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Major, Trace Element and Sr–Nd–Pb Isotopic Geochemistry of Gorshkov Vent (18.02–21.03.2021), Klyuchevskoy Volcano (Kamchatka, Russia): Restarting a New Cycle of Volcanic Activity?

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Abstract—The new flank eruption named after G.S. Gorshkov started on 18 February, 2021 at Klyuchevskoy volcano (Kamchatka). The Gorshkov vent has erupted after a long time (~30 years) dominance of terminal eruptions, on the lower altitude (~2850 m a.s.l.) of the volcano. Lavas of Gorshkov vent are basalts–basaltic andesites (51.6–53.26 wt %) with low MgO (5.48–6 wt %), high Al_2O_3 (16.6–17.68 wt %), higher K_2O (0.85–0.9 wt %) contents and the highest $^{87}Sr/^{86}Sr$ (0.70367–0.70374) and $^{206}Pb/^{204}Pb$ (18.307–18.326) isotopic ratios in comparison to pre-historical and historical lavas of Klyuchevskoy volcano. The $^{143}Nd/^{144}Nd$ isotopic ratios of Gorshkov vent (0.51307–0.51310) are not so different to previously erupted lavas. The whole-rock composition and Sr–Nd–Pb isotopic ratios of the lavas from Gorshkov vent suggest for contribution of AFC (assimilation and fractional crystallization) processes in the crust. The newly erupted Gorshkov vent opens a question for possibility of the beginning a new cycle of activity on Klyuchevskoy volcano.

Keywords: Gorshkov vent, Klyuchevskoy volcano, cycle of volcanic activity, Kamchatka, Sr–Nd–Pb isotopic geochemistry

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INTRODUCTION

The Klyuchevskoy volcano is the highest (~4750 m a.s.l.) and most productive volcano (~90 × 10^6 t/year of lava and tephra) in a subduction-related setting on Earth (Fedotov et al., 2010; Portnyagin and Ponomareva, 2012). It is situated in the Central Kamchatka Depression, Kamchatka (Figs. 1a, 1b) and developed during the last ~7000 years. Numerous flank eruptions have occurred since ~ 3500 BP (Braitseva et al., 1995). The first historical record of the Klyuchevskoy eruptions dates back to 1697 AD (Piip, 1956). Before 1932 AD volcanic activities were concentrated at the summit of the volcano. Then flank eruptions restarted and formed cinder cones on the lower altitudes of the volcano (Menyailov, 1947; Tokarev, 1990), while summit activities continued. Since 1932 AD the tendency to increase altitude of cinder cones positions from ~450 to ~4250 m a.s.l. in 1989 AD was observed. The eruptions occurred in north-eastern to south-eastern slopes of Klyuchevskoy volcano (Ozerov, 2000). After the paroxysmal eruptions of 1993–1994 AD volcanic activities have been concentrated at the top of the volcano.

Seismic data indicate the location of the deep magma reservoir at a 25–30 km depth under Klyuchevskoy volcano (Fedotov et al., 2010; Koulakov et al., 2017). Degassing of the volatile-rich basaltic magmas generates deep long-period volcanic earthquakes and marks the feeding of the pipe-shaped conduit (Melnik et al., 2020). Microprobe analyses of phenocrysts suggested for the existence of two magma chambers at the levels of 6 and 1–2 kbar (Khubunaya et al., 2007). Polybaric fractional crystallisation of high MgO primitive melts produce evolved high Al_2O_3 magmas (Ariskin et al., 1995; Leonova and Kirsanov, 1974; Mironov et al., 2001). The erupted Klyuchevskoy basalts preserve a slab signature based on major, trace elements, volatiles and Pb–Sr–Nd isotope data (Bergal-Kuvikas et al., 2017; Kersting, Arculus, 1995; Portnyagin et al., 2007a). A ^{210}Pb–^{226}Ra–^{230}Th–^{238}U study of Klyuchevskoy lavas shows influence of both fluid addition from the subducting plate and the extension and decompression melting (Turner et al., 2007). Voluminous basic lavas of Klyuchevskoy volcano require melting of lower crustal metabasalts with variably high $\delta^{18}O$ and

