ISSN 1028-334X, Doklady Earth Sciences, 2023, Vol. 511, Part 1, pp. 550–557. © The Author(s), 2023. This article is an open access publication, corrected publication 2023.
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VOLCANOLOGY

The Holocene Explosive Eruption on Vetrovoi Isthmus (Iturup Island) as a Source of the Marker Tephra Layer of 2000 cal. yr BP in the Central Kuril Island Arc

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Presented by Academician E.I. Gordeev March 27, 2023

Received March 27, 2023; revised March 28, 2023; accepted March 28, 2023

Abstract—Geochemical study of volcaniclastic material and radiocarbon dating of charred plant debris from Holocene deposits of the Guram site, which is located in vicinity of Vetrovoi Isthmus on Iturup Island, demonstrate that an explosive eruption (VEI 4-5) occurred there about 2000 years ago. The geochemical and age similarity with the tephra of marker layer CKr that was distinguished on Iturup, Urup, Simushir, Rasshua, and Matua islands of the Kuril Island Arc led to the conclusion that this eruption is possibly a source of this tephra. The data presented are proposed as a motivation for revision of the volcanic hazard on Iturup Island.

Keywords: volcanic hazard, tephra, Holocene, geochemistry, volcanic glass

DOI: 10.1134/S1028334X23600597

INTRODUCTION

Large explosive eruptions, accompanied by the creation of calderas and thick pyroclastic deposits, have a significant impact on the climate and pose a threat to human civilization and wildlife. Most of these eruptions are confined to subduction zones and are located on active continental margins and volcanic arcs [1]. Although large eruptions are much rarer than smaller events involving landform reorganization and ejection of volcanic material, the catastrophic nature of their consequences calls for specifying the periodicity of such events, especially for the near-contemporary time span.

There are about 20 eruptive centers within the Kuril Island Arc (KIA) that appeared in the Late Pleistocene and Holocene [2, 3]; their formation was accompanied by powerful explosions and calderas formations. They are located practically on all the islands, but most of them are concentrated in the most populated southern part of the island arc, especially on Iturup Island. In the Late Pleistocene and Early Holocene, at least five powerful explosive events occurred on this island, resulting in the formation of four major collapse calderas (Medvezhya, Tsirk, Urbich, L'vinaya Past') and a thick stratum of pumice tuffs on Vetrovoi Isthmus [1] (Fig. 1a).

Regional tephrostratigraphic study carried out in the years 2007–2008 revealed a horizon of acidic tephra (~74–79 SiO_2 wt %, ~1.4–1.8 K_2O wt %) in soil–pyroclastic sections on the islands of Urup, Chirpoi, Simushir, Ushishir, Rasshua, and Matua, which was given index CKr. The age of tephra established by the radiocarbon (^{14}C) dates of the underlying organogenic deposits is within the interval of about 2490–2100 years (Fig. 1b) [4–6]. The thickness of the horizon decreases in the northeasterly direction (Fig. 1b). This suggested that the potential source of the eruption could have been located on Iturup Island [4, 5], and the isopachyte axis had a predominantly northeasterly direction (azimuth between 49° and 63°) (Fig. 1b). The occurrence of this horizon suggests that eruptions

