ISSN 0742-0463, Journal of Volcanology and Seismology, 2011, Vol. 5, No. 1, pp. 17–30. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © I.V. Melekestsev, E.V. Kartasheva, T.P. Kirsanova, A.A. Kuz'mina, 2011, published in Vulkanologiya i Seismologiya, 2011, No. 1, pp. 19–32.

Water Contaminated by Fresh Tephra as a Natural Hazard Factor: The 2008–2009 Eruption of Koryakskii Volcano, Kamchatka[1]

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Received January 12, 2009

Abstract—This study is the first to show, using data from the eruption of Koryakskii Volcano, Kamchatka that began in December 2008 and continued through 2009 that the water in permanent and temporary streams that start on the slopes of the volcanic cone and in temporary lakes when contaminated with fresh tephra is a specific hazard factor related to long-continued hydrothermal–phreatic eruptions on that volcano. This water is characterized by increased acidity (pH 4.1–4.35) and large amounts (up to 50–100 cm^3/liter) of solid suspension and is unfit for drinking and irrigation. When combined with tephra, it probably produced mass destruction of a number of animals who lived on the slopes and at the base of the volcano. The water contaminated with tephra is an important component of the atmospheric mud flows occurring on Koryakskii Volcano; for several future years it will be a potential source for enhancing the acidity of ground water in the volcanic edifice.

DOI: 10.1134/S0742046311010064

INTRODUCTION

The active Koryakskii Volcano (53°17′N, 158°54′E, absolute height of the summit is 3456 m) (Fig. 1) in Kamchatka is the nearest (25–26 km to the northeast) to the town of Elizovo, which is second in population in Kamchatskii Krai. Still nearer (24–25 km to the northeast) to the volcano is the international Elizovo airport. The southwestern and southern sectors of the volcano's base contain numerous lawn-and-garden associations (LGA) and the end segment of the gas pipeline of Krai significance going from the Kshuk gas field in western Kamchatka to the town of Petropavlovsk-Kamchatskii. The distance to the volcano's crater is a mere 15–20 km. Moreover, Koryakskii Volcano itself is considered to pose a very great hazard by many investigators [Marenina et al., 1962; Masurenkov et al., 1991; Melekestsev, 1996; Melekestsev et al., 2009]. For this reason any data relating to known or other possible kinds of volcanic hazard, as well as other dangerous phenomena and processes due to its eruptions, have practical importance in addition to theoretical significance. The greater the amount of these data, the more accurately one can predict dangerous consequences from future eruptions and minimize the related loss to the population and infrastructure close to the volcano.

On the other hand, there is little information on the volcanic hazard associated with eruptions of Koryakskii Volcano or with the processes and phenomena that are directly related to these. This state of affairs is due to two main factors. In the first place, the volcano did not show significant activity during the 18th–19th centuries, with even moderate eruptions being absent, while fumarole activity occurred episodically separated by long intervals of time. For this reason the first explorers of Kamchatka, S.P. Krasheninnikov [1994] and G.V. Steller [1999] did not classify Koryakskii either as a "fire-emitting" (erupting) volcano or as a "smoking" one, which showed appreciable fumarole activity in the first half of the 18th century. Some signs of the latter kind of activity were discovered there by A. Postel's [1836] as late as in 1827–1828: "a little smoke" on the northward slope. Even in later times K. von Ditmar [1901] thought the volcano to be extinct, since he never noticed any traces of its activity during the time of his observation (1851–1855), nor could he find any indication of such activity in publications of other explorers, although an acquaintance of his, the chief of the village of Avacha, said that some smoke was occasionally emitted by the volcano's crater.

The first convincing evidence for Koryakskii activity was published by V. Margaritov [1899]: "steam is emitted in a continuous and comparatively thin jet"

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[1] Contamination as understood here is the enrichment of rain and thaw water, as well as the water in rivers, brooks, "dry" rivers, and lakes around Koryakskii Volcano (in the zone of the 2008–2009 most intensive and frequent ashfalls) with the components that were leached and washed out of fresh volcanic ash and with ash itself (in the form of solid suspension.

Fig. 1. Koryakskii Volcano at the start of the eruption (December 28, 2008). View from the south. Photographed by A.F. D'yakov.

from a fissure somewhat down the southwestern slope [Margaritov, 1899, p. 54]. The fissure probably appeared in 1894–1895 as a response to a major, nearly simultaneous eruption of the neighboring Avacha Volcano, because almost every large eruption of this volcano has been accompanied by increased fumarole activity of Koryakskii Volcano since 1827 during the 19th–20th centuries [Melekestsev, 2009].

The first known historical eruption of Koryakskii was recorded [Novograblenov, 1926] on December 22, 1926, when the volcano emitted a black gas plume from the vent of the western summit at 15 h 30 min local time; the snow on the slopes of the volcanic cone became black from the ash that fell down from the eruptive plume. Such an event can probably be classified as a weak phreatic eruption.

Later, until the end of 1956 (i.e., during 30 years), the volcano merely showed episodic, low-intensity, fumarole activity [Marenina et al., 1962].

The only eruption of Koryakskii that has been studied in more or less detail (its products and the kinds of volcanic hazard) occurred in 1956–1957. The start of this eruption was recorded by G.S. Gorshkov [1958] during a flight in late December 1956, the course of the eruption was observed by A.N. Sirin between January 20 and March 15, and the ejecta were studied by K.M. Timerbaeva [Sirin et al., 1959]. According to these observations, the event was a weak phreatic eruption, with some inconsiderable hazard being posed by small ashfalls at distances of 20–30 km from the eruptive center and by short-lived lahars in the near-summit portion of the volcano's northwestern sector. The area that was covered by ash at one time did not exceed 3–4 km^2. The mean height of ejecta thrown by explosions was 150–200 m (with the maximum 350 m) above the vent at velocities ranging between 40–50 and 150 m/s. Each explosive series consisted of 3–4 explosions with interexplosion intervals occasionally reaching 30 min.

The explosions at the summit crater were nearly vertical, and inclined when in the fissure. In the latter case the gas plume began (after a delay of 1–2 s) sliding down the slope of the cone at velocities as large as 30–35 m/s for distances of 500–700 m. Some 10–15 s after an explosion, the ash particles from the eruptive plume completely precipitated and the gases were scattered [Sirin et al., 1959].

To sum up, there have been only three kinds of volcanic hazard associated with the historical Koryakskii eruptions of the 19th–20th centuries: weak phreatic explosions, small ashfalls, and short-lived lahars.

