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GEOCHEMISTRY

Magma Degassing During 7600 ^{14}C Kurile Lake Caldera-Forming Eruption and Its Climatic Impact[1]

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Abstract—The main goal of this investigation is estimating volume of volatile emission, atmospheric and climatic impact of the Kurile Lake caldera-forming eruption, one of the Earth's largest Holocene explosive eruptions. The volatile content of magma before the eruption was estimated by comparing H_2O, S, Cl and F contents in natural quenched glassy melt inclusions trapped by plagioclase phenocrysts. The volatile content of igneous rocks after eruption was estimated by comparing concentrations of degassed matrix glasses. As a result of KO-eruption not more than $3.7–4.2 \cdot 10^{12}$ kg of water, $4.3–4.9 \cdot 10^{10}$ kg of chlorine, $8.6–9.8 \cdot 10^{9}$ kg of fluorine and $2.6–2.9 \cdot 10^{10}$ kg of sulphur were injected into the atmosphere. This eruption had to produce an important climatic impact.

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Kurile Lake (Southern Kamchatka) was created by caldera-forming eruption ~7600 years ago [1]. This eruption (here and after KO) has formed 76-km^2 caldera. Total tephra volume conservatively estimated of 140–170 km^3 (70–80 km^3 DRE) was dispersed over an area of >2 million km^2 [1]. Pyroclastic material of KO is recorded in Greenland glacier shield [2]. This shows a global effect of this eruption. The main goal of this study was estimation of volatile components volume injected into the atmosphere during KO eruption and its possible climatic impact.

The volatile content in magma before the eruption was estimated by direct measurements of H_2O, S, Cl and F contents in natural quenched glassy melt inclusions trapped by plagioclase phenocrysts. The volatile content in rocks after the eruption was estimated by analyses of matrix glasses in tephra. The major elements were measured with a JEOL JSM-6480LV electron microscope equipped with a EDS (Laboratory of Local Methods, Petrology department, Moscow State University); S, Cl, Mn contents were analyzed with a Cameca SX-100 electron microprobe (Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences); H_2O and F contents were measured by secondary ion mass-spectroscopy with a Cameca 5f ion microprobe (Institute of Microelectronic and Informatic, Russian Academy of Sciences, Yaroslavl).

Samples for the investigation were collected in 2006 from the outcrop on the left bank of the Varvarina river (N 51°09'33", E 157°03'59"), about 2 km to NW from the place of its inflow into the Pacific Ocean ("Three Sisters" bay) and 28.3 km to S from Kurile Lake. KO pyroclastic layer here has a width of about 1.8 m, the upper ~1.5 m of which consists of pyroclastic tuff and the rest part (~0.3 m) consists of two-component tephra. KO tephra represents well-sorted material consisting of pumice fragments up to 3 cm.

300 separate crystals of plagioclase from 0.5–1 mm fraction were selected and mounted into a sample for the study of melt inclusions. Plagioclase phenocrysts from KO have complex zoning, composition variations An_{42}–An_{54} and contain large (up to 200-μm in diameter) glassy natural quenched melt inclusions (figure). Inclusions shape vary from isometric to elongated (length/width ratio is up to 5/1). Most of large inclusions do not contain visible bubbles, but some have a small gas bubble (1% of total volume), which testifies to very fast quenching of tephra during the eruption.

Both melt inclusions and matrix glass in pumice have rhyolitic composition, representing the composition of the main portion of magma in magma chamber before eruption (table). Matrix glasses are slightly depleted in TiO_2 and FeO and richer in SiO_2, Al_2O_3, CaO and Na_2O as compared to melt inclusions that could be explained by Ti-magnetite crystallization during the stages preceding the quench.

