Bull Volcanol (1996) 57: 649–662

ORIGINAL PAPER

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Deposits of the 30 March 1956 directed blast at Bezymianny volcano, Kamchatka, Russia

Received: 19 December 1994 / Accepted: 12 December 1995

Abstract On 30 March 1956 a catastrophic directed blast took place at Bezymianny volcano. It was caused by the failure of 0.5 km^3 portion of the volcanic edifice. The blast was generated by decompression of intra-crater dome and cryptodome that had formed during the preclimactic stage of the eruption. A violent pyroclastic surge formed as a result of the blast and spread in an easterly direction effecting an area of 500 km^2 on the lower flank of the volcano. The thickness of the deposits, although variable, decreases with distance from the volcano from 2.5 m to 4 cm. The volume of the deposit is calculated to be 0.2–0.4 km^3. On average, the deposits are 84% juvenile material (andesite), of which 55% is dense andesite and 29% vesicular andesite. On a plot of sorting vs median diameter (Inman coefficients) the deposits occupy the area between the fall and flow fields. In the proximal zone (less than 19 km from the volcano) three layers can be distinguished in the deposits. The lower one (layer A) is distributed all over the proximal area, is very poorly sorted, enriched in fragments of dense juvenile andesite and contains an admixture of soil and uncharred plant remains. The middle layer (layer B) is distributed in patches tens to hundreds of metres across on the surface of layer A. Layer B is relatively well sorted as a result of a very low content of fine fractions, and it contains rare charred plant remains. The uppermost layer (layer C) forms still smaller patches on the surface of layer B. Layer C is characterized by intermediate sorting, is enriched in vesicular juvenile andesitic fragments, and contains a high percentage of the fine fraction and very rare plant remains which are thoroughly charred. Maximum clast size decreases from layer A to layer C. The absence of internal cross bedding is a characteristic of all three layers. In the distal zone (more than 19 km from the volcano) stratigraphy changes abruptly. Deposit here consists of one layer 26 to 4 cm in thickness, is composed of wavy laminated sand with a touch of gravel, is well sorted and contains uncharred plant remains. The Bezymianny blast deposits are not analogous with known types of pyroclastic surges, with the exception of the directed blast deposits of the Mount St.Helens eruption of 18 May 1980. The peculiarities of deposits from these two eruptions allow them to be separated into a special type: blast surge. This type of surge is formed when failure of volcanic edifice relieves the pressure from an inter-crater dome and/or cryptodome. A model is proposed to explain the peculiarities of the formation, transportation and emplacement of the Bezymianny blast surge deposits.

Key words Directed blast · Pyroclastic surge · Pyroclastic density current · Bezymianny volcano · Kamchatka

Editorial responsibility: T. H. Druitt

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Introduction

The eruption of Bezymianny volcano (BZ) in central Kamchatka took place on 30 March 1956 and was one of the strongest explosive eruptions of the twentieth century. Unusual aspects of the eruption, such as the great destruction of the volcanic edifice which formed a large horseshoe-shaped crater, trees all knocked down in the same direction over a large area of the eastern foot of the volcano and deposits of peculiar character, allowed Gorshkov (1963) to single out this explosion as a special type-directed blast (or Bezymianny type).

After the catastrophic eruption of Mount St. Helens (MSH) on 18 May 1980 (Lipman and Mullineaux 1981), which turned out to be similar in many aspects to the Bezymianny eruption (Bogoyavlenskaya et al. 1985), the interest in directed blasts increased sharply. The similarity turned out to be even greater when Belousov and Bogoyavlenskaya (1988) showed that large-scale failure of a portion of the volcanic edifice preceded the

BZ directed blast in the same way as in the case of MSH.

Despite the fact that the MSH directed blast deposits have been studied in detail, many aspects of their formation need to be discussed. This is connected with the fact that the MSH directed blast deposits turned out to be different from known types of pyroclastic deposits. They show features of both pyroclastic surge and pyroclastic flow. As a result of this fact, Moore and Sisson (1981) interpreted the MSH deposits as pyroclastic surge deposits, Hoblitt et al. (1981) as a combination of pyroclastic surge and pyroclastic flow, and Walker and McBroome (1983) as pyroclastic flow. Hoblitt (1990) proposed that these deposits were formed by the process of not one, but two, sequential explosions. Fisher (Fisher et al. 1987; Fisher 1990) proposed to distinguish the transport system (blast surge), which carried fragments from the volcano to depositional sites and depositional system in the form of two moving sediment gravity flows with independent flow regimes. Druitt (1992) supported the surge nature of MSH blast deposits and applied to it the known dynamics of turbidity currents.

This paper presents the results of a study of the deposits ("directed blast sand" of Gorshkov and Bogoyavlenskaya 1965) from the 30 March 1956 directed blast at BZ and its comparison with MSH blast deposits. The goal of the paper is to relate diagnostic features of the deposits with the mechanism of their formation, transportation and deposition.

The eruption of 1955–1956

The catastrophic directed blast on 30 March 1956 was one episode of prolonged eruption during which several types of eruptive activity alternated with each other. Descriptions of this eruption have been presented by Gorshkov (1959) and Gorshkov and Bogoyavlenskaya (1965). It was the first eruption of BZ during historical time (in this region beginning in 1697) and, according to data from tephrochronological investigations, it occurred after approximately 1000 years of dormancy (Braitseva et al. 1990).

Before the eruption, the volcanic edifice was a regular cone 3085 m in height (Fig. 1). It was a stratovolcano mainly andesitic in composition with summit and flank extrusive domes.

The eruption began on 22 October 1955 after a swarm of earthquakes which lasted 23 days. Until 30 March 1956 the eruption was vulcanian in character (preclimactic eruption stage). In this period a crater 800 m in diameter formed at the top of the volcano. Frequent ash outbursts to the heights of 2–7.5 km occurred from the crater. As a result of prolonged volcanic activity, a fine-laminated sequence of fine- to medium-grained ash with a thickness up to 1 m was deposited around the volcano.

Fig. 1 The Bezymianny volcano before the eruption on 30 March 1956. View from the east. (Photo was taken by B. I. Piip in 1950)

At the end of November the height of the ejections decreased to 1–1.5 km. In this period dome growth began in the crater. Simultaneously, strong bulging of the southeastern slope of the volcano began. The amount of deformation, evaluated by studying photographs, reached 100 m (Gorshkov 1959). This deformation of the flank of the volcano was probably a result of intrusion of a cryptodome.

The catastrophic directed blast occurred suddenly on 30 March 1956 after a period of decreasing eruptive and seismic activity. The blast was preceded by the failure of 0.5 km^3 of the eastern slope of the volcanic edifice (Belousov and Bogoyavlenskaya 1988). After the directed blast a Plinian eruption occurred which left an extensive airfall deposit (volume 0.2–0.3 km^3) to the north, and pyroclastic flows of pumiceous andesite with a volume 0.5 km^3.

Visual observations gave limited information about the directed blast because they were carried out from locations unfavourable for observations. Based on photos made during the paroxysm it is possible to estimate only the general height of the eruptive cloud which reached 34–38 km.

As a result of slope failure and the directed blast, a horseshoe-shaped crater approximately 1.5 km in diameter, opening towards the east, was formed (Fig. 2). Following the directed blast and Plinian eruption, a dome began to grow in the crater and its formation continues to the time of this writing (spring 1995).