Secondly, the lack of data on the other kinds of hazard due to prehistoric eruptions of the volcano stems from the insufficient knowledge of its eruptive activity for the few past millennia. For example, judging from the materials of publications [Marenina et al., 1962; Masurenkov et al., 1991] concerned with the geological structure and evolution of Koryakskii Volcano during Holocene time (the last 11500–11600 years as recently defined), the hazards of historical time must be supplemented with only the hazard due to lava flows and catastrophic lahars.

Now the continuing eruption of 2008–2009 supplied data from which one can refine its type, as well as identifying and describing (see sections 1 and 2) another, as yet unknown type of hazard due to Koryakskii eruptions, viz., the water of permanent and temporary streams that originate on its slopes and are flowing along the southwestern and southern sectors of the volcano's base within developed and populated territories and the water of temporary lakes and pools at the sources of these streams. The material for the

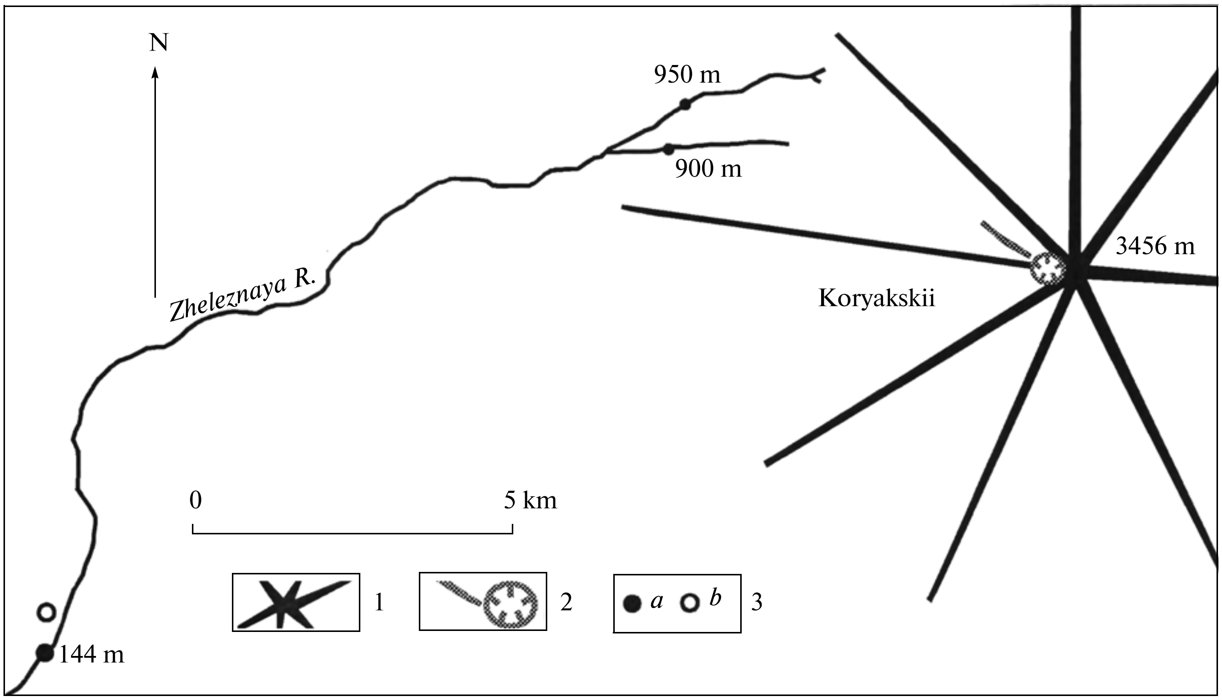

Fig. 2. Water sampling sites (the Zheleznaya River and its left tributary): (1) Koryakskii edifice, (2) western crater and eruptive fissure responsible for the 1956–1957 and 2008–2009 eruptions on Koryakskii, (3) water sampling sites (*a*) and the well (*b*) in the Shiveluch LGA.

assessment of this kind of hazard was acquired by I.V. Melekestsev and colleagues during field surveys of Koryakskii Volcano erupting in the summer of 2009; samples of water and solid precipitates were analyzed by E.V. Kartasheva, S.V. Sergeeva, and A.A. Kuz'mina at the Analytical Center of the Institute of Volcanology and Seismology (IV&S), Far East Division (FED) of the Russian Academy of Sciences (RAS).

Water samples were deposited in 1.5-liter plastic vessels (Fig. 2); the sampling sites were the bed of the Zheleznaya River in the Shiveluch LGA (at an altitude of 144 m), in its middle reaches; in the river's upper reaches (at an altitude of 900 m), and the bed of the left tributary of the Zheleznaya River (at an altitude of 900 m). For comparison purposes we also took a water sample from a 110 m deep well in the Shiveluch LGA, which was drilled down to an altitude of ≈79 m, i.e., 65 m below the level of the Zheleznaya River in this LGA.

We have determined the anion–cation macrocomposition and the concentrations of several microcomponents. We did not seal the samples for future determinations of trace elements. For this reason some heavy metals may have partly precipitated from the volume being analyzed into the precipitate and the vessel walls. The solid phase contained in the samples was analyzed. On decanting and drying we determined the mass percentage of the solid ash phase and this material was used to make pressed radiators for X-ray fluorescent analysis. For comparison we also quote results from an analysis of fresh ashes discharged by Koryakskii Volcano in the hope of detecting the elements that enrich the water of a natural spring during the leaching of volcanic ash.

The above set of analytical studies was primarily required because the composition of the natural surface water and ground water is a major geochemical and ecological factor, considering that the properties of water exert direct biochemical effects on all living things, including the human body and its physiological functions [Krainov et al., 2004; Fomin, 1995]. This is all the more necessary around active volcanoes, because surface water and ground water are under direct effects due to volcanic eruptions.

SOME FEATURES IN THE 2008–2009 ERUPTION OF KORYAKSKII VOLCANO

The first eruption of Koryakskii to occur in the 21st century began in late December of 2008 following a 52-year period of relative repose and it is still continuing (September 2009). It is true, the eruption was not altogether unexpected, since it was preceded by noticeable premonitory seismicity around the volcano and beneath it since the spring of 2008 as recorded by workers at the Kamchatka Branch of the RAS Geophysical Service [Koryaksky..., 2009]. The seismicity

Fig. 3. Three eruptive vents in the northwestern sector of the Koryakskii summit portion in January 2009. Photographed by A.V. Sokorenko.

in question began occurring in late March—early April as an earthquake swarm (Ks = 3.5–7.8) at depths of 4–10 km below sea level in a 8-kilometer-long nearly north–south zone that is situated both north of Koryakskii and beneath its northern flank. Since mid-June 2008 small seismic events began to be recorded beneath the volcano itself. This seismicity was on the increase in October nearly simultaneously with increased fumarole activity on the volcano. The first signs of ash mixed in with the eruptive plume were detected from December 24, 2008, and this date should be considered as the beginning of the eruption.

