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# The Distribution of Tephra Deposits and Reconstructing the Parameters of 1973 Eruption on Tyatya Volcano, Kunashir I., Kuril Islands

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**Abstract**—We studied the distribution of tephra deposits discharged by the basaltic (52–54% $SiO_2$) explosive eruption of 1973 on Tyatya Volcano (Kunashir I., Kuril Islands). We made maps showing lines of equal tephra thickness (isopachs) and lines of maximum size of pyroclastic particles (isopleths). These data were used to find the parameters of explosive activity using the standard techniques for each of the two phases of this eruption separately. The first, phreatomagmatic, phase discharged 0.008 $km^3$ of tephra during the generation of maars on the volcano's northern slope. The tephra mostly consisted of fragmented host rocks with admixtures of fragments of low vesiculated juvenile basalt. The phase lasted 20 hours, the rate of pyroclastic discharge was $2 \times 10^5$ kg/s; the eruptive plume reached heights of 4–6 km with wind speeds within 10 m/s. The second, magmatic, phase discharged 0.07 $km^3$ of tephra during the generation of the Otvazhnyi scoria cone on the volcano's southeastern slope. The tephra mostly consisted of juvenile basaltic scoria. The highly explosive Plinian part of this phase lasted 36 hours, the rate of pyroclastic discharge was $8 \times 10^5$ kg/s; the eruptive plume reached heights of 6–8 km with wind speeds of 10–20 m/s. The total tephra volume discharged by the eruption was approximately 0.08 $km^3$; the total amount of ejected pyroclastic material (including the resulting monogenic edifices) was 0.11 $km^3$; the volume of erupted magma was 0.05 $km^3$ (the conversion was based on 2800 $kg/m^3$ density); the volcanic explosivity index, or VEI, was 3. The production rate of the Tyatya plumbing system is estimated as $3 \times 10^5$ $m^3$ magma per annum.

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## INTRODUCTION

Tephra is pyroclastic material that is deposited from a floating/drifting (in the atmosphere) plume due to a volcanic eruption (Thorarinsson, 1981; Bonadonna et al., 2015). The size of tephra particles may be anything, ranging from ash to lapilli or still larger. The parameters that characterize the distribution of tephra over an area (e.g., the variation of tephra layer thickness and particle size with varying distance from the vent) provide important information from which to judge about the responsible explosive eruption. There are algorithms that can make use of the above data to find the total volume of ejected tephra, eruption duration, the discharge of pyroclastic material per unit time, the maximum height of the eruptive plume, the wind speed at the plume height, and others (Williams, 1983; Carey and Sparks, 1986; Wilson and Walker, 1987; Pyle, 1989; Fierstein and Nathenson, 1992; Sparks et al., 1997). These data are also used to find the volcanic explosivity index, or VEI, which characterizes the relative magnitude of an eruption (Newhall and Self, 1982). Tephra layers are well preserved in geologic sections (e.g., in soil), providing material for reconstructing past eruptions. Maps of lines of equal tephra thickness (isopachs) make the basis for zoning of volcanic hazard.

The mostly basaltic and basaltic andesite Tyatya stratovolcano (the absolute altitude is 1822 m) is the second highest volcano on the Kuril Islands and the highest point on Kunashir Island (Fig. 1).

G.S. Gorshkov (1967) made the first detailed description of the morphology and geologic structure of the volcanic edifice; the volcano is considered a most beautiful structure worldwide. It erupted in 1812 and 1973 (Gushchenko, 1979). The 1812 eruption was comparatively weak. It was accompanied by ejections of "black smoke" from the summit and probably by effusion of a small lava flow (Gushchenko, 1979; Nak-

