Specificity of the products of Tyatya volcano eruption in 1973

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Abstract. Based on 198 determinations of the complete silicate analysis of Tyatya volcano (Kunashir Island), we compared the data of the latter (1973) and all previous eruptions to reveal their differences and determine the evolution of Tyatya volcanism in the Holocene. The application of the estimation of the thermobaric parameters of the upper mantle magma chamber of the volcano made it possible to determine the temperature decrease in the magma chamber in 1973. An assumption was made about the polycyclic magmatic activity of the Tyatya volcano. The results of statistical processing of data on the thickness of tephra and the size of its fragments from the 1973 eruption are presented. Polynomial regressions of various degrees are applied. Models of tephra distribution based on three-dimensional trend analysis have been constructed. The results of the study are recommended for the creation of information databases on the petrochemistry of eruption products and the distribution of pyroclastics from volcanoes in the Kuril Island arc.

1. Introduction
The objectives of this paper are to compare the results of the analysis of the main oxides of the products of the last and all previous eruptions of Tyatya volcano to determine their evolution, assess the thermobaric characteristics of the products of the volcano's magmatic activity and the main features of the areal distribution of ash-stone deposits of the volcanic eruption in 1973.

Tyatya stratovolcano, one of the most impressive volcanoes of the Great Kuril Ridge, is in the north of Kunashir Island (figure 1). The height of its central cone is 1819 m, the height of the somma is 1485 m, and the base diameter is up to 18 km. At the ring ridge of the caldera, the diameter is up to 2.5 km. The exact age of the volcano's appearance has not yet been determined. However, based on the results of the description of the sections of the volcano's paleosols, in which samples were taken for radiocarbon and geochemical analyzes of pyroclastics, it can be concluded that the volcano began to form at the end of the Late Pleistocene [1]. During its formation, its height probably exceeded 2 km. As a result of one of the powerful explosions, which occurred, probably at the beginning of the fourth century AD, the upper part of the volcano collapsed with the formation of a caldera, in which a cone later grew, reaching the height of more than 1800 m. The last manifestations of volcanic activity of the volcano were observed in 1812 and 1973.
Figure 1. The scheme of the Tyatya volcano, craters, maars, zones of distribution of erupted material [2].
1 – direction of propagation of erupted material and its predominant distribution; 2 – craters, maars, cracks with explosion funnels; 3 – funnels of the explosion of previous eruptions; 4 – zones of forest damage by stone, slag and hot ash; 5 – zone of ash, lapilli, slag bombs with a layer thickness of more than 30 cm; 6 – zone of ash and coarse-grained material with a layer thickness of 15–30 cm; 7 – zone of ash and fine-grained material with a layer thickness of 3–15 cm; 8 – ash zone with a layer thickness of less than 3 cm.

The 1973 eruption began on July 14 and lasted two weeks. On the first day, explosions occurred on the northern slope of the volcano with the formation of maars and rupture cracks at an altitude below 500 m. Further, powerful explosions formed two craters at an altitude of about 400 m on the southeastern slope of the volcano, from which the main amount of the explosive material was ejected. Two cones of deposits have grown over the funnels – Pogranichnik and Otvazhny. The most powerful ejections of pyroclastics occurred from the Otvazhny. Ash clouds, carried over with north-western winds, reached the Kuril deep-water trench. The mechanism of lateral breakthroughs of magmatic products of the volcano during the 1973 eruption is described in detail in [3]. It occurred at the intersection of ring and radial faults in the body of the volcano. According to publications [2, 4], the total volume of ejected material was at least 200 million m³. By estimate of later studies [5], the volume of stony-ash deposits on the slopes of Tyatya volcano reached 110 million m³.