Description of deposits

The directed blast deposits were studied in detail at 19 points along the radial profile which coincides with the axis of the area affected by the directed blast (Fig. 3).The profile starts 8 km away from the volcano at an altitude of 1100 m above sea level and ends 27 km away from the volcano at an altitude of 250 m. A significant part of the profile encompasses the wide watershed between the rivers Sukhaya Zimina and Yagodny

Fig. 2 The Bezymianny volcano after the eruption on 30 March 1956.View from the east, 1988. In the crater generated on 30 March 1956, the dome has formed

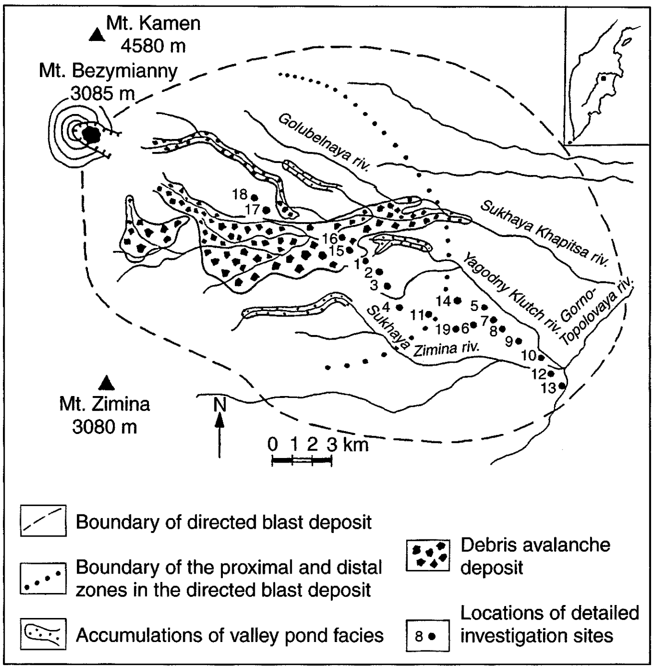


Fig. 3 Sketch map of the directed blast deposits on 30 March 1956

Klutch. Additionally, the deposits were studied at 27 other points over the rest of the blast zone. All of the main characteristics detected along the main profile are representative of the character of the remainder of the deposits. The only exception is the area immediately near the foot of the volcano where the blast deposits are discontinuous and represented by very coarse gravel–boulder material.

Along the profile directed blast deposits compose, as a rule, the uppermost part of sections. The deposits lie either on the pre-1956 soil or on the ash of the preclimactic eruption. There is great variability in the texture, structure and thickness of the blast deposits over the region. Flat and planar areas were chosen for detailed investigations so that local irregularities of the relief did not substantially affect depositional processes.

More than 70 channel samples with the weights 1–8 kg were obtained for sieve and component analysis. Each layer was sampled through its total thickness. Component analysis was carried out on 100 rock fragments from each sample mainly for the fraction 2.5–5 mm. In the case of deposits in the fine-grained distal zone, the fraction 1–2.5 mm was sometimes used.

Areal distribution, thickness and volume of blast deposits

As a result of the directed blast, an area approximately 500 km^2 at the eastern foot of BZ volcano was covered by loose pyroclastic material. The deposit boundary was mapped by Gorshkov (1959) immediately after the eruption (Fig. 3). Deposits are distributed in a 130-degree-wide sector like an ellipse elongated from the volcano on 29 km in the direction of generally lower relief. The dimension of the area in a transverse direction is approximately 19 km.

The results of measurements of the total thickness of the directed blast deposit along the profile are shown in Fig. 4. Thicknesses were measured in areas thought not to have been affected by erosion. The thickness of directed blast deposit is subject to rapid local fluctuations. In every area minimum and maximum thicknesses can be distinguished. The behaviour of minimum and maximum thickness relations is different with increasing distance from the volcano. The minimum thickness of deposit does not change essentially with the distance from the volcano and is usually equal to 5–10 cm. The maximum thickness of the blast deposit generally decreases with distance from the volcano in the range from more than 2.5 m (8 km from the volcano) to less than 4 cm (27 km from the volcano). Up to a distance of 18–19 km, thickness decreases slightly, then a rapid decrease in maximum thickness occurs from 1–1.5 m to less than 30 cm (Fig. 4). Beyond a distance of 19 km a gradual decrease in maximum thickness of the blast deposit is observed again. The zone of change of the maximum thickness values marks an important boundary in the directed blast deposit. In addition to that, rapid changes of stratigraphy and granulometry

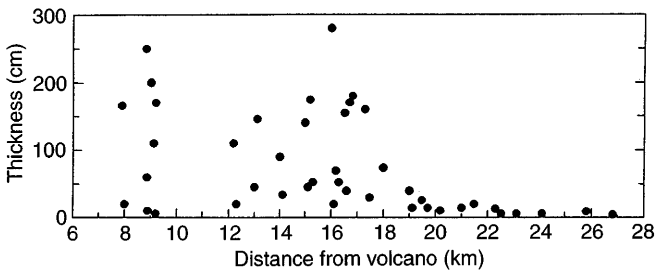


Fig. 4 Total thickness of the directed blast deposits vs distance from the volcano along the profile. Thickness values for valley pond facies are excluded

take place there. Hereafter, the area between the volcano and this boundary at approximately 19 km is referred to as the proximal zone, and the area beyond this boundary, the distal zone (Fig. 3).

Especially significant thickness fluctuations (up to several metres) are observed in the proximal zone. On smooth, flat areas thickness variations are associated with gradual (inclinations of a few degrees) changes of height of upper surface of the deposit. Areas with greater thicknesses have variable shapes in plain view, with dominant sizes of tens to hundreds of metres across. Distances between areas of maximum thickness are hundreds of metres. This variability is not connected with the presence of dunes which are frequently reported in surge deposits (Fisher and Schmincke 1984). It was produced by unsteady patchy emplacement of layers B and C (described below) of the blast deposits.

In the proximal zone the thickness of blast deposit, as a rule, has a tendency to increase in depressions. The thickness increases in this case can be of two types:

1. In wide, gently sloping depressions the thickness of deposits has the tendency to increase, i.e. in the depressions, areas of thick deposits are seen more often than on the nearby uplands. This is caused by the overthickening of some layers of the blast deposit (mostly layer C, described below).
2. In the large river valleys with steep slopes the deposit not only increases in thickness, often to several tens of metres, but it also changes stratigraphy and granulometry (details see in "Valley deposits").

In the distal zone local fluctuations of thickness of the directed blast deposit are substantially less (in the range of several centimetres), and they do not implicitly depend on the relief. Wave lamination preserved in some locations allow us to suppose that these fluctuations are connected with primary dune relief of the blast deposit in the distal zone.

Rapid variations of the thickness make estimation of the volume of the blast deposit very difficult. Available data suggest a volume in the range of 0.2–0.4 km^3.

Composition of deposits

The directed blast deposits can be divided into three groups of rock fragments. The first group consists of dense dark-grey (with bluish tint) hornblende andesite. The second group includes a light-grey vesicular hornblende andesite. The third group consists of all fragments not included in the two previous groups and includes clasts that are very different in composition, colour, vesicularity and degree of alteration.

Table 1 Comparison of major-oxide composition of vesicular and dense juvenile andesite from the directed blast deposits erupted on March 30, 1956. Analyses were made in the Institute of Volcanology by G. P. Novoseletskaya by using of wet chemistry method

Element	Vesicular	Dense
SiO_2	57.92	58.96
TiO_2	0.72	0.65
Al_2O_3	18.39	18.10
Fe_2O_3	2.90	2.37
FeO	4.20	4.42
MnO	0.15	0.15
MgO	2.84	2.55
CaO	7.37	6.97
Na_2O	3.51	3.51
K_2O	1.39	1.44
H_2O^-	0.02	0.12
H_2O^+	0.43	0.49
P_2O_5	0.17	0.19
Total	100.01	99.92

Chemical analyses (Table 1) and studies of thin sections show that the clasts of the first and the second groups are identical in composition, except for differences in vesicularity, and represent juvenile material of the directed blast. This conclusion is supported by the characteristics of bread-crust bombs that sometimes present in the blast deposits. Their outer carapace is composed of dense andesite of the first group, and the inner core is composed of vesicular andesite of the second group. The third group consists mainly of rock fragments of the old edifice of Bezymianny and represents the accidental (non-juvenile) material of the directed blast.