It should be noted, however, that an increased rate of small earthquakes around Koryakskii Volcano and beneath it cannot be an ambiguous precursor of an eruption. This was the case in 1994 with a similar increased seismicity rate in the volcano area that did not culminate in an eruption.

The 2008–2009 eruptive centers were confined to the 500–600-m set of fissures going down the slope in the northwestern sector of the near-summit part of the volcanic cone, in the range of absolute altitude between 3000 and 2700 m. This was the same set of fissures that was operative in 1956–1957 during the previous eruption. The only difference consisted in the fact that the eruptive centers during the paroxysmal phase of the previous eruption, in January 1957, were situated along the entire length of the fissure zone and were at least ten in number, while there were three such centers in January 2009 (Fig. 3) and afterwards two, at the absolute altitudes of 2980 and 2745 m (measurements by A.V. Sokorenko and N.V. Gorbach made on August 1, 2009). The first ashfalls occurred in December 28, 2008 and continued at a varying rate and intensity in the spring and summer of 2009. The most recent ashfall took place during a few days in the second half of August 2009. The ashfall zones were usually close to the volcano and the maximum ashfall length did not exceed 15–20 km. Some rare exceptions included ashfall zones as long as 30–40 km. However, the KVERT (Kamchatkan Volcanic Eruption Response Team) IV&S analyzed satellite imagery taken by the TERRA, NOAA, and MTSAT spacecraft to conclude that aerosol plumes with increased concentrations of SO_2 extended for over 220 km from Koryakskii Volcano [Koryaksky..., 2009]. One feature that distinguished the eruption during the entire time of visual observation consisted in the absence of powerful explosions. Even smaller explosions seem to have occurred only at the very earliest phase of the eruption when the volcano was shrouded in clouds and was inaccessible to direct observation. At all other times the vents discharged steam and steam-and-gas jets with mixed ash particles at great velocities. In January 2009, when three vents were active (see Fig. 3), volcanic ash was discharged from the upper vent only. The ash concentration in the steam-and-gas jet varied in wide limits, which could well be discerned by noting the varying color of the eruptive plume, from very light grey, nearly white (with a low concentration of ash particles) to dark grey (with a much higher ash concentration). The tephra intensity and distance of precipitation varied accordingly. However, in all cases the intensity of individual ashfalls remained rather low; the thickness of fallen tephra was a fraction of a millimeter at distances of 10–20 km from the eruptive centers and only very fine tephra that was not in a continuous layer was recorded at greater distances on the ground surface. As reported by Ovsyannikov et al. [2009], the ash density per unit area on the north–northwestern slope of Koryakskii Volcano was 5.84 g/m^2 at a distance of 5.5 km from the eruptive center; the figure for the northwestern slope 2.5 km from the eruptive center was 25.55 g/m^2. With the volumetric density common to fresh-fallen Kamchatka ashes (0.6–1.2 g/cm^3), the ash layer would be 0.005–0.010 mm thick for the former case and 0.020–0.040 mm for the latter case, as estimated by I.V. Melekestsev. The tephra can be characterized in terms of its grain size as aleuropelitic, with the <0.1-mm fraction making 91 to 85%, respectively [Ovsyannikov et al., 2009]. It was only on the main summit of Koryakskii that mountaineers found a sequence of tephra mixed with snow, with the total being 4–5 cm thick (personal communication by O.A. Girina). It is not known how many ashfalls were involved in it, or the length of time.

In the west–northwestern sector of the volcano's base (absolute altitude 950 m, ≈5 km from the eruptive center), I.V. Melekestsev measured the total thickness of fine aleuropelitic tephra that was deposited in January–June 2009 from the snow on the flat surface of stone blocks and obtained values of 0.5 to 1.5 cm.

There were two active vents after January, ash was still discharged from the upper vent only episodically, with the intervals between ash discharges being a few days to 1 month. The observed behavior of ash discharge episodes during this eruption (the discharges were longer and more frequent at the initial phase and shorter and less frequent afterwards) suggests that the first 1–2 months included a thorough cleaning of conduits that supplied material to the fissure zone throughout the entire length of these conduits; the later activities involved cleaning of some segments in these conduits that had been blocked up during the continuing eruption.

According to a crude estimate by I.V. Melekestsev based on a limited number of observation sites, the total volume of discharged ash for the period December 2008 to September 2009 did not exceed 0.5–1 million m^3. With this volume converted to the density of the edifice ($\rho = 2.0–2.5$ g/cm^3), we get about 0.35 million m^3.

During the "quiet" intervals between ash discharges, when the eruption was less vigorous (e.g., in July 2009), one could frequently see that the vent was emitting two jets, a steam jet (white and opaque) and a gas jet (bluish and almost transparent). The steam was soon scattered in the air and the gas was borne away by the wind in the shape of a well-pronounced plume. Occasionally there was no steam discharge at all and only gas was emitted.

One specific feature of the 2008–2009 tephra was its invariable habit, which persisted during the entire period. The tephra was very fine (aleuropelitic with a small mixture of fine-grained sand), both near the eruptive center and 15–20 km from it, where the tephra could still be sampled without admixtures. The tephra also had a constant chemical composition (Table 1) during the eruption (from late December 2008 to September 2009). The same composition was typical of the tephra that was found in suspended form in the waters of the rivers and brooks originating on Koryakskii Volcano (see Table 1). The composition is formally consistent with dacite judging by the concentration of SiO_2 (64.34–64.46%) in the tephra samples (dry basis analysis). However, both the morphology and the mineral composition of tephra particles are obviously inconsistent with this inference. According to [Ovsyannikov et al., 2009], the ash particles are mostly rounded and consist of fragments of rocks and crystals of plagioclase, pyroxene, pyrite, and other minerals of hydrothermal origin. There are also unusual crusts of unknown origin and septaria with tiny mottled particles sticking around them. A high (≈1%) concentration of sulfur is typical. The presence of pyrite crystals and other minerals of hydrothermal origin provides a clear indication that the 2008–2009 Koryakskii tephra is not juvenile.

One also notes a high concentration of SiO_2 in the tephra that is unusual for Koryakskii. This high concentration of SiO_2 has not been reported to date for the rocks in the volcanic edifice itself, in the lava flows at the base, or in the tephra horizons that certainly derive from the earlier eruptions of the volcano. According to [Marenina et al., 1962; Masurenkov et al., 1991], the concentration does not exceed 57–58% anywhere. However, the increased concentration of SiO_2 in the 2008–2009 tephra can be attributed to a considerable admixture of amorphous silica particles based on X-ray analysis results (personal communication of L.P. Vergasova).

