New data on the morphology and development of volcanic lakes of the Kuril-Kamchatka region

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Abstract. Volcanic lakes are of particular interest to geomorphologists and other professionals due to the diversity of the basins forms and the very dynamic development of lake systems. The origin and evolution of these water bodies are closely related to active volcanic and post-volcanic processes; they are characterized by rapid changes of shape, level, composition of water and characteristics of the coast. Usually bounded by craters, calderas and in the immediate vicinity of volcanoes, these lakes present a kind of by-product of volcanism. In the Kuril-Kamchatka region, two types of lakes can be distinguished: 1) dynamically developing young, some of them ephemeral, located on active volcanoes, in active craters. In these lakes, as a rule, there are active gas-hydrothermal manifestations, and their waters are highly mineralized; 2) stable (relict) lakes in the calderas of dormant and extinct volcanoes. Lakes of this type usually do not have explosive funnels or active gas hydrotherms, and the water in them is slightly mineralized. It suggests a much more ancient age and the decreasing of post-volcanic activity in caldera depressions. Lakes of different types can exist close to each other and form a single communicating systems.

Key words: volcano, lake, morphology, caldera, crater, lava flow, Kamchatka, Kuril Islands

1. Introduction

Among the total number of 8.45 million lakes existing on the Earth only ~1200 are of the volcanic origin [1, 2]. Geologically and geomorphologically, those unique water bodies are noted due to a number of specific characteristics. Among the latter are configuration of the enclosing depressions; rapidly changing water level (and, consequently, the water volume); quite commonly found high mineralization; gas- and hydrothermal phenomena in the lake basin or in its close vicinities; etc. The listed characteristics may change essentially in either direction over a few years or decades. All the above depends heavily on specific characteristics of the volcanic centres functioning which is responsible for the lake in question coming into being. Volcanic lakes attract the specialists’ attention also because of their high recreational potential (often related to thermal waters). At the same time, they may bring a threat to the nearby infrastructure and population because of active volcanoes in their immediate vicinities.

By now there have been accumulated a great amount of information on volcanic lakes in general as well as on various regions of the Earth [3, 4]. In Russia volcanic lakes are most common in the Far East, in the regions of recent volcanic activities, such as the Kuril Islands and Kamchatka Peninsula (Figure 1). In spite of their remoteness and inaccessibility, a considerable volume of data on the lakes’ morphology and other characteristics is now available. 16 relatively large water bodies of that type were studied, 8 of...
them in the Kuril Islands and 8 – in Kamchatka (Table 1). The lakes are confined to calderas and craters of active or extinct volcanoes. Besides, there are numerous small lakes dammed by lava flows or by landfalls (landslides) in the region; they are well distinguishable in aerial and space photographs.

Between 2005 and 2017 integrated studies were performed by the specialists from the Institute of Marine Geology and Geophysics FEB RAS in collaboration with colleagues and gained abundant new information on the lake basin morphology in the Kuril Islands and some lakes in Kamchatka Peninsula. The studies were performed using the modern technique of digital echosounding survey with synchronized satellite fixation of the profiles [5, 6, 7]. Volcanic lakes of the Kuril Islands being most difficult to access in Russia, recent works permitted to obtain unique materials on the lake floor landforms and gave an insight into the structure of their basins. The data on a few best studied lakes provide information on the specific features of the lake origin and evolution. Though volcanic lakes of Kamchatka have been better studied and the integrated approach has been more commonly used there than in studies of lakes in the Kuril Islands, still the dynamics of submerged landforms and the basin parameters were often left beyond the scope of studies. The performed studies specified the morphometric characteristics of the lakes (Table 1) and described their present state as well as specific features of the origin and functioning of the lake systems.

