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DISTRIBUTION OF VOLCANIC ERUPTIONS IN KAMCHATKA BY MAGNITUDES DURING THE LAST 50,000 YEARS

THE GEOLOGICAL EFFECT OF AN EXPLOSIVE VOLCANISM AND PREDICTIVE ESTIMATES

РАСПРЕДЕЛЕНИЕ ВУЛКАНИЧЕСКИХ ИЗВЕРЖЕНИЙ НА КАМЧАТКЕ ПО МАГНИТУДАМ ЗА ПОСЛЕДНИЕ 50 ТЫСЯЧ ЛЕТ

ГЕОЛОГИЧЕСКИЙ ЭФФЕКТ ЭКСПЛОЗИВНОГО ВУЛКАНИЗМА И ПРОГНОЗНЫЕ ОЦЕНКИ

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Abstract: In Kamchatka volcanism has occurred since the Cretaceous period. There are about 7100 volcanic structures with age from 2-2.5 million years to the present. There are 20 active and 14 potentially active polygenetic volcanoes, as well as 10 modern and Holocene fields of monogenic volcanism, zones of multi-edifice extrusive volcanism and calderas [1]. Over the past 1000 years, the linear heat power of eruptive volcanism in Kamchatka is estimated at about 10 MW per 1 km of its volcanic arc. This is 4–5 times more than in the Kuril Islands, in Japan or in New Zealand, and is only inferior to the linear power of Icelandic volcanism (15 MW) [2]. In historical times, about 10% of all volcanic eruptions in the world occurred in Kamchatka (for the range of volcanic explosivity index, *VEI* = 2–5). This is quite a lot because the length of the volcanic arc of Kamchatka is approximately 900 km, which accounts for only about 2% of the sum of the lengths of all volcanic arcs on Earth. This is due to the unprecedented high productivity of the giant volcanoes of the Northern group of Klyuchevskoy, Shiveluch and Ploskiy Tolbachik, each of which erupts from 20 to 60 million tons of volcanic products per year. The distribution of the volume of ejected pyroclastic (V_p) for eruptions of Kamchatka volcanoes in the last 50,000 years obeys a power law with the index – b_{diff} = –0.90 ± 0.14 (95%). Assuming a steady state volcanism [3], the average intervals (T) between future eruptions in Kamchatka are estimated as follows: once a year (*VEI* = 2), every 5 years (*VEI* = 3), every 40 years (*VEI* = 4), every 300 years (*VEI* = 5), every 3,300 years (*VEI* = 6) and every 22,000 years (*VEI* = 7). The total geological effect of Kamchatka volcanoes is estimated at about 50 km^3 of pyroclastic over 1000 years (*VEI* = 2–7).

Keywords: Kamchatka, linear thermal power of eruptive volcanism, explosive magnitude of eruption, power distribution of the volume of eruptive pyroclasts, expected time intervals between eruptions.

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Резюме: На Камчатке вулканизм происходил, начиная еще с мелового времени. Здесь выявлено около 7100 выраженных в рельефе вулканических построек с возрастом от 2-2,5 млн лет до современных. Насчитывается 20 действующих и 14 потенциально активных многоактных вулканов, а также 10 современных и голоценовых полей моногенного вулканизма, зон многовыходного экструзивного вулканизма и кальдер [1]. За последние 1000 лет линейная тепловая мощность эруптивного вулканизма Камчатки, приходящаяся на 1 км длины ее вулканической дуги, оценивается примерно в 10 МВт. Это в 4–5 раз больше, чем на Курильских островах, в Японии или в Новой Зеландии, и уступает только линейной мощности исландского вулканизма (15 МВт) [2]. В историческое время на Камчатке происходило около 10% всех вулканических извержений мира (для диапазона эксплозивных вулканических индексов *VEI* = 2–5). Это довольно много, поскольку длина вулканической дуги Камчатки примерно 900 км, что составляет всего около 2% суммы длин всех вулканических дуг на Земле. Это объясняется беспрецедентно высокой продуктивностью гигантских вулканов Северной группы Ключевского и Шивелуча, а также региональной зоной шлаковых конусов Плоского Толбачика, каждый из которых выносит от 20 до 60 млн т вулканических продуктов в год. Распределение объема выброшенной пирокластики (V_p) для извержений камчатских вулканов за последние 50 тысяч лет подчиняется степенному закону с показателем степени – b_{diff} = –0,90 ± 0,14 (95%). В предположении устойчивого вулканизма [3] средние интервалы (T) между будущими извержениями на Камчатке оцениваются следующим образом: 1 раз в год (*VEI* = 2), каждые 5 лет (*VEI* = 3), каждые 40 лет (*VEI* = 4), каждые 300 лет (*VEI* = 5), каждые 3000 лет (*VEI* = 6) и каждые 22 000 лет (*VEI* = 7). Общий геологический эффект камчатских вулканов оценивается примерно в 50 км^3 пирокластики за 1000 лет (*VEI* = 2–7).