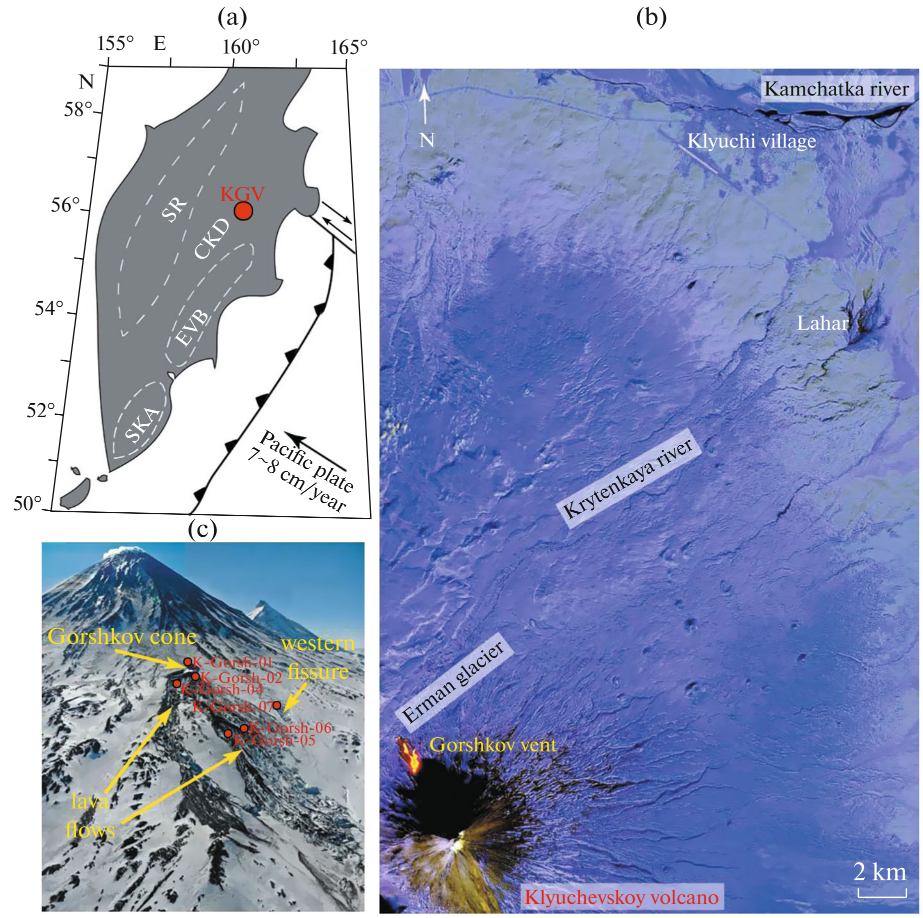

Fig. 1. (a) Position of Klyuchevskoy volcano and Gorshkov vent. (b) A satellite image was provided by Landsat-8 on 16 March 2021 AD. (c) Photo of Gorshkov vent. Note: KGV—Klyuchevskaya group of volcanoes, EVB—Eastern volcanic belt, CKD—Central Kamchatka depression, SR—Sredinny ridge, SKA—Southern Kamchatka arc.

$^{87}Sr/^{86}Sr$ (Bindeman et al., 2004). Alternatively high isotope values could originate from the assimilation of hydrothermally altered mafic lithosphere (Portnyagin et al., 2007b). Pb isotope compositions of Klyuchevskoy lavas confirm their assimilation in the lower crust (Kayzar et al., 2014).

After thirty years of dominant terminal eruptions on 18 February 2021 AD the new flank eruption formed on the north-western slope of the volcano (Ozerov et al., 2021). A cinder cone located at 2850 m a.s.l. (Fig. 1c). The lava flow moved down ~1.2 km and intruded into the Erman glacier. Numerous lahars were formed in the valley of Krytenkaya river (Ozerov et al., 2021). The flank eruption ended on 21st March 2021. It has been named after G.S. Gorshkov, an associate member of the USSR Academy of Science and president of IAVCEI during the 1971–1975 years.