Table 2 and Fig. 5 present the percentage of dense, vesicular and accidental clasts in each portion of the blast deposits. Dense juvenile andesite (40–72%; average 55%) is the dominant clast type in the blast deposits. Vesicular juvenile andesite (13–45%; average 29%) is the second most numerous group. Thus, in the blast

Table 2 Content (%) of the juvenile and accidental andesite clasts in the blast deposits. Number in brackets is the content of vesicular and dense andesite clasts recalculated to 100% of juvenile material

Deposits	Dense juvenile	Vesicular juvenile	Dense and vesicular	Accidental clasts	No. of samples
Proximal zone					
Layer A	64 (73)	24 (27)	88	12	15
Layer B	53 (66)	27 (34)	80	20	16
Layer C	52 (63)	31 (37)	83	17	17
Average for proximal zone	56 (67)	27 (33)	83	17	48
Distal zone	52 (61)	33 (39)	85	15	11
Valley pond facies	53 (64)	30 (36)	83	17	9
Average for all samples	55 (65)	29 (35)	84	16	68

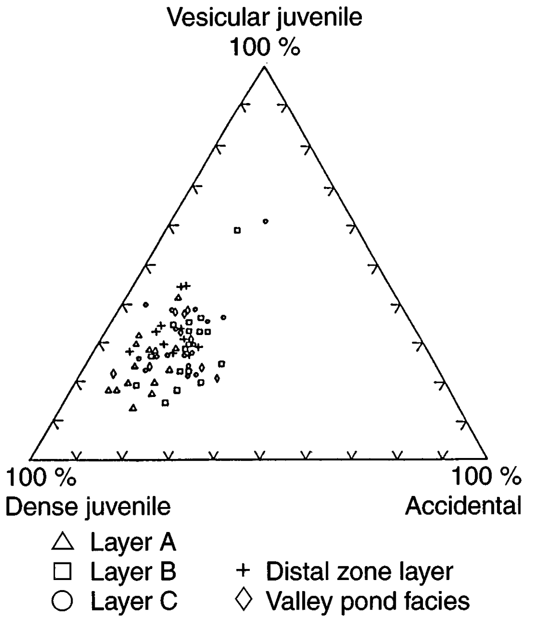


Fig. 5 Percent relationships between vesicular juvenile, dense juvenile and accidental fragments in the directed blast deposits

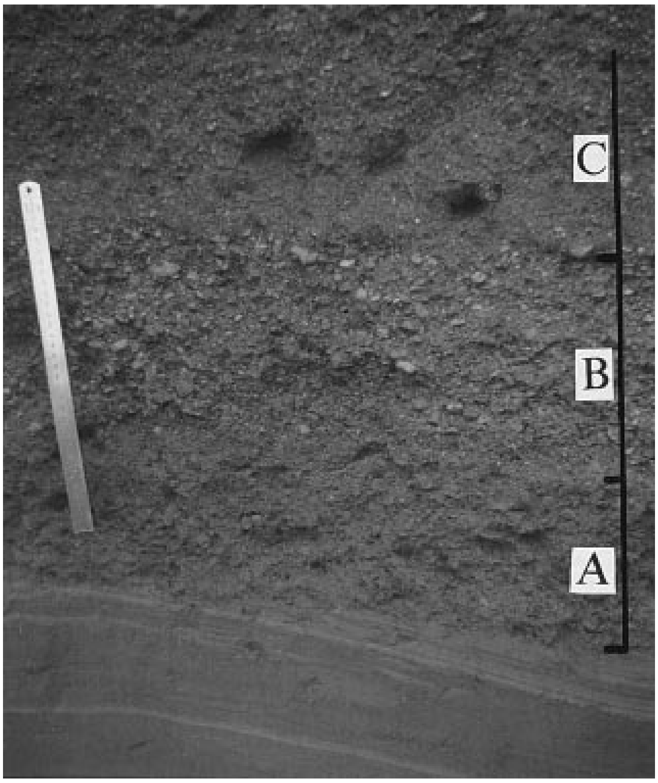


Fig. 6 Directed blast deposits in the proximal zone on preclimactic ash deposits (near the point 17). *Brackets* divide the layers A, B and C. The upper part of the layer C is not shown. Length of the scale is 30 cm

deposits, juvenile material (70–95%; average 84%) is the dominant component. Accidental material makes up 5–30% and averages 16%. Estimates made in the field show that the relations between the clast component groups described above are generally the same for larger fragments as well.

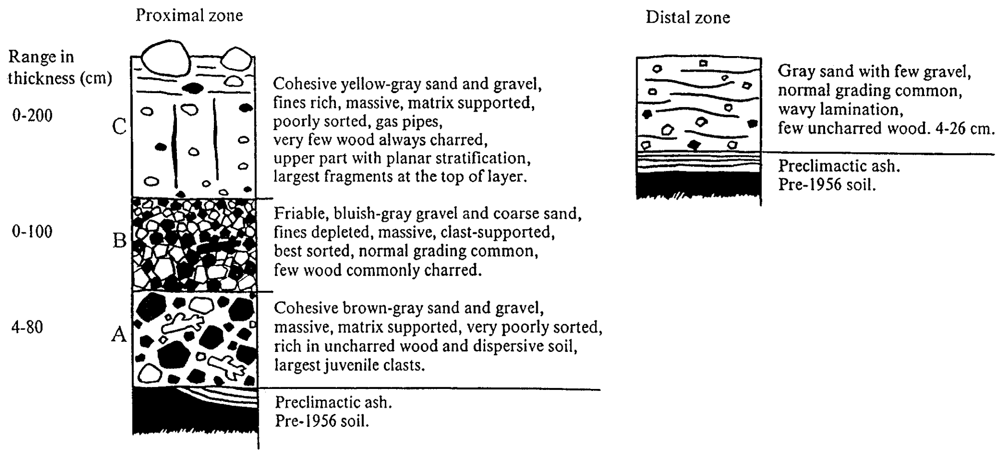
Stratigraphy in the proximal zone

In the area of the proximal zone on uplands three layers have been distinguished in the blast deposits (from the base to the top): layers A, B and C (Figs. 6–8).

Layer A

Layer A usually rests with strongly erosive contact either on the pre-1956 soil or on ashfall deposit from the preclimactic stage of the eruption (Fig. 6). It consists of a very poorly sorted sand–gravel mixture with a small quantity of finer material (Fig. 9; Table 3). The layer is massive, matrix supported and has no grading. The orientation of elongated clasts in the layer is chaotic. A diagnostic feature of this layer is dispersed admixture of soil which gives the whole layer a brown-grey colour. Layer A is characterized by a lower content of accidental material, averaging 12% (Fig. 5; Table 2). In the juvenile material, the content of dense juvenile andesite is high (average 64%), and that of the vesicular

Fig. 7 Composite stratigraphic sections of Bezymianny blast deposits for proximal and distal zones



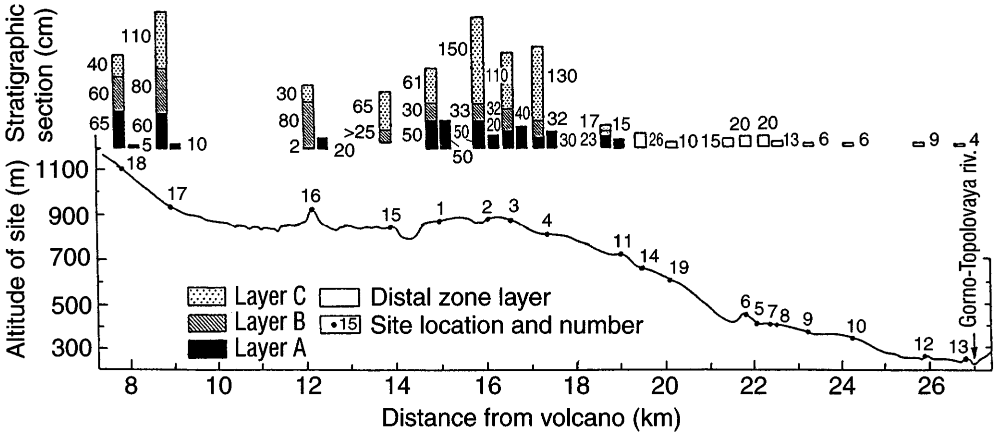


Fig. 8 Topography and stratigraphic sections along profile. For the proximal zone locations it is given two sections: inside the "patches" with layer A, B and C, and between the "patches" (for explanation see text and Fig. 11)

juvenile fragments is low (average 24%). Uncharred plant remnants are admixed in layer A. They are represented by small fragments of fine twigs. In locations where the deposits are thick there can be large branches of bushes.