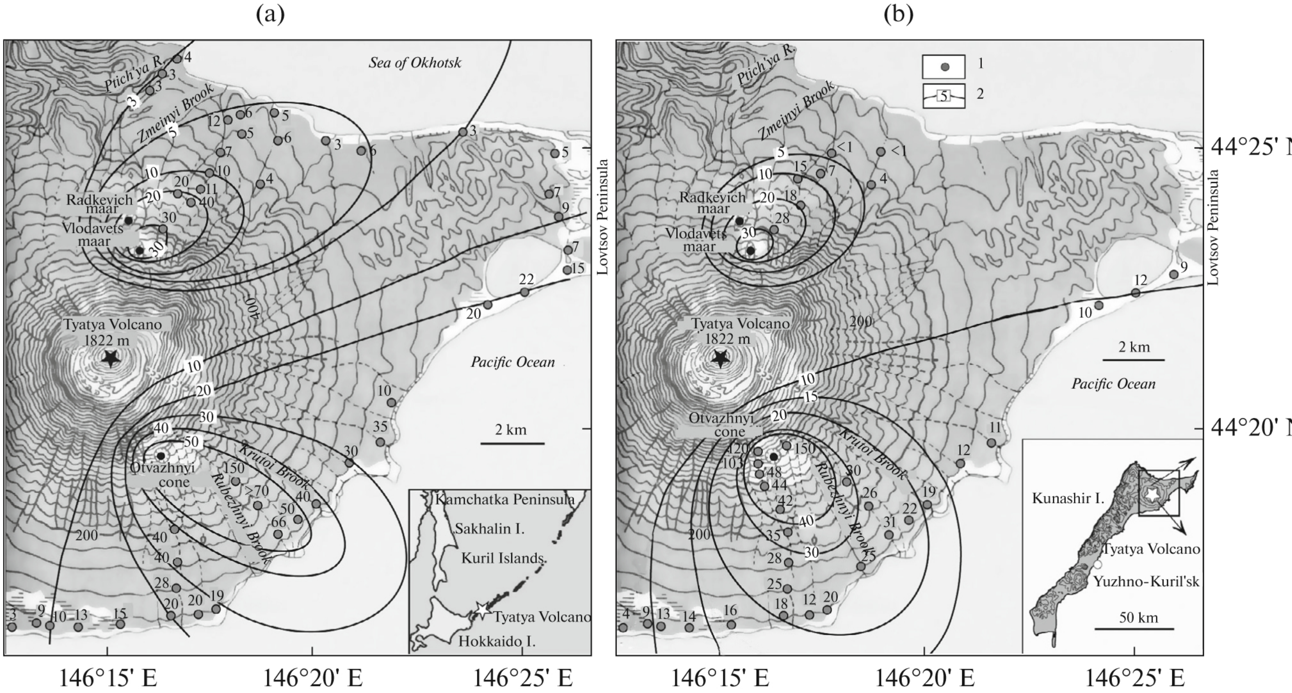


**Fig. 1.** Deposits of maar tephra and Otvazhnyi tephra due to the 1973 eruption of Tyatya Volcano.
(a) isopachs (in cm), (b) isopleths (in mm).
(1) measurement sites, (2) values at isolines. The insets show (a) the location of Tyatya Volcano at the Kuril arc, (b) the area of study on Kunashir I. and the directions of the principal axes for the 1973 ashfalls.

agawa et al., 2002). The parasitic explosive eruption of 1973 was a significant historical eruption on the Kuril Islands and is comparatively well studied (Markhinin et al., 1974, 1979; Maleev, 1976; Nakagawa et al., 2002).

Although there are several papers devoted to the 1973 eruption of Tyatya, the information on the dynamics of its explosive activity and the distribution of tephra over the island is far from satisfactory. This state of knowledge stems from the fact that the observations were few, and because the eruption itself was complex in character. It occurred successively from two eruptive centers that were formed on the opposite slopes of the volcano.

The goal of the present study is to reconstruct the dynamics of the volcano's explosive activity during the 1973 eruption. To do this we studied the distribution of tephra over the island; the tephra makes over 95% of the total pyroclastic volume discharged by the eruption (less than 5% consists of large pyroclastic fragments that were hurled along ballistic paths). A walking tour around the northern part of Kunashir Island lasted many days. The observations involved systematic measurements of layer thickness and maximum particle size of tephra. This allowed us to make maps of isopachs and isopleths separately for the eruption centers on the northern and the southeastern slope of the volcano. These data were used to find parameters of explosive activity for this eruption using the standard techniques.

## THE 1973 TYATYA ERUPTION

The substantially truncated cone of Tyatya stratovolcano stands at approximately 1400 m above sea level with its summit caldera 2 km across. The caldera is completely filled with lava and pyroclastic material due to post-caldera eruptions, which also make an intra-caldera cone whose relative height is 400 m. The cone summit has two coalesced craters 150 m and 200 m in diameter. The slopes of the pre-caldera edifice contain several cinder cones and maars due to pre-historical parasitic eruptions (Gorshkov, 1967).

The evolution of the 1973 eruption was described in (Markhinin et al., 1974, 1979; Maleev, 1976; Nakagawa et al., 2002). The eruption took place on the slopes of the pre-caldera part of the volcanic edifice (it was a parasitic event) and was characterized by purely explosive activity lasting 14 days. The explosions started on July 14 on the northern slope of the volcano at altitudes of 400–550 m and produced two small maars (which received the names of Vlodavets and Radkevich). There are virtually no descriptions of maar eruption, because a strong ashfall made any visual observation impossible. This first phase of the eruption lasted a few hours only; the volume of discharged pyroclastics was estimated to be $7 \times 10^6$ $m^3$ (Markhinin et al., 1974).

The explosive activity continued on the opposite, southeastern, slope of the volcano on July 15, where two explosive vents were opened at altitudes of 500–700 m (the second eruption phase). According to visual observation, the eruptive plume reached a height of 8 km on July 15. The frequency and violence of the discharges from these vents gradually subsided, and the eruption ceased altogether on July 28. The activity of the vents on the southeastern slope produced the Otvazhnyi cinder cone as high as 100 m (for simplicity of description we treat a small cinder cone that E.K. Markhinin named *Pogranichnik* as part of the Otvazhnyi cone). The Otvazhnyi summit crater was 570 m in diameter and its maximum depth was 100 m. The volume of the pyroclastic material that has been discharged during the second eruption phase was estimated to be 0.2 $km^3$ (Markhinin et al., 1974).

The total volume of the pyroclastic material ejected by the eruption was estimated to be 0.2–0.25 $km^3$ (Markhinin et al., 1974; Maleev, 1976). The juvenile material due to this eruption consists of basalts and basaltic andesites (referred to as simply "basalt" below) with concentrations of $SiO_2$ 52–54% (Markhinin et al., 1974; Nakagawa et al., 2002).

## TEPHRA CHARACTERISTICS AND ITS AREAL DISTRIBUTION

The 1973 tephra makes a clear-cut, easily detectable, dark-grey layer in the topmost part of the soil–pyroclastic cover in the northern Kunashir Island (the tephra is overlain by a 6-cm-thick duff). The areas of occurrence and the characteristics of the tephras erupted onto the northern and the southeastern slope of the volcano differ appreciably.