Ключевые слова: Камчатка, линейная тепловая мощность эруптивного вулканизма, эксплозивная магнитуда извержения, степенное распределение объема изверженной пирокластики, ожидаемые интервалы времени между извержениями.

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Introduction

Volcanic eruptions come in a variety of sizes: from weak, not harmful, to strong, catastrophic and climatic ones, with tremendous destructive power. The latter can cause loss of life, significant damage, global consequences and even temporary climate changes. Catastrophic eruptions occurred in Kamchatka in historical time, fortunately in sparsely populated areas. However, in the Holocene time (up to 10 thousand years ago) there were repeatedly two orders of magnitude larger, colossal caldera-forming eruptions. Similar dangerous events will occur in the future. With an increase in the magnitude of eruptions, the frequency of their occurrence decreases, but it still remains significant. For a general description of the modern volcanic activity of Kamchatka, the construction of mechanisms for the generation and accumulation of magma, long- and short-term forecasting, insurance of volcanic risks, it is important to know how often volcanic eruptions of various sizes (magnitudes) occur on average. This is especially true for catastrophic and colossal eruptions, including eruptions of the maximum possible size, the most destructive volcanic events. Here, the eruption magnitude refers to the decimal logarithm of some parameter characterizing the size of the eruption. Making reliable forecasts, assessing risks and possible damage from volcanic eruptions is an important practical task for the Kamchatka region.

This problem has not yet been solved due to the lack of reliable source data for analysis. Compiling eruption catalogs containing reliable volumes of erupted products is a rather complicated task. Only now, more than 80 years after the start of regular volcanological observations (in 1935), the minimum necessary amount of data has been accumulated in Kamchatka to solve it. In the author's article in the issue 5–6 for 2018 of the journal "Transport and Storage of Oil Products and Hydrocarbons" it was investigated the frequency distribution of the volcanic explosivity index (*VEI*) and proposed two physical mechanisms for explaining the power-law type of *VEI* distribution with a degree of less than one [4]. That work was done on the basis of historical data only. Since the most dangerous catastrophic and climatic eruptions are much less common than weaker ones, to obtain reliable estimates of their recurrence in this work, we analyze not only historical data, but data from several tens of thousands of years.

In this work, the author restricts himself to analyzing only the explosive size of the eruption, for which he takes the total volume of ejected pyroclastic, i.e., all fragmentary (clastic) material, both juvenile and resurgent. Methods for assessing the volume of such material are well developed and there are corresponding catalogs.Unfortunately, there are very few reliable estimates of the volumes and masses of erupted lava materials to date.They appeared only from the beginning of the use of instrumental aerial photogrammetric methods in Kamchatka in the 1970s [5]. This is a very time-consuming and expensive work, involving the compilation of relief models of the earth's surface before and after the eruption. Such work is not always possible. The aim of this work is to obtain statistically reliable estimates of the average recurrence intervals of eruptions of various magnitudes in Kamchatka based on an analysis of data on historical and prehistoric eruptions up to 50 thousand years ago.

The article gives a brief analytical review of the literature data on the problem, describes the source data and the methodology for their processing. A summary graph of the frequency of eruption magnitudes in Kamchatka over the past 50,000 years is given.Taking the state of volcanic activity in Kamchatka in the Holocene as "steady state volcanism" [3], it is estimated the average expected repeatability intervals and the volumes of ejected and displaced volcanic clastic material that will be carried by Kamchatka volcanoes over a certain time interval (1000 years).This is done for each magnitude range separately, and in total for all magnitudes, evaluating the geological effect of explosive volcanism of Kamchatka.

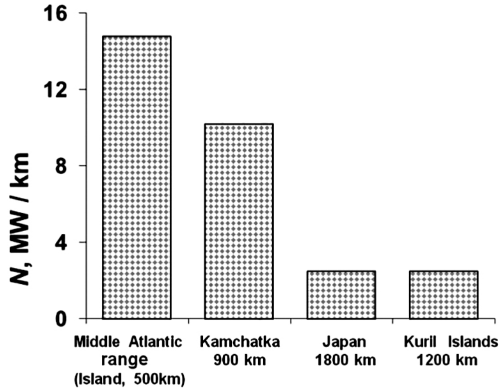
Brief description of volcanic activity and volcanic hazards in Kamchatka

The average productivity of all Kamchatka volcanoes over the past 30,000 years is estimated at about 0.13 km^3 of volcanic products per year. Over the past 850000 years, Kamchatka volcanoes have erupted at least 22,000 km^3 of volcanic products. Over the past 1,000 years, the linear heat power of eruptive volcanism in Kamchatka was about 10 MW per 1 km of volcanic arc (total length about 900 km). This power is about 4–5 times more than in the Kuril Islands, in Japan or New Zealand, and is only inferior to the linear power of Icelandic volcanism (15 MW) [2, 6] (Figure 1). This is due to the unprecedented high activity of the volcanoes of the Northern Group of Kamchatka.