Gorshkov vent appears especially interesting for study, because it is a first flank eruption after a long time of the dominant volcanic activities on the summit. The previous cycle of Klyuchevskoy volcano activity, as well as the Gorshkov vent, began on the lower slope of the volcano in 1932 AD (Tokarev, 1990). This could suggest that the new activation of the volcanic cycle started in February, 2021 AD. During the historical time flank eruptions have not formed in the north-western segment. Moreover, monogenetic cinder cones of pre-historical Klyuchevskoy's eruptions were not observed there too (Fig. 2). According to Vlodavets (1940), the cones located on the north-western of Klyuchevskoy volcano had the same magma source as the Plosky Sopki volcano. Consequently, it is important to compare the current conditions of the magma plumbing system of the Klyuchevskoy volcano and the temporal evolution of the geochemical and isotopic characteristics of the generated magmas. The lavas of future flank eruptions on the north-western slope of Klyuchevkoy volcano will potentially interact with Erman Glacier, causing

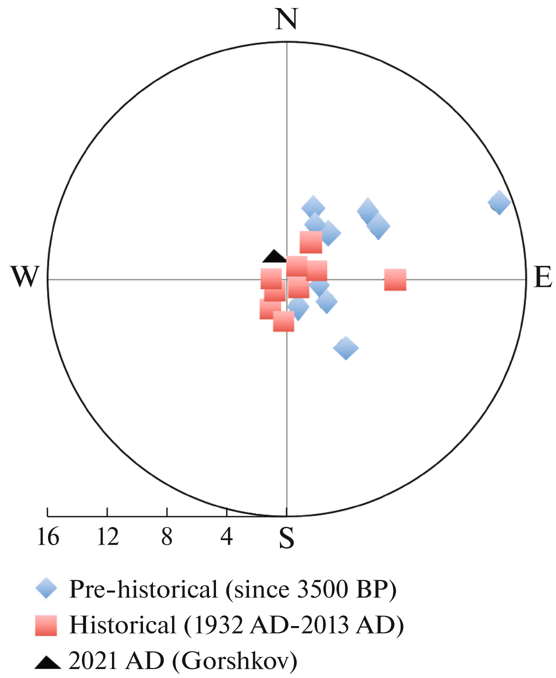

Fig. 2. Polar diagram illustrating the schematic spatial distribution of pre-historical and historical cinder cones around the summit. Locations of pre-historical cinder cones are shown according to Ermakov (1969), historical are according to Fedotov et al., (2010) and Tokarev (1990).

lahars to form and flow down the Krutenkaya River and increasing the danger of mudflows in the vicinity of the Klyuchi village.

Here based on newly presented high-precision major, trace element and isotopic (Sr–Nd–Pb) data of lava samples from the Gorshkov vent compared with previous eruptions we discuss the possibility of restarting a new cycle of volcanic activity on Klyuchevskoy volcano. We believe that this paper will appeal to a broad spectrum of specialists and complement the knowledge obtained from the studies of feeding systems of active volcanoes and their cycles of activities.

SAMPLES AND ANALYTICAL TECHNIQUES

Ten samples were selected from the Gorshkov vent. Samples are lavas and scorias, which were collected from the first days of eruption (2nd March) to the final portion of lava flows (5th April). Sampling points were on various parts of lava flows and represented a unique collection of rock samples from the Gorshkov vent.

All analytical works were carried out at the Analytical center and Laboratory of Isotope Geochemistry of the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Moscow. The major elements geochemistry was studied on an Axios mAX vacuum wavelength dispersive XRF spectrometer (PANalytical Company (Netherlands)). The trace element compositions were analyzed via inductively coupled plasma mass spectrometry (ICP-MS) using NEXION 2000C (USA). The measurement accuracy was controlled by international standard samples AGV-2 and BIR-1. The analytical uncertainties were estimated from the systematic analysis of the international standards and calculated less than 10%. The high-precision MC-ICP-MS method (Rehkämper and Halliday, 1998) was used in this study for analysis of the Pb isotope compositions in volcanic rocks (Chugaev et al., 2013). Analyses of Pb isotope ratios were carried out on a NEPTUNE mass-spectrometer (Thermo Scientific, Germany). Precision and accuracy of the results were monitored by systematic analyses of the SRM 981 and reference andesite sample AGV-2. The total error (±2SD) of analysis for Pb did not exceed ±0.03%. The Sr and Nd isotope compositions were measured by a Sector 54 mass spectrometer (Micromass, United Kingdom), using a multidynamic mode. The effects of mass-fractionation were corrected using an exponential law, via normalizing to $^{86}Sr/^{88}Sr$ = 0.1194, $^{146}Nd/^{144}Nd$ = 0.7219. The $^{87}Sr/^{86}Sr$ ratio of the SRM-987 and $^{143}Nd/^{144}Nd$ of the La Jolla measured during the period of the analytical session averaged 0.710242 ± 11 (±2SD, N = 10) and 0.511844 ± 12 (±2SD, N = 8) respectively. Addition-