2. Characteristics of volcanic lake basins and the composition of their water
The Kuril Islands, together with Kamchatka and the northeastern end of Hokkaido form a specific geotectonic structure typical for the Western Pacific – a double island arc known as the Kuril-Kamchatka Island Arc. The arc is about 2000 km long, of which 1250 km fall on the Kuril Islands. The Pacific island arcs are widely known as the regions of the present-day volcanism, active neotectonics and a high seismicity. Their origin and further evolution are closely related to volcanic activities, as well as to the general tectonic uplift of the arc. At present the island arc zones are distinct for an active deposition and redeposition of thick volcanic-sedimentary series.

Volcanic lakes both in the Kurils and Kamchatka Peninsula are mostly confined to ancient or modern volcanic edifice or occur in their immediate vicinity; accordingly, there are several groups distinguished, namely crater lakes; caldera lakes; dammed lakes; and lakes of complex genesis. Due to specific features of the volcanic relief-forming processes, crater lakes are funnel-shaped in profile, while those in calderas are noted for steep sides and flat bottom (occasionally distorted by various tectonic or volcanic structures). As to the dammed lake morphology, it depends on the local erosional and depositional landforms. It should be noted that young volcanic domes may appear within large calderas and craters. The process results in considerable changes in the lake bottom morphology, a single water body may break down into several smaller ones or take a specific shape – a ring (Koltsevoye Lake), half-moon (crescent), horseshoe, etc., occupying the lowermost places.

Quite often the volcanic activity is accompanied by outflowing lava, vertical displacements (subsidence or rise) of individual parts of volcanic depressions, volcanic material ejection, etc., which
results in distortions of the lake coastlines. By way of example, the eruption of 1907 may be mentioned: that event was marked by an instantaneous destruction of the north wall of the Shtyubelya cone; practically at the same moment the Shtyubelya Lake doubled its area and took a form of trefoil [8]. Another similar case was described in the north of Karymsky Lake, in Akademii Nauk caldera, where Novogodny Peninsula appeared as a result of a submarine eruption in 1996 [9].

Some of ancient calderas holding lakes and occurring in the immediate vicinities of the sea may suffer from a partial destruction of their coasts and the sea water invasion through the breach. As a result, the lakes are changed into sea bays, such as Lion’s Past’ (Iturup Is.), Kraternaya and Brouiton bays (Yankich and Simushir Islands). More often, however, volcanic lakes occur at considerable elevations a.s.l. and are relatively small in size, such as Kipyashechee (‘Boiling’) Lake in Golovnin caldera, Kunashir Is.; Glazok (‘Eye’) Lake on Pallas volcano, Ketoy Island; Verkhneye Lake on Mutnovsky volcano, Kamchatka; and many others. Caldera lakes are noted for a considerable size, in particular Koltsevoye Lake in Onekotan Island (26 km² in area and 369 m deep) and Kurilskoye Lake on Kamchatka Peninsula. The latter is the largest caldera lake in the studied region and presents originally a volcanic-tectonic basin resulted from an eruption ~8.5 ka BP and partly filled with water [10]. The area of the lake is 77 km², its depth is 316 m.

Volcanic lake outlines and their number in a caldera depends on the lake level, and accordingly, on the water volume, which is a value changing rather irregularly. For example, changes may result from fluctuations in output of springs (including thermal ones) feeding lakes. For example, observations carried out on Zelyonoye Lake in the Troitsky crater (Maly Semyachik volcano, Kamchatka) have shown that the thermal water coming to the lake increases drastically in volume during the volcano activation; accordingly, the lake level rises, along with an increase in depth, as well as temperature and mineralization of water [11].

As a result of the Shtyubelya cone eruption (1907) the Teplaya River draining the lakes in Ksudach caldera had been dammed; in consequence, the water level in the intra-caldera lakes rose by 15 m [12, 13] and a single water body existed in the caldera for a few decades [14]. Later on, after the dam had been destroyed and the water level had dropped, the water body broke in two having formed lakes – Klyuchevoye and Shtyubelya [15]. According to the data obtained by I.V. Melekestsev and his colleagues [16], a single lake existed in the caldera in early Holocene also (8.5 – 8.7 ka BP), its depth could be even greater (more than 200 m).