In Kamchatka, there are 20 active and 14 potentially active polygenetic volcanoes, as well as 10 modern and other Holocene volcanic formations (fields of monogenic volcanism, zones of multi-output extrusive volcanism, calderas, etc.) [1, pp. 189–190], [7]. In Kamchatka there are three very large modern igneous centers (Shiveluch, Klyuchevskoy and Ploskiy Tolbachik with its regional zone of slag cones) with a flow rate of volcanic products from 20 to 60 million tons per year. The productivity of each of these centers is comparable to that of Mount Etna and Hawaiian volcanoes [8]. In the 20th century, four strong (catastrophic) predominantly explosive eruptions of volcanoes occurred with volumes of erupted products from 0.7 to 2 km^3: Ksudach in 1907, Bezymyanny in 1955–56, Shiveluch in 1964, as wellas the Great Fissure Tolbachinskiy eruption in 1975–1976 within Tolbachinskiy Dol. These eruptions caused regional environmental disasters. Ashes of the eruption of Bezymyanny volcano spread in the stratosphere over long distances; the sound wave of its main explosion three times circled the globe [9]. In addition, there were several tens of moderate (with the volume of products from 0.1 to 1 km^3) and significantly weaker (less than 0.1 km^3) eruptions [10]. In the Holocene (the last 10000 years), Kamchatka experienced 1–2 orders of magnitude larger eruption in volume. The largest was the eruption associated with the Kurile Lake caldera formation with a volume of erupted material equal to 140–170 km^3 [11]. Certainly, catastrophic eruptions in Kamchatka will occur in the future.

Kamchatka is relatively poorly populated, but there are a number of factors that significantly increase the volcanic hazard [12]. These factors include: a) a high level of volcanic activity; b) the predominantly explosive nature of its arc volcanism; c) expansion of the human habitat and economic infrastructure up to the immediate vicinity of volcanoes; d) a significant number of international and domestic airlines passing over the territory of the peninsula and the northwestern part of the Pacific Ocean, for which ash volcanic clouds are of great danger [13, 14] (Figure 2). The danger is further increased due to the formation of extended mud flows as a result of the interaction of hot eruptive products with snow, which cover the slopes of Kamchatka volcanoes most of the time of the year. To study the active volcanic process, forecast parameters of eruptionsin real-time and estimate of their degree of danger, a comprehensive system for monitoring volcanoes has been created in Kamchatka [15,16].

Figure 1. *Energetic effect of eruptive volcanism in several areas of the world (in the last 1000 years). N – linear heat power of volcanism per one kilometer of a volcanic arc in MegaWatts. Figures under arc names are length of arcs [4], datafrom [2]*



Comparison of volcanic activity of the World and Kamchatka in historical time

Volcanic explosivity index (*VEI*) is a widespread semi-quantitative explosive magnitude for evaluating sizes of historical eruptions. *VEI* makes it possible to compare individual eruptions or eruptions of volcanic zones in size. This is a logarithmic size scale; *VEI* takes integer values from 0 to 8 [17].

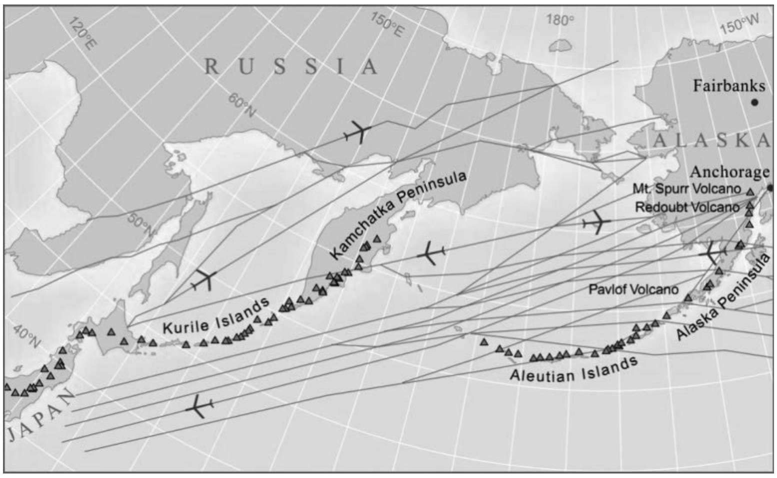
The distributions of *VEI* for the eruptions of the World and Kamchatka from the beginning of the 19th century to 2016 are given in Figure 3 [4].