2. Geological and petrological characteristics of the eruption products
According to the literature, at least 198 determinations of the complete silicate analysis of the Tyatya volcano igneous rocks are known, including the explosive products of 1973 account for > 42 % [4, 3, 6, 7, 2, 8, 9, 10, 11, 12].
Analytical data for all groups of determinations of basic oxides conform to the requirements for their geochemistry. This made it possible to compare the petrochemical characteristics of the rocks of the 1973 explosions with all the products of previous eruptions to reveal their differences. Variational diagrams of the dependence of basic oxides on SiO₂ were constructed (figure 2).
Figure 2. Classification diagrams of the Tyatya volcano igneous rocks (Kunashir Island): 1 – the eruption of 1973, 2 – eruptions until 1973 (content of oxides indicated in wt. %): A – TAS diagram of (SiO₂ – (K₂O + Na₂O)) [13] and the scheme of alkali seriality [10], alkalinity series: I – low, II – medium, III – increased, IV – high; B – diagram SiO₂ – FeO*/MgO according to A Miyashiro's criterion [14]; C – AFM diagram (K₂O + Na₂O – FeO* – MgO) [15] with trends in the differentiation of the tholeiitic series of the volcano; D – diagram SiO₂ – K₂O; E – diagram SiO₂ – MgO; F – diagram SiO₂ – Al₂O₃; G – diagram SiO₂ – FeO*; H – diagram SiO₂ – CaO; I – diagram SiO₂ – TiO₂.
In general, the rocks of all Tyatya eruptions are enriched in alumina, iron oxide, and depleted in magnesium oxide in comparison with typical continental basaltoids. The products of the 1973 eruption are mainly represented by basaltic andesites: 65 of 86 samples are basaltic andesites (75%), while in previously igneous rocks, 67 of 112 samples are basalts, 35 are basaltic andesites, and 10 are andesites. The wide range of composition of rocks erupted before 1973 indicates a prolonged evolution of the volcano's magma chambers. In classification diagram SiO$_2$ – (Na$_2$O + K$_2$O) (wt.%) supplemented series of alkalinity (figure 2A), volcanic rocks are in the field of medium alkalinity under the rules of terminology Commission of Petrographic Committee RAS. As can be seen from the analysis diagram SiO$_2$ – FeO* / MgO, volcanic rocks of Tyatya volcano eruptions are in tholeiites field according to criterion A Miyashiro [14] (figure 2B). This conclusion is supported by the AFM diagram (figure 2C). The finding of the Tyatya igneous rocks in the tholeite field indicates that its basaltic magmatism belongs to the Fennerow type of magma differentiation. Basaltoids of this type are characterized by intense accumulation of iron in the residual melt, which, in the opinion of petrologists [16], is associated with a large proportion of plagioclase in the separating phenocrysts. The increased content of ferrous monoxide in the melt (FeO / Fe$_2$O$_3$ > 1), as a rule, indicates the reducing conditions for the formation of magmas and the low fugacity of oxygen. Therefore, the gas components H$_2$ and CO are oxidized to H$_2$O and CO$_2$, forming independent systems that leave the melt and do not significantly affect the evolution of basaltic magma. The low water content in the igneous rocks of Tyatya volcano (the average value in 82% of the samples is 0.08 wt.%) confirms this conclusion. From an analysis of the diagrams SiO$_2$ – (Na$_2$O + K$_2$O), SiO$_2$ – FeO* / MgO, SiO$_2$ – MgO, SiO$_2$ – CaO (figure 2A, B, E, H), which clearly demonstrates the solid concentration of figurative points, it follows that the relatively constant thermobaric conditions of the formation of magmas of the Tyatya volcano and the unity of the genesis of the rocks of the volcano during the activity of its upper mantle chamber in the Holocene. However, the geochemistry of the products of the previous and the last eruptions differs markedly, which can be seen in several Harker diagrams (figure 2B, F, G, I). It follows from the analysis of these diagrams that the rocks of the 1973 eruption are enriched in iron, titanium, reduced content of aluminum and to a small extent in calcium in comparison with the basaltoids of previous eruptions, which suggests a decrease in the temperature parameters of the main magma chamber of Tyatya volcano. The basalt and basaltic andesites of the early stages of volcanic activity have a higher alumina composition, which indicates more high temperatures of magmas of the early stages of magmatic activity of the volcano (figure 2F).

