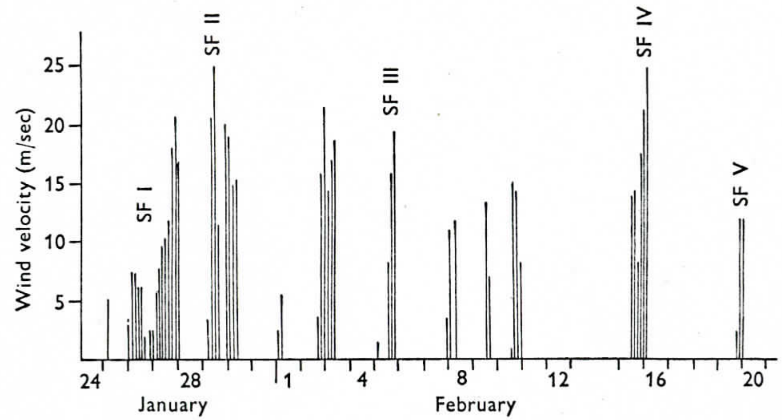

Figure 1. The average wind velocities over 3 h periods within the sector 90–160° from the Eldfell cone are shown plotted against time. The periods of the Scoria Falls studied coincide with the peak winds.

σ_ϕ is plotted against Md_ϕ (Fig. 2*b*). The Heimaey deposits plot within the field defined by Walker & Croasdale (1972) for strombolian deposits. It is found that the sorting tends to be slightly poorer in the finer-grained samples. Scoria Fall II was sampled over its whole extent and shows a systematic decrease in both median diameter (Fig. 3*b*) and σ_ϕ away from the source, and a decrease in the average maximum diameters of the 5 largest fragments measured (Fig. 3*a*). Considerable break-up of fragments on landing was observed during some of the scoria falls, and the original air-borne population is coarser and perhaps better sorted than that found on the ground. In addition the grain size varied at single localities during the course of the same scoria fall. For example, 2 samples collected at intervals of a few minutes during the height of Scoria Fall IV on the night of 15 February varied in median diameter from −2.4 to −2.65 phi due to minor fluctuations in eruptive vigour. The measured rate of accumulation at this site, near the harbour at a distance of 1300 m NW of the cone, amounted to 1.1 kg m^{-2} s^{-1}.

The Eldfell scoria fall is thoroughly typical of strombolian deposits (Walker, 1973), containing very little material finer than 1 mm. Only 2.9 % of Scoria Fall II on the island is finer than 1 mm, and only 5.2 % of Fall I. In the southern part of the island there was a sharp truncation at the margin of the dispersal area, both in grain size and thickness. This suggests that little fine material is normally produced by such activity. Walker (1973) has proposed definitions for different styles of explosive volcanic eruptions based on the empirical parameters D (the dispersal area) and F (the degree of fragmentation). The D value for the Eldfell scoria deposit on 1 February was 1.4 km², including the estimated