In coordinates ($\log_{10}\tilde{N}$ – *VEI*) the graph approximated by a linear dependence of the form

$$\log_{10}\tilde{N} = \log_{10}N_0 - \gamma_{diff}VEI \qquad (1)$$

where $\tilde{N}$ – expected number of eruptions per 1000 years for a given *VEI*, γ_{diff} – tangent of the slope angle of the repeatability curve ($0 < \gamma < 1$), N_0 is the initial value depending on the activity level of the volcanic zone, N_{0k} and N_{0w} – are values for Kamchatka and the world, respectively. (N_{0k}/N_{0w}) 100% ≈ 10 %. Consequently the frequency of occurrence of volcanic eruptions in Kamchatka in the range of volcanic explosivity indexes *VEI* = 2–5 is about 10% of the global one. This is quite a lot, since the length of the volcanic arc of Kamchatka (about 900 km) is only about 2% of the sum of the lengths of all volcanic arcs on Earth.

Figure 2. *North Pacific and Russian Far East air routes (gray lines) pass over or near more than a hundred potentially active volcanoes (red triangles). Aircraft flying along these routes, some of them are the busiest in the world, carry more than 10,000 passengers and millions of dollars of cargo each day to and from Asia, North America, and Europe. In the North Pacific region several explosive eruptions occur every year. Ash from these eruptions, which has caused jet engines to fail, is usually blown to the east and northeast, directly across the air routes. (Compiled from [4])*



A brief review of the literature on the topic

The frequency distribution of the volcanic explosive eruption index (*VEI*) for the entire planet was considered in [18] (Figure 4). A representative time interval was determined for each *VEI*, within which the number of eruptions was calculated, which were then normalized to a single 1000-year time interval. It can be seen from the figure that in the coordinates ($\log_{10}N$ – *VEI*) the graph takes a linear form, where N is the normalized number of eruptions. It follows that for volcanoes of the world, the volcanic explosivity index *VEI* in the range from 2 to 7 inclusive is distributed exponentially with an index of about –0.8. If we assume that *VEI* is an approximate logarithmic characteristic of the volume of ejected pyroclastic (see the scale of tephra volumes in Figure 4), then this corresponds to the power-law distribution of the tephra volume. Here, tephra refers to all pyroclastic. For *VEI* = 8, there is an approximately 20-fold deficit in the number of events if the original graph were continued to this value. It can be assumed that *VEI* = 7 is the maximum magnitude of volcanic eruptions on earth and super eruptions with *VEI* = 8 and 9 are extremely unlikely. However, this question requires further research, since ancient calderas that could have generated super eruptions are strongly eroded, covered by younger sediments, and far from being discovered.

P.I. Tokarev [19] introduced the term of class (K) of an eruption as the decimal logarithm of the mass of all erupted

Figure 3. *The differential graph ofdistributions of VEI of the World (solid line) and Kamchatka (dashed line) in 1800–2016. The numbers above the dots indicate the number of eruptions in the sample for each VEI which then are normalized to a single 1000 year interval.$\gamma_{diffwand}$ γ_{diffk} – are values for Kamchatka and the World, respectively*

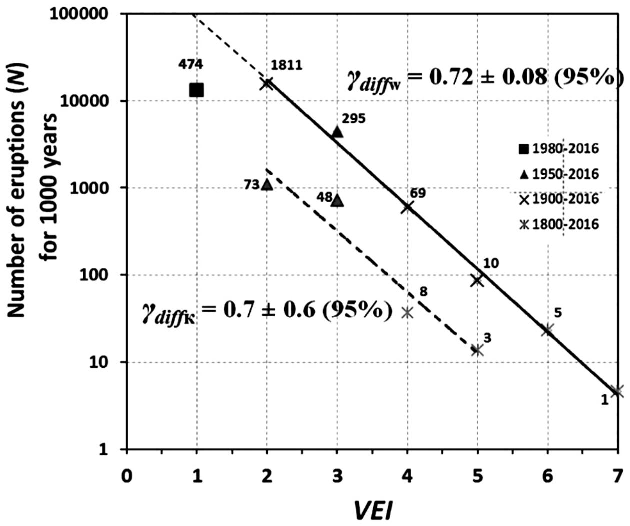
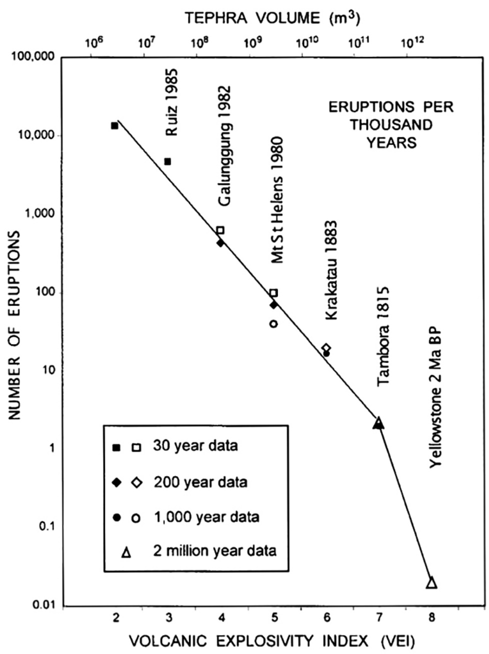