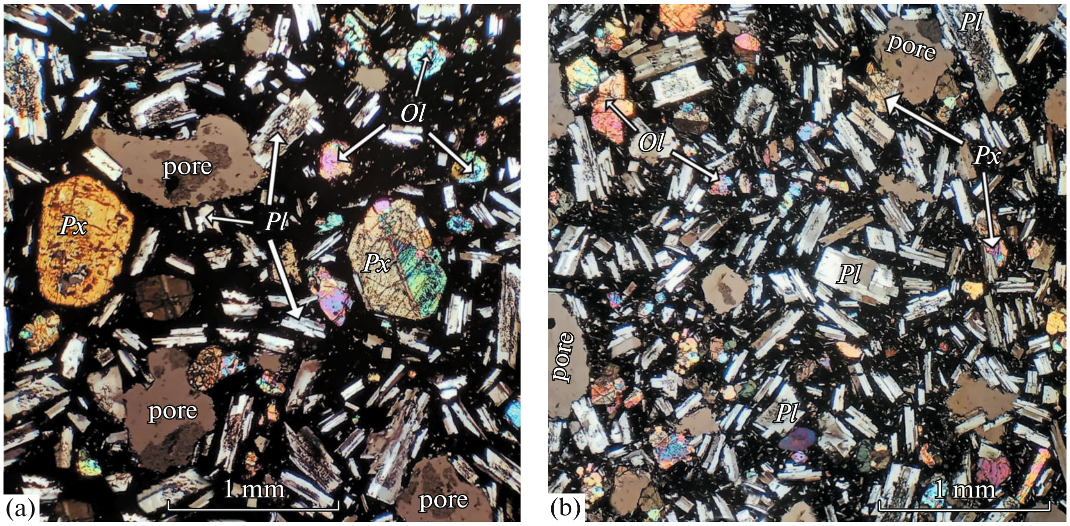

Fig. 3. Photos of thin sections of Gorshkov vent's lavas: (a) more mafic (sample K-Gorsh-04, SiO_2 = 51.60%), and (b) more felsic (sample K-Gorsh-06, SiO_2 = 53.26%) varieties of lava. Note: Pl—plagioclase, Ol—olivine, Px—pyroxene.

ally, the results for SRM 981 (N = 14) for the same period were: $^{206}Pb/^{204}Pb$ = 16.9424±20, $^{207}Pb/^{204}Pb$ = 15.5003 ± 12, and $^{208}Pb/^{204}Pb$ = 36.7266 ± 26. La Jola, SRM 981, AGV-2 are international standards, which usually used for checking precision of analytical measurements (Thirlwall, 1991; Weis et al., 2006). All listed standards and data of samples from Gorshkov vent were included in supplementary.

RESULTS AND DISCUSSION

The basalts-basaltic andesites of the Gorshkov vent are characterized by a fine porphyritic texture and a high degree of porosity (20–30%) (Fig. 3). Quantity of phenocrysts reaches 40% of rock's volume; they are mainly represented by plagioclase in various generations, as well as, in a subordinate amount, olivine and clinopyroxene. The predominant size of the phenocrysts is 0.4–0.6 mm, olivine and clinopyroxene rarely reach 1.0–1.2 mm. The groundmass of lavas is hyalopilitic, with poorly crystallized glass, filled with needle-like and tabular plagioclase microliths. The more mafic lavas of the Gorshkov vent (SiO_2 = 51.6%) differ from the more felsic ones (SiO_2 = 53.2%) by lower porosity and fresher glass in the groundmass in comparison to each other, as well as by the larger size of plagioclase, olivine and clinopyroxene phenocrysts (Fig. 3).