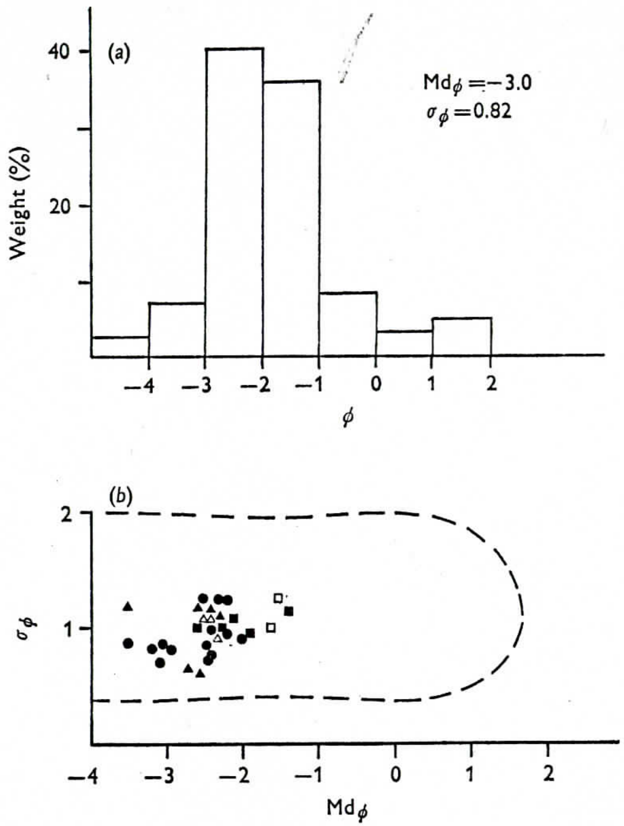

Figure 2. (*a*) The average grain size distribution for the whole of Scoria Fall II, which may be considered to be representative of all the Heimaey Scoria Fall deposits. (*b*) A plot of σ_ϕ against Md$_\phi$ for the Heimaey Scoria Fall deposits. ■, Scoria Fall I; ●, Scoria Fall II; △, Scoria Fall III; ▲, Scoria Fall IV; □, Scoria Fall V. The dotted line is the boundary of the field of Strombolian deposits taken from Walker & Croasdale, 1972.

part of the dispersal area at sea. D increased as the eruption progressed: the thickness of scoria steadily increases with time, whereas the cone reaches its optimum height comparatively quickly and may even lose height by auto-destruction, as was observed to happen on Eldfell on 19 February. The F value is

5 %, and the deposit lies in the middle of the normal strombolian field on a D/F plot.

The grain size data for the samples have been converted to terminal fall velocity data, using the published conversion curves of Walker, Wilson & Bowell (1971), and the median terminal fall velocity of each sample determined from a cumulative curve in the same manner as the median diameter.

3. Styles of eruption

The Eldfell eruption displayed varying styles of activity during the period of observation. Outbursts from the crater occurred every 1–3 sec and sent incandescent material normally to a maximum height of 250 m above the crater rim, although individual bombs sometimes reached at least twice that height, and the dark-coloured column of gases, fumes and ash reached an even greater height. It was estimated that 30–50 m³ of material was ejected with each burst. When the lava level was low in the vent, blasts were always vertical and had a narrow angle of divergence, whereas when the lava level was high the blasts varied widely in direction from vertical to 45° or less, (the lower limit being set by the angle of slope of the inside of the crater) and had a wide angle of divergence.

When the vent was open a brightly incandescent eruptive column hurled large fragments of lava and scoria into the air. During a particularly vigorous blast thick layers of incandescent material would rapidly accumulate on the inside of the cone: occasionally these became unstable and avalanched back into the vent, partially blocking it. After such avalanches dense black clouds of much finer grained ash were ejected until the vent became unblocked. Such activity may explain the anomalous fine grained beds occasionally found in basaltic scoria deposits.

The viscosity of the lava fragments ejected by the blasts was, for basalt, relatively high. Very little spatter was produced and scoria bombs sometimes broke up explosively in flight (presumably due to rapid vesiculation), and by impact on landing. Most of the largest fragments (those exceeding 32 mm) had a density considerably greater than 2.0 g cm^{-3}, in contrast to the highly vesiculated low density scoria which constituted the smaller fragments (those less than 32 mm). There appeared to be few fragments of intermediate density.

4. Effect of wind

Wind strength is critical in determining the shape of the isopachs and grain size isopleths of a fall deposit. The isopach map of the scoria fall deposit at the end of the first 8 days of activity shows a main lobe over the town and a minor lobe to the S; these two lobes correlate well with the rose diagram of the wind speed and direction over the same period (Fig. 4). Winds blew from the SW to the NW quadrants, and scoria fell into the sea, for 440 h out of 672 in the first week, and it is believed that 65 % of the pyroclastic material fell into the sea. Taking this into account the total volume of scoria, including the cone, is estimated as 40×10^6 m³, or 8.2×10^6 m³ dense rock ($\rho = 2.6$ g cm^{-3}) equivalent.