Figure 4. *A cumulative graph of the frequency – VEI distribution for world eruptions. The numbers of eruptions are normalized to a single 1000-year interval. Bug fixed: the tephra volume scale (above) is shifted half a decimal order to the left. The marks on the VEI scale are also offset so that it can be seen that each VEI corresponds to a whole range of pyroclastic volumes (tephra). (Compiled from[18], figure 6, p. 259)*



products in kilograms. He studied the differential frequency distributions of (K) for Kamchatka and the Kuril Islands over historical time and over the past 10 thousand years. It is shown that for large classes ($K \geq 10$), the distributions (K) are approximated by a linear function with close slopes equal to 0.58 for Kamchatka and 0.62 and 0.68 for the world (in the coordinates $\log_{10}N – K$, where N is the number of eruptions of this class).Unfortunately, in this work, data on the number of eruptions in Kamchatka for classes K = 10 and 11 were taken starting from 1901, but representative data for these classes begin from 1950. This leads to a noticeable underestimation of the frequencies and an underestimation of the slope of the repeatability graph. In addition, the frequency of eruptions in this work is not normalized to a single time interval, which makes it difficult to compare world and Kamchatka volcanic activities. However, this is the first work on this topic on Kamchatka volcanoes.

A.A. Gusev et al [20] studied the irregularity of the frequency (temporal groupability) of eruptions of Kamchatka volcanoes. In this work, additional cumulative and differential graphs of the distribution of pyroclastic volumes (V_p) for the most powerful Holocene eruptions in Kamchatka are presented. The slope angles of these plots on the double logarithmic scale b_{cum} and b_{diff} are 0.65 and 0.67, respectively. In the author's opinion, these parameters are underestimated, since for their adequate assessment it is necessary to use data for larger eruptions, up to Holocene ones. This article presents detailed tables of the volumes of ejected pyroclastic for both historical and Holocene eruptions and their dating, which is an undoubted advantage of the work. Neither Tokarev nor Gusev set forecast tasks. This is the main goal of this work.

A number of works are devoted to studying super eruptions (VEI = 8 and 9), which, if initiated, will pose a serious threat to civilization [21, 22].The data on these eruptions are not yet complete and it is not yet possible to reliably estimate the probability of their occurrence.

Frequency – magnitude distribution of Kamchatka volcanic eruptions

Terminology used

In this paper the author confines himself to considering volumes only of fragmented (clastic) material ejected during eruptions (pyroclastics). According to the generally accepted terminology in Kamchatka, by tephra, the author means that part of pyroclasts that is ejected and moved through the air of a wide variety of sizes, from large blocks, bombs to the smallest ash. Another part of the pyroclastics is spread by flowing along the slopes of the volcano in the form of pyroclastic flows, pyroclastic waves, landslide-explosive deposits and others. It should be taken into account that all types of pyroclastic are always a mixture of juvenile and resurgent materials, which are almost impossible to separate in field work (Bazanova L.I., personal communication). That is why the catalogs usually contain the total volume of pyroclasts ejected during a particular eruption.

On explosive magnitudes

By the explosive magnitude (M_{ex}) of an eruption, the author means the decimal logarithm of the volume of the total ejected pyroclastic (V_p) in cubic meters

$$M_{ex} = \log_{10} (V_p, m^3) \quad (2)$$

Explosive magnitude M_{ex} is a quantitative logarithmic characteristic of the volume of pyroclastic, and it is a real number.This is its fundamental difference from another semi-quantitative logarithmic characteristic of the explosive size of an eruption, the volcanic explosivity index (*VEI*), widely used in practice [17]. The necessity of introducing *VEI* is connected with the fact that in catalogs of historical eruptions there are very few eruptions for which data on the volumes of erupted pyroclastic are available. Since *VEI* is estimated using a number of qualitative and some quantitative parameters of the eruption known from historical observations, this significantly increases the number of possible estimates of magnitudes of this type. By analogy with magnitude in seismology, *VEI* was invented to compare the explosive size of historical eruptions among themselves and, generally speaking, cannot serve to accurately estimate the volume of ejected pyroclastics. Nevertheless, in Table 8 of [17], each *VEI* is assigned a certain range to a certain logarithmic range of pyroclastic volumes (V_p) of unit width. For example, an eruption with VEI = 5 is associated with a range $10^9 < V_p \leq 10^{10}$ m^3 (Figure 4). It can be assumed that such association was made on the basis of some correlation relations between *VEI* and pyroclastic volumes for those eruptions for which these volumes were known. Due to the low accuracy of the estimates of pyroclastic volumes, the *VEI* accepts only integer values from 0 to 8. Therefore, knowing the *VEI* of the eruption, it is impossible to determine the exact value of the volume of the ejected pyroclastic from it and you have to assign the average value of the volume to the corresponding logarithmic range.