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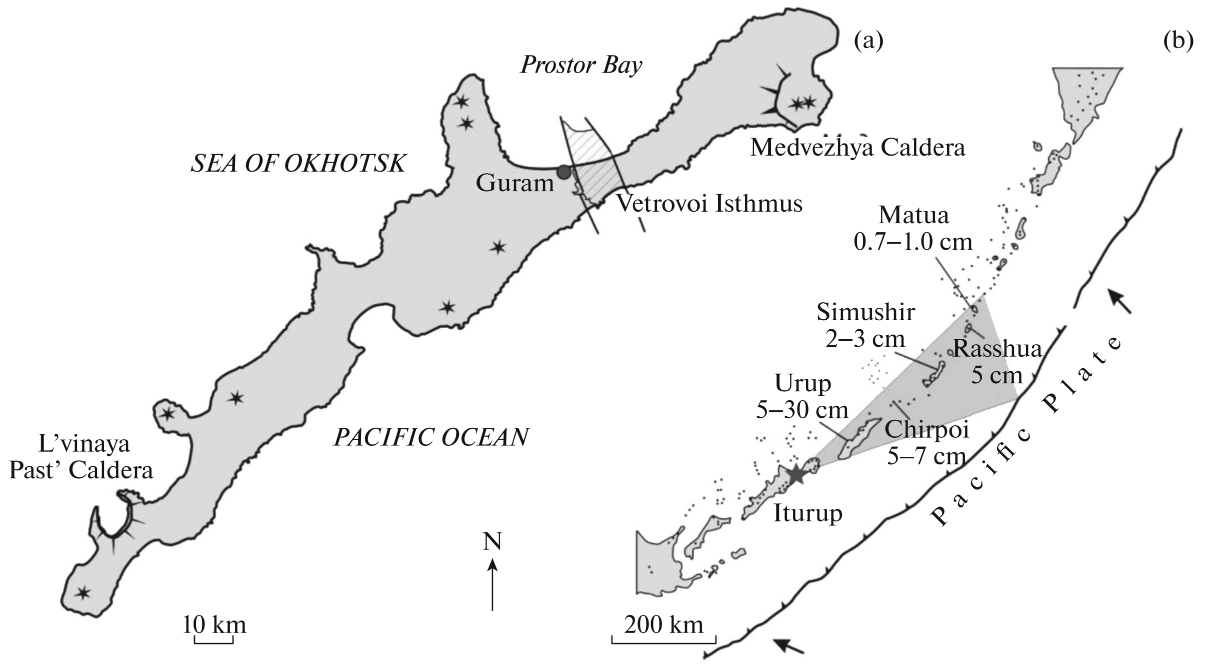

Fig. 1. (a) Location of Vetrovoi Isthmus and the Guram section on Iturup Island, the asterisks indicate active volcanoes, shaded is the area of pumice distribution of the Pleistocene eruption on Vetrovoi Isthmus ~20000 yr BP according to [9]; (b) reconstructed tephra distribution area (gray triangle) from the eruption that occurred ~2100–2000 yr BP in the area of Vetrovoi Isthmus in the central and southern parts of the Kuril Island Arc; thicknesses of the CKr layer are given under the island names according to the published data [4–6, 18]. The dashed line represents the axis of the Kuril–Kamchatka Deep Sea Trench; arrows show the motion of the Pacific Plate.

of fairly thick acid magmas occurred on the southern islands of the KIA not only at the Pleistocene–Holocene boundary, but also during the last several thousand years. This determines the need for detailed study of the powerful explosive volcanic centers in the southern, most populated part of the KIA, in order to estimate the scale of their eruptions and the nature of pyroclastic material distribution.

The inaccessibility and difficult condition for studying the manifestations of powerful explosive eruptions on the Kuril Islands make detailed mapping of the eruptive centers and associated pyroclastic strata virtually impossible, thus impeding estimation of the scale of past eruptions. An alternative way to obtain information on these events is to study tephra interbeds in island and continental land sediments, sea basins, and continental ice by correlating their compositions near and far from eruption centers [7, 8].

PUMICE STONES OF THE VETROVOI ISTHMUS AND GURAM SECTION

The pumice tuffs on Vetrovoi Isthmus are of great interest because, despite the large amount of erupted material, the exact location of the eruptive center for this event is unknown, and the timing and duration of the eruption itself remains debatable. The pumice sequence fills the Vetrovoi Isthmus Graben on Iturup Island and is exposed in the cliffs to the west between the Isthmus and Mount Shirokaya, forming the Belye Skaly landmark (Fig. 1a). Two levels of marine terraces are cut into the tuff strata from the Sea of Okhotsk. According to [9], its underlying rocks were observed not far from the coast of the Sea of Okhotsk in the northwestern part of the pumice tuff distribution area. The maximum thickness of the pyroclastics probably exceeded 260 m. A large part of the pyroclastic material forms a plume at the bottom of Prostor Bay in the Sea of Okhotsk (Fig. 1a) [10]. Preliminary estimates have shown that the volume of erupted rock was about 100 km^3 [11]. The composition of the pyroclastics corresponds to low to moderately potassic, moderately aluminous dacites of normal alkalinity [12]. Despite the large volume of eruptive material, which is characteristic of caldera-forming eruptions, no clear evidence of a caldera depression has been identified on the island. It was assumed that the eruptive center is located in Prostor Bay [13], but this assumption requires further verification.