Magmas of Gorhkov vent are characterized by low MgO (5.48–6.0 wt %), high Al_2O_3 (16.60–17.68 wt %) contents and could be classified as high aluminium basalt-basaltic andesites (51.60–53.26 wt % SiO_2). The lavas from Gorshkov vent form a new trend on MgO vs SiO_2 pattern, which has lower MgO at the same SiO_2 contents in comparison to the previously analyzed pre-historical and historical lavas (Fig. 4a). K_2O contents coincide with the general trend of variations. However, the higher contents of K_2O were observed in samples with 51.5–52.0 wt % SiO_2 (Fig. 4b). The $^{143}Nd/^{144}Nd$ isotopic ratios of Gorshkov vent vary from 0.513066 to 0.513099, which are similar with other various aged lavas of Klyuchevskoy volcano (Fig. 4c). The $^{87}Sr/^{86}Sr$ (0.70367–0.70374) and $^{206}Pb/^{204}Pb$ (18.307–18.326) isotopic ratios of the Gorshkov vent have the highest isotopic ratios in comparison to all previously analyzed samples from Klyuchevskoy volcano (Figs. 4d, 4e), as same as the highest contents of high field strength elements (e.g., Nb ~1.95–2.24 ppm, Ta ~ 0.15–0.19 ppm etc), Eu (~1.19–1.22 ppm), Y (~22.61–23.98 ppm) and heavy rare-earth elements (e.g., Yb ~ 2.41–2.55 ppm etc) (Fig. 5).

The increasing isotopic ratios of the $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ with decreasing MgO in historical lavas from early to late eruptions is observed on Figs. 4, 6. The maximum values of radiogenic isotope ratios are typical for Gorshkov vent in comparison to historical lavas from Klyuchevskoy volcano (Figs. 4d, 4f, 6c, 6d). The variations of MgO decreased since 1932 to 1945 AD and after that time the contents of MgO have not changed significantly (Fig. 6b). The major element variations suggest that evolved magmas formed lavas from the Gorshkov vent, because MgO contents are relatively low in comparison with previously erupted magmas (Fig. 4a). Obviously, crustal processes have controlled the magma formation of the Gorshkov vent. The higher average radiogenic isotopic values of