Source data and processing technique

To analyze the frequency-magnitude distribution of Kamchatka eruptions, it was used data on the volumes of ejected pyroclastic: a) for historical eruptions from ([20], Table 2); b) for Holocene eruptions from ([23], Table 1); c) for pre-Holocene, the largest caldera-forming eruptions from ([11], Table 2).

The table of pyroclastic volumes of historical eruptions from [20] is mainly based on *VEI* values, which are taken from the Smithsonian Institute (Global volcanism) database [24]. At the same time, the authors to each *VEI* assigned the minimum value of the pyroclastic volume according to Table 8 from [17], which seems incorrect. For example, for an eruption of VEI = 4, the authors of the article assumed a pyroclastic volume $V_p = 10^8$ m^3. It is more justified to assign the average value of the pyroclastic volume ($\bar{V}_p$) for the corresponding logarithmic range of volumes according to the formula

$$V_p,\ \text{m}^3 \approx \bar{V}_p\ ,\ \text{m}^3 \approx 10^{(VEI\ +\ 4.5)}, \qquad (3)$$

which is true for $VEI \geq 2$. For example, for VEI = 4, this formula yields = $3.12 \cdot 10^8$ м^3. It is taken into account that the author analyzes the frequency distribution of explosive magnitudes of eruptions, and not the distribution of the pyroclastic volumes themselves.

The table of ejected pyroclastic volumes for Holocene eruptions ([23], Table 1) contains information obtained by the tephrachronological method. It is compiled by O.V. Dirksen, taking into account all currently available data. Unfortunately, two-thirds of the estimates presented there are the minimum values of the volume of the species (≥1.2 km^3, ≥2 km^3, etc.) and are not limited at all from above.

In order to improve the reliability of the estimates, we also used data on the most strong caldera-forming eruptions (class III with volumes of pyroclasts from 50 to 500 km^3) in Kamchatka for the last 50,000 years, for which dating was known ([11], Table 2). The volumes of ejected pyroclastics of the largest and, accordingly, the most ancient of these eruptions, were approximately estimated by I.V. Melekestsev based on the correlation relationships he constructed between caldera sizes and pyroclastic volumes.

Thus, the initial data used by the author for analysis were obtained by different methods, they contain significant errors, as well as omissions. Nevertheless, these data cover the entire range of explosive magnitudes of eruptions that have occurred in Kamchatka over the past 50,000 years. This allows the author to hope for adequate estimates of the parameters of the frequency distribution of the explosive magnitude (M_{ex}).

Data processing technique and results

Based on the pyroclastic volumes of eruptions (V_p), their explosive magnitudes (M_{ex}) were calculated according to formula (2). Then the frequency – magnitude distribution was analyzed. The entire range of magnitudes was divided into the optimal number of intervals, each of which had a unit width. For each magnitude interval, cumulative graphs of the number of eruptions were constructed, based on the analysis of which representative time intervals were selected (not given here). In these intervals, the numbers of eruptions were calculated, which were then normalized to a single 1000 – year interval.

The frequency- explosive magnitude distribution graph in the last 50,000 yearsis depicted in Figure 5.The frequency distribution was approximated by the following dependence shown on the graph in a solid line

$$\log_{10}\tilde{N} = \log_{10}N_0 - b_{diff}M_{ex}, \qquad (4)$$

Where $\tilde{N}\,(M_{ex})$ is the predicted number of eruptions in a unit interval of magnitudes (M_{ex}-0.5, M_{ex}+0.5] for 1000 years, N_0 and b_{diff} are the experimental regression coefficients, N_0 is the initial value depending on the level of volcanic activity, and b_{diff} is the slope of the approximating straight line (fractal dimension of magnitude dozens). For example, for M_{ex} = 9.5, according to the graph, it can be obtained that, in the range of magnitudes ($9 < M_{ex} \leq 10$), an average of three eruptions is predicted over 1000 years. Note that the parameter b_{diff} = 0.90 of the frequency-magnitude distribution in Figure 5 is substantially larger than the analogous parameter γ_{diffk} = 0.8 for the *VEI* distribution (Figure 4). At the same time, the approximation shown in Figure 5 by the dotted line for only historical eruptions has a value close to 0.7

Forecast Estimates

Assuming the state of volcanic activity in Kamchatka in the Holocene as "steady state volcanism" [3], the following forecast estimates can be made:

1)the expected average interval ($\bar{T}$) between eruptions belong to a single interval of explosive magnitudes (M_{ex}-0.5, M_{ex}+0.5] is given by the following expression.