According to the ^{14}C dates obtained from the underlying soil lignite and mollusk shells in the overlying coastal–marine pebbles [9], thick pumice tuffs were formed in the interval between 38500 ± 500 and 5350 ± 50 years ago. The thermoluminescent method estimated the age of the pumice at 20000 ± 6000 years [9]. Thus, the formation of the pumice strata on Vetro-

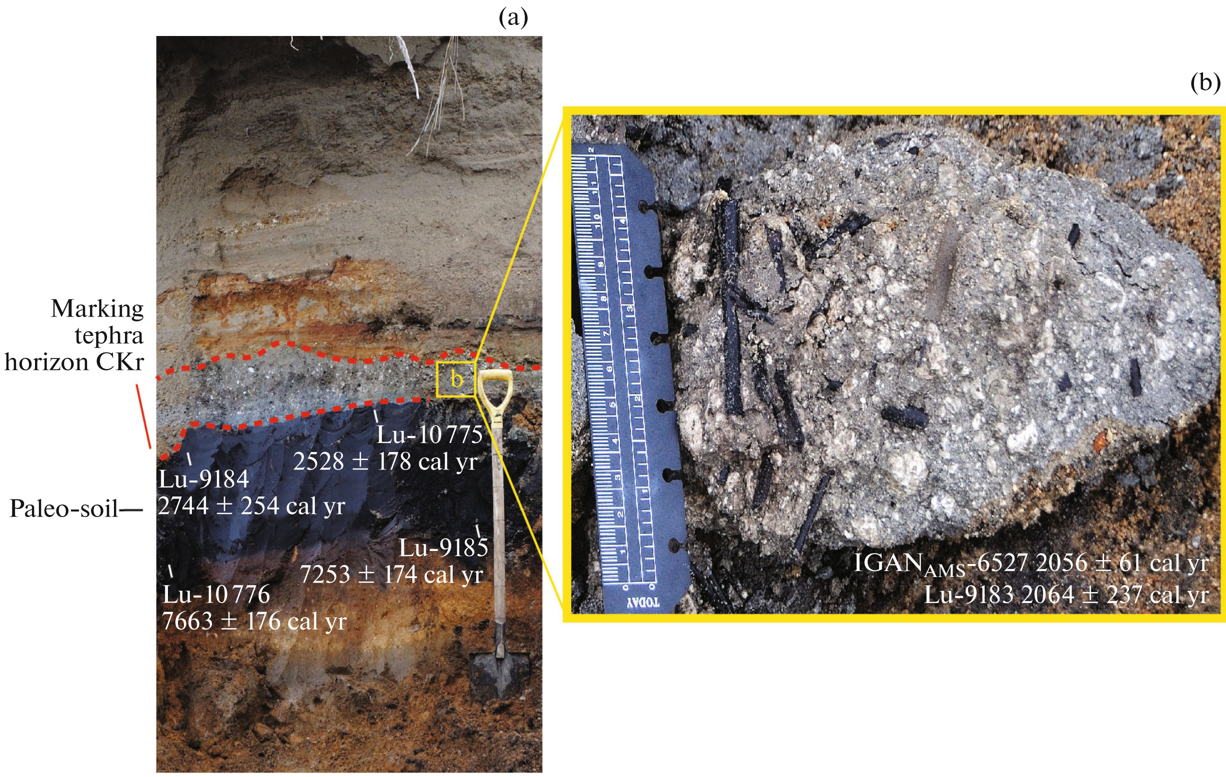

Fig. 2. (a) Location of the CKr pyroclastic layer in the Guram section; (b) stems of charred bamboo and pumice in the CKr layer. Calibrated (2σ) radiocarbon dates are given. Detailed description of the Guram section and the stratigraphic column are given in Supplementary Information (Appendix 1); the radiocarbon dating procedures, ^{14}C dates, and results of their calibration are presented in Supplementary Information (Appendix 2).

voi Isthmus in the Belye Skaly area occurred no later than the Late Pleistocene.

It has also been suggested that this eruptive center could have been active in the Holocene some 1000 years ago [14], but this conclusion was based on the dating sediments containing volcanogenic material rather than the tephra horizon as such. Accordingly, the identification and dating of these events requires further clarification. Thus, despite the fact that there is currently no evidence of volcanic activity in the Vetrovoi Isthmus area, there is reason to believe that explosive eruptions may have occurred here in the last few thousand years.