What the origin of this silica is and how it came to be present in the tephra remains unknown. One can merely hypothesize that it was most probably deposited from a hot hydrothermal fluid. The source of this fluid may have been the hydrothermal system confined to an extensive volcano-tectonic feature, which is given different names by different investigators: Avacha graben [Moroz, 2009, etc.], a thermal rift [Masurenkov et al., 1991], and (I.V. Melekestsev) a giant caldera (caldera complex) of the Krakatau type. This structure contains the active Late Pleistocene–Holocene Koryakskii Volcano and the Arik–Aag volcanic massif that became extinct long ago. The massif was formed during Middle to Early Upper Pleistocene time; its rocks compose the base of the Koryakskii edi-

Table 1. Chemical composition and concentration (ppm) of rare earths in the 2008–2009 tephra and in the solid suspension contained in the water

Components	Tephra		Suspension in water	
	M-2	M-3	950 m	900 m
SiO_2	63.10	62.40	64.40	63.84
TiO_2	0.842	0.802	0.796	0.749
Al_2O_3	13.10	13.20	15.60	15.43
$Fe_2O_3 + FeO$	7.05	7.43	6.65	6.83
MnO	0.148	0.115	0.077	0.074
CaO	5.64	5.49	4.69	4.24
MgO	3.63	2.79	2.46	2.76
Na_2O	2.43	2.37	2.45	2.42
K_2O	1.23	1.26	1.21	1.25
P_2O_5	0.168	0.173	0.192	0.196
LOI	2.00	2.52	–	–
S	0.938	1.03	1.30	0.534
F	0.0306	0.0297	0.033	0.072
S	99.97	99.95	99.86	98.40
Sc	27	29	24	24
V	205	195	162	157
Cr	35	34	29	33
Ni	12	14	6.3	0
Cu	79	82	40	20
Zn	103	103	59	30
As	9	4	13	5
Rb	20	18	16	4
Sr	428	379	447	154
Y	30	26	17	18
Zr	108	95	105	41
Nb	2	2	2	3
Mo	0	0	4	4
Ba	549	549	526	535
La	7	2	5	4
Ce	59	60	24	26
Pb	22	17	23	21
Th	5	4	3	3

Notes: M-2 and M-3 denotes tephra from A.P. Maksimov's collection (December 2008 to January 2009); 950 m (July 17, 2009) and 900 m (July 18, 2009) denotes solid suspension in the water of the Zheleznaya and its tributary. The analyses were made at the Analytical Center, IV&S FED RAS by X-ray fluorescent spectrometry. Analysts E.V. Kartasheva, S.V. Sergeeva, and N.I. Chebrova

fice. The Arik–Aag massif and Koryakskii Volcano are in contact at the pass between the two at an absolute altitude of 1540 m. Graphical constructions made by I.V. Melekestsev show that the base of the central part of the Koryakskii cone is supposedly at absolute altitudes of 0 to 500 m, while the caldera bottom is 1000–2000 m below sea level. It can therefore be supposed that the maximum length of the conduit of the eruption must be on the order of 4–4.5 km (from +3000 m to –1500 m).

According to Moroz [2009], the above volcanic–tectonic feature is filled with high conductivity deposits from hydrothermal solutions and a lower density of rocks, which is due to the origin of these deposits, in the opinion of I.V. Melekestsev. The deposits are probably intracaldera pyroclastic sequences (pumice and pumice-like rocks) saturated with hot mineralized solutions that were produced by caldera-generating eruptions of andesitic or more acid compositions. Moroz [2009] even recommends drilling wells 4 km deep in this feature in order to assess the potential of a hypothetical hydrothermal field. The position of the caldera bottom below sea level beneath Koryakskii Volcano is fairly well consistent with an analyses of its fumarole gases sampled in 1983 [Taran, 1985]. It was shown that the isotope composition of gases in these fumaroles is obviously similar by deuterium concentration to the compositions of the so-called metamorphic or sea waters that have been altered by hot interaction with the rock and been mixed with meteoric waters.

Potapov et al. [2003] demonstrated how silica accumulates in hydrothermal solutions in the Mutnovskii hydrothermal system, which is also confined to a large caldera, and how it is liberated at the surface. It is to be thought that similar processes are probably occurring during the present eruption of Koryakskii Volcano. The silica-rich hot jet(s) of the hot hydrothermal fluid rapidly rises from the magma chamber of the buried caldera along the fissure zone, but loses its high velocity on leaving the vent and rapidly cools, thus precipitating amorphous silica, because the solution becomes oversaturated with silica. According to Potapov et al. [2003], the solubility of amorphous silica in a water solution decreases with decreasing temperature, being 940.8 mg/kg at 200°C, 405.3 mg/kg at 100°C, and 130.8 mg/kg at 25°C.

It is supposed that the heat of the magma chamber beneath the buried caldera, the hydrothermal fluid rising from it, and the amorphous silica particles deposited from the fluid constitute one of the main sources that supplied the motive force for and the ejecta of the 2008–2009 eruption. As to the hot gas enriched with SO_2, it can more probably be produced by degassing of the still warm large-volume "roots' of Koryakskii Volcano, which still comparatively recently maintained its powerful explosive–effusive and effusive activity in the time spans from 9700–6000 and 3350–3150 years ago [Bazanova et al., 2009], as well as by degassing of conduits that supplied large volumes of material for Holocene lava flows. To a first approximation it may be supposed that these are sill bodies and thick dikes that are similar in chemical composition to the coeval igneous rocks that were emplaced into the volcanic edifice itself and under its base. Judging by the total volume and weight of the lavas discharged at that time and the ejected juvenile pyroclastics (by a preliminary estimate due to I.V. Melekestsev, on the order of 8–10 km^3 and 16×10^9 t), the volume of these sill bodies must be at least 10 km^3. A contribution of their own might be also supplied by the magmatic "roots" of very young (650 and 730 years as estimated by Bazanova et al. [2009]) explosive–effusive formations of Koryakskii Volcano itself and the forms that were related to the operation of transitional basaltic (magnesian basalts) volcanism occurring during the last 3000 years.

It can therefore be concluded that there were probably three sources of heat and steam–gas supply for the 2008–2009 eruption: the heat and gas came from the hydrothermal system in the large caldera buried under Koryakskii Volcano; the heat, gas, and steam were due to the magmatic "roots" that still remained at depth, which were the source of supply for the summit and parasitic eruptions on Koryakskii Volcano, as well as for the parasitic centers of transitional magnesian-basaltic volcanism.

The tephra of this eruption is also a polygenetic product judging from its habit and mineral composition. On the whole it is obviously resurgent, since no juvenile material has been detected in it, and it consists of at least two components. Its main component includes fragments of rocks, variously altered by fumarole and hydrothermal processes, from the fissure zone that bisects the northwestern sector of the Koryakskii edifice. The second component consists of particles of amorphous silica that precipitated from hydrothermal fluids.