Figure 5. *The differential graph off requency–explosive magnitude distribution of Kamchatka eruptions in the last 50,000 year for magnitude ranges of unit length. The numbers above the dots indicate the number of eruptions in the sample for each magnitude range, which then are normalized to a single 1000 year interval. Solid approximating straight lineis drawn by all available data. Dotted lineis drawn only by historical data*

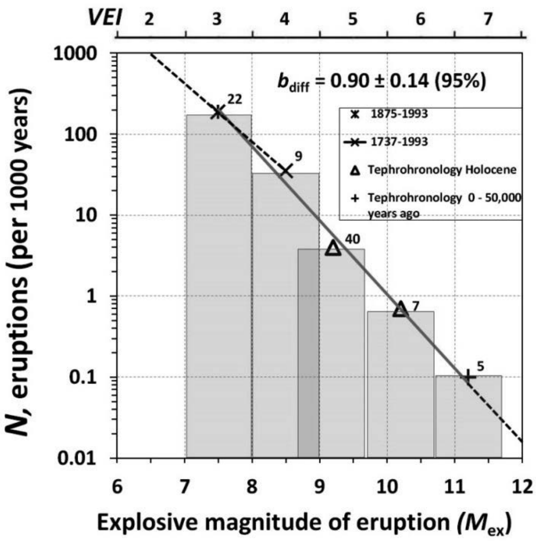
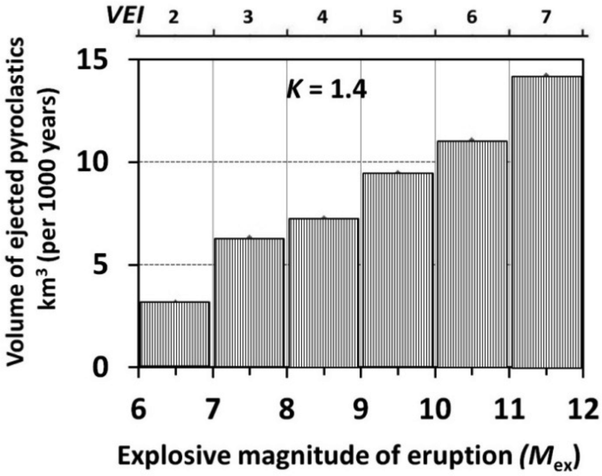


Figure 6. *The differential graph of the volume of pyroclast ejected by volcanic eruptions of Kamchatka for the following ranges of explosive magnitudes (6–7];(7–8], ..,(11–12]. Volumes are normalized to a 1000 year interval. K is an average coefficient of increase in the volume of pyroclast in the transition from the previous to the next magnitude interval*



$$\bar{T}\text{, years} = 1000/\tilde{N}(M_{ex}), \quad (5)$$

where $\tilde{N}(M_{ex})$ is the predicted number of eruptions over 1000 years in a single interval of magnitudes (M_{ex}-0.5, M_{ex}+0.5], calculated by the formula (4);

2) the expected average volume of pyroclastic ($\overline{\Sigma V_p}$) that will be ejected by all eruptions with explosive magnitudes in the interval (M_{ex}-0.5, M_{ex}+0.5] for 1000 years

$$\overline{\Sigma V_p}\text{, m}^3 = \tilde{N} \cdot 10^{Mex}, \quad (6)$$

where 10^{Mex} is the pyroclastic volume corresponding to the average value of the explosive magnitude of this interval equal to M_{ex}.

Figure 6 shows a graph of pyroclastic that will be ejected by Kamchatka volcanoes for 1000 years in each magnitude interval according to formula (6). An unlimited increase in the volume of ejected pyroclastic with an increase in explosive magnitudes is caused by the fact that the parameter b_{diff} is less than unity.

Forecast estimates are presented in the following table.

Note that estimates of the average repeatability interval and pyroclastic volume for *VEI* = 2 were made on the basis of extrapolation of only the historical data shown in dashed line in Figure 5.