During 2018 field work on Iturup Island, a section of Holocene sediments containing tephra interbeds was uncovered on the right bank of an unnamed creek, the mouth of which is located 2.25 km west of the mouth of Pemzovyi Creek and 9.4 km west-southwest of Vetrovoi Isthmus. The section was named Guram (Fig. 2a). The thickest (about 20 cm) tephra bed in this section, consisting of light gray volcanic sand with white pumice lapilli up to 5 cm in size (see Supplementary Information (Appendix 1) for a description of the section) and deposited directly on the paleosoil, is indicative of an explosive eruption. According to radiocarbon dating (see Supplementary Information (Appendix 2)), the formation of the paleosoil underlying the tephra horizon occurred about 7700–2500 years ago (Fig. 2, Supplementary Information (Appendix 2)). AMS ^{14}C dating of the charred stems of *Sasa kurilensis*, which evidently died after being covered by tephra (Fig. 2b), provided a reliable age determination of 2115–1995 yr BP (cal) for the explosive eruption on Iturup Island in the area of Vetrovoi Isthmus. This event is significantly younger than the earlier estimates of the time of formation of thick pumice tuffs in the Belye Skaly area and at Vetrovoi Isthmus at the end of the Late Pleistocene and thus suggests another explosive eruption in the area during the Late Holocene.

The pumice lapilli are light gray to yellowish gray in color, with a maximum size of 3–5 cm (Fig. 2b). They contain about 30% phenocrysts of plagioclase, augite, hypersthene, quartz, magnetite, and ilmenite. The phenocrysts are embedded in a bubbly vitrified matrix, composed mostly of colorless, transparent volcanic glass. In terms of the mineral composition, the Guram pumice is nearly the same as the pumice of Vetrovoi Isthmus and the Belye Skaly area.

Study of the bulk composition of individual pumice lapilli (see Supplementary Information (Appendix 2) for analytical methods) has shown that the Guram section pumice corresponds to dacite of normal alkalinity with a moderate potassium and alumina content. The glass in the bulk of the pumice (see Supplementary Information (Appendix 2) for details of the analysis) is composed of rhyolites of normal alkalinity with a moderate potassium content and a high to moderate alumina content (Fig. 3).

IDENTIFYING THE SOURCE OF THE PUMICE STONE IN THE GURAM SECTION

To identify potential sources of the pumice of the Guram section, its composition should be compared with the acidic products of the explosive eruptions of the volcanoes of Iturup Island. Such a composition is characteristic of pumice from (1) the L'vinaya Past' Caldera, situated 115 km to the southwest, with eruption ages of 12300 and 13000 cal yr BP [15], (2) Medvezhya Caldera, 49 km to the northeast, and (3) Vetrovoi Isthmus and the Belye Skaly area, located in close proximity to the Guram section (Fig. 1).

Glass of the Guram section pumice differs from the bulk glass from the L'vinaya Past' Caldera in a lower alkali content, mainly due to the lower K_2O content, higher FeO at a similar MgO, and lower alumina content (Fig. 3, Supplementary Information (Appendix 4)). As can be seen in Fig. 3 and Supplementary Information (Appendix 4), the bulk compositions of L'vinaya Past' Caldera pumice differ significantly from the Guram section pumice, on average, in the lower SiO_2 content and higher Al_2O_3 and K_2O contents. The distribution of trace element concentrations in the L'vinaya Past' pumice is similar to that in the Guram section (Figs. 4, 5), distinguished only by a prominent Sr maximum. Nevertheless, taking into account the significant difference in concentrations of petrogenic elements and considerably earlier eruption in the L'vinaya Past' Caldera compared to the time interval of interest, we do not consider it as a potential source of pumice from the Guram section.

Another occurrence of acidic pumice is located near the Men'shii Brat volcano in Medvezhya Caldera [16], north of Iturup Island. The bulk composition of pumice collected from the Guram section differs significantly from that of the Medvezhya Caldera (Fig. 3, Supplementary Information (Appendix 4)). In contrast to the pumice of the Guram section, the pumice of the Medvezhya caldera was defined as rhyolite (Fig. 3, Supplementary Information (Appendix 4)), enriched in K_2O and LILE, and depleted in CaO and Al_2O_3 (Figs. 3–4). The bulk composition of glass of these pumices is similar with glass compositions of the pumices from L'vinnaya Past' caldera (Fig. 3, Supplementary Information (Appendix 4)).