The tephra that was discharged by the vents on the northern slope (by the Vlodavets and Radkevich maars) during the first eruption phase is typically dominated by host rock fragments and has a low concentration of juvenile basalt particles, which have a density of 1760 $kg/m^3$ and a vesicularity of 37% as determined using the method of Hoblitt and Harmon (1993). The grain-size distribution of the maar tephra has a high content of fine fractions and poor sorting (Figs. 2 and 3). The sorting–median diameter plot (see Fig. 3) shows the maar pyroclastics reside in the Surtseyan type field after (Walker and Croasdale, 1972). The characteristics of this pyroclastic material show that the mechanism of explosive activity was phreatomagmatic during the first eruption phase (magma fragmentation occurred on coming in contact with ground water).

The tephra that was discharged during the second phase (by the Otvazhnyi cinder cone) largely consists of particles of juvenile basalt, which have an appreciably greater vesicularity than the juvenile particles of maar pyroclastics. The grain-size distribution of this tephra typically shows a low concentration of finer fractions (see Figs. 2 and 3). These tephra characteristics show that the mechanism of explosive activity during the second eruption phase was largely magmatic (magma fragmentation was caused by vesiculation due to release of dissolved volatiles).

The deposits of the tephra that was discharged by the maars during the first eruption phase are found on the Sea-of-Okhotsk coast of the island; the ashfall axis was northeastward. On the coast the maar tephra layer is the thickest to the east of the mouth of Zmeinyi Brook, rapidly thinning out along the shoreline westward to the mouth of Ptichii Brook, and to the east toward the Lovtsov Peninsula (see Fig. 1a). The tephra deposits rapidly wedge out above the maars on the Tyatya slope.

The tephra that was discharged by the vents on the southeastern slope during the second eruption phase was deposited on the Pacific coast of the island (see Fig. 1). Overall, this tephra is the thickest between Rubezhnyi and Krutoi Brooks, with the thickness rapidly decreasing along the shoreline westward, toward the mouth of the Tyatinka River, the decrease being much slower northeastward, to the Lovtsov Peninsula (see Fig. 1a). The tephra is 5 to 9 cm thick at the isthmus of the Lovtsov Peninsula. The deposits rapidly wedge out above the Otvazhnyi cone on the Tyatya slope. The ashfall axis was southeastward. The isopachs and isopleths of the tephra discharged by the vents on the southeastern slope are not axisymmetrical, because the axis changed its direction during the second eruption phase from eastward to southeastward (because of wind direction change).

The tephra discharged by the Otvazhnyi cone lies in two distinct layers whose materials and areal extents are somewhat different (the section is described in detail by Nakagawa et al. (2002)). The juvenile particles in the lower layer are subject to lower vesiculation; the layer was deposited when the Otvazhnyi just began its activity. Magma fragmentation during this period might occur both by vesiculation as volatiles were released and could also result from contact with underground water (when phreatomagmatic fragmentation was giving way to magmatic fragmentation). The axis of that ashfall was eastward. The upper layer has larger particles and consists of high-vesiculated particles of basaltic scoria; it was deposited later on, when the Otvazhnyi cone activity became pure magmatic. The axis of that ashfall was southeastward.

## THE PARAMETERS OF TEPHRA DISTRIBUTION; RECONSTRUCTION OF ERUPTION PARAMETERS

The parameters of tephra deposits and the eruption characteristics for eruptions of the maars and the Otvazhnyi cone are collected in table. The method for