At what time the fissure zone came into being or how deep its bottom is have not been exactly determined. It is however known [Margaritov, 1899] that the fissure zone was in place in the late 19th century. Indirect evidence of the great depth for this fissure zone can be found in fresh volcanic glass with a refractive index of 1.513 [Sirin et al., 1959], which was discovered in the tephra of the 1956–1957 eruption; the refractive index is typical of a glass with SiO_2 concentration equal to 67%, a value typical of dacite or andesitic–dacite rocks. No such rocks have been found in the Koryakskii volcanic edifice, but they are typical of the Arik–Aag volcanic massif. Now the rocks of that massif underlie Koryakskii Volcano, hypothetically at depths of 2500–3000 m below the issues of the vents that were active in 1956–1957 and 2008–2009 (see above).

Based on the above data relating to the phenomenology and geological and geomorphic impact of the 2008–2009 eruption, one can define its type as hydrothermal–phreatic, in size it is weak to moderate, and its conduit can be compared with the giant natural "well" that rises from a depth of 4–4.5 km, parallel and almost abutting the conduit of Koryakskii Volcano. The last conclusion is based on the fact that the mouth of the upper vent, the most active one that was involved in the eruption under study is close to the youngest crater of that volcano, being a mere 300–350 m along a straight line from the rim of that crater. In addition, it transpired as a result of the aerial photographic survey conducted on Koryakskii Volcano on October 19, 2009 that the heating took place also immediately at the center of the Koryakskii crater where an oval-shaped funnel was thawed in the glacier 70 by 60 m along the rim and about 20 m deep with a hypothetical lake in the bottom.

The previous multicenter eruption of 1956–1957 was very similar to the 2008–2009 eruption in nearly all parameters; in 1956–1957, more than ten eruptive centers were situated on a radial fissure, but fumarole activity was also observed in the summit crater [Gorshkov, 1958; Sirin et al., 1959]. Judging by the description in [Novograblenov, 1926], the 1926 eruption can be regarded as phreatic, with a single explosion occurring on December 22. The explosion was preceded by increased fumarole activity, which also continued after the eruption in a reduced form. Neither this author (in 1994–1995 and 2009) nor other investigators have succeeded in discovering any traces of fallen ash. It seems that the 1926 eruption was also generally similar to the subsequent eruptions of 1956–1957 and 2008–2009. The similarities consist, among other things, in characteristic features observed in the discharge, deposition, accumulation, and preservation of the tephra. In all cases tephra was discharged, but in insignificant volumes, the ashfalls were low in intensity, and no extended tephra layers and members thicker than 1 cm formed, even near to the eruptive center. It is because of this that any traces of ashfalls, even very recent ones, rapidly disappeared. For example, nobody saw the 1956–1957 tephra in sections of the soil–pyroclastic cover on Koryakskii, although it was deposited there [Sirin et al., 1959]. The same fate probably awaits the 2008–2009 tephra.

The fact that all three eruptions of Koryakskii that occurred in 1926 were of the same type and were associated with the fissure zone in the northwestern sector of the Koryakskii cone that appeared (or was pre-existent but showed low activity) in the late 19th century, along with the absence of any considerable volcanic activity of a different type during the previous few hundred years, all suggest a preliminary conclusion (until more complete data on its historical eruptions become available) that hydrothermal phreatic eruptions are the most characteristic type for the current phase in the evolution of this volcano. The phase is an understandable sequel to the 3000-year phase of rapidly waning eruptive activity of the volcano [Bazanova et al., 2009].

It is also a logical supposition that the precursory processes before hydrothermal phreatic eruptions occurring during the recent phase of the Koryakskii eruptive history follow one and the same pattern. The culminating phase accompanied by ash discharges is followed by a gradually waning eruptive activity with simultaneous decrease in fumarole activity, but this activity does not completely cease, even after the lapse of several decades. At the same time, the system of conduits in the fissure zone begins to experience colmatage by fine-grained clay minerals that form by disintegration of volcanic rocks due to chemically aggressive hydrothermal solutions and steam-and-gas mixtures, as well as by gypsum, amorphous silica, limonite, and other minerals precipitating in fissures. All these widely occur in the mineral part of the resurgent tephra [Ovsyannikov et al., 2009] that was discharged during cleaning of the renewable conduits that supply material for the next eruption. The transport of gaseous products from great depths decreases at first and then stops altogether, even though they continue to accumulate there. When a deeper caldera source is cut off, the weaker fumarole activity between eruptions seems to be largely maintained by the heat and degassing of the magmatic “roots” that had been emplaced in the Koryakskii edifice, these roots supply the material for its parasitic and summit eruptions during Holocene time.

The accumulation of heat and material for each subsequent hydrothermal phreatic eruption continued for approximately 30 years. Next, probably when the accumulated deep-seated steam-and-gas mixture reached the critical pressure, the colmatage-affected fissure zone began to be cleaned with accompanying seismicity increase, and the system of conduits for a new eruption formed.

It should, however, be noted that the 2008–2009 eruption was as a matter of fact in preparation for nearly 52 years rather than 30 years. However, it could just as well have occurred in 1994, when the premonitory phase of increased seismic activity was observed beneath Koryakskii Volcano, i.e., after approximately 28 years (March 1957 to late December 2008). At that time, however, the fissure zone was probably not opened and no eruption took place. It is not impossible that the processes that were then occurring beneath Koryakskii Volcano proved to be less powerful than was needed to produce an eruption. This can in particular be inferred from the lower (at least by an order of magnitude) overall seismicity in 1994 compared with that in 2008–2009.

WATER STRONGLY CONTAMINATED BY FRESH TEPHRA AS A SPECIFIC HAZARD FACTOR DURING HYDROTHERMAL PHREATIC ERUPTIONS

The study of permanent and temporary streams that start from the cone of the erupting Koryakskii Volcano and of the water in these streams was conducted by workers at the Laboratory of Dynamical Volcanology of the IV&S FED RAS as part of the continuing work to assess volcanic hazard emanating from the current and future eruptions of that volcano.

The first thing that was noticed during field work was the erosional and accretional activity of water streams, which was uncommonly vigorous for the season (the second half of July to August), a high flow velocity (up to 3–5 m/s), grey color, and the great turbidity of the dirty water (Fig. 4). The beds of temporary streams generally dry up in the second half of the summer here, the water in permanent small rivers and brooks is clear, while the flow velocity does not exceed 1–2 m/s. Field work around the sources of the streams revealed that all of these anomalous phenomena and processes were due to exceptionally rapid thawing of perennial snow patches that supply water. The snow patches occupied much smaller areas (by factors of 2–3) in July 2009 compared with the September 1974 aerial photographs. Many larger snow patches shown in these photographs have disappeared.