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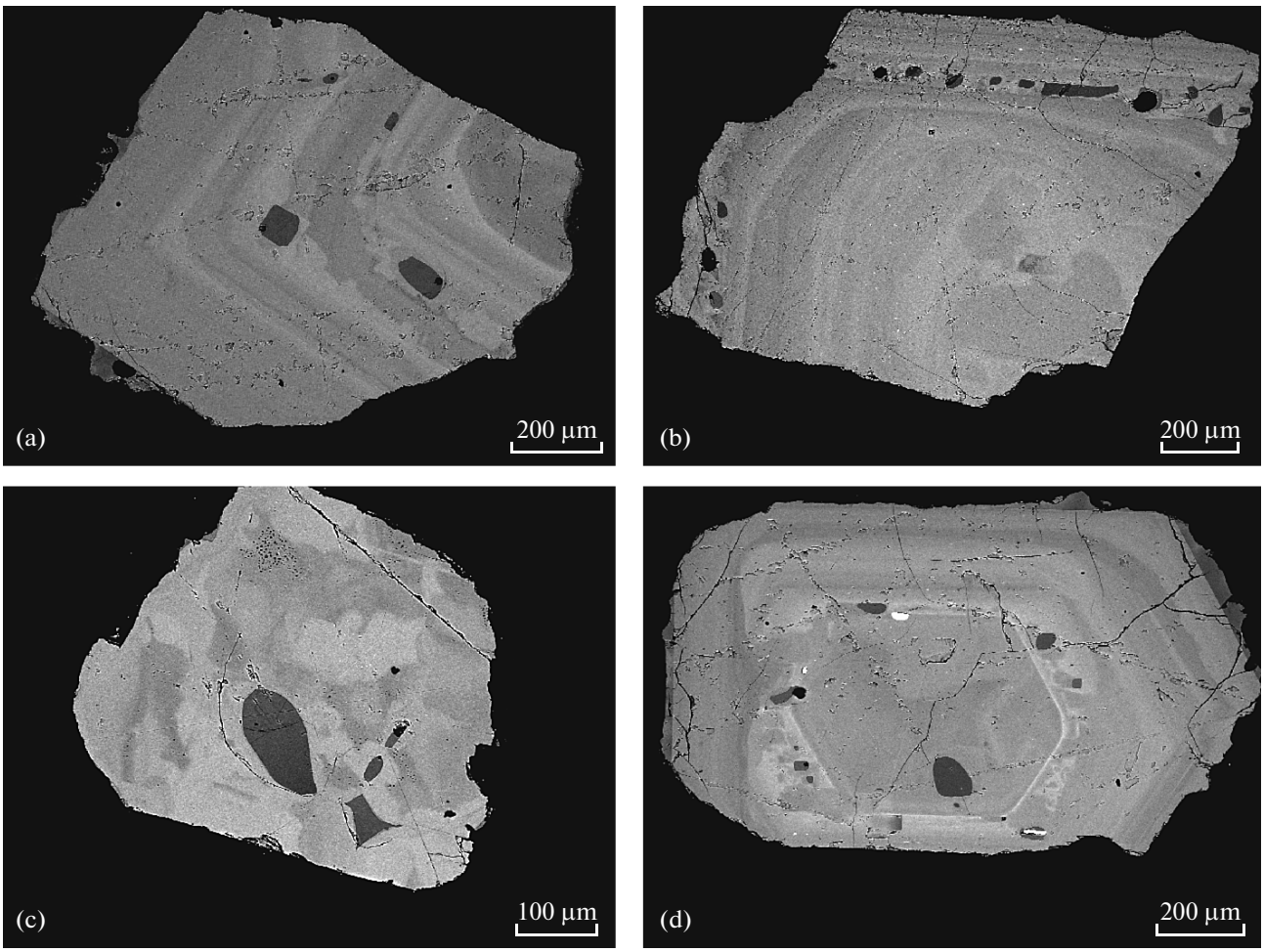

Fig. 1. Glass inclusions in phenocrusts of plagioclase and matrix glass in Kurile Lake tephra: (a) elongated glass inclusion (170 · 60 μm) not in crystal zoning (analyse MI-77); (b) isometric glass inclusion (100 · 100 μm)with bubble(diameter 10 mm) (analyse MI-16); (c) elongated glass inclusion (200 · 30 mm), located in crystal zone (analyse MI-18); (d) matrix glass soldered on phenocryst of plagioclase (analyse Pumice-7).