Figure 3 and Appendix 4 (Supplementary Information) clearly show that the composition of pumice lapilli in the Guram section is close to the most siliceous pumice varieties on Vetrovoi Isthmus and the Belye Skaly area (Fig. 3, Supplementary Information (Appendix 4)). The bulk glass compositions also overlap with those of pumice from Vetrovoi Isthmus and the Belye Skaly area, differing by slightly higher average SiO_2 concentrations and lower alkali contents. The potassium contents in the glass are similar, while the concentrations of Na_2O and Al_2O_3 display wider variations and lower average values. Most pumice glasses in the Guram section have slightly elevated FeO concentrations and similar MgO concentrations. The distribution of normalized concentrations of rare and trace elements in the Guram section pumice is similar to that on Vetrovoi Isthmus. The spectra of the latter sometimes exhibit a positive Sr anomaly, which is absent in compositions of the Guram pumice (Fig. 4).

Thus, in view of these similarities in the contents of rock-forming and trace elements and the geographic location, we believe that the source of the Guram section tephra was an eruption that occurred on Vetrovoi Isthmus and was not related to the activity of the Medvezhya and L'vinaya Past' calderas.

THE MARKING TEPHRA HORIZON CKr ON THE KIA ISLANDS

The presence of the CKr ash over a considerable distance allows it to be used as a marker horizon in the study of Holocene sediments of the KIA. Radiocarbon dates obtained earlier by different researchers from underlying organogenic deposits on Urup, Chirpoi, and Matua islands show that the CKr horizon was formed around 2490–2100 yr BP (cal.) [4–6, 18].

The close ages of the CKr horizon (about 2490–2100 yr BP) and tephra in the Guram section on Iturup Island (about 2100–2000 BP) suggests their possible genetic relation. In this connection, we studied the ash particle glass compositions and the bulk ash compositions from CKr horizons in the deposits of Matua and Urup islands (Fig. 2b). On Matua Island, the CKr horizon was sampled from the section of soil-pyroclastic sediments in its southeastern part [18]. The ash horizons on Urup Island, also identified as a CKr layer, have been sampled in two sections of peat on Van der Linde Peninsula [5]. The age of the ash-buried soil on Matua Island is about 2100 yr BP [18], while the ^{14}C dates obtained for peat layers underlying the pyroclastic horizons on the island of Urup lie within the interval of 2490–2100 yr BP [5]. The samples from the above horizons contained particles of homogeneous bubble glass similar to the most of the pumice of the Guram section and containing crystals of plagioclase, orthopyroxene, clinopyroxene, quartz, and magnetite (Fig. 5). We note that the nucleus parts of plagioclase crystals from the tephra horizon on Urup Island often contain associations of glassy melt and essentially gas fluid inclusions, which are typical of the plagioclase from the Guram section and older pumice from Vetrovoi Isthmus and the Belye Skaly area [12].