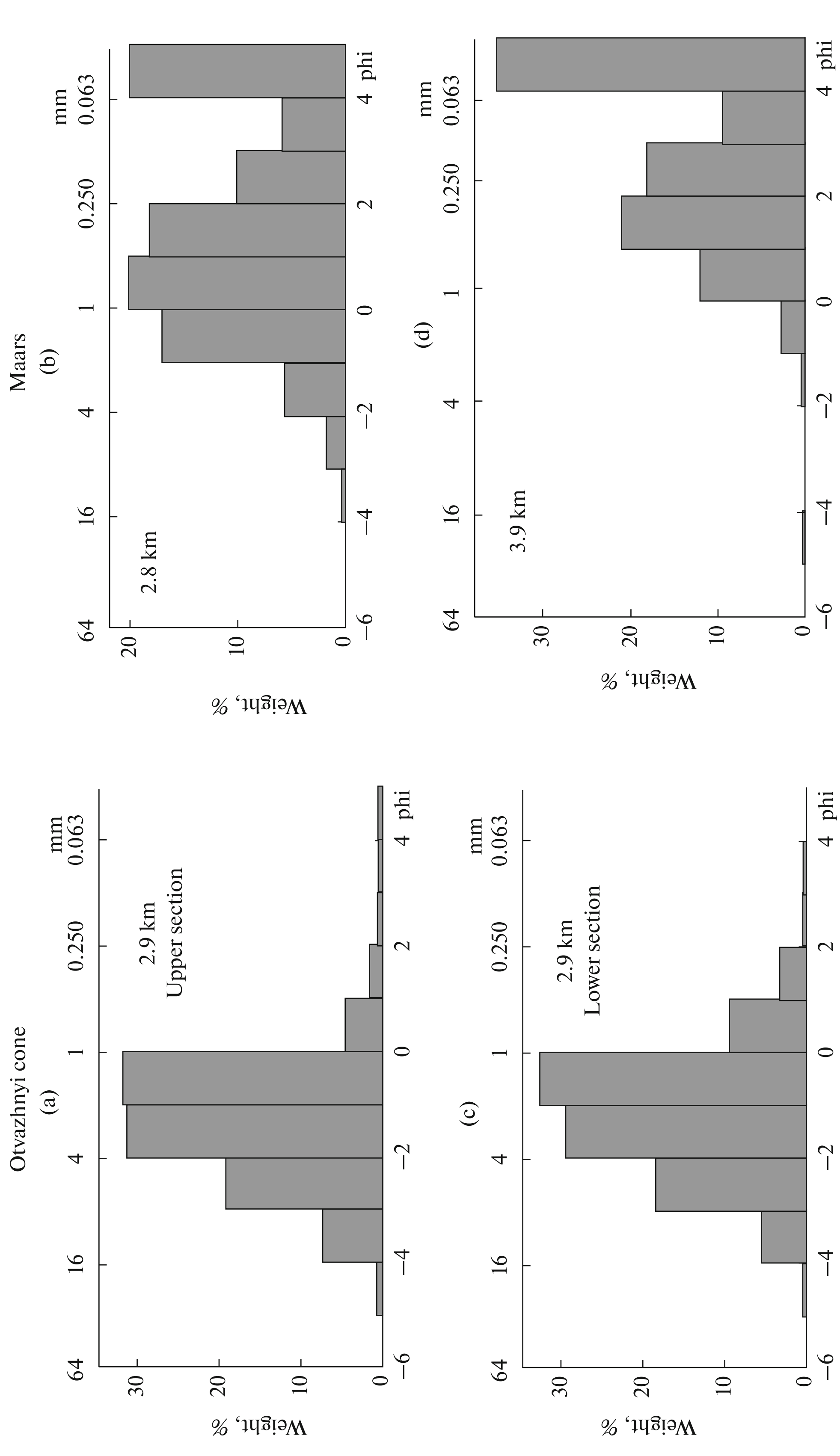


**Fig. 2.** Sample histograms of the 1973 tephra grain-size distribution. The Otvazhnyi tephra was sampled from one section at a distance of 2.9 km, the maar tephra was sampled at two sites at distances of 2.8 and 3.9 km.
The distances are from the respective vents. The grain size at the horizontal axes is on two scales: in millimeters and in the phi units (phi = $-\log_2$ mm).

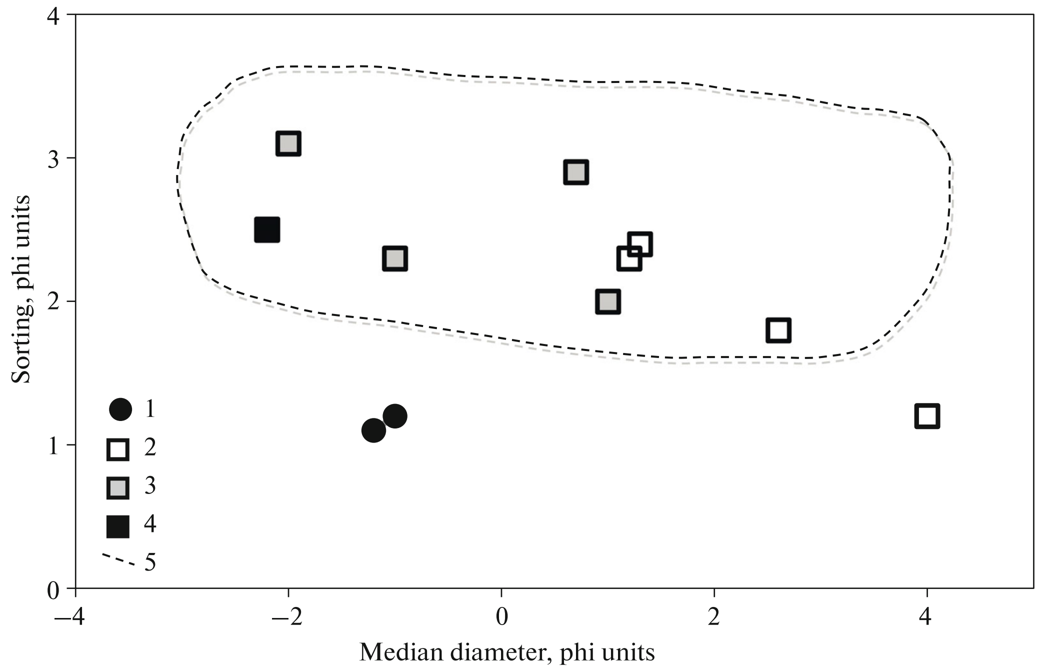


**Fig. 3.** The relationship between sorting and median diameter, the parameters are after (Inman, 1952; Walker, 1971). (1) Otvazhnyi tephra at 2.9 km distance; (2) maar tephra at distances of 2.2–5.4 km; (3) tephra sampled from the rim of the Vlodavets maar; (4) tephra sampled from the rim of the Radkevich maar; (5) area of Surtseyan type deposits, after (Walker and Croasdale, 1972). The distances are from the respective vents. For the relationship between the phi unit and millimeters see Fig. 2.

calculating the parameters and the calculation algorithms are described in the Appendix. The layer thicknesses and the maximum size of tephra particles erupted by the maars and by the Otvazhnyi cone decay exponentially along the ashfall axes as one moves away from the respective eruption centers (Figs. 4 and 5). The maximum extrapolated tephra particle sizes at the source ($M_0$) are identical for the maars and the Otvazhnyi cone. The maximum extrapolated thickness of tephra layers at the source ($T_0$) is smaller than that for the Otvazhnyi cone by two times (38 and 80 cm, respectively). The tephra thickness and the maximum particle size for the maars decay faster as one moves away from the eruption center compared with the behavior for the Otvazhnyi tephra (as appears from the relationships among $b_t$, $k_t$, $b_c$, and $k_c$).