The distance travelled by individual fragments from the vent is controlled by

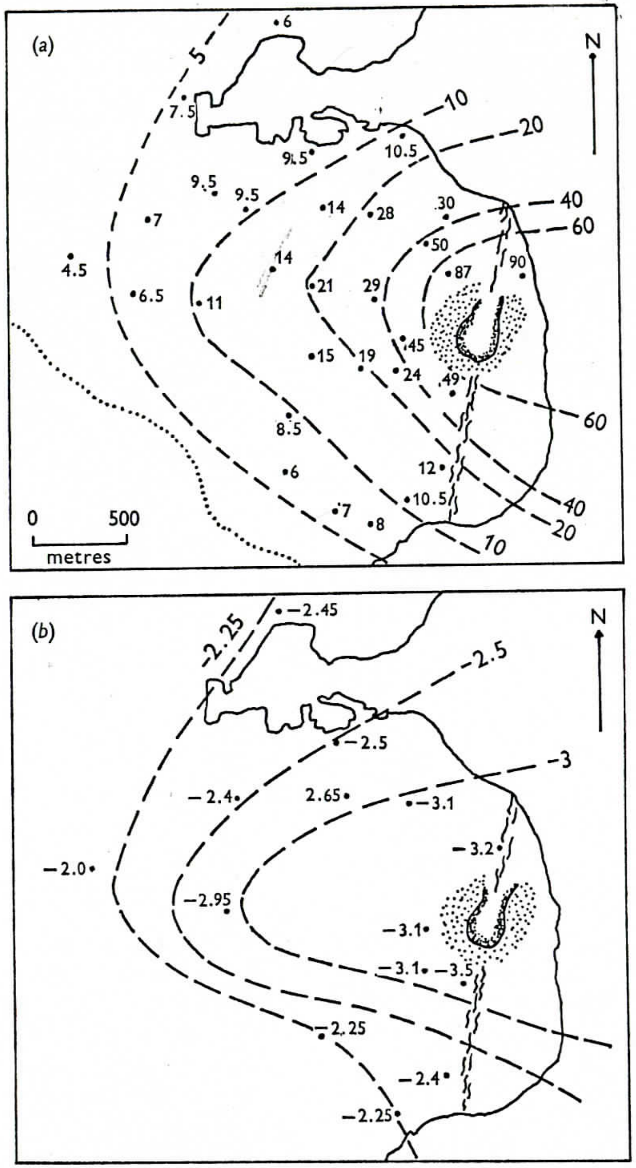

Figure 3. (*a*) An isopleth map of the average maximum scoria diameter, from the 5 largest fragments measured at each locality, for Scoria Fall II. All data in cm. (*b*) Map showing isopleths of median diameter (Md_ϕ) in phi units, for Scoria Fall II on 1 February 1973.

many interacting factors. The most important are the height the fragments reach in the eruptive column, the angle of ejection, the wind speed and the terminal fall velocity of the fragments. As the terminal fall velocity decreases, the farther will a fragment travel down-wind for a given set of conditions. Figure 5(a) shows the relationship between the median terminal fall velocity of the scoria samples and the distance of the sampling point from the source for Scoria

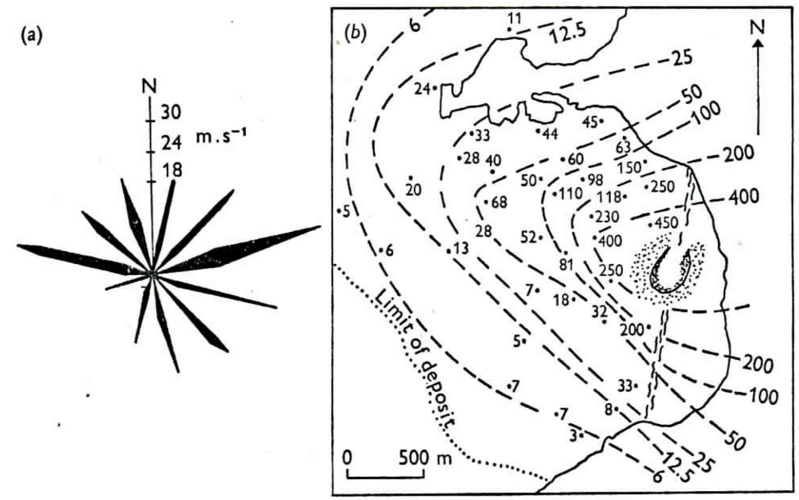

Figure 4. (*a*) Rose diagram of wind direction, speed and duration over the Eldfell cone. The directions have been resolved into 30° sectors. The length of the bars is proportional to the wind speed, see radial scale, and the width is proportional to the time for which winds of each speed blew, up to a maximum of 48 h (represented by 15° of arc). (*b*) Isopach map, giving the thickness in cm, of the whole Heimaey Scoria Fall deposit up to 1 February 1973.

Falls II and IV. Three other Icelandic eruptions for which the wind speed is known are also plotted (Fig. 5*b*), namely Hekla 1947 and 1970 and Askja 1875. For all 5 deposits the wind strength was of the same order of magnitude, and the slope of the line (Fig. 5*b*) is largely a function of the height of the eruption column for constant wind conditions.