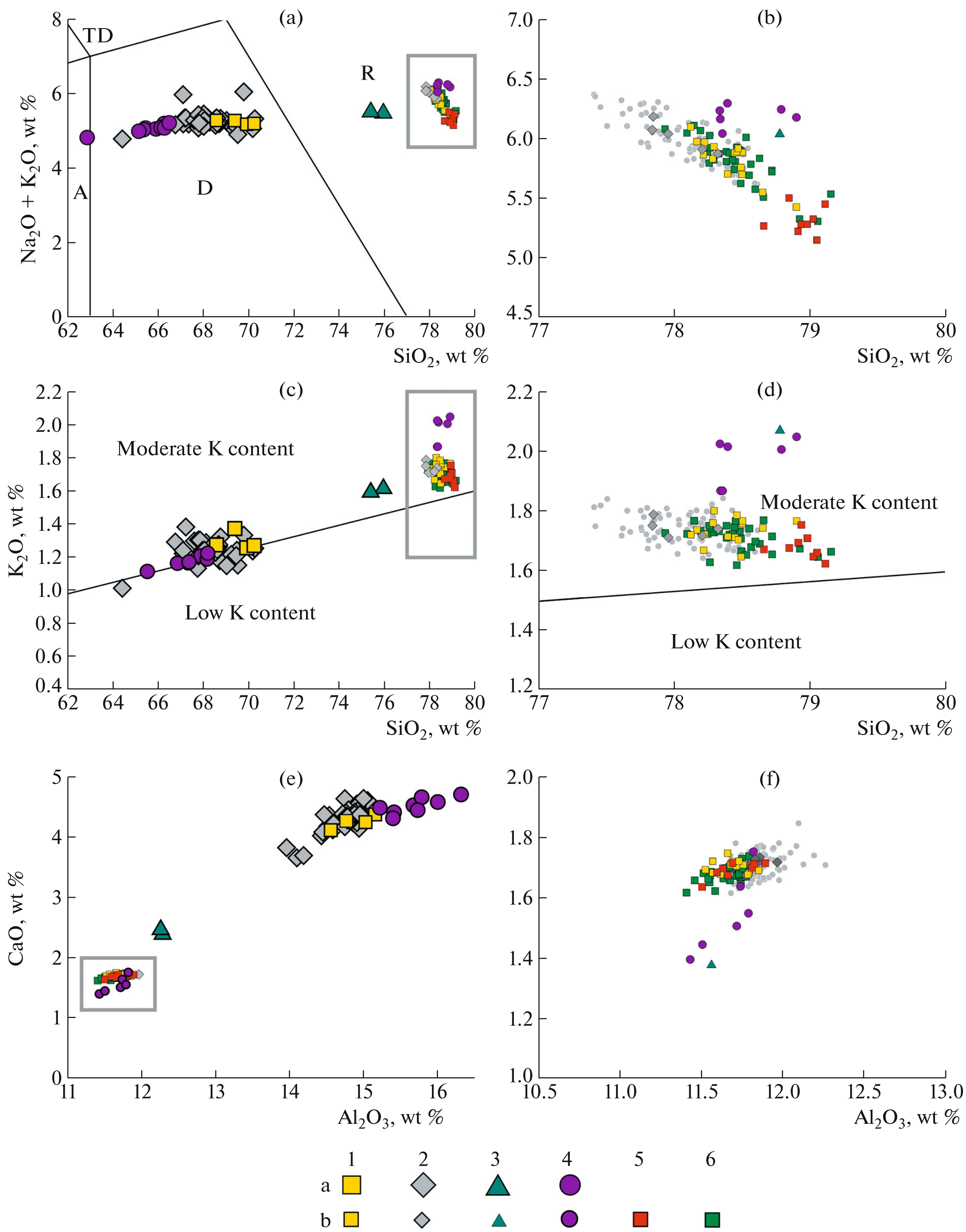

Fig. 3. (a, c, e) Compositions of pumice lapilli and bulk glasses and (b, d, f) enlarged plot sections showing the compositions of the bulk glasses. Legend: 1, Guram section; 2, pumice tuffs from Isthmus Vetrovoi and Belye Skaly [12]; 3, pumice tuffs from Medvezhya Caldera; 4, pumice tuffs from L'vinaya Past' Caldera; 5, CKr ash from Matua Island; 6, CKr ash from Urup Island (section 3709), (a) compositions of individual pumice lapilli, (b) compositions of the glass of pumice lapilli and ash particles (average values are given for Vetrovoi Isthmus and L'vinaya Past' Caldera). The gray circles show the whole range of compositions of the bulk glass of Vetrovoi Isthmus and Belye Skaly pumice. A, andesite; D, dacite; R, rhyolite; TD, trachydacite. See more diagrams in Supplementary Information (Appendix 4).