Dammed volcanic lakes result from the rivers being dammed by lava flows. A few lakes in Kamchatka were formed in this way. Among them are Palanskoye Lake (28 km² in surface area and 15 m deep on average), Etamyn, Ulyanin, Tolmacheva (~15 km²) and many other lakes. Another noteworthy lake belonging to the same group is Lake Kronotskoye with the water table of 245 km² in area and the depth up to 136 m. The lake was formed after eruptions of Kronotsky and Krasheninnikov volcanoes when lava and pyroclastic flows dammed the old channel of the paleo-Kronotskaya River [17].

Seismotectonic activities accompanying volcanism may lead not only to river damming with seismic-initiated landslides and landslides, but also to vertical movements of individual blocks and gravitational displacements; the latter often results in changes of the coastline and considerable volumes of debris coming into the lake basins. The photogrammetric analysis of the Troitsky crater (Maly Semyachik volcano) photographs taken at different time revealed considerable changes in the morphology of inner walls of the crater due to gravitation processes [18], the debris having been mostly deposited in the Lake Zelyonoye basin. The total volume of pyroclastic material deposited on the crater bottom from 1968 to 2012 is estimated at 1.5 million m³; that would necessarily affect the lake bottom morphology and, consequently, the lake level [19], the latter having risen from 1139 to 1176 m a.s.l. during the period under consideration. The lake volume increased by 9 million m³ altogether; it should be taken into account that 17% of the value may be accounted for by the scree and fall material coming into the lake basin. That is why the volume of waste material should be considered when estimating dynamics of volcanic lakes, along with volumes of water supply and drainage.

Typically volcanic lakes are highly diversified in chemical composition of their water; quite possibly, it may be poorly mineralized neutral – fresh, for all the practical purposes, or highly mineralized, acid
or alkaline. Gas-hydrothermal outlets are often found within the lake basin or in its immediate vicinities. Among acid lakes of Kamchatka, there are those located in Maly Semyachik and Gorely craters. The lake in the Semyachik crater is very young, it originated no more than 400 years ago as a result of an extremely strong underground explosion, part of the crater having been caved-in subsequently. The volcano is still active; its latest eruption was recorded about 150 years ago. The water mineralization in Zelyonoye Lake is as great as 40-50 g/l; about 20 g/l of that value is accounted for by sulphuric acid. The temperature of water in the lake is 70° C, temperature of emitted gases is 100° C.

An unnamed lake in the Gorely volcano crater began drying-up since the eruption in 2010 and now is devoid of its turquoise color; it is possible, however, that the crater will be filled with water after the next eruption. Another lake with hot water is Fumarolnoye in Uzon caldera. That is a small lake with acidified water about 0.4 km² in size and 25 m deep. Chloride-sodium subaqueous springs with water temperature of 125-130°C are found at the lake bottom.

The water composition may undergo considerable changes as time passes, depending on the volcanic activities and the volume of incoming fresh water (from atmosphere or streams). For example, before eruption 1996 the water in Karymsky Lake (Akademii Nauk caldera, Kamchatka) was fresh (pH 7.1) poorly mineralized (110-130 mg/l), hydrocarbonate-sodium in composition; fish occurred in the lake. According to Nikolayeva et al. [9], characteristics of the water changed drastically immediately after the eruption: pH lowered to 3.2, total mineralization rose to 1 g/l, proportion of chlorine and sulphur compounds increased sharply. By 2004, as a result of the subsequent dissolution of lacustrine water by rainwater and inflowing streams, the mineralization notably fell, as well as pH value (to 5.5-6.0).