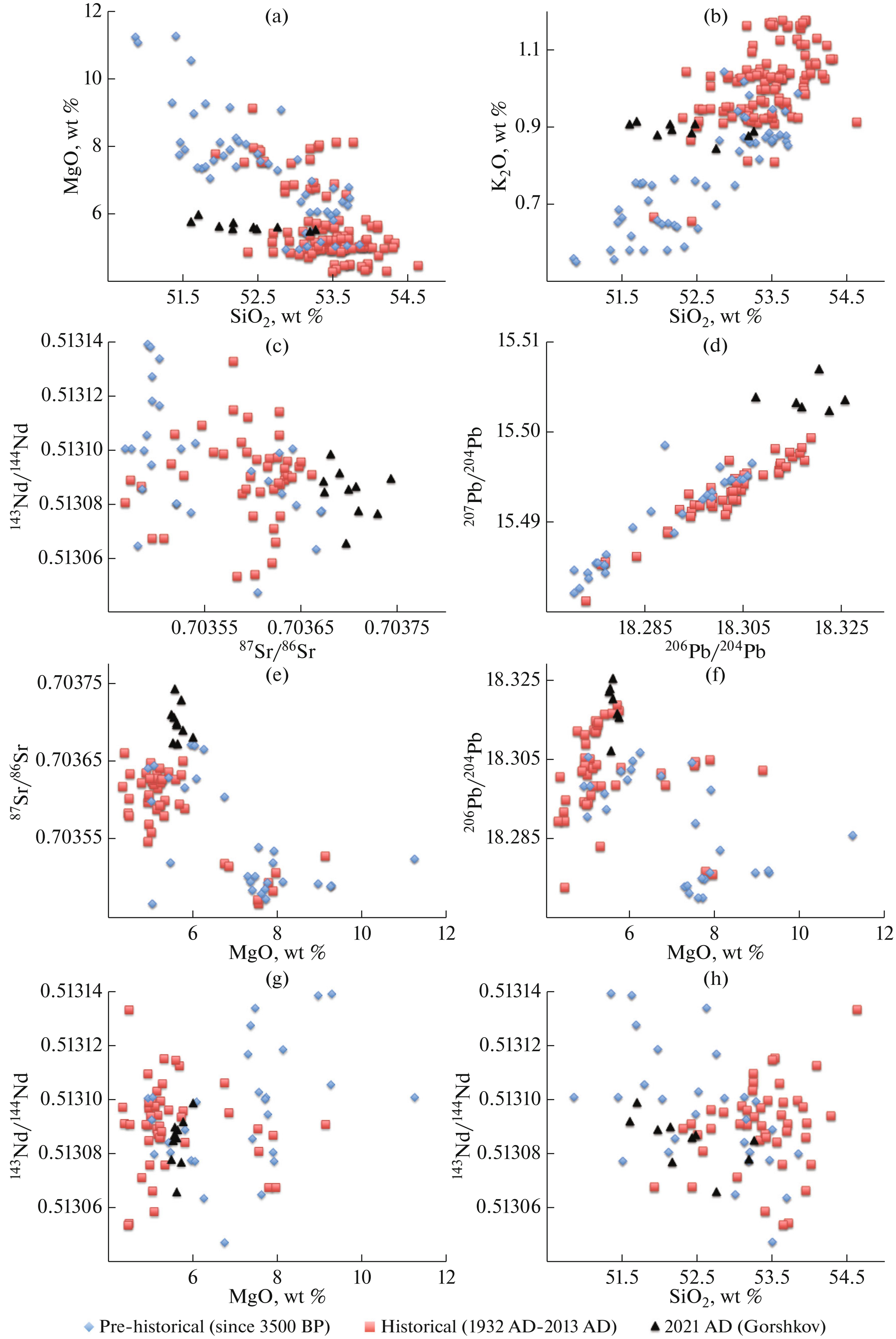

Fig. 4. Major elements geochemistry and Sr–Nd–Pb isotopic variations of lava samples from Klyuchevskoy volcano. Magma compositions of pre-historical and historical eruptions are taken from Bergal-Kuvikas et al., 2017.

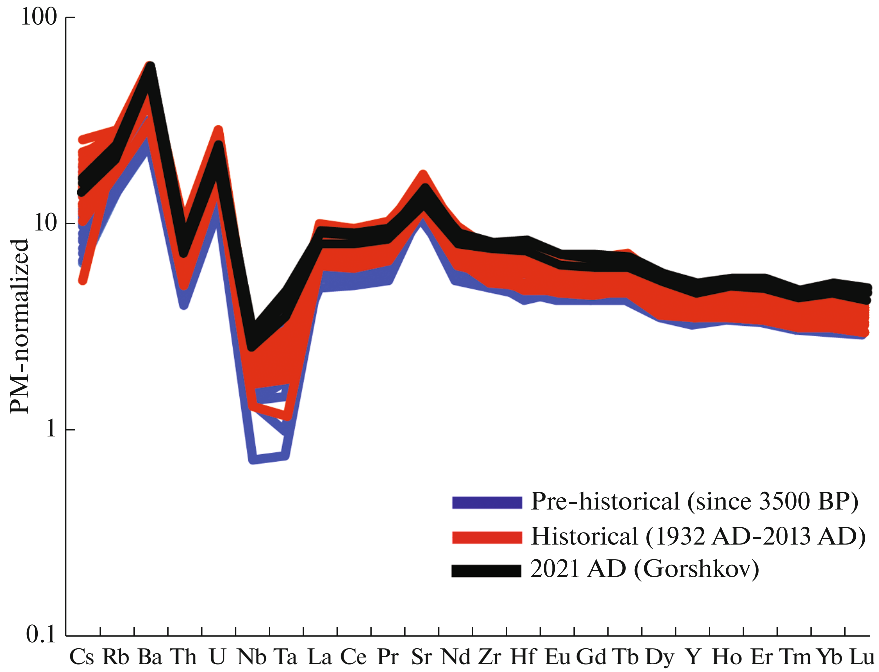

Fig. 5. Primitive mantle–normalized multi-element concentration diagram for representative samples of Klyuchevskoy volcano. Trace element concentrations of the primitive mantle are taken from Sun and McDonough (1989), magma compositions of pre-historical and historical eruptions of Klyuchevskoy volcano are from Bengal-Kuvikas et al., 2017.