3. Thermobaric characteristics of the Tyatya volcano magma chambers

The almost dry composition of the Tyatya volcano igneous rocks makes it possible to use the formulas obtained in experiments with dry samples of ultrabasic and basic rocks to determine the thermobaric parameters of its magmatic melts, these results confirm the conclusion that the MgO content in the magmatic melt, relative to most other rock-forming oxides, most reliably correlates with temperature and pressure (depth) of the magma chamber.

In [17], the relationship between the conditions of existence of magmas before their crystallization and the petrochemical characteristics of igneous rocks was studied through the ratio of various petrogenic elements, in particular, through the coefficient $\omega = \text{MgO} / \text{(CaO + Na}_2\text{O + K}_2\text{O)}$ (mol. %). Based on a statistically reliable data set of basic oxides of Cenozoic volcanic rocks, a close relationship between the $\omega$ ratio, magma composition and magma changes has been confirmed. For this ratio, a regression equation was derived, which determines the depth of the magma chamber (km):

$$H = 24.17 + 22.28 \omega.$$  \hspace{1cm} (1)

Based on the improvement of laboratory methods for studying the separation of the melt from the substrate, which served as natural peridotites, equations were obtained that relate the melting temperature of the upper mantle substance and the concentration of SiO$_2$ and MgO in them. How it was indicated below, these regression equations derived from experimental data indicate that the MgO...
content in the magma melt relative to other rock-forming oxides most reliably correlates with the temperature and pressure (depth) of the magma chamber, if the melt is in equilibrium with olivine. Representation in several publications [18, 19, 20, 21, 22] of relatively simple empirical relations between SiO$_2$, MgO, alkalis and thermobaric parameters magma chambers in subcrustal of the upper mantle volcanic zones allows to solve the problem of calculating the temperature and pressure characteristics of the magma chamber before the eruption of Tyatya volcano to assess the evolution of the temperature regime of its magma chambers. These regression equations are:

\[
T_1(\degree C) = 1091.7 + 21.5 \text{MgO (wt. %)}; \\
T_2(\degree C) = 1019.8 + 1384.2 \frac{\text{MgO}}{\text{MgO + SiO}_2} \text{(wt. %)}. 
\]

Calculations of the thermodynamic conditions for the formation of magma chambers were performed using the above equations and based on a statistically reliable amount of data on the total silicate composition of the Tyatya volcano igneous rocks. The results are shown in figure 3.

In the most of estimates of the thermodynamic state of magma chambers of ancient eruptions of Tyatya volcano, the maximum melt temperatures of 1150 and 1200 °C were at the depths of 31.0 and 36.4 km, respectively. In the magma focus of the 1973 eruption, the maximum temperatures of 1150 and 1200 °C are determined at the depths of 29.0 and 37.3 km, then during this event the magma temperatures has decreased below 34 km and increased in the earth's crust. The temperature at the mouths of the 1973 breakthroughs reached 930 °C.

Figure 3. Temperatures and depths of formation of the eruption products in magma chambers of Tyatya volcano. 1 – products of eruptions before 1973, calculated by the formula (3); 2 – products of eruptions before 1973, calculated by the formula (2); 3 – products of the 1973 eruption, calculated by the formula (3); 4 – products of the 1973 eruption, calculated by the formula (2).

In real time the temperatures of the upper mantle chambers of Tyatya volcano lower than those of the magma chambers of many previous eruptions. This conclusion confirms the assumption made in [23] that the ancient rocks of Tyatya volcano had a higher degree of melting. Nevertheless, from the results of the calculations, it follows that there was a period when the temperatures in the magma chamber were even lower than the existing ones. This is also evidenced by the presence of a small amount of andesites among the igneous rocks. It should be assumed that the dynamics of the thermobaric regime of the upper mantle magma chamber was cyclical in the Holocene.

The absence of clear boundaries between basalts and rocks of intermediate silicic acidity indicates their close relationship and unity of origin. In [24, and others], thermodynamic conditions of the liquidus-solidus area are presented at different depth intervals, in particular, at pressures up to 1210 MPa, which corresponds to a depth of about 40 km. For these pressures, the difference between
liquidus and solidus is in the range of 45–50 °C. According to our calculations of the thermodynamic characteristics of the Tyatya volcano magma chambers using formulas (1) – (3), the difference between the two thermograms is within 52–60 °C. Noting the closeness of these thermograms with the diagrams in [24, et al.], we can assume that the temperatures calculated by formula (2) correspond to the liquidus boundary of the upper mantle substance, and the temperatures calculated by formula (3) correspond to the solidus boundary of the volcano's igneous rocks.