The heights reached within the eruption column by various-sized fragments in the 2–10 mm range, have been estimated from the median terminal fall velocities of the samples and their horizontal distance from the source (Fig. 6). These estimates assume that fragments in this size range are carried vertically above the vent by the rising gas stream, against which they offer little resistance. These heights are plotted against the terminal velocity of the fragments (Fig. 6). Estimates made with an Abney Level of the height from which most of the fall-out took place varied from 300 to 600 m, showing close agreement with the heights calculated from the grain size data.

5. Muzzle velocity

One of the most useful physical parameters in the comparison of explosive eruptions is the initial or 'muzzle' velocity at the vent. The Eldfell eruption gave the opportunity to estimate this value by several alternative methods. The first method was to measure the fall times of lava bombs from the maximum height to which they were thrown, and to assume air resistance is a relatively minor factor. The second was to measure the largest fragments and their distance from the vent (Fig. 3*a*), and to calculate the minimum muzzle velocity using the data of Wilson (1972), assuming an optimum ejection angle of 45°. This is a useful way of obtaining the muzzle velocity of past eruptions from ancient pyroclastic fall deposits. The third and most accurate method was to measure the actual

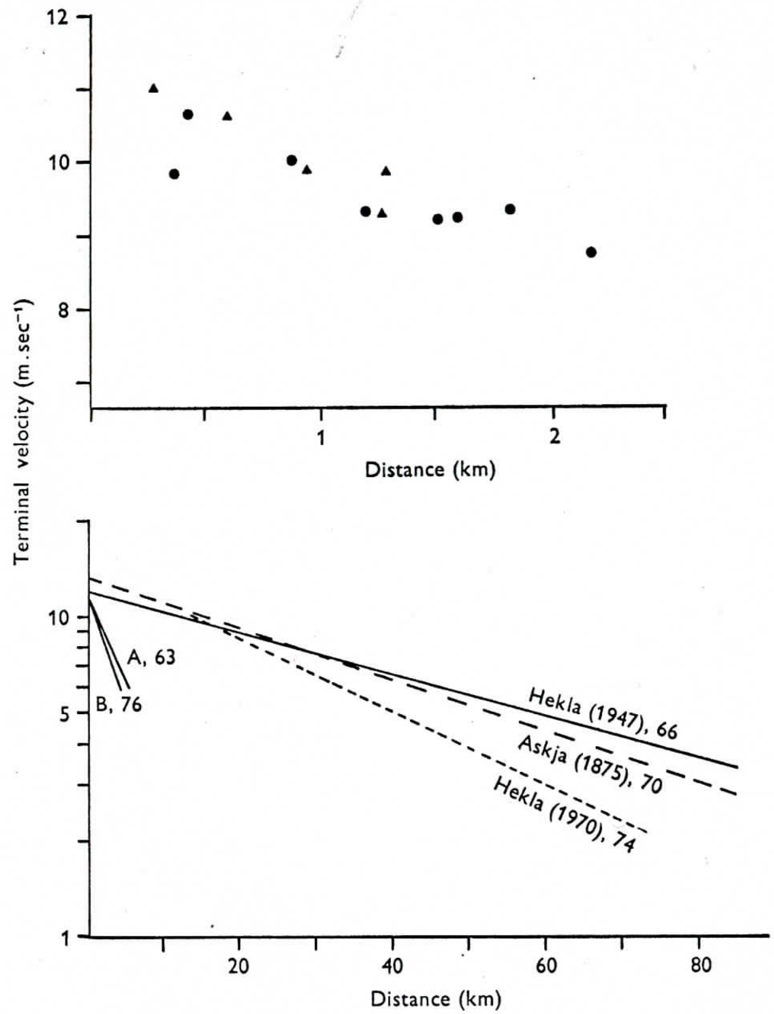

Figure 5. (*a*) The median terminal velocity of samples of Scoria Fall II (dots) and Scoria Fall IV (triangles) plotted against distance from the cone of the sampling point. (*b*) Median terminal velocity plotted against distance from the vent for 3 large Icelandic eruptions and the smaller Heimaey Scoria Falls II (A) and IV (B). The wind speed at the time of eruption is shown in km h^{-1}.