Tephra volumes (see table) were found following the method of J. Fierstein and M. Nathenson (1992). Since the volcano stands on an island, it has not been feasible to study more distant tephra. This circumstance, combined with the method itself, impose restrictions on the accuracy of volume calculation (see the Appendix). The resulting volumes of erupted tephra are to be treated as the minimum values.

## RESULTS AND DISCUSSION

The above mapping resulted in the first-ever isopachs and isopleths for the tephra deposits, separately for the two phases of the 1973 eruption of Tyatya Volcano, while advanced methods allowed calculation of parameters that characterize the respective explosive activities.

Calculations showed that the maars that were formed on the northern slope of Tyatya Volcano during the first eruption phase have discharged 0.008 km$^3$ of tephra with a mean discharge of pyroclastic material being $2 \times 10^5$ kg/s. This tephra largely consists of host rock fragments, so that the amount of fresh magmatic material ejected by these vents is insignificant. The height of the eruptive plume during the maar formation reached 4–6 km with wind speeds below 10 m/s; the ashfall axis was northeastward. The eruption was phreatomagmatic during this phase; the eruptive plume was relatively cold and contained much steam. For this reason the plume was at a low height and could not transport much pyroclastic material, manifesting itself in a rapid decrease of layer thickness and tephra particle size with increasing distance from the eruption center (see Fig. 5). Steam condensation in the plume made finer ash particles to coalesce and fall down along with coarser fractions, resulting in a bimodality of the grain-size distribution and low sorting of maar tephra (see Figs. 2 and 3). We estimate that the explosive activity lasted approximately 20 hours, and this estimate is corroborated by visual observations showing that the maars ceased activity during the first day of the eruption.

The bulk of tephra (0.07 km$^3$) was discharged during the second phase by the vents on the southeast-

**Table 1.** The parameters of tephra deposits and parameters of the 1973 eruption on Tyatya Volcano based on these

| Parameters of tephra deposits | Maars | Otvazhnyi cone | Method of calculation |
|---|---|---|---|
| $T_0$: maximum extrapolated tephra thickness at the source, m | 0.38 | 0.8 | (Pyle, 1989) |
| $b_t$: the value of $A^{1/2}$ at which $T_0$ is diminished by two times, km | 2 | 4.7 | " |
| $k_t$: slope of plot in Fig. 5a | –0.33 | –0.15 | " |
| $M_0$: maximum extrapolated size of clasts in crater, cm | 6 | 6.1 | " |
| $b_c$: the value of $A^{1/2}$ at which $M_0$ is diminished by two times, km | 1.2 | 3.6 | " |
| $k_c$: slope of plot in Fig. 5b | –0.66 | –0.17 | " |
| $b_c/b_t$ | 0.6 | 0.77 | " |
| $\alpha_t$:“ellipticity” of isopachs | 0.68 | 0.5 | " |
| $\alpha_c$: “ellipticity” of isopleths | 0.76 | 0.85 | " |
| Eruption parameters | | | |
| $H_m$: max. height of eruption plume, km | 4-6 | 6-8 | (Carey and Sparks, 1986; Sparks et al., 1997) |
| $v$: wind speed, m/s | 0–10 | 10–20 | " |
| $R$: discharge of pyroclastics, kg/s | $2 \times 10^5$ | $8 \times 10^5$ | (Wilson and Walker, 1987) |
| Eruption duration, h | 20 | 36 | see Appendix |
| $V$: volume of erupted tephra, km$^3$ | 0.008 | 0.07 | (Fiersteinand Nathenson, 1992) |
| $V_{DRE}$: volume of erupted magma, km$^3$ | –* | 0.05 | see Appendix |

The heights of eruptive plumes are relative to sea level. Explanations for the determination of parameters and reconstruction method see in main text and in the Appendix. The volumes of erupted tephra indicated here do not include the volumes of monogenic eruption structures themselves (Vlodavets and Radkevich maars and Otvazhnyi cone).

* Maar tephra contains little juvenile material, hence the volume of erupted magma is low.

ern slope, which were formed on July 15, 1973. Judging from visual observations, the height of the eruptive plume was at the maximum during that day (8 km), with the eruption vigor gradually subsiding afterwards. This is in agreement with our data which show the maximum plume height in the range 6–8 km. The parameter $b_c$, which characterizes the rate at which the thickness of that tephra layer decreases with distance, is above 3, which is characteristic for sub-Plinian eruptions (Pyle, 1989). Our calculations showed that the highly explosive sub-Plinian (second) phase lasted 36 hours, with the mean discharge of pyroclastic material being $8 \times 10^5$ kg/s. The ashfall axis was at first eastward; the wind changed direction subsequently during the sub-Plinian phase, and the axis turned to point southeast. Obviously, the eruption vigor became so low after this that the ejected pyroclastics was not transported far beyond the foot of the Otvazhnyi cinder cone (the eruption became Strombolian, and this lasted until July 28).