Table 1. Morphometric characteristics of some volcanic lakes of the Kuril-Kamchatka region

| Name of the lake | Island/ Peninsula | Volcano | Coordinat es | All. of water surface, m a.s.L | Area of water surface, km² | Coaselin e length, km | Water volume, km³ | Length, km | Max. width, km | Max. depth, m | Age, th. years. | Genesis | Hydrological regime |
|-----------------|-------------------|---------|---------------|-------------------------------|---------------------------|---------------------|-------------------|-------------|---------------|---------------|----------------|---------|-------------------|
| Koryaksky | Kamchatka | Koryak | 55°17′N, 156°47′E | 253,5 | 4.5 | 42.5 | 42,5 | 124 | 3 | 118 | 159 | Drained HT, HT, Crater |
| Kusnevichy | Kamchatka | Kusnevichy | 55°17′N, 156°47′E | 253,5 | 4.5 | 42.5 | 42,5 | 124 | 3 | 118 | 159 | Drained HT, HT, Crater |
| Koryaksky | Kamchatka | Koryak | 55°17′N, 156°47′E | 253,5 | 4.5 | 42.5 | 42,5 | 124 | 3 | 118 | 159 | Drained HT, HT, Crater |
| Kusnevichy | Kamchatka | Kusnevichy | 55°17′N, 156°47′E | 253,5 | 4.5 | 42.5 | 42,5 | 124 | 3 | 118 | 159 | Drained HT, HT, Crater |
| Koryaksky | Kamchatka | Koryak | 55°17′N, 156°47′E | 253,5 | 4.5 | 42.5 | 42,5 | 124 | 3 | 118 | 159 | Drained HT, HT, Crater |
| Kusnevichy | Kamchatka | Kusnevichy | 55°17′N, 156°47′E | 253,5 | 4.5 | 42.5 | 42,5 | 124 | 3 | 118 | 159 | Drained HT, HT, Crater |

Note: Linear dimensions and size of lakes have been calculated using SASPlanet software designed for viewing and processing of maps and high-resolution space photographs. Data on the lakes of the Kuril Islands and Kamchatka are given according to publications as follows: [5, 6, 7, 17, 20, 21, 22, 23, 24] «HT» is a shorthand form for hydrothermal springs «GW» is a shorthand form for ground water
3. Conclusion
The above-considered volcanic lakes of the Kamchatka Peninsula and Kurile islands are of particular interest among other hydrological objects. They are noted for rapid changes (over a few decades) of their outlines, water volume and composition, as well as of sources of water supply. They depend heavily on the nearby volcano activities and may disappear and then reappear time and again. The depth and size of the magmatic chamber are of considerable importance for the lake development. Particularly important is the chamber accessibility to groundwater. The latter is heated and enriched with various chemical elements before coming to volcanic lakes. Numerous gas- and hydrothermal vents are recorded in many lakes on active volcanoes; the water in the lakes is distinct by a high mineralization of water. Other lakes, such as Krasivoye and Chernoye lakes (Onekotan Is.), have no explosion funnels, nor hydrothermal vents, their water is fresh. That suggests their older age, and/or damping post-volcanic activities in the calderas occupied by the lakes.

Accordingly, there are two types of lakes distinguishable in the region: 1) highly dynamic young ones, some of them ephemeral, located on active volcanoes, and 2) more stable (“relict”, according to I.V. Melekestsev) lakes in calderas of dormant or extinct volcanoes. It should be noted, however, that young active volcanic cones and craters may be found in immediate vicinities (or even within) of large older (Holocene) calderas; so the lakes of different types may exist closely to each other and even form united lake system. Quite naturally, the lakes belonging to different types would differ essentially in their parameters. To take but a few examples, the interconnected Klyuchevoye and Shtyubel'ya lakes in Ksudach caldera (Kamchatka) differ in the basin configuration, size, age, and the chemical composition of their water. The same is true for Goryacheye and Kipyashcheye lakes in the Golovnin caldera (Kunashir Is.). Similar situation is with lakes on Ketoy Island – Malakhitovoye and Glazok lakes differ considerably both in their morphometry and in the gas- and hydrothermal vent activities.