Significant variations of water content in melt inclusions are due to partial loss of water during magma decompression [3]. Small variations of water content in the sample (5.9–7.5 wt %) argued that degassing effect was not significant. To avoid the effect of water loss in melt inclusions, we approve the maximum measured value (7.5 wt %) as water content in the pre-eruptive melt. Total volume of KO magma is estimated as 70–80 km^3 [1] with total mass $1.7–1.9 \cdot 10^{14}$ kg. Tephra contains ~15% of phenocrysts, most of them are represented by plagioclase and unhydrous mafic minerals. Thus, we can estimate the mass of magmatic melt as $1.4–1.6 \cdot 10^{14}$ kg, and this melt should contains $1–1.2 \cdot 10^{13}$ kg of water.

Each pumice particle has the own degassing and crystallization history, which depends on magma viscosity, particle size, cooling rate, kinetics of bubbles nucleation and other parameters [4]. The solubility of water in rhyolitic melt under atmospheric pressure is less than 0.2 wt %. Water contents measured in KO matrix glasses are much higher than its solubility under 1atm (4.5–5.5 wt %, average 4.94 wt %), which shows partial degasing. Partial degassing is characteristic of caldera-forming and plinian types of volcanic eruptions [5], which related to effective quenching of small particles in the atmosphere. Measured water contents in volcanic ash and pumice particles are similar. It allows us to accept this data for all tephra that has similar cooling regime. Ignimbrites, pyroclastic flows and intracaldera deposits (about 40 vol % of total volume of erupted material) possibly has a lower cooling rate and, therefore, could be more degassed than ash and pumice particles. Volatiles contents in ignimbrites and tephras for caldera-forming eruptions (for example Baitoushan [6]) do not differ systematically, so we can roughly accept the equal water content for all types of tephra.

High water content in matrix glass can be explained by hydration after eruption without visible changes in glass morphology [7]. Positive correlation between

Compositions of glassy melt inclusions and matrix glass in pumice FeO* total iron

Number of grains	An	Size @@@@@ @@, μm	SiO_2[a]	TiO_2[b]	Al_2O_3[a]	FeO*[a]	MnO[b]	MgO[a]	CaO[a]	Na_2O[a]	K_2O[a]	H_2O[в]	Cl[b]	S[b]	F[c]	Total
@@@@@@@@@@@@																
7	50	100 × 20	72.80	0.29	11.76	1.50	0.01	0.29	1.41	4.37	1.87	7.52	0.150	0.014	0.028	102.02
16	51	120 × 120	71.98	0.31	12.16	1.63	0.02	0.30	1.58	4.26	1.96	6.68	0.142	0.012	0.038	101.07
18	42	150 × 20	72.89	0.23	11.61	1.22	0.01	0.18	1.12	4.32	1.91	5.96	0.161	0.012	0.027	99.64
35	54	100 × 120	70.34	0.22	12.20	1.32	0.02	0.29	1.37	3.97	2.19	7.44	0.142	0.019	0.040	99.56
40	42	80 × 80	74.30	0.29	11.42	1.60	0.01	0.33	0.94	4.21	2.00	7.19	0.166	0.002	0.038	102.50
60	45	50 × 50	71.11	0.41	12.75	1.44	0.02	0.24	1.63	4.00	2.17	6.90	0.159	0.004	0.036	100.87
75	51	80 × 60	73.69	0.15	12.05	1.34	0.01	0.27	1.38	4.02	2.15	5.71	0.139	0.013	0.037	100.96
77	52	150 × 70	73.11	0.34	11.82	1.68	0.02	0.30	1.12	4.25	1.97	5.94	0.162	0.012	0.041	100.76
91	43	120 × 80	73.11	0.25	12.35	1.31	0.01	0.22	1.40	4.16	2.04	6.93	0.170	0.021	0.040	102.61
Average			72.66	0.28	12.01	1.45	0.01	0.27	1.33	4.17	2.03	6.70	0.155	0.012	0.036	101.11
@@@@@@@@@			1.67	0.01	0.16	0.03	0.00	0.00	0.05	0.02	0.01	0.46	0.000	0.000	0.000	
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7			74.44	0.23	12.07	1.26	0.01	0.16	1.24	4.23	1.99	4.78	0.129	0.001	0.034	100.57
38			73.73	0.27	13.01	1.53	0.02	0.28	1.48	4.29	1.94	4.60	0.131	0.009	0.039	101.33
40			73.94	0.25	12.52	1.25	0.02	0.22	1.43	4.31	1.92	5.34	0.143	0.000	0.031	101.38
60			75.40	0.28	12.50	1.52	0.02	0.25	1.39	4.16	2.04	4.47	0.150	0.003	0.037	102.22
91			74.26	0.23	12.38	1.41	0.01	0.25	1.48	4.19	2.02	5.49	0.135	0.001	0.033	101.89
Average			74.35	0.25	12.50	1.40	0.02	0.23	1.40	4.24	1.98	4.94	0.138	0.003	0.035	101.48