Amongst layers of the proximal zone, layer A has as a rule the poorest sorting, intermediate values of median diameter and percentage of fine fractions, and contains the largest clasts of juvenile andesite (Table 3).

The thickness of layer A varies locally. On flat, horizontal areas, layer A reaches its maximum thickness (40–60 cm) at a distance of 15–17 km from the volcano (Fig. 10). Near the volcano and at the boundary between the proximal and distal zones the thickness of layer A decreases. In topographic depressions the thickness increases. In ravines it can exceed 2 m.

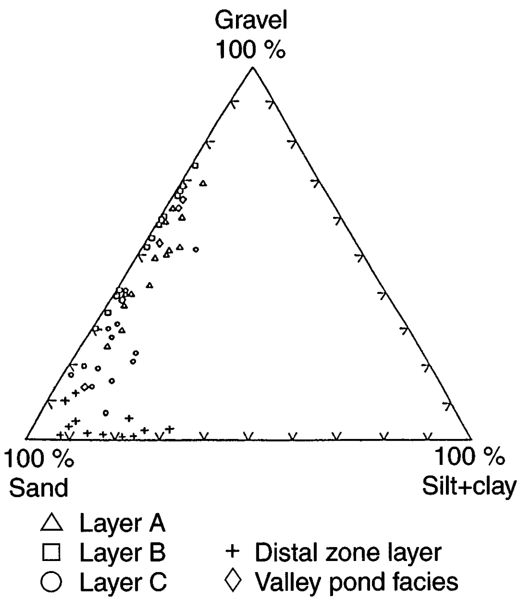


Fig. 9 Percentage of gravel (> -1ϕ), sand (from -1ϕ to $+4\phi$) and silt+clay (< $+4\phi$) in the blast deposits

Layer B

Layer B lies with sharp contact on the surface of layer A. It consists of a mixture of gravel and coarse sand (Fig. 9; Table 3). A very low content of fine fractions is the most typical feature of layer B and gives it an openwork texture with a large amount of void space between the clasts. The colour of layer B is dark-grey with a bluish tint. Layer B shows graded bedding of various types, but normal grading is the most common. Elongated clasts in layer B are often oriented subparallel to the ground surface. Layer B is enriched in accidental material (average 20%; Fig. 5; Table 2). Plant remnants seldom occur in layer B and, when they do, they are usually charred. Among the layers of proximal zone for each given outcrop, layer B has as a rule the best sorting, largest median diameter and lowest percentage of fine fractions (Table 3).

The thickness of layer B varies from several centimetres to several tens of centimetres. These variations have no noticeable correlation with the relief of the underlying surface. The maximum thickness of layer B reaches 1 m near the volcano. It decreases with the distance away from the volcano, and at the boundary between the proximal and distal zones the maximum thickness does not exceed 30 cm (Fig. 10).

Layer C

Layer C forms the uppermost part of the blast deposit section in the proximal zone. It lies on the surface of layer B with a sharp contact. In rare cases the contact may be gradual. Layer C is composed of poorly sorted gravel–sand mixture with an abundant fine fraction (Fig. 9; Table 3). The colour of layer C is light-yellow-grey with a characteristic pink tint, the intensity of which usually increases toward the top of the layer. Most of layer C is massive matrix supported, it commonly shows reverse grading of gravel- to block-sized clasts. Fine (3–10 mm) parallel laminations sometimes occur in the upper 20–30 cm of layer C. This layering is produced by a sequence of sand laminae of slightly dif-

Table 3 Granulometric characteristics of the directed blast deposits. Median diameter and deviation in phi units. Number of samples in parenthesis, the lowest and highest values in braces

	Layer A	Layer B	Layer C	Distal zone	Valley pond facies
Median diameter	−0.5 (13) {−2.9–2.2}	−1.1 (18) {−2.9–1.2}	1.1 (19) {−1.3–2.2}	2.1 (16) {−1.1–3.4}	−0.2 (5) {−2.2–1.6}
Deviation	3.0 (13) {2.4–3.7}	2.3 (18) {1.9–2.9}	2.6 (19) {1.9–3.7}	1.6 (16) {1.1–2.2}	2.6 (5) {2.1–3.1}
F_1 (%)	41.7 (13) {22.8–60.7}	33.1 (18) {11.4–66.8}	64.2 (19) {40.9–83.2}	76.7 (16) {30.0–98.0}	50.9 (5) {36.6–70.4}
F_2 (%)	4.8 (13) {1.7–7.7}	0.5 (18) {0.1–1.3}	6.8 (19) {1.4–14.3}	11.5 (16) {1.6–27.1}	3.6 (5) {1.7–6.4}
Gravel (%)	46.5 (13) {25.6–69.5}	49.6 (18) {20.5–74.0}	24.6 (19) {7.0–52.0}	8.0 (16) {1.0–52.0}	29.0 (5) {5.9–52.5}
Sand (%)	48.7 (13) {25.7–69.4}	49.8 (18) {25.9–76.7}	68.4 (19) {37.4–81.3}	80.5 (16) {46.2–92.0}	67.5 (5) {44.5–87.7}
Maximum size of clasts in layer (cm)	6.5 (6) {3.2–11.0}	5.8 (8) {3.8–5.7}	5.0 (9) {2.1–8.6}	1.6 (11) {0.6–4.8}	
Maximum size of clasts at surface (cm)			15.8 (9) {8.6–21.8}		

ferent grain sizes, and it is marked by larger clasts, the long axes of which are often subparallel to the layering. In the massive part of layer C clast orientation is chaotic. The contact between the laminated and massive parts of layer C is gradual.

The content of juvenile and accidental material in layer C is similar to the average for the proximal zone as a whole and reaches 83 and 17%, accordingly (Fig. 5; Table 2). A higher content of vesicular andesite (average 52%) and a lower content of dense andesite (average 31%) are characteristic for layer C juvenile material. Plant remnants are very rare in layer C and are always charred. Thin vertical degassing pipes sometimes occur in layer C.

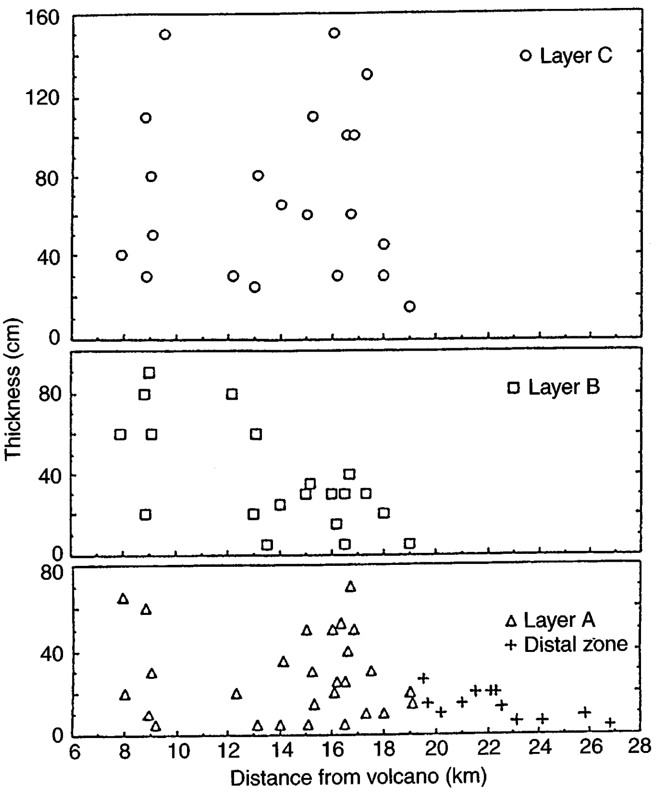


Fig. 10 Thickness of individual layers of the blast deposits vs distance from the volcano along the profile