The tendency of rapid crystallization of the mineral phases of the melt in a narrow liquidus-solidus temperature range at the depths less than 40 km does not promote to the differentiation of the melt, forming a basalt and basaltic andesite composition of igneous rocks, which indicates the formation of all rocks from one permanent magma source. We emphasize that the basaltic andesites of 1973 were formed in a magma focus with temperatures of 1210–1150 °C. The main concentration was in the focus with temperatures of 1190–1170 °C, corresponding to the depths of 36–33 km.

Comparison of the temperature model of the volcano with the deep seismic section of the Kunashir Island [25, 26] shows that the region of magma chambers of Tyatya volcano coincides with the zone of absence of converted waves of earthquakes.

4. Application of statistical methods to the estimation of the tephra distribution of the 1973 eruption

Turning to a more detailed analysis of the distribution of the products of the explosive eruption in 1973, we believe that the scheme of the intensity of the fallout of stone, slag and ash material given in [2] can be clarified by applying the methods of statistical analysis of the processing of samples collected even several decades after eruption. In 2006, employees of the IMGG FEB RAS D.N. Kozlov and A.B. Belousov measured the thickness of tephra and the maximum sizes of its fragments on the northern and southeastern slopes of Tyatya volcano at 53 points [27, 5] (table). At the same time, there were 45 measurements of the tephra thickness and 34 measurements of the maximum fragment sizes.

Table 1. The results of measuring the thickness of tephra and the size of its fragments of the eruption of the Tyatya volcano in 1973. m is the thickness of the pyroclastic deposits, d is the size of the tephra fragments, a dash means the absence of data.

| Point number | m, cm | d, cm | Point number | m, cm | d, cm | Point number | m, cm | d, cm | Point number | m, cm | d, cm |
|--------------|-------|-------|--------------|-------|-------|--------------|-------|-------|--------------|-------|-------|
| 1            | 3     | 4     | 15           | 10    | -     | 29           | -     | 103   | 43           | 40    | 18    |
| 2            | 9     | 9     | 16           | 20    | 10    | 30           | -     | 420   | 44           | 11    | -     |
| 3            | 10    | 13    | 17           | 22    | 12    | 31           | -     | 150   | 45           | 10    | -     |
| 4            | 13    | 14    | 18           | 15    | 9     | 32           | 150   | 30    | 46           | 7     | 1     |
| 5            | 15    | 16    | 19           | 7     | -     | 33           | 70    | 26    | 47           | 5     | -     |
| 6            | 20    | 18    | 20           | 9     | -     | 34           | 3     | -     | 48           | 6     | -     |
| 7            | 20    | 12    | 21           | 7     | -     | 35           | 6     | -     | 49           | -     | 1     |
| 8            | 19    | 20    | 22           | 5     | -     | 36           | 3     | -     | 50           | 4     | 4     |
| 9            | -     | 25    | 23           | 28    | 25    | 37           | 5     | -     | 51           | 4     | -     |
| 10           | 66    | 31    | 24           | 40    | 28    | 38           | 6     | -     | 52           | 3     | -     |
| 11           | 50    | 22    | 25           | 40    | 35    | 39           | 12    | -     | 53           | 3     | -     |
| 12           | 40    | 19    | 26           | -     | 42    | 40           | -     | 15    | -            | -     | -     |
| 13           | 30    | 12    | 27           | -     | 44    | 41           | 20    | -     | -            | -     | -     |
| 14           | 35    | 11    | 28           | -     | 48    | 42           | 30    | 28    | -            | -     | -     |