Two main causes of this rapid thawing and the unusually vigorous dynamics of the associated streams were identified. The first is the abnormally sunny and hot (for Kamchatka) weather in July–August. Secondly, the thin (from 1–2 mm to 1–2 cm), nearly continuous cover of a grey to dark grey, wet volcanic ash on the surface of the snow patches (Fig. 5) favors intensive ablation. The bulk of this ash was deposited on the ground from the seasonal snow cover that melted: the ash was buried during winter snowfalls. The rest of the ash is the contribution of still more recent spring–summer ashfalls from this eruption and this ash was deposited upon the surface of thawing snow patches.

The same process occurred in June and the first half of July, before our field work began. The main causes were the same, viz., the summer heat and the volcanic ash that had been deposited and was still falling. However, the bulk of the water came into the beds of permanent and temporary streams from the thawing, thick (2–3 m), seasonal snow cover that was saturated with tephra admixture and interlayers throughout its thickness due to the winter and spring eruption. Gradually, the dark deposited ash that constantly covered the snow surface, combined with the sunny and hot weather, had so intensified the thawing process that the cover completely disappeared in June, a month earlier than usual. Naturally enough, the pereletok snow patches and glaciers were thawing too, but the contribution due to these was smaller at the time.

As a result of the active influence of all these factors, it was only the thickest (20 m) pereletok snow patches that persisted until early September 2009, but these were much reduced in size. As before, their surface continued to be covered with ash, and they continued thawing, although less rapidly. Much less water was then coming from the glaciers, which were then become much thinner. The overall thawing of the preserved snow patches and glaciers was decelerated thanks to the dramatic temperature drop and increased cloudiness in September. The much smaller volume of thaw water resulted in most of the temporary streams drying up, while the remaining ones had water for several hours per day. The water discharge of the permanent streams was reduced by factors of 5–10, the same was true of turbidity.

However, at the same time as the 2008–2009 ash lying on the ground surface was being washed down (including the ash lying on the preserved glacier fragments), the role of the start of intensive rain grew and water contaminated with this ash gave rise to episodic mudflows. One of these mudflows went along the Khitryi Brook valley on September 1, 2009, reached a busy highway in the southern sector of the Koryakskii base, and flooded several houses; its deposits, which were as thick as 2–2.5 m, blocked the road and completely stopped the drainage collector under it.

All these changes could be clearly seen in the Zheleznaya River and its tributaries that start in the western and southwestern sectors of the Koryakskii cone. The task was facilitated by the fact that the Zheleznaya middle and upper reaches lie in LGA areas and the changes in flow velocity, discharge, and turbidity were noticed by the residents in early June 2009 when the thawing of the snow cover dramatically intensified, while the eruption on Koryakskii continued.

The Zheleznaya River was usually a small brook with almost transparent water and a flow velocity of 1–1.5 m/s at that time of year in the past. In 2009, however, the situation thoroughly changed, the river became an impetuous stream with very muddy water and a flow velocity of about 3 m/s, the discharge increased by a factor of 5–10, and the water acquired a grey color. Accordingly, water was sampled at an altitude of 144 m in the Shiveluch LGA and was afterwards subjected to hydrochemical analysis to study the salinity and material composition of the solid suspension. The sample was taken in the first half of the day when the discharge was close to the daily minimum and the flow velocity did not exceed 2 m/s. Observation showed that the maximum flow velocity, discharge and turbidity of the water were characteristic for evening and the first morning hours at this location.

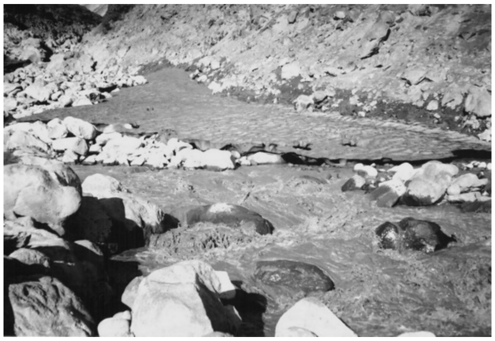

Fig. 4. Rapid current of dirty water in the Zheleznaya River, absolute altitude ~950 m. At middle distance is a residual snow patch covered with ash. Photographed by I.V. Melekestsev.

Fig. 5. Ash layer (dark) on the surface of a snow patch. Photographed by A. Yakovleva.

A water sample was taken at 950 m altitude in the upper reaches of the Zheleznaya River at about 06:00 p.m. on July 17; the flow velocity was on the order of 3–3.5 m/s with a discharge of 8–10 m^3/s. Later observations showed that these values too are not the limit for the river locality sampled with regard to all the parameters recorded. Sometimes “semi-mud” (Fig. 6) sped at a great velocity along the river bed with the volume of solid suspension (mostly volcanic ash) up to 50–100 cm^3 per liter in this “water.” It was next

Fig. 6. "Semidirt" in the Zheleznaya upper reaches. At the center is an intact fragment of a snow patch covered by volcanic ash. The white ash cover envelopes blocks and boulders on the banks. Photographed by I.V. Melekestsev.

to impossible to cross the Zheleznaya at times such as these, even with a depth of 40–50 cm.

The water sample in the Zheleznaya middle reaches at 900 m altitude was taken at 10:00 a.m. on the morning of July 18, when the water had nearly its minimum velocity (≈2 m/s), discharge (1–1.5 m^3/s), and turbidity (milky, light grey color). In the evening the situation changed radically, as was the case for the Zheleznaya: the flow velocity exceeded 3 m/s, the discharge increased by factors of at least 2–3, while the milky, light grey water has also become "semi-mud" carrying great amounts of a solid suspension, mostly volcanic ash again.

The results of chemical analysis for all these samples are shown in Table 2.

It can be clearly seen that the Zheleznaya water in the lower and middle reaches is of one and the same type, in spite of some differences (in salinity and the quantitative concentrations of the components that are directly controlled by the ash suspension volume). In both cases the water is sulfate–calcic, acid, and has a similar chemical formula: $M_{0.064} = \frac{SO_4 85 HCO_3 7 C17}{Ca88Mg10Nal}$ pH 4.15 (the Shiveluch LGA, altitude 144 m) and $M_{0.083} = \frac{SO_4 95 HCO_3 5 C11}{Ca79Mg19Na2}$ pH 4.2 (altitude 950 m). The water in the tributary of the Zheleznaya is acidic as well, but of a sulfate–aluminum type: $M_{0.035} = \frac{SO_4 71 HCO_3 28.5 C110}{Al48Ca26Mg13Na11}$ pH 4.35 (altitude 900 m).