Among the layers of proximal zone layer C has, as a rule, the intermediate sorting, minimum median diameter and maximum percentage of fine fractions. The dimensions of largest juvenile clasts inside the layer are the minimum in comparison with those of layers A and B . In layer C the size of separate large clasts often increases toward the top of the layer, but sometimes the reverse occurs. A concentration of large juvenile vesicular and dense andesite clasts characterises the surface of layer C (Table 3). Rare individual boulders of pumiceous andesite 0.3–2.0 m in diameter occur among them. These clasts are significantly larger than those inside layers A, B and C. Where layer C is absent concentration of large clasts on the surface of deposits is not observed. The thickness of layer C shows the most variability among the three layers; it varies locally from zero to more than 2 m (Fig. 10). Layer C reaches a maximum thickness in topographic depressions. On flat, horizontal areas the maximum thickness is 60–120 cm. There is no dependence of the thickness on distance from the volcano.

The areal distribution of each of these layers decreases successively from A to C (Fig. 11). Layer A covers practically the whole area of the proximal zone, excluding deep valleys and steep slopes. Layer B forms separate patches or very gently sloping mounds, whose shapes are irregular in plain view, on the surface of layer A. The typical size of the patches is tens to hundreds of metres across. Layer C forms patches of equal or smaller dimension on top of the surface of

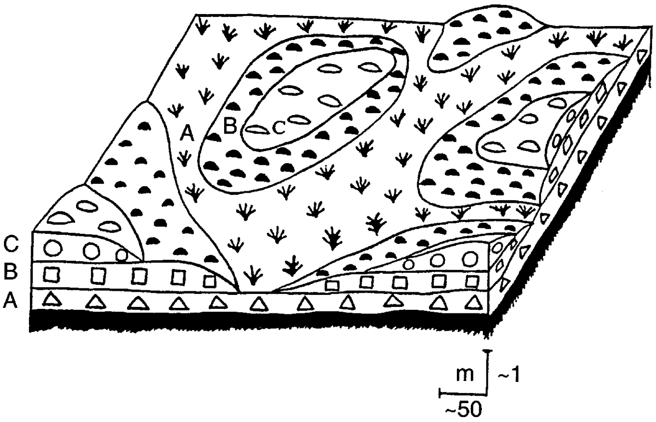


Fig. 11 Sketch showing patchy areal distribution of layers B and C on the surface of layer A

layer B. Areas of the proximal zone where only layer A is present correspond to places of minimum total thickness of the directed blast deposits (Fig. 4). Areas where all three layers are present correspond to points of maximum thickness. There are locations where only layers A and B are present, but layer C is absent. Described patchy emplacement of layers B and C on the surface of layer A is an important characteristic of the stratigraphy of the proximal zone. Observations show that the relationship of layers B and C was formed during the process of deposition and was not the result of later erosion or re-deposition. It was produced by unsteady patchy emplacement of layers B and C.

Variations in the layer A–B–C stratigraphic sequence described above are observed very rarely. At the boundary between the proximal and distal zones it is not easy to single out the separate layers because they may not have their usual character and gradual contact. Part of the anomalies associated with the stratigraphic sequence are related to (very rare) repetition of some stratigraphic layers, e.g. stratigraphy showing layers A–B–A–B–C. Repetition of layers occurs usually in the vicinity of large topographic irregularities. The repetitions are probably the result of deposition from overlapping lobes of the blast cloud which were deflected by topography.

At a distance of approximately 18 km from the volcano, the patches where layers B and C are present become rare, and further from the volcano, they disappear completely. At a distance of approximately 19 km from the volcano, the admixture of soil in layer A disappears and layer A is gradually replaced by the distal zone deposits.

Valley deposits

In large valleys of the proximal zone the character of blast deposits is essentially different from that of the uplands. Two types of valley facies are distinguished: (a) deposits in valleys that begin directly on the east slopes of the volcano, and (b) deposits in valleys situated in the limits of the proximal zone, but separated from the volcano by topographic barriers (valley pond facies).

In the first case the blast deposit overlies the debris avalanche deposit, the formation of which preceded the directed blast. The blast deposit is represented by very coarse gravel–boulder material, which forms a layer with a thickness from tens of centimetres to several metres. In some cases the deposits are composed of fragments of gravel size, but they are always coarser than blast deposit of nearby uplands. No inner stratification is observed in the valley deposits. Plant remains are absent. These valley deposits consist of debris with the same compositional characteristics (clast composition and density) as those on the uplands. Based on visual estimates they are distinguished by a higher content of accidental material, due probably to erosion of the debris avalanche. Component contents have been calculated for one sample as 38% dense juvenile, 37% vesicular juvenile and 25% accidental. Avalanche material is also presented in the blast deposit as rounded inclusions of highly crushed rocks of the volcanic edifice. The dimensions of these inclusions are up to several metres across.

Upwards the blast material is usually covered by the pyroclastic flows of the Plinian stage of the eruption. The contact between the debris avalanche and blast deposits is sharp and very irregular with several metres of amplitude. The blast material sometimes forms "clastic dykes" several tens of centimetres in thickness which penetrate several metres downward into the debris avalanche deposit. The character of the lower contact of the directed blast deposit, the coarse composition and high content of accidental material suggest that the blast deposit was deposited near the volcano on the moving debris avalanche and the two were moved together for some distance.

Deposits of the directed blast have also been found under the debris avalanche deposits in two outcrops at a distance more than 10 km from the volcano. The explanation may be that at approximately 10 km from BZ the blast overran the debris avalanche and their deposition occurred simultaneously.

In narrow deep valleys separated by topographic barriers from the volcano (the second case) the directed blast deposit sometimes forms accumulations up to several tens metres in thickness. These accumulations were named "pyroclastic flows of directed blast" in the work of Bogoyavlenskaya et al (1985). The largest flow was formed in the head of Sukhaya Zimina river. The maximum thickness of the facies reaches 50 m. Granulometric characteristics of valley pond material are similar to those of the blast deposits of the proximal zone (Table 3). Component percentages vary widely (Fig. 5), but on average it corresponds closely to the directed blast deposits in general (Table 2). Remnants of intensively charred vegetation (usually the fragments of bush branches) occur in the valley pond facies. A particular feature is the presence of rounded inclusions of charred soil 1–50 cm in size. Degassing pipes are rare.

In addition to the large valley pond deposits in the head of Sukhaya Zimina river, small flows of the same type were formed in the heads of Yagodny Klutch and Golubelnaya rivers. The main mechanism for accumulation of this valley facies was probably the back flow of directed blast sediment from steep valley slopes. Measurements show that blast material is absent on slopes steeper than 22–24°.

Stratigraphy of the distal zone

The distal zone deposits are composed of grey, fine- to medium-grained sand with admixture of gravel size clasts (Fig. 9; Table 3). The lower part of the layer is usually slightly more coarser (medium-coarse-grained sand). Well preserved, fine-wavy layering was found in one section of the distal zone; in other places it was possibly destroyed by the processes of freeze–thaw and bioturbation.

The proportion of accidental material in these distal zone deposits is a little less (average 15%) than the general proportion for blast deposits (Fig. 5; Table 2). Among the juvenile material fraction, the proportion of vesicular fragments is notably higher than blast deposits in general (average 33%).