In publications [27, 5], schemes of tephra distribution in isopachs and isopleths (lines of equal thickness of pyroclastic deposits and equal size of tephra fragments, respectively) are presented, as well as features of changes in the sequence of deposits. Within the framework of this study, two- and three-dimensional regression mathematical models of the distribution of tephra thickness have been built.
For the entire set of measurements, the coefficient of linear correlation between the thickness of the pyroclastic deposits and the size of tephra fragments was 65.9%. A joint analysis of the samples taken on the southeastern slope of the volcano and in the maar eruption zone shown that the residual variance amount 56.5%. It excludes the possibility of linear approximation of the values of one quantity based on another. Considering the difference in the mechanism and intensity of the eruption on the northern and southeastern slopes, the relationship between the thickness of the pyroclastic deposits and the size of tephra fragments was studied separately for the products of the Otvazhny crater eruption and the tephra of the Vlodavets and Radkevich maars. Two-dimensional least squares regression models are constructed. The correlation coefficient in the first case was 89.9%, in the second 98.6%. These indicators make it possible to use the obtained linear models for approximating the thickness of the pyroclastic deposits at the points where only the size of its fragments was measured, as well as for inverse approximation. We also constructed polynomial regression equations for the two studied factors of degrees from 2 to 6 but none of them provided an approximation quality higher than 60%, exponential curve interpolation shown a result of 64%. In addition, equations in polar coordinates are obtained for isopachs and isopleths constructed in [5].

Three-dimensional trend analysis allowed to construct tephra scatter models. To describe the distribution of the thickness of the pyroclastic deposits, a logarithmic regression model is effective, the equation of which is (figure 4):

\[
\bar{m} = 65.5073 - 23.1728 \ln \sqrt{(x - 4.275)^2 + (y + 4.195)^2},
\]

**Figure 4.** Logarithmic regression model of the thickness of the pyroclastic deposits erupted in 1973 (m) as of 2006. The abscissa axis is to the east, the ordinate is to the north.

Analysis of variance allowed us to evaluate the quality of approximation of the tephra distribution pattern represented by the trend surface with a multiple correlation coefficient equal to 71%. A logarithmic regression model was also obtained for the size distribution of tephra fragments.

In [2], a model of distribution of the thickness of the igneous material from the Otvazhny crater to the southeast at up to 3 km is presented, and in [27] a curve was constructed for the same process but already up to 10 km. Over 34 years, as a result of erosion and consolidation on the southeastern slope of the volcano, the pyroclastic deposits thickness in 1973 decreased from the Otvazhny crater to the coast according to the dependence, which can be determined by the exponential relationship: \( \Delta z = ax^b e^{cx} \), where \( \Delta z \) is the change in the pyroclastic deposits thickness,
\( x \) is the distance from the Otvazhny crater ridge to the coast; \( a, b, c \) – constants \((a = 0.5375, b = 0.61974, c = -0.001856)\) (figure 5).

![Figure 5. Estimation of the pyroclastic deposits thickness and the rate of its decrease based on the results of measurements in 1973 and 2007 on the southeastern slope of Tyatya volcano 120° in azimuth. Mark 0 corresponds to the ridge of Otvazhny crater: A – deposits thickness in 1973 and 2007; B – change in deposits thickness in 1973 over 34 years.](image)

The resulting exponential relationship made it possible to assess the influence of erosion and consolidation of deposits on the change in their thickness. The rate of decrease in the pyroclastic deposits thickness near the Otvazhny crater in the most intense distribution of igneous material averaged 29.4 cm/year.

5. Conclusion
1. All the products of the Tyatya volcano eruptions are in the tholeiite field. The products of the 1973 eruption mainly characterized by basaltic andesite composition (75%), are enriched in FeO, partly TiO\(_2\), depleted in alumina, which indicates a change in the thermobaric state of the upper mantle magma chamber.
2. As a result of the evolution of the magmatic activity of Tyatya volcano, the temperature of the upper mantle part of the volcano's magma focus decreased by 1973, while in the upper crustal part of the volcano it increased. The identified zone of the upper mantle magma chamber coincides with the zone of absence of converted waves of earthquakes.
3. The use of two- and three-dimensional regression mathematical models is an effective method for describing the distribution of the pyroclastic deposits thickness erupted in 1973 from two eruption centers. These methods are recommended to be applied to assess the distribution of products of explosive volcanic eruptions in the Kuril Island arc.

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