The most probable cause of this difference might be tephra ejected in discrete portions that were enriched with different sets of particles of rocks from the volcanic edifice that had been differently altered by hydrothermal and fumarole activities and also contained the respective mineral complexes; the tephra was deposited during discrete ashfall episodes in different sectors of the Koryakskii volcanic edifice. The sulfate–calcic type of water in the Zheleznaya is largely due to the dissolved gypsum that tephra contains, the sulfate–aluminum type is a consequence of the probable presence of alunite. Both gypsum and alunite stem [Margaritov, 1899] from the components that come from fumarole gases and from their interaction with volcanic rocks.

The nearly limpid water in shallow (0.5–1 m) temporary lakes (Fig. 7) around the source areas of the Zheleznaya River and other streams that start on the Koryakskii cone was also acidic. This higher acidity was due to the ash deposits that lie as a continuous blanket on the bottom.

The thaw water that was collected together with fresh ash near the eruptive center of the 1956–1957 eruption proved to be sulfate–calcic, but with higher salinity (by factors of 40–100) and acidity ($M_{3.39} = \frac{SO_4 80 C117}{Ca63Mg13Nal2}$ pH 3.5) [Sirin et al., 1959].

As to the ground water from the well in the Shiveluch LGA, its composition is hydrocarbonate–sodic with calcium and magnesium, and low alkaline $M_{0.083} = \frac{HCO_3 83 SO_4 9 C18}{Na45Ca35Mg13K7}$ pH 7.6 According to a personal communication from Yu.F. Manukhin, this water is the subtype typical of volcanogenic basins of stratovolcanoes situated in volcanogenic hydrogeological structures whose recharge is mostly due to copious precipitation (up to 2000 mm/yr in eastern Kamchatka). Note that the high filtration properties of volcanic rocks found in stratovolcanoes ensure that all precipitation completely percolates. Additional recharge occurs when surface waters of various origins are absorbed, including thaw water from snow patches and glaciers. Koryakskii stratovolcano is no exception in this respect. The water from a well in the southwestern sector of the volcano's base was analyzed and found to have a low salinity and to be nearly neutral (pH 7.6); this water mostly derives from precipitation too: the rain water and the thaw water from the seasonal snow cover, pereletok snow patches, and present-day glaciers, when Koryakskii Volcano was in repose for several decades. The water received additional salinity and, in particular, was enriched with SiO_2 and HCO_3^- by leaching of Late Pleistocene and Holocene volcanic rocks that were previously discharged from the volcanic edifice. Comparison of

Table 2. Chemical analyses of water sampled in the Koryakskii area (in µg/dm^3), hardness in meq/l)

Parameter	Feature sampled				MPC for drinking water	Order of concentration value (mean for Kamchatka)	Analysis method
	well LGA	950	900	144			
pH	7.6	4.2	4.35	4.15	from 6 to 9	from 6 to 7	potentiometry
Salinity	83.5	83.21	35.42	64.34	1000	<100	calculation
hardness	0.223	1.04	0.13	0.8	7	n	AAS
aluminum		<0.3	1.35		0.5	0.0n	photometry
boron	<0.1	<0.1	<0.1	<0.1	0.5	0.n	potentiometry
iron	<0.005	0.8844	0.5542	0.245	0.3	0.n	AAS
manganese	<0.005	0.071	0.0024	0.0406	0.1	0.0n	AAS
copper	<0.001	0.0096	0.0149	0.0069	1	0.00n	AAS
nickel	<0.005	0.0249	0.0148	0.0186	0.1	0.00n	AAS
nitrates	1.51	<0.1	<0.1		45	n · 10	photometry
lead	<0.01		0.0131	0.0256	0.3	0.00n	AAS
sulfates	2.86	57.64	16.33	43.2	500	n · 100	titrimetric analysis
fluorides	<0.1	0.2	<0.1		1.2	0.n	potentiometry
chlorides	1.64	0.71	2.13	2.8	350	n · 100	titrimetric analysis
zinc	<0.005	0.0048	0.0022	0.0075	5	0.0n	AAS
lithium	<0.001	<0.01	<0.01	<0.005	0.03	0.00n	FES
cobalt	0.0117	0.016	0.0058	0.0202	0.1	0.00n	AAS
ammonia	<0.1	<0.1	<0.1	<0.1	2	0.n	photometry
silica	8.32	7.93	3.25	2.4	10	n · 10	photometry
sodium	4.86	0.368	0.807	0.22	200	n · 10	FES
nitrite	<0.01	<0.01	<0.01	<0.1	3	0.00n	photometry
hydrocarbonate	31.73	3.9	10	4.88		n · 100	potentiometry
potassium	1	0.192	0.34	0.35		n	FES
calcium	3.27	16.83	1.6	14.4		n · 10	AAS
magnesium	0.73	2.43	0.49	0.97		n	AAS

Note: The chemical analyses of the samples were made at the Analytical Center IV&S FED RAS by Researchers E.V. Kartasheva and Junior Researcher A.A. Kuz'mina. The data for comparison (average for Kamchatka) were based on long-term observations of water compositions observable in the drinking water supply system. AAS stands for atomic absorption spectrometry, FES for flame emission spectrophotometry, well LGA denotes a water sample from the well in the Shiveluch LGA (at the base of Koryakskii Volcano), depth 110 m, 950 denotes a water sample from the Zheleznaya River at 950 m altitude, 900 denotes a water sample from the tributary of the Zheleznaya at 900 m altitude, 144 is a water sample from the Zheleznaya at 144 m altitude.

these analytical figures with the regulatory requirements on drinking water safety (according to the SanPin 2.1.4 1074-01 Drinking Water. Hygienic Requirements on Water Quality in Centralized Water Supply Systems. Quality Control) clearly demonstrates that the resulting water composition is close to the mean figures for low-salinity surface waters in Kamchatka, including nonvolcanic areas. It is for this reason that this water is used as a source of centralized drinking water supply for the Shiveluch LGA and for irrigation purposes. The water from the Zheleznaya was also partly used for irrigation prior to the 2008–2009 eruption.

The rain water and thaw water that were affected by the Koryakskii eruption substantially differ from the ground water from the well (see Table 2). This is clearly seen not only in the water samples from the Zheleznaya River and its tributary but also in the recent snow deposited on the Koryakskii slopes without any admixture of volcanic ash in it. For example, the low salinity thaw water (5.27 and 6.26 µg/l) from this snow is already weakly acidic (pH 5.64 and 6.25) and has the set of components and the relationships between these, according to A.A. Ovsyannikov, who sampled the snow, closely comparable to those in the water that was strongly contaminated with volcanic

Fig. 7. Temporary lake containing whitish acidic water (at middle distance) at the edge of a lava flow (in the foreground), Koryakskii Volcano. Photographed by I.V. Melekestsev.

ash. It is not ruled out that the snow that fell during the eruption was contaminated when it was still in air with gases and aerosols from eruptive plumes rising above the summit of Koryakskii and around the volcano.