Remnants of vegetation in distal zone deposits are not charred. It is difficult to evaluate their initial abundance because the deposits are penetrated by the roots of present-day vegetation.

In the distal zone the directed blast deposits form a continuous blanket, the thickness of which has only small local fluctuations in the range of several centimetres. Valley pond facies is absent in the distal zone. The thickness of the deposits decreases gradually from 26 cm at 18 km from the volcano to less than 4 cm at the outer boundary (Figs. 8 and 10).

The distal zone deposits cannot be determined to be a continuation of any one of the proximal zone layers. Layer A continues into the distal zone deposits spatially, but according to granulometric characteristics and relations between the various groups of fragments, deposits in the distal zone are more closely related to layer C. Distal zone deposit also has the specific feature – fine-wavy layering – which is completely absent in proximal zone deposit.

Variation of granulometric characteristics with increasing distance from vent

On a plot of deviation vs median diameter (Inman coefficients) the directed blast deposits occupy an intermediate area between the fields of airfall and pyroclastic flow deposits (Fig. 12). This position is generally characteristic of pyroclastic surge deposits (Walker 1971). Areas occupied by individual layers are clearly divided. On a plot of F_1(fraction <1 mm) and F_2 (fraction <1/16 mm) relations, the directed blast deposits occupy the area below the area which characterises pyroclastic flows (Fig. 13), which indicates that a significant depletion in fines has occurred.

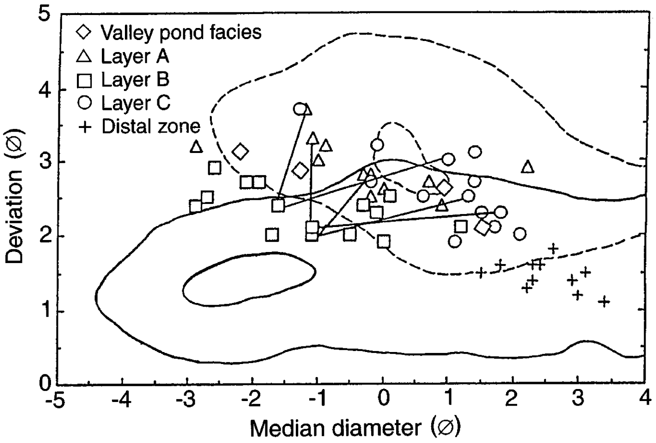


Fig. 12 Relationship between sorting and median diameter (Inman coefficients) for the blast deposits. *Solid lines* connect the cases when all three layers of the proximal zone were sampled from the same outcrop. *Dashed lines* mean pyroclastic-flows area and continuous-airfall area according to Walker (1971; inner contours correspond to maximal points density)

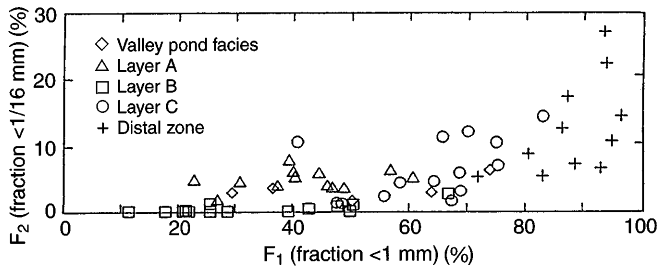


Fig. 13 Relationship between F_1 (fraction <1 mm) and F_2 (fraction <1/16 mm) in the blast deposits

All measured granulometric characteristics show both random local fluctuations, especially significant in the proximal zone, and regular gradual changes due to increasing distance from the volcano (Figs. 14 and 15).

Within the limits of the proximal zone, due to local fluctuations, granulometric characteristics of layers A, B and C change independently and randomly, but general trends of changes are the same for all layers. With increasing distance from the volcano, for every layer median diameters and dimensions of largest juvenile clasts tend to decrease, sorting tends to improve and F_1 (fraction <1 mm) values tend to increase. F_2(fraction <1/16 mm) values in the proximal zone do not change in any regular pattern with distance from the volcano.

Transition to the distal zone marked by sharp jumps of all granulometric characteristics: median diameters decrease, sorting improves, percentages of fine fractions (F_1 and F_2) and dimensions of largest juvenile clasts decrease. Within the limits of the distal zone

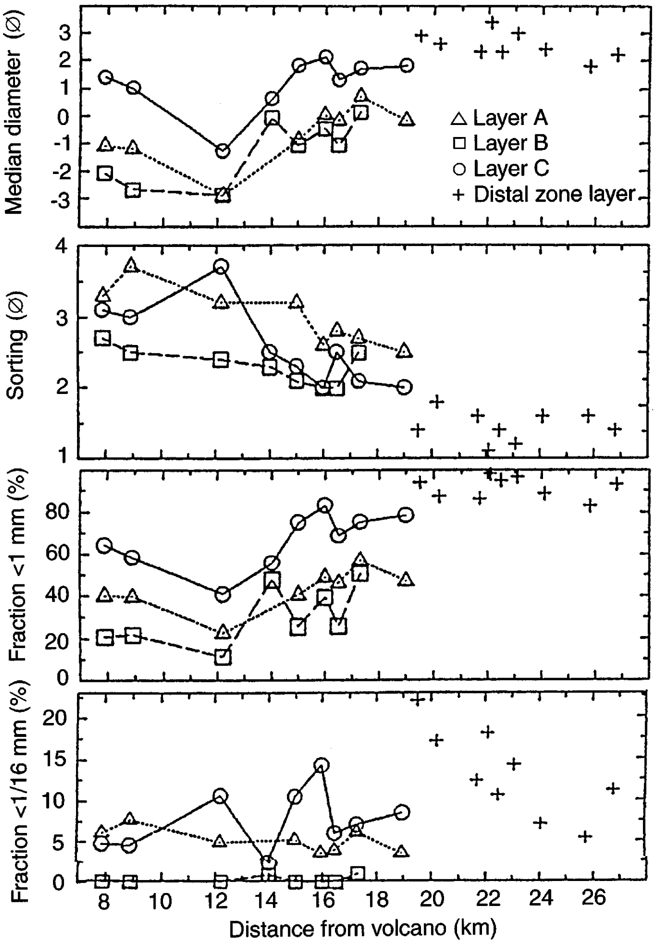


Fig. 14 Granulometric characteristics of directed blast deposits vs distance from the volcano along the profile

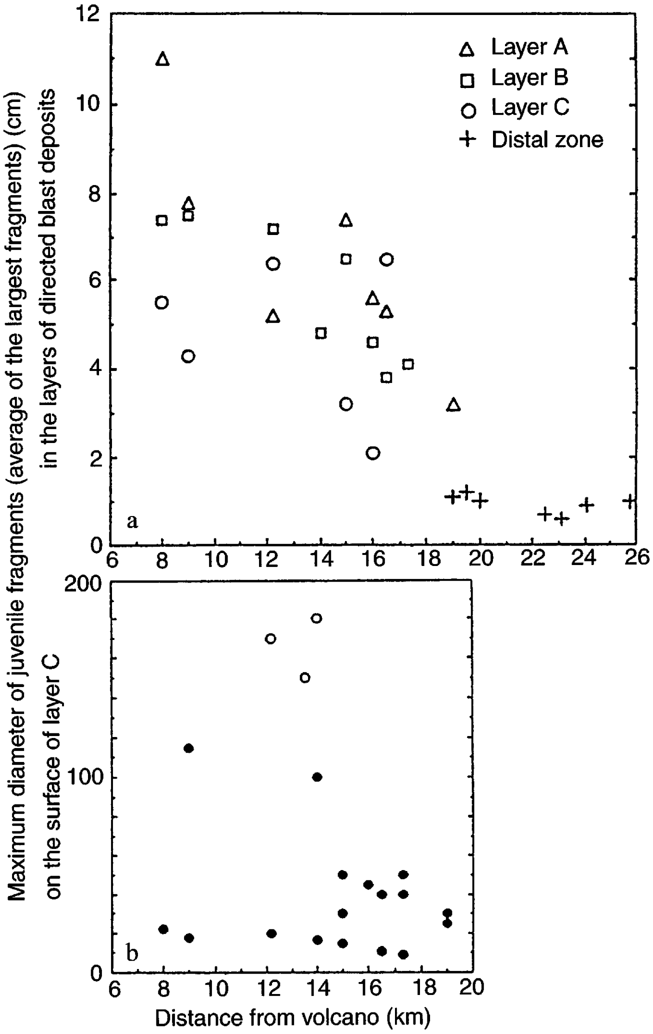


Fig. 15a, b Maximum diameter of juvenile fragments (average of ten largest fragments) **a** in the layers of directed blast deposits vs distance along the profile, and **b** on the surface of layer C vs distance along the profile. *Empty circles* represent anomalously high values in places where measurements were carried out on debris avalanche deposits

granulometric characteristics again begin to change gradually towards the margin of the blast deposits, but their trend is quite different from that of the proximal zone. Median diameter increases, percentages of fine fractions decrease, and sorting and dimensions of largest juvenile clasts remain on a constant level.