The total volume of pyroclastic material discharged by the vents on the southeastern slope during the second eruption phase is a sum of the pyroclastic volume due to the Otvazhnyi cone itself (approximately 0.03 km$^3$) and the pyroclastics that was borne by the wind as tephra (0.07 km$^3$), i.e., amounts to approximately 0.1 km$^3$. These pyroclastics mostly consist of particles of juvenile basalt. Assuming the mean volumetric weight of the pyroclastics to be 1300 kg/m$^3$ (Markhinin et al., 1974) and the volumetric weight of basaltic and basaltic andesite magma to be 2800 kg/m$^3$ (Stolper and Walker, 1980), we find that the volume of magma ejected during the second eruption phase would be 0.05 km$^3$. Since the vents on the northern slope (the maars) mostly discharged fragmented material of host rocks, it follows that the above value is approximately the amount of magma discharged by the entire eruption.

The total amount of the 1973 tephra as found here turned out to be approximately 0.08 km$^3$ (the total volume of discharged pyroclastic material together with the volume of the maar and Otvazhnyi edifices is approximately 0.11 km$^3$), which is twice as small as the previous estimates (Markhinin et al., 1974, 1979; Maleev, 1976; Nakagawa et al., 2002). The volcanic explosivity index (VEI) for this eruption is 3. Assuming that the amount of magma that came to the surface in

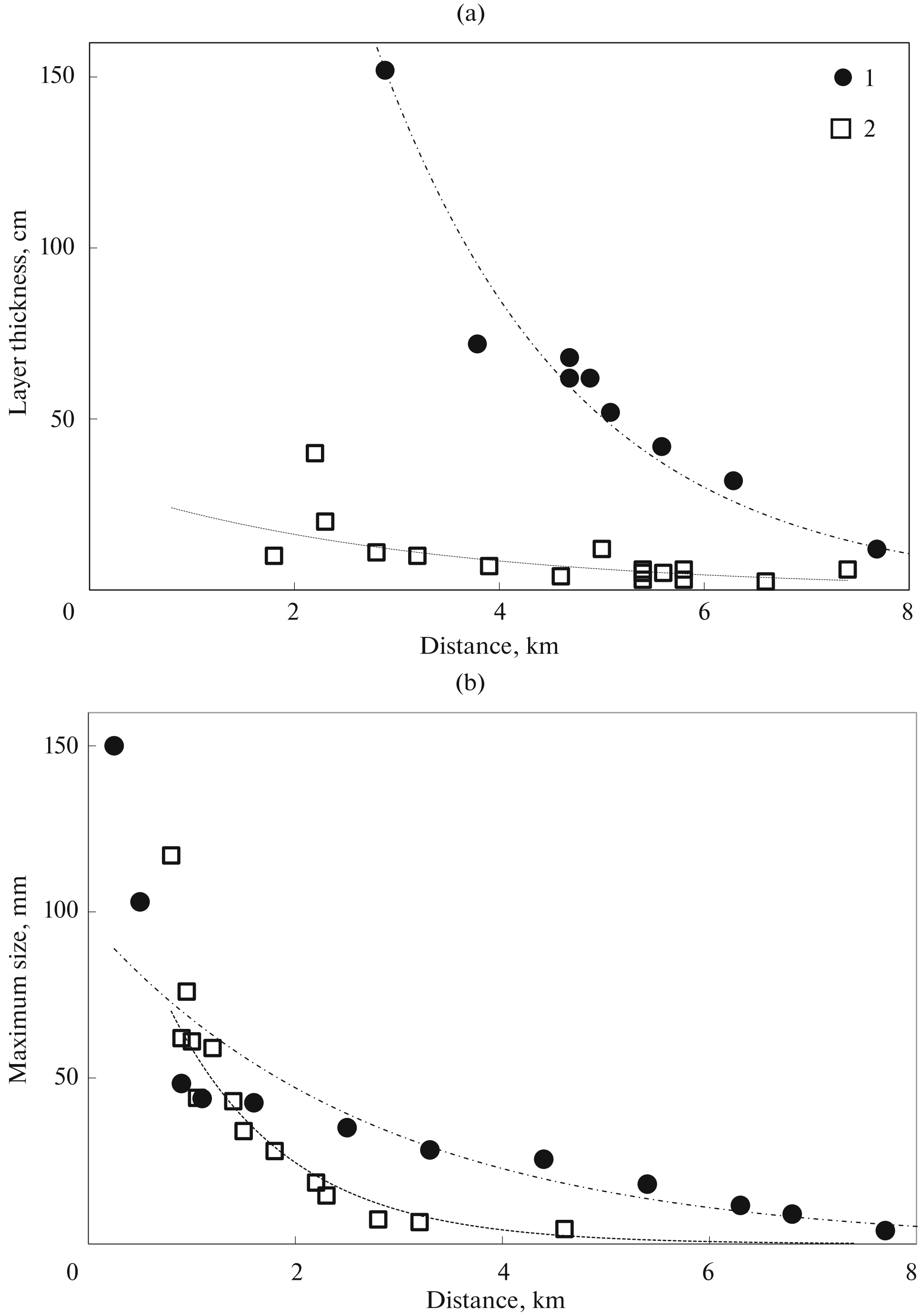


**Fig. 4.** The variation in tephra parameters along ashfall axes with increasing distance from the respective vents.
(a) tephra thickness, (b) maximum size of tephra particles.
(1) Otvazhnyi cone, (2) Vlodavets and Radkevich maars.
The maximum particle size was found as the mean of the maximum sizes of 10 largest particles found in a tephra section.

1973 (0.05 $km^3$) had been accumulating in the plumbing system during the 160 years that had elapsed since the preceding eruption of 1812, we find that the productivity rate of Tyatya Volcano is $3 \times 10^5$ $m^3$ per annum.