Note: Compositions of glassy melt inclusions and matrix glass in pumice FeO* total iron.
[a] JEOL JSM-6480LV electron microscope equipped with a EDS.
[b] Cameca SX-100 electron microprobe.
[c] Cameca 5f ion microprobe.

water and chlorine content in matrix glasses argues against significant hydration of tephra by meteoric water. Hydration effect of glasses after eruption cannot be precisely estimated that is why the average volume of water in matrix glass can be regarded as maximum estimation for igneous products. So KO deposits contain $7.1–8.1 \cdot 10^{12}$ kg of water, and as a result of the eruption $3.7–4.2 \cdot 10^{12}$ kg of water was injected into the atmosphere. We used the same method for estimation of Cl, F and S emission and we can conclude that ~$4.3–4.9 \cdot 10^{10}$ kg of chlorine, ~$8.6–9.8 \cdot 10^{9}$ kg of fluorine and ~$2.6–2.9 \cdot 10^{10}$ kg of sulphur were injected into the atmosphere during eruption. Note, that KO glasses kept the essential part of chlorine and fluorine, while most part of sulphur appeared in the atmosphere.

Water vapor, forming clouds, fixes most part of eruption halogenes. It can cause acid rains during the first weeks after the eruption. The cloudy cover significantly affects the atmosphere permeability for solar radiation, but this effect does not last long and has local character. The main effect of volcanic eruptions is the formation of long-living sulphur aerosols in the atmosphere, which leads to the decrease of its permeability for solar radiation and cooling of the earth's surface [8].

Water content in primary melt has maximum values for volcanic fronts and tends to decrease from volcanic fronts to rear-arc [9]. Fluorine and sulphur concentrations, on the opposite, are in the minimum for magmas from volcanic fronts and increase to rear-arc [9]. KO magmas confined to active volcanic front and characterized by high water concentrations and low S and F concentrations, therefore the climatic effect of KO eruption can be compared with much smaller historical eruptions from other geodynamical settings. The amount of sulphur injected into the stratosphere during KO eruption was about 2 times more than after eruptions of Krakatau (1883), Katmai (1910) and Mount Pinatubo (1991), which produced a significant climatic impact [10]. Similar amounts of sulfur degassing were defined for eruptions of the Peruvian volcano Huaynaputina in 1600 (~$2.3 \cdot 10^{10}$ kg of sulphur) and Tambora (Indonesia) in 1815 (~$2.8 \cdot 10^{10}$ kg of sulphur) [10]. The climatic effect of Huaynaputina (1600) and Tambora (1815) is studied relatively well. Both eruptions caused extremely cold summer seasons in many regions for 2–3 years. Tambora eruption

(1815) caused the cold 1816 year in Europe ("year without summer") [10], while Huaynaputina (1600) is responsible for snow in August, 1601 and famine in Russia in 1601–1603 years [11].

Unlike subequatorial volcanic eruptions of Tambora and Huaynaputina, climatic effect of KO eruption, located in north-temperate latitudes, had to be more local and, subsequently, more bitter and long-standing because the transport of sulphuric acid aerosols could be realized only in some parts of Northen Hemisphere and the concentration of those aerosols must be higher.

As a summary, Kurile Lake's eruption (7600 ^{14}C) influx into the atmosphere is $3.7–4.2 \cdot 10^{12}$ kg of water, $\sim 4.3–4.9 \cdot 10^{10}$ kg of clorine, $\sim 8.6–9.8 \cdot 10^{9}$ kg of fluorine and $\sim 2.6–2.9 \cdot 10^{10}$ kg of sulphur. This eruption must have had essential climatic effect, one of the most significant during Holocene.

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