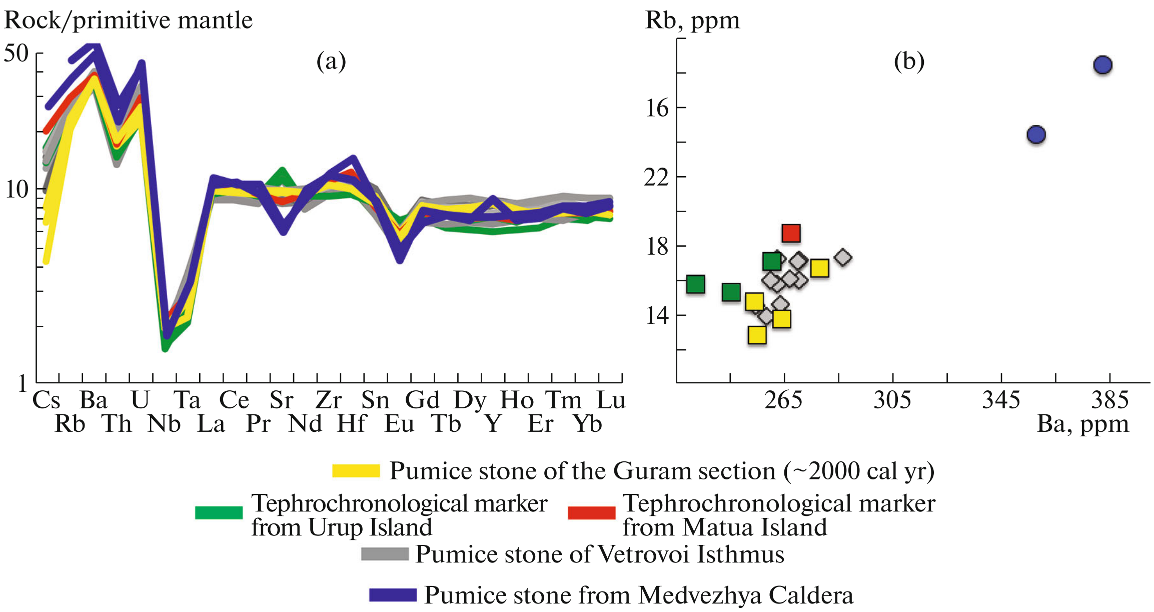

Fig. 4. Distribution of trace elements normalized to the primitive mantle composition [17] in bulk compositions of pumice lapilli of the Guram section and Vetrovoi Isthmus in comparison with transit ashes of the CKr horizon on Matua and Urup islands. Methods of ICP-MS measurements of trace elements are given in Supplementary Information (Appendix 2); measured values are given in Supplementary Information (Appendix 3).

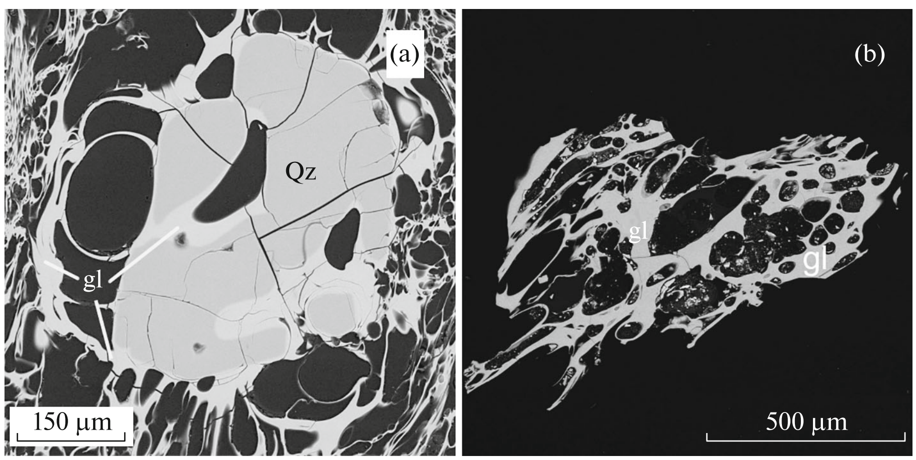

Fig. 5. (a) Bubble structure of the bulk glass around the quartz phenocryst (Guram section), (b) glassy ash particle from the peat on Urup Island (sample 11/3709). The images were made using a TESCAN MIRA 3LMU scanning electron microscope in the backscattered electron (BSE) mode.

Figure 3 shows that ash particle glasses of the CKr tephra horizons from Urup and Matua islands have rhyolite compositions with a moderate potassium content. The compositions of ash particles from Urup Island are the closest to those of the Guram section; tephra from Matua Island has a slightly higher SiO_2 and lower Na_2O content, although the contents of Al_2O_3, CaO, K_2O, FeO, and MgO are similar to those of Guram. The bulk ash from the CKr horizon of Urup and Matua islands and the pumice of the Guram section show a similar distribution of rare and trace elements (Fig. 4).

RESULTS AND DISCUSSION

In the Late Pleistocene and Early Holocene, Iturup Island was the scene of powerful explosive volcanism, accompanied by the formation of calderas and thick strata of acidic pyroclastic deposits. The Late Pleistocene eruption in the area of the present-day Vetrovoi Isthmus was apparently one of the most powerful volcanic events [2, 12]. However, no traces that would indicate significant volcanic activity in the Late Holocene have been found so far in this part of the island.