Directed blast impact

The flow, in the broad sense of a gas-pyroclastic mixture, formed as a result of the directed blast and affected vegetation and soils both mechanically and thermally in the course of its movement. The area impacted by the blast transects three belts of vegetation: mountain tundra (1700–900 m); alder bushes (900–700 m) and birch forest (700–250 m).

In the zone of tundra (the part of profile 3–10 km from the volcano) all vegetation was carried away by the blast. In the zone of bushes (10–20 km of the profile) a small number of bushes remained but were knocked down in the direction of the flow. Remaining bushes show effects of prolonged abrasion by the blast. At the upper boundary of the birch forest (20 km from the volcano), trees with diameters exceeding 40 cm were knocked down or broken off at a height of approximately 1–1.5 m above the ground. All the trees were killed. At distances greater than 22 km many trees that were bent over or otherwise damaged survived. Directions of bush and tree blowdown show that the blast surge was locally strongly deflected by topography. With increasing distance from the volcano, the average height at which trees were broken off gradually increases. At the outer margin of the profile the majority of trees often have only their tops broken and some large branches remain. In accordance with Gorshkov (1957), a narrow band of the singed forest existed along the boundary affected by blast.

The lower contact of the blast deposit in the proximal zone (contact layer A/ground) shows that before the blast surge began to deposit, it intensively eroded the underlying surface. Over most of the proximal zone, ash of the preclimactic eruption (more than 1 m in thickness) was scraped off and the pre-1956 soil was eroded by the blast to a depth of at least several centimetres. Preclimactic ash remains preserved under the blast deposits only as rare occasional lenses. Erosion of the laminated ash generated "anglular unconformity" below the blast deposit. The material of layer A sometimes forms finger-like dykes in the preclimactic ash.

In the distal zone the base of the blast deposit shows no distinct evidence of erosion. The erosive capacity of the flow was probably insufficient here to destroy the snow cover, which was 2–3 m in thickness. Blast deposits on the snow surface in the distal zone were described by Gorshkov (1957).

The main part of blast deposits in the proximal zone (layers B and C) had temperatures sufficiently high to char entrained vegetation. The degree of charring indicates that the temperature of deposits increased from layer A (uncharred) to layer C (charred intensively). Because the degree of charring changes sharply from one layer to another, this temperature distribution is not the result of cooling post-depositional thermal gradient, but is a reflection of the real temperature distribution at the moment of deposition. The temperature increase from layer A to layer C has no direct correlation with percentage of vesicular juvenile fragments. Firstly, layer A in several cases contains a higher percentage of vesicular fragments than layer C, in conjunction with uncharred vegetation. Secondly, layer A contains the maximum percentage of dense juvenile andesite fragments, which also had high temperatures. Uncharred vegetation in layer A shows that it was deposited from the lowest-temperature part of the flow. It is most likely that it was deposited from the flow head (frontal part), where intensive mixing with air and erosion of the snow cover and underlying surface took place. Despite charring of entrained vegetation in proximal deposits, standing trees and bushes were not charred over the total area affected by the blast. In some places where branches of bushes penetrate through all layers in the deposits, they have been charred only where they are in contact with layers B and C. The distal zone deposits had a temperature insufficient to char vegetation.

Analysis of the impact of the blast allows us to infer that the blast had a great destructive force and eroded the underlying surface. Flow impact was prolonged in duration, but weaker with increased distance from the volcano. Thermal impact can be explained by the absence of temperature equilibrium between hot juvenile clasts and relatively cold gas in the blast cloud. The effective temperature of the gas-pyroclastic mixture was lower than the temperature necessary for charring of standing wood during the time interval of its exposure. Only after deposition could the deposits char wood because of the more prolonged exposure and additional heating on account of the high temperature of inner parts of large fragments.

Comparison with Mount St. Helens

Bezymianny (BZ) blast deposits differ from most known pyroclastic surge deposits. A notable exception is the directed blast deposit from the 18 May 1980 eruption of Mount St. Helens (MSH). The BZ and MSH blast deposits are quite similar in lateral extent, areal volume, thickness, granulometry and stratigraphy. Although their chemical compositions are different (andesite for BZ and dacite for MSH), both exist in dense and vesicular forms (Hoblitt and Harmon 1993). The stratigraphy of MSH blast deposits has been described in many papers (Hoblitt et al. 1981; Moore and Sisson 1981; Waitt 1981; Fisher et al. 1987; Fisher 1990; Druitt 1992), but for comparison herein reliance is placed on two of the most recent papers (Fisher 1990; Druitt 1992). The proximal zones of the MSH and BZ blast deposits both consist of three main layers. The lowest of these is composed of poorly sorted debris containing soil and abundant uncharred fragments of vegetation; the underlying ground surface is strongly eroded. In the MSH example this layer (A0) is heterogeneous – it contains clots of soil and stretched lenses of fine-depleted debris rich in juvenile material (Fisher 1990). In the BZ example this layer (A) is homogeneous – it has no internal stratification and soil is dispersed uniformly. The stratigraphic difference may be due to different ground surface conditions.

The middle layer of the proximal sequence in both examples consists of relatively well-sorted, fines-poor debris, with some partially charred plant fragments. In both examples this layer may display any type of grading (reverse, normal or complex combinations), and the selection of the most common type is difficult. The middle layer at MSH (A1) commonly displays reverse-to-normal grading (Fisher 1990). In contrast, the equivalent layer at BZ (B) commonly displays normal grading. Because of rugged terrain, much of the MSH deposit was emplaced on steep slopes. Fisher (1990) suggested that reverse grading is a secondary feature produced by dispersive forces as material moved downslope after dropping out of the blast surge.

The upper layer of the proximal blast sequence in both examples is poorly sorted, massive and rich in fines. In both examples the upper part of the layer has fine subhorizontal lamination. At MSH the laminations (A2b) tend to be wavy, whereas at BZ the lamination tend to be planar.

Druitt (1992) noted that blast sand waves in MSH proximal zone are commonly associated with surface irregularities. This observation is consistent with the dearth of sand waves at BZ, where vegetation was sparse and the topography was smooth and gentle.

Valley pond facies are present in the deep canyons of the proximal zones at MSH and BZ.

The stratigraphy of distal zones at BZ and MSH is identical. In general, it is one unit composed predominantly of poorly sorted sand with well-developed sand wave laminations, sparse granules and some uncharred wood.

The strong similarity of the BZ and MSH blast deposits suggests that the character of the transporting system and depositional process operating within it were the same in both cases.

Depositional model

Presented now is the model of origin, transportation and deposition for Bezymianny blast deposits. It can probably be applied for MSH also. Coincidence of the areal distribution of layers in the proximal zone, gradual contacts sometimes observed between layers, the transition of proximal deposits to distal ones and the similar compositions of constituent clasts in all layers support the interpretation that blast deposits of BZ were deposited from a single flow.