Sr and Pb in lavas from the Gorshkov vent could be interpreted as a contribution of the AFC processes. There are opposite correlations between $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$ isotopic ratios and MgO contents for samples from Gorhkov vent (Figs. 4e, 4f). The highest isotopic ratios were observed for evolved magmas with MgO < 7 wt %. It suggests the higher contribution of crustal assimilation during the formation of the more evolved lavas of Gorshkov vent. Hence, based on geochemical and isotopic data, we suggest that the magmas from the Gorhkov vent mostly completed the previous cycle of Klyuchevskoy activity. Nevertheless, during the historical time, the cycle began only once in 1932 AD. The absence of enough observations does not enable us to predict closely the future of the Klyuchevskoy volcano and the question about starting new cycle of activity on Klyuchevskoy volcano is still open.

CONCLUSION

We present the new analytical data of major and trace elements geochemistry and isotopic ratios of lavas and scorias from a flank eruption named Gorhkov vent. This eruption occurred on the north-western slope of the Klyuchevskoy volcano, where no cinder cones of monogenetic eruptions have been observed before. Gorshkov vent was formed after 30 years of dominant terminal eruptions and could potentially mark a restart of a new cycle of Klyuchevskoy volcano activity indicating a change in its plumbing system. The highest Sr and Pb isotopic ratios of Gorshkov vent lavas in comparison to all previous analyzed samples from Klyuchevskoy volcano may correspond to the impact of the intensive AFC processes in the crust during magma formation. Consequently, despite on formation of Gorshkov vent on the low altitude of Klyuchevskoy volcano, which could be potentially suggest for restarting new cycle of activity, geochemical characteristics tend to magma evolution since 1932 AD. The future studies of newly formed cinder cones potentially will illustrate the tendency of magma plumbing system formation and cycles of activity on Klyuchevskoy volcano. The proposed here hypothesis of beginning or ending of a new cycle of activity will be tested in the future by study of the new flank eruptions, their position and geochemical characteristics.

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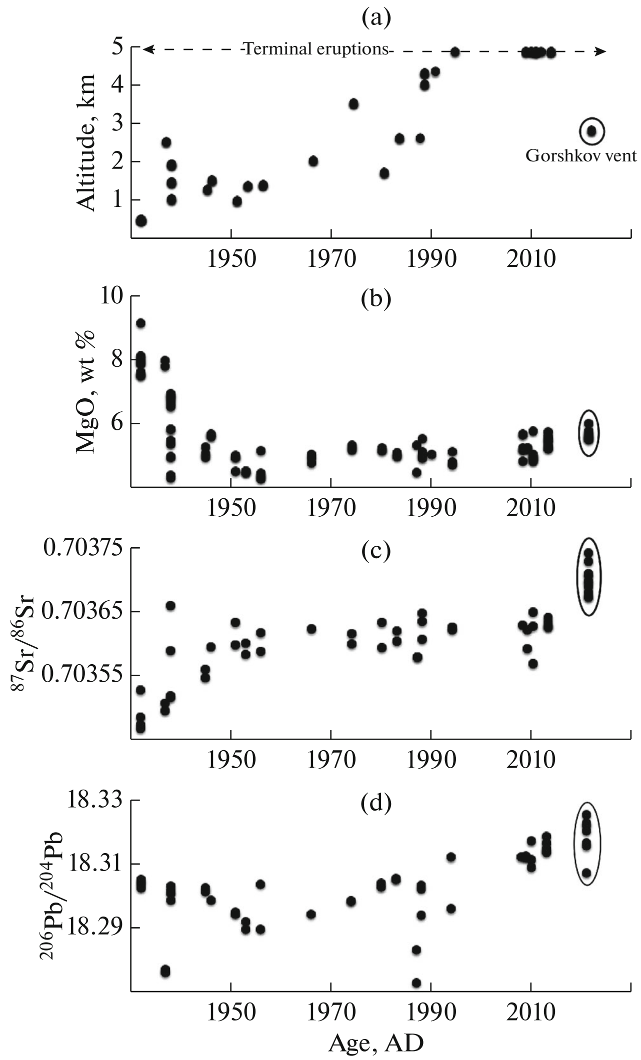

Fig. 6. Temporal variations of historical Klyuchevskoy eruptions and Gorshkov vent: (a) altitudes of historical flank (and terminal) eruptions; (b) MgO contents, (c) $^{87}Sr/^{86}Sr$ and (d) $^{206}Pb/^{204}Pb$ ratios. The geochemical data for comparison are shown for flank (1932-1989 AD) and terminal eruptions (1994–2013 AD) according to Bergal-Kuvikas et al., 2017.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY INFORMATION

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