The results of mineralogical and geochemical analysis of the Guram section pumice show that its origin is related to the magma, similar in composition to the source magma of the pumice layer of Vetrovoi Isthmus and the Belye Skaly landmark. Slight differences in the compositions of bulk glasses of the Guram and Vetrovoi pumices may be explained by crystallization differentiation in a shallow basin. As was shown in [12], the evolution of the melt composition in the chamber feeding the eruption on Vetrovoi Isthmus was caused mainly by crystallization of plagioclase with a composition varying from basic to intermediate, and to a lesser extent of Fe and Ti oxides. The formation of quartz is related only to the latest crystallization stages immediately preceding the eruption. These features explain the minor increase in the silica content and the decrease in alumina and alkali metal concentrations in the melts, which distinguish the compositions of pumice glasses of Guram from those of Vetrovoi Isthmus and Belye Skaly. Thus, our data indicate that the ash particles of the CKr horizon on Urup and Matua islands represent the tephra of the eruption that occurred in the area of Vetrovoi Isthmus, found in the Guram section.

The dating of the earliest pyroclastic layer and underlying sediments in the Guram section suggests that the eruptive activity that led to tephra accumulation began no later than 2100–2000 yr BP. The power of the eruption, which led to the CKr formation, is currently difficult to estimate because of the absence of reliable estimates of the tephra distribution area. Assuming, however, that the isopachites are elliptical in shape, with their axes oriented towards the bisector of the area shown in Fig. 1b and taking into account the thickness of the CKr tephra horizon on different islands, we can calculate the minimum eruption volume. In this case, the maximum size available for measurement will be the 1 cm isopachite, with the outermost edge in the vicinity of Matua Island. Using the procedure described in [19], the minimum eruption volume from this isopachyte can be estimated to be about 1.5×10^9 m^3. This value may be 2–5 times lower than the estimates that would more accurately take into account the shape of the isopachyte and the regular thinning of the power with distance from the eruption center [19]. The volume obtained corresponds to a Plinian eruption with an eruptive column height of about 25 km (VEI ~ 4–5) according to [20]. Thus, a sufficiently strong explosive eruption occurred in the area of Vetrovoi Isthmus in the recent geological past, after the formation of the main volume of pumice–pyroclastic deposits developed there at the end of the Late Pleistocene. This confirms the earlier assumption [14] about several pulses of explosive volcanic activity on this part of the island. The data obtained unequivocally indicate that the latest pulses occurred no earlier than in the Late Holocene. This conclusion raises the question of revising the volcanic hazard of the northern part of Iturup Island and requires consideration of possible highly explosive eruptions. Vetrovoi Isthmus itself should be considered as an area of active volcanism.

Considering the above, we believe that the spreading and thickness patterns of the CKr horizon indicate the spreading of tephra of the aforementioned eruption in the northeasterly direction (Fig. 1b), which confirms the assumption that the source of tephra was an eruption on Iturup Island [4, 5]. The data we obtained suggest that the center of this eruption was located in the area of Vetrovoi Isthmus.

CONCLUSIONS

This paper describes the discovery of Late Holocene acid pyroclastics in the area of Vetrovoi Isthmus on Iturup Island, which gives grounds to consider it as a potential volcanic area, with an eruptive center capable of producing large eruptive eruptions (VEI 4–5). The results obtained suggest that an eruption occurred in the area of Vetrovoi Isthmus around 2100–2000 yr BP, which caused the formation of the CKr tephra horizon, distributed in the central part of the KIA between Matua and Iturup islands. The CKr horizon thus can be used as a tephrochronological and tephrostratigraphic marker for the islands of the central part of the KIA for paleogeographic reconstructions, correlation of sections, and dating of sediments and landforms.

The signs of active explosive volcanism during the last few thousand years in the southern part of KIA, close to the densely populated and economically developed areas of the Russian Far East and Japan, requires revision of the volcanic hazard in the region. This is particularly important because Iturup Island belongs to the territories of advanced development of the Russian Far East, which means expansion of economic activity on the island in the coming years.

ACKNOWLEDGMENTS

The authors are sincerely grateful to A.V. Rybin (Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences), who discovered the Guram section during fieldwork in 2018.

SUPPLEMENTARY MATERIALS

The online version contains supplementary material available at https://doi.org/10.1134/S1028334X23600597.

FUNDING

The tephra of the Guram section was supported by the Russian Foundation for Basic Research, project no. 18-05-00819, and within the framework of a State Assignment of the Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, and the Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences. Correlation of the remote eruption sources on Urup Island and Matua Island. ICP MS analysis of rare elements was supported by a grant of the Russian Science Foundation, project no. 21-17-00049, https://rscf.ru/project/21-17-00049.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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Translated by M. Hannibal