Conclusion

In 1800–2016 in Kamchatka about 10% of all volcanic eruptions of the world took place (for range of *VEI* = 2 – 5). This is quite a lot, since the length of the volcanic arc of Kamchatka is about 900 km, which is only about 2% of the total length of all volcanic arcs on Earth. This is due to the unprecedented high productivity of giant volcanoes of the Northern group of Klyuchevskoy, Shiveluch and Ploskiy

Table

Projected average intervals between eruptions and volumes of ejected pyroclast in Kamchatka over a 1000-year interval for every unit range of explosive magnitude

Range of explosive magnitude (M_{ex})		Average interval between eruptions (years)	The most likely amount of ejected pyroclasts in 1000 years (km³)	Forecast Estimates
Pyroclastic volume, (km³)	VEI			
0.001-0.01	2	1	3 (extrapolation)	Karymsky 1996
0.01-0.1	3	5	6	Fissure Tolbachik eruption 2012-2013
0.1-1	4	40	7	Shiveluch 1854 and 1964, GFTE 1975-1976
1-10	5	300	9	Ksudach, Stübel cone 1907; Bezymyanny 1956
10-100	6	3300	11	Krakatau 1883; Khangar 6850 (^{14}C); Karymskaya caldera 7889 (^{14}C)
100-1000	7	22000	13 (extrapolation)	Opala 39–40 ka (^{14}C); Tambora 1815

Total: ~ 50 km³ of pyroclast (*VEI* = 2–7)

Tolbachik with its regional zone of slag cones, each of which carries out from 20 to 60 million tons of volcanic products per year.

The distribution of the ejected pyroclastic volume (V_p) for the eruptions of Kamchatka volcanoes over the past 50,000 years obeys the power law with the parameter b_{diff} = 0.90 ± 0.14 (95%). This is significantly more than the analogous one in the distribution of seismic moment for strong Kamchatka earthquakes, equal to about 0.6 [25, 4].

Assuming that Kamchatka has conditions of a "steady state volcanism" [3], the average intervals ($\bar{T}$) between their future eruptions are estimated as follows: once a year (*VEI* =2), every 5 years (*VEI* = 3), every 40 years (*VEI* = 4), every 300 years (*VEI* = 5), every 3,300 years (*VEI* =6) and every 22,000 years (*VEI* = 7). We believe that these estimates are more reliable than the ones obtained by extrapolating data only for historical eruptions [4]. This is especially important for the most powerful eruptions (*VEI* = 5, 6 and 7). Obviously, actual time intervals between eruptions of definite magnitude will have significant random variations. Nevertheless, estimation of reliable average values of these parameters represents a significant advance and, undoubtedly, will be in demand in volcanological practice.

The total geological effect of Kamchatka volcanoes is estimated at about 50 km^3/1000 years of pyroclastic (*VEI* = 2–7). This is consistent with the total productivity of Kamchatka volcanoes over the past 30 thousand years, which is estimated at 130 km^3/1000 years of all volcanic products, calculated according to geological data [2].

There is unlimited increase in the volume of ejected pyroclastic with an increase in explosive magnitude of eruptions (Figure 6). This is because the parameter b_{diff} of the frequency-magnitude distribution is less than unity. From the considerations of the finiteness of the energy of the magmatic process, there should exist marginal explosive magnitude of eruptions.

The largest explosive eruption of the Opala volcano, 39–40 ka (^{14}C), there was ejected about 250 km^3 of pyroclastics [11]. This corresponds to the explosive magnitude M_{ex} = 11.4. According to available data in the 50,000-year time interval, the author was not able to determine if it is the maximum possible magnitude of the caldera-forming eruptions in Kamchatka or not. In order to answer this question, data are needed on larger eruptions, which are currently not available.

The above estimates for Kamchatka give a general description of modern and ancient volcanic activity on the peninsula and will be useful both for long-term and short-term forecasting, insurance of volcanic risks, and for constructing models for the formation of magmas and their accumulation in the lithosphere. This is especially true of catastrophic eruptions, the most destructive volcanic events.

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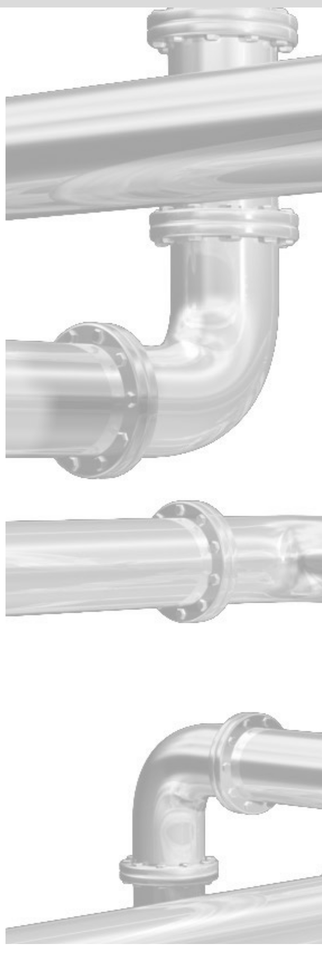

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