Considered in the context of the historical eruptions on the Kuril Islands, the eruption of the Otvazhnyi cone is similar to the 1853 and 1986 eruptions of Chikurachki Volcano on Paramushir Island

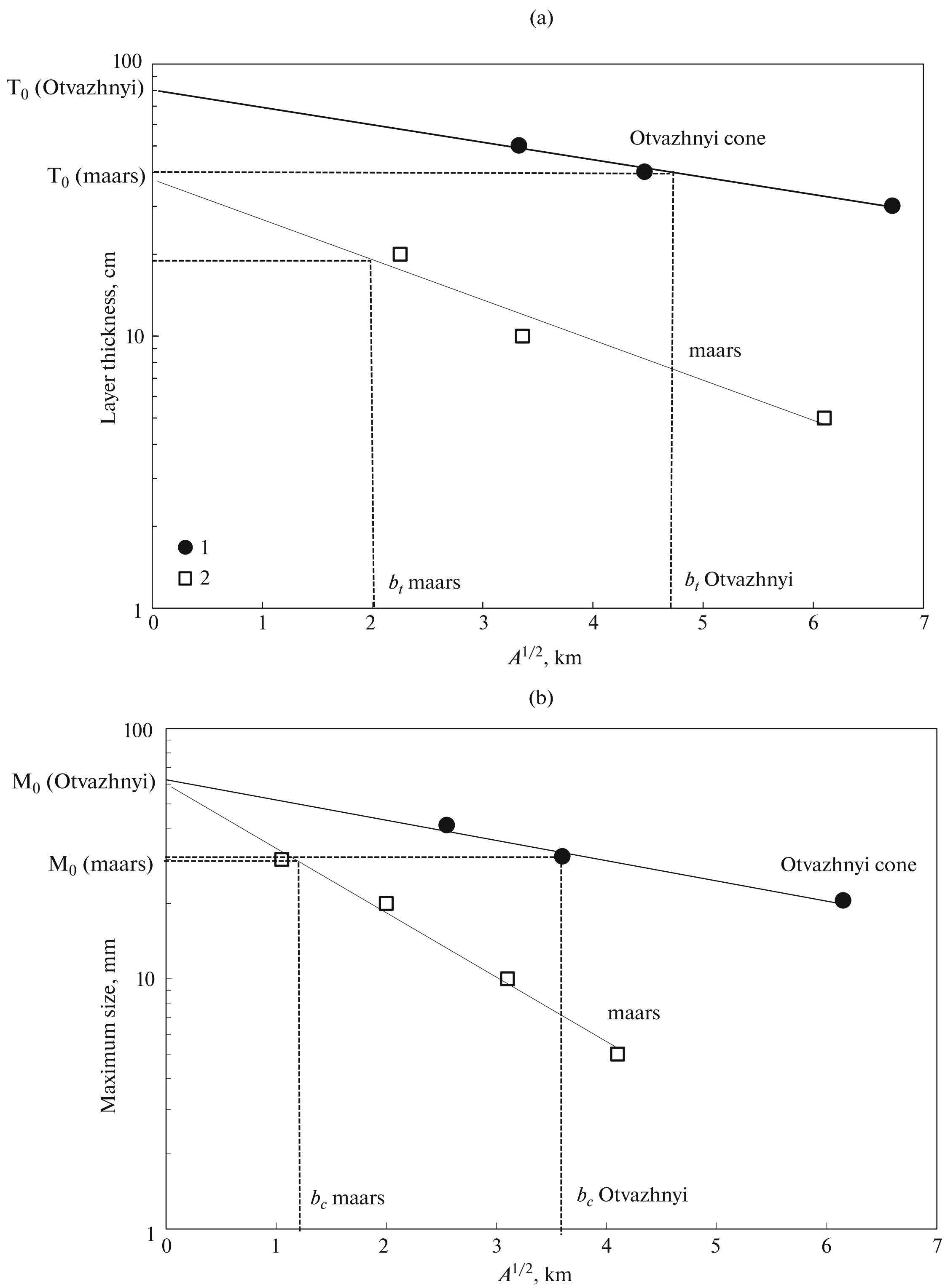


**Fig. 5.** Tephra thickness versus the square root of the area of the associated isopach.

(a) shows the determination of maximum extrapolated tephra thickness at the source (vent) ($T_0$) and $b_t$, the value of $A^{1/2}$ where $T_0$ is twice as small; (1) Otvazhnyi cone, (2) maars;

(b) the maximum size of tephra particles discharged by the maars and by the Otvazhnyi cone as a function of the square root of the area enclosed within the associated isopleth. This figure shows the determination of maximum extrapolated size of tephra particles at the source (vent), $M_0$, and $b_c$, which is the value of $A^{1/2}$where $M_0$ is twice as small.

For legend see Fig. 5a. The determination of parameters is explained in the Appendix.

(Belousov et al., 2003; Gurenko et al., 2005) with regard to the type of explosive activity and the composition and volume of erupted magma. However, the discharge of pyroclastic material during the sub-Plinian phase of the Otvazhnyi eruption was several times smaller, and its duration was several times longer (the eruption extended itself over time).