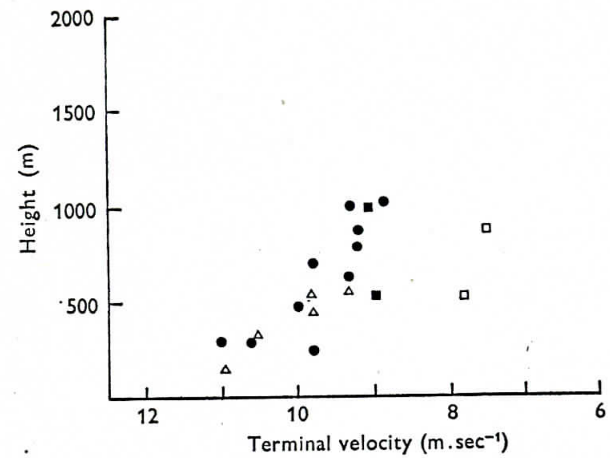

Figure 6. A plot of median terminal velocity against the calculated height to which particles of that terminal velocity are carried in the eruption column. Designation of Scoria Falls as in Figure 2(*a*).

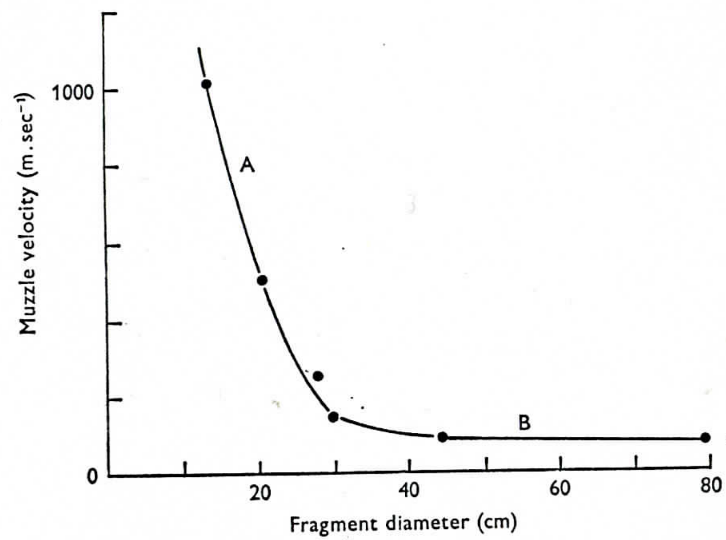

Figure 7. A plot of the calculated muzzle velocity against grain size, using the maximum grain size data for Scoria Fall II (Figure 3*a*). (B) Truly ballistic fragments virtually unaffected by the wind. (A) Partly ballistic fragments affected by wind giving spurious muzzle velocities.

ejection velocities from cine film taken during the eruption. Table 1 gives the results of these studies and shows that the values obtained by the 3 methods are in good agreement.

Table 1. Muzzle velocity

Muzzle velocity (m/s)	Time measured	Method
75	Wed. 31 Jan., 20.00 h	Fall times of bombs 50–100 cm
77	Wed. 31 Jan., 22.15 h	Fall times of bombs 50–100 cm
110	15 Feb. (Ash IV)	Fall times of bombs 20–40 cm
87	16 Feb.	Fall times of bombs 20–40 cm
105	20 Feb.	Fall times of bombs 20–40 cm
80	27 Jan. (Ash II)	Wilson's data for ejection of ballistics using data from Figure 3
90 to 95	15 Feb. (Ash IV)	Estimate from film taken during Ash IV

Theoretical considerations demonstrate that the smaller the fragment the more rapidly it attains its terminal fall velocity and the greater is its dispersal controlled by wind. The 'muzzle' velocity has been estimated from fragments of various sizes using the data for Scoria Fall II (Fig. 3*a*). It is found that the velocity is increasingly over-estimated the smaller the fragments (Fig. 7). These results also suggest that only the very largest available fragments, those 40 cm or more in diameter, should be used to estimate the 'muzzle' velocity.

6. Conclusions

A great wealth of valuable information on explosive volcanic eruptions is locked up in the countless scoria and pumice deposits of past activity. One of the great difficulties has been to correlate the characteristics of these deposits with the activity that produced them. In most recent eruptions, measurements to determine the parameters of the physical processes that lead to the formation of volcanic deposits, and eventually to the form of the volcano itself, have been sadly neglected in favour of chemical and petrological measurements. While these latter have been rightly considered vital in the routine studies of volcanic eruptions the authors believe that the study of the physical processes involved (which are less well understood) deserve at least equal treatment.

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