Origin of blast and pyroclastic surge formation

The high percentage of juvenile clasts, the high temperature of deposits and the presence of bread-crust bombs support a magmatic origin for the directed blast on 30 March 1956.

The andesitic dome and cryptodome, which were formed during the preclimactic stage of the eruption, served as a "charge" for the directed blast. Growth of the dome and cryptodome strongly disturbed the volcanic edifice which lost its stability and failed in an eastern direction. The failure rapidly depressurised the magmatic system of the volcano and caused the blast. The process of explosive destruction of the dome and cryptodome probably occurred in the form of a "disruption wave mechanism" , as proposed by Alidibirov (1994). The resulting blast cloud was denser than the surrounding air and flowed down along the eastern foot of the volcano. The asymmetry of flow propagation was connected firstly with the direction of the explosion, and secondly with the morphology of the volcanic edifice at the moment of the blast. Both of these factors are connected in turn with the failure of the volcanic edifice which preceded the blast.

Immediately near the volcano the flow became internally stratified under ,the influence of gravity into (a) a coarse-grained basal flow of rock fragments which were too heavy to be supported by turbulence, and (b) relatively fine-grained turbulent upper flow. The basal flow moved along the valley of Sukhaya Khapitsa river above and together with the debris avalanche which preceded the blast. The basal flow produced the facies of the blast deposit in valleys which begin directly on the east slopes of the volcano. The upper flow surmounted the walls of river valleys and spread along a wide sector of the eastern foot of the volcano. Its emplacement both in depressions and on uplands, and the fact that intensive sorting of pyroclastic material took place in the flow, allows it to be classified as a pyroclastic surge. Considered below is the depositional process only in this surge, which is referred to as "blast surge" due to its specific origin and stratigraphy. The same term was suggested also for the transport system of MSH blast (Fisher 1990).

The blast surge had a speed of more than 60 m/s at a distance approximately 10 km from the volcano, so that at this distance it overran the debris avalanche. The velocity of debris avalanche (60 m/s) was calculated on the basis of run-up height (Belousov and Bogoyavlenskaya 1988).

Transportation and deposition

Pyroclastic surges are types of sediment gravity flows in which particles are suspended by turbulence or moved along the ground by traction (Fisher and Schmincke 1984). In the proximal zone the carrying capacity of the Bezymianny blast surge was very high and probably near its base there was no well-developed continuous bed load and/or sediment gravity flow(s) with independent flow regime. Near the base of the blast surge only rare very large boulders were transported by rolling and saltation. Under the influence of gravity, particle concentration and the size and percentage of dense clasts increased downwards in the blast surge. The upper part of the flow was enriched in vesicular and fine-grained particles. Gas escaping from the flow also modified this process, resulting in a part of the fine fraction being carried out from the flow in a convective cloud. The lowest layer (A) was deposited continuously from the leading edge (head) of the blast surge (Fig. 16a). Deposition of layers B and C occurred episodically from the blast surge body (patchy distribution). It began in the form of rapid suspended load fallout only when the concentration of particles at the base of the surge reached such a level that it began to suppress turbulence. Areas of suppressed turbulence appeared from time to time near the base of the blast surge body. They existed a short time such as came to rest forming at first layer B and then layer C. Deposition of layer B occurred under more diluted conditions with some residual turbulence. Deposition of layer C occurred under total suppression of turbulence. Action of this process removed the densest and largest clasts from the base of the blast surge. The upper part of the pyroclastic density current, with better sorting and enriched by small and/or vesicular clasts, had the possibility to continue to move. When the concentration of particles in the blast surge became less than some threshold level (approximately 19 km from the volcano) the mode of emplacement process changed qualitatively to traction sedimentation (Fig. 16b), which is common for less energetic surges. Traction sedimentation operated in the distal zone until the moment when the blast surge lost most of its pyroclastic load, became lighter than surrounding air and lifted buoyantly off the ground.

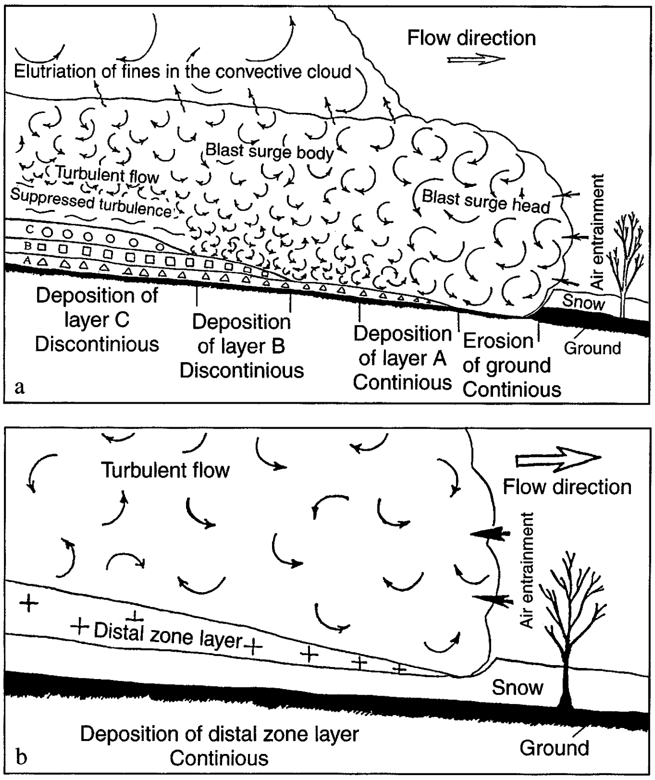


Fig. 16a, b Sketch illustrating behaviour of blast surge and depositional processes in the **a** proximal zone and **b** distal zone. Flow direction is from left to right. Length of *circular arrows* within flow is proportional to intensity of turbulence. Number of arrows is proportional to concentration of particles

Conclusion

The deposits studied herein differ substantially from widely known pyroclastic surge deposits. The absence of internal wavy laminations is characteristic of the deposits of 30 March 1956. Layering of this type is considered to be an important diagnostic feature of pyroclastic surges. Despite this, many facts show that these deposits were emplaced by a highly energetic turbulent pyroclastic surge. The most similar deposits to those described above are the pyroclastic surge deposits of the 18 May 1980 eruption of Mount St. Helens.

The similarity of deposits in both cases is apparently related to their formation from powerful directed blast provoked by volcanic edifice failure. The high density of fragments in the deposits corresponds to the peculiar material conditions which result from explosive destruction of the partially crystallised, highly viscous melt of an intra-crater dome and/or cryptodome. Pyroclastic surge formed under these conditions involve a set of parameters (volume, concentration and granulometry of clasts, as well as their temperature, etc.) in which the processes of deposition in the proximal zone are qualitatively different from those in less-energetic types of pyroclastic surges. The sharp boundary between a proximal zone where the deposits were formed by rapid suspended-load fallout and a distal zone with traction sedimentation is the evidence that for surges there is a threshold of particle concentration which determine the type of sedimentation. The strong similarities between the eruptions of Bezymianny and Mount St. Helens, and the close similarities of the resulting deposits, suggest that we are dealing with a general natural phenomenon. The peculiar character of the formation and unique attributes of these pyroclastic surge deposits allow them to be singled out as a separate type of pyroclastic surge: blast surge.

Acknowledgements I am very grateful to GE Bogoyavlenskaya, YuB Slezin, OA Braitseva, IV Melekestsev, VYu Kirianov and MA Alidibirov for some useful comments and discussion of this work. The author expresses special gratitude to MG Belousova for her assistance in field work and laboratory treatment of the data. I am very grateful to CD Miller and RV Hoblitt for improvements to the English translation. Comments by the editor (TH Druitt) helped to improve the manuscript. The research described in this publication was made possible in part by grant RMF000 from the International Science Foundation.

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