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References
[1] Meybeck M 1995 Global distribution of lakes J. Physics and Chemistry of Lakes (Berlin, Heidelberg) 1–36
[2] Ryzhzhin S V and, Ulyanova T Y 2000 Geographical information system “World Lakes” GIS WORLDLAKE Doklady Russian Academy of Sciences 4, 370, 542–5.
[3] Larson G L 1989 Geographical distribution, morphology and water quality of caldera lakes: a review Hydrobiologia 171, pp 23–32
[4] Pastermack G B and Varekamp J C 1997 Volcanic lake systematics. I. Physical constraints J Bulletin of volcanology 58, 528–38
[5] Kozlov D N and Belousov A B 2006 Hydrothermal eruption – the most probable scenario of volcanic disaster in the Golovnina Caldera, Kunashir Island, Southern Kuriles JKASP-5 (Hokkaido University, Japan,) pp 140–1
[6] Kozlov D N and, Zharkov R V 2009 New data on the morphology of intra-caldera lakes on Kunashir and Simushir islands J. Vestnik KRAUNTs, Earth sciences 2, 14 159–64
[7] Kozlov D N 2015 Crater lakes of the Kurile Islands Sakhalin Region Museum, (Yuzhno-Sakhalinsk) p 112
[8] Pilipenko G F, Razina A A, and Fazlullin S M 2001 J. Volcan. and Seismol 6 43–57
[9] Nikolayeva A G, Karpo V A, Lupikina E G and Ushakov S V 2005 Changes in the salt composition in water of thermal springs and of Karymsky lake after 1996 eruption Materials of the Annual Conference on the Volcanologist’ Day IVS FEB RAS. pp 37–47
[10] Ponomareva V V 2010 The greatest explosive volcanic eruption and their tephra usage for dating and correlation of landforms and deposits Thes. Dr. Sc. in Geography Institute of Geography
[11] Gavrilenko G M 2000 Hydrological model of the crater lake of Maly Semyachik volcano (Kamchatka) J. Vulkanologiya i seismologiya 6 21–31
[12] Lebedeva E V 2017a J. Geomorfologiya 3 60–75
[13] Lebedeva E V 2017b J. Geomorfologiya 4 35–49
[14] Kell N G 1928 Map of the volcanoes of Kamchatka Map (2 sheets, scale 1:750 000), explanatory text and illustrations. Russian Geographic Society (Leningrad) p 75
[15] Piip B I 1941 On the strength of the Ksudach volcano eruption in March 1907 J Bulletin of Volcanological Station 10, 23–29
[16] Melekestsev I V, Braitsева O A, Ponomareva V V, and Sulerzhitskii L D 1995 J. Volcan. and Seismol. 4–5 28–53
[17] Arakelyants A D and Tkachenko O V 2012 Hydrological characteristics of Kronotskoye Lake (Kamchatka) at the beginning of the 20th century J. Vestnik Moskovskogo Universiteta Ser. 5. Geography 6 77–83
[18] Shevchenko A V, Dvigalo V N and Svirid I Y 2018 Remote sensing survey of geomorphological processes on volcanic objects in Kamchatka In: Proc. 36th Plenary Meeting of Geomorphological Commission. Altai State University Press (Barnaul) pp 403–10
[19] Svirid I Y, Shevchenko A V and Dvigalo V N 2013 Studies of Maly Semyachik volcano activities based on morphodynamics parameters of Troitskiy crater J. Vestnik KRAUNTs, Earth Sciences 2. 22 129–43
[20] Kozlov D N and Lebedeva E V 2018 XXXVI Plenum of the Geomorphological Commission of the Russian Academy of Sciences (Barnaul: publishing Alt. University) pp 186–192
[21] Agarkov A Y, Dmitrieva L Y and Doganovsky A M 1975 Izv. VGO. L.: NAUKA 107 pp 352–57
[22] Bondarenko V I 1990 J. Vulkanologiya i seismologiya 4 92–111
[23] Ushakov S V and Fazlullin S M 1997 J. Vulcanologiya i seismologiya 5 134–41
[24] Gavrilenko G M J. Vulkanologiya i seismologiya 6 1–11