As to the water from the Zheleznaya and its tributary, it shows the enrichment with Koryakskii ejecta in a much more pronounced form, because the chemical composition of the water sources under investigation experienced substantial changes owing to great amounts of volcanic ash which was captured and transported along with this water. We note in the first place a dramatic increase in the concentration of hydrogen ions (pH) toward greater acidity. With the resulting pH values the water becomes unfit for drinking and irrigation. Judged by organoleptic parameters, in particular, by turbidity (4.0 FTU or greater, the mean value being 2.6 FTU with the MPC), the samples do not satisfy the drinking water standards. The change in pH entailed increased concentrations of heavy metals (nickel, cobalt, lead, and copper) by an order compared with the mean values.

The changed chemical composition of the samples is very mobile: an active chemical process occurs in open vessels and pH further decreases down to 3.5; the concentration of heavy metals increases and metals continue to be leached from the precipitate, which mostly consists of ash.

The samples contain ash suspensions that precipitate to form solid sediment, so we examined the solid phase the samples contained. After decanting and drying we determined the weight percentage of the solid ash phase and this material was used to make pressed radiators for X-ray fluorescent analysis. The results are presented in Table 1. For comparison purposes this table also gives the results from an analysis of the Koryakskii ashes themselves and this allows us to trace the elements that enrich the water of a natural spring during the leaching of volcanic ash.

One notes that the solid suspension contained in the water samples and in the tephra from the Koryakskii eruption is practically the same in its chemical composition and set of trace elements. This provides unambiguous evidence that the main cause of contamination for the water (which is essentially of atmospheric origin) in the Zheleznaya and its tributary is fresh volcanic ash. By the concentration of SiO_2 (dry basis analysis without sulfur and fluorine), the solid suspension and the ash have a dacite composition: 65.28–65.36% SiO_2 in the suspension and 64.34–65% SiO_2 in the ash. No rocks of such composition have been found in the Koryakskii volcanic edifice. It is therefore a logical inference that the excess of SiO_2 in both of these cases is due to the volcano's rocks being altered by fumarole and hydrothermal activity, as pointed out above (see the previous section).

In assessing the water of atmospheric origin that was strongly contaminated by fresh tephra using the water that was found on Koryakskii Volcano in various forms (rain, thaw water, snow, and ice), one should distinguish between two main components, a surficial and, let us say, a deep-seated component, as factors of the natural hazard associated with hydrothermal phreatic eruptions.

The surficial component includes hazardous processes and phenomena that occur nearly simultaneously with the eruption itself. These include: (1) erosion and accretion due to permanent and temporary streams, processes that experienced a dramatic increase to reach a cataclysmic scale; (2) the generation of atmospheric mudflows where tephra-laden water is one of the main components; (3) strong contamination of all kinds of surface water with tephra, thus enhancing its acidity and making it unfit for drinking and irrigation; (4) negative effects on animal life.

Since the factual material bearing on points (1) through (3) has been discussed above, we shall give data only that can prove our point (4). Summing up these data, one can assert that the 2008–2009 Koryakskii eruption has set up a kind of "natural experiment" on the survival of the animals that lived at the volcano's location (campagnols, marmots, hares, foxes, and other animals). The question arose because we did not see any rodents during our 2009 field work on the volcano, although we saw many holes. Neither did we see the predators that hunt for these rodents. It is most likely that the small rodents that left their holes in the spring died due to the absence of drinking water (see above) and because of the finest ash that covered the ground and vegetation everywhere. The ash flew at once into the air in hot dry weather during the summer of 2009 via light wind or by their movements. On the other hand, hares, foxes, and other, larger animals seem to have left these dangerous localities as early as in the winter, before the eruption was over. A similar situation occurred, e.g., on Avacha Volcano (a neighbor of Koryakskii) after its violent eruption of 1827, but in a more disastrous form [Ditmar, 1901].

It is also necessary to pay attention to another aspect of the potential hazards due to water enriched with elements leached from fresh tephra; this concerns animals, more specifically, the salmon that spawn in the Avacha River and in the Pinachevskaya, its left tributary. We mean that the Zheleznaya River, which has its source on the Koryakskii slopes, falls into the Pinachevskaya and its water, enriched in new elements, could affect the overall water geochemistry in this hatchery river. This must in turn hamper the fish that were born in the Pinachevskaya River from coming to spawn, since it is supposed that they use familiar geochemical guidance to find "their own" river.

The deep-seated component of the natural hazard considered here consists in the future contamination by components of ash-contaminated water affecting the ground water horizons at the Koryakskii base, which have by now reached many wells and are widely used for drinking and industrial purposes in the LGAs situated there. This can occur in two ways: (1) leaching of ashfalls by atmospheric precipitation if the precipitation can reach the ground water together with the components extracted from the ash and (2) percolation of contaminated surficial running water and the water in temporary lakes, which is also characteristic for the bases of Kamchatkan stratovolcanoes.

CONCLUSIONS

(1) It is argued that the 2008–2009 eruption of Koryakskii Volcano was of the hydrothermal–phreatic type, which is typical of the last several hundred years in the recent phase during the evolution of that volcano. It is supposed that such eruptions will also occur in the near future, unless a radical rearrangement in the volcano's plumbing system occurs.

(2) The motive power of the eruption included heat and gas from the magma chamber; hydrothermal fluid from the hydrothermal system that is buried beneath the volcano of a hypothetical caldera; and the heat, gas, and steam from the magmatic "roots" that still remain in the volcanic edifice and at depth. These roots until recently supplied material for the volcano's summit and parasitic eruptions, as well as the parasitic centers of transitional basaltic magnesian volcanism.

(3) The discharged tephra is resurgent and consists of at least two components, viz., particles from the volcano's rocks that have been altered by fumarole and hydrothermal agents and particles of amorphous silica that have been deposited from the hydrothermal fluid.

(4) Water that is contaminated with fresh tephra is among the main and typical kinds of the multifactor natural hazard associated with the 2008–2009 hydrothermal phreatic eruption and other similar eruptions that occurred during the 19th–20th centuries on Koryakskii. This hazard will also be typical of future hydrothermal phreatic eruptions on Koryakskii.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, grant no. 09-05-00718a.

The authors wish to thank V.N. Dvigalo for the help in sampling, A.P. Maksimov, A.A. Ovsyannikov, O.A. Girina, I.K. Dubrovskaya, D.V. Mel'nikova, and A.V. Sokorenko for the current information on the course and impact of the 2008–2009 eruption.

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