## APPENDIX

### *Computing the Parameters of Tephra Deposits ($T_0$, $b_t$, $k_t$, $M_0$, $b_c$, $k_c$, $\alpha_t$, $\alpha_c$) and of the Volumes of Erupted Tephra and Magma*

The parameters $T_0$, $b_t$, and $k_t$ are found from the $T/A^{1/2}$ plot (see Fig. 4a), where $T$ is tephra thickness on a logarithmic scale and A is the area within the isopachs of the same thickness (Pyle, 1989). If the plot is a straight line, then we conclude that the tephra layer decays exponentially with increasing distance from the source (vent). $T_0$ is the maximum extrapolated tephra thickness at the source to be found by extending the line into the region where $A^{1/2} = 0$.

$b_t$ is the value of $A^{1/2}$ where $T_0$ becomes twice as small. This quantity provides a graphic illustration of how tephra thickness decreases with increasing distance from the source.

$k_t$ is the slope of the $T/A^{1/2}$ plot to be found from the relation

$$k_t = [\ln T_2 - \ln T_1]/[(A_2)^{1/2} - (A_1)^{1/2}].$$

$M_0$, $b_c$, and $k_c$ are found from the $M/A^{1/2}$ plot (see Fig. 4b), where M is the maximum size of tephra particles on a logarithmic scale and $A$ is the area within the respective isopleth. If the plot is a straight line, it follows that tephra particle size decays exponentially with increasing distance from the source.

$M_0$ is the maximum extrapolated size of tephra particles at the source to be found by extending the $M/A^{1/2}$ line into the region of $A^{1/2} = 0$.

$b_c$ is the value of $A^{1/2}$ where $M$ becomes twice as small. This quantity is a graphic illustration of the rate at which the maximum size of tephra particles decreases with increasing distance from the source.

$k_c$ is the slope of the $M/A^{1/2}$ plot, to be found from the relation

$$k_c = [\ln M_2 - \ln M_1]/[(A_2)^{1/2} - (A_1)^{1/2}].$$

$\alpha_t$ and $\alpha_c$ are found as the ratio between the lengths of the shorter ($Y$) and longer ($X$) axes of the isopach and isopleth ellipses, respectively, and characterizes their "ellipticity", i.e., the degree of elongation. Since the isopachs and isopleths do not form ideal ellipses, we used the mean values of $Y$ and $X$.

The volume of erupted tephra was found from the relation $V = 2T_0/k_t^2$ (Fierstein and Nathenson, 1992). It is known that this method, like the other methods based on measurements of tephra thickness, generally underestimates the volume (Fierstein and Nathenson, 1992). This occurs, because it is impossible to find accurately the volume (which is generally large) of fine tephra that is deposited at great distances from the volcano. Tephra transported over great distances is less than a few millimeters thick when deposited; it vanishes in the sections and is not amenable to measurement. Straightforward extrapolation of the $T/A^{1/2}$ line into the region of zero tephra thickness as is done in such calculations underestimates the volume, because it is known that the plot frequently flattens out in the far zone (the rate of decrease becomes slower with increasing distance). For this reason the volumes indicated in table, as well as the eruption durations based on these (see below), should be viewed as lower bounds. The conversion to the volume and mass of erupted magma ($\rho = 2800$ kg/m$^3$) was based on the volumetric weight of tephra deposits, viz., 1500 kg/m$^3$ for the maar tephra and 1300 kg/m$^3$ for the Otvazhnyi tephra.

### *Calculating Wind Speed and the Height of the Eruptive Plume*

The maximum plume height affects one single parameter in deposited tephra, that parameter being the maximum distance from the ashfall axis (as measured across the axis, i.e., across wind direction) where tephra particles of any definite size and density were deposited. In case we also know the maximum distance from the vent where particles of the same size and density were deposited at the ashfall axis, i.e., in down-wind direction, then we can find the wind speed during the eruption, i.e., plume height and wind speed can be determined, when at least one isopleth of the associated tephra has been constructed (Carey and Sparks, 1986).

We used the technique of Carey and Sparks (1986), which when applied to historical eruptions yields parameters of eruption plumes and wind speed that are fairly well consistent with the observations. The necessary distances were measured in the isopleth map (see Fig. 1b) and plotted as in (Carey and Sparks, 1986, p. 121). For maar eruption we used the following diameters of tephra particles: 20 mm (for distances 1.9 km cross-wind and 2.7 km down-wind), 10 mm (3.1 km and 4 km, respectively), and 5 mm (4 km and 5.3 km, respectively). For the Otvazhnyi eruption we used the diameters 20 mm (for distances 6.3 km cross-wind and 7.7 km down-wind), 16 mm (7.7 km and 9.2 km, respectively), and 13 mm (9.2 km and 10.2 km, respectively). The volumetric weight of tephra particles (basaltic scoria) was assumed to be 1800 kg/m$^3$ for the maars and 1500 kg/m$^3$ for the Otvazhnyi (not to be confused with the volumetric weight of a tephra layer, which is smaller owing to interparticle space). In addition, plume height was found using the following relation from (Sparks et al., 1997):

$$H_t = 0.236(R)^{1/4},$$

where $R$ is the discharge rate of pyroclastic material in kg/s.

The resulting heights were 5 km for the maar eruption and 7 km for the Otvazhnyi.

### *Calculating the Discharge of Pyroclastic Material and Eruption Duration*

The discharge of pyroclastic material was determined using a plot from (Williams, 1983) where the hydraulic size of tephra particles (the diameter times the density of particles) is plotted against the distance across the ashfall axis where particles fall at different discharges. We used the same basic data as for determining the height of eruptive plumes. The durations of eruption phases were found by dividing the mass of erupted pyroclastic material by the discharge of the material.

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