

Modeling a Potential Collapse on Koryaksky Volcano and Assessing the Volcanic Hazard for the Elizovo–Petropavlovsk Agglomeration, Kamchatka

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Abstract—Simulation of a potential collapse on Koryaksky Volcano showed the most likely direction of movement for a debris avalanche. The periodic fumarolic activation of the volcano provides evidence of the circulation of meteoric waters and of favorable conditions for replacement of the bedrock in the volcanic edifice resulting in landslide deposits. Satellite data were used to study surface ground deformation. The north-eastern slopes of Koryaksky are rising relative to the subsiding southwestern slopes. Recalling that Koryaksky volcano stands at a distance of 10 km from Avachinsky Volcano which has produced massive explosive debris deposits during its history, the present study is of utmost urgency. The Elizovo–Petropavlovsk agglomeration (which includes the town of Elizovo and Petropavlovsk-Kamchatsky, as well as adjacent population centers in Elizovo District), which is in immediate vicinity of Koryaksky Volcano, harbors more than a half of all population of Kamchatka, as well as facilities that produce over half of all income in the region. Consequently, the assessment of naturally occurring processes on the volcano with a view to further development of a plan to minimize their negative impact is critically important for the economy of Kamchatka.

Keywords: gravitational collapse, debris avalanche, volcanic hazard, Koryaksky Volcano, Kamchatka

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INTRODUCTION

Debris deposits are widely abundant and known for many volcanoes worldwide such as Roque Nublo, Canary Islands, Spain (Cacho et al., 1994), Taranaki, New Zealand (Roverato et al., 2015), Antuco, Chile (Romero et al., 2022), Mt Shasta, California, USA (Crandell, 1989), and Iriga, Philippines (Yoshida, 2013). Kamchatka contains about 30 active volcanoes, of which 18 have produced numerous debris avalanches, ranging from small (0.001 km³) to catastrophic (20–30 km³) volumes (Ponomareva et al., 2006). The development of modern geoinformation technologies has enabled researchers to simulate the potential hazard due to debris avalanches on volcanoes, e.g., for Süphan Volcano, Turkey (Ozdemir et al., 2016), Pico de Tancitaro, Mexico (Morelli et al., 2010), and for Iriga Volcano, Philippines (Minimo and Lagmay, 2016). For Koryaksky Volcano V.V. Adushkin et al. (1995) considered a mechanism that can be responsible for failure in the volcanic edifice due to nearly horizontal magma injection from the conduit into the body of the volcanic edifice.

The nearly three decades that have elapsed since that time saw the development of new technologies

and methods in the study of volcanic processes, as well as another activation of Koryaksky Volcano; all of these events combined prompted us to formulate the goal of the present study as simulation of a potential collapse on Koryaksky Volcano using modern geoinformation technologies and as a study of possible scenarios for future developments. It is especially important to note that a catastrophic collapse occurred on Avachinsky Volcano, at a distance of 10 km from Koryaksky, whose collapsed volume of material was about 16–20 km³ (Ponomareva et al., 2006). Recalling the fact that both of these volcanoes, Koryaksky and Avachinsky, are in the same geodynamic setting, and are part of the same volcanic cluster, a similar scenario can well occur on Koryaksky. The importance of the present study is due to the fact that Koryaksky is at a distance of 30 km from the Elizovo–Petropavlovsk-Kamchatsky agglomeration with about 77% (~220 thousand people) of the entire population in Kamchatka (*Baza ...*, 2023). It thus appears that a study of potential hazard emanating from debris avalanches on Koryaksky is important for understanding possible risks and for the future development of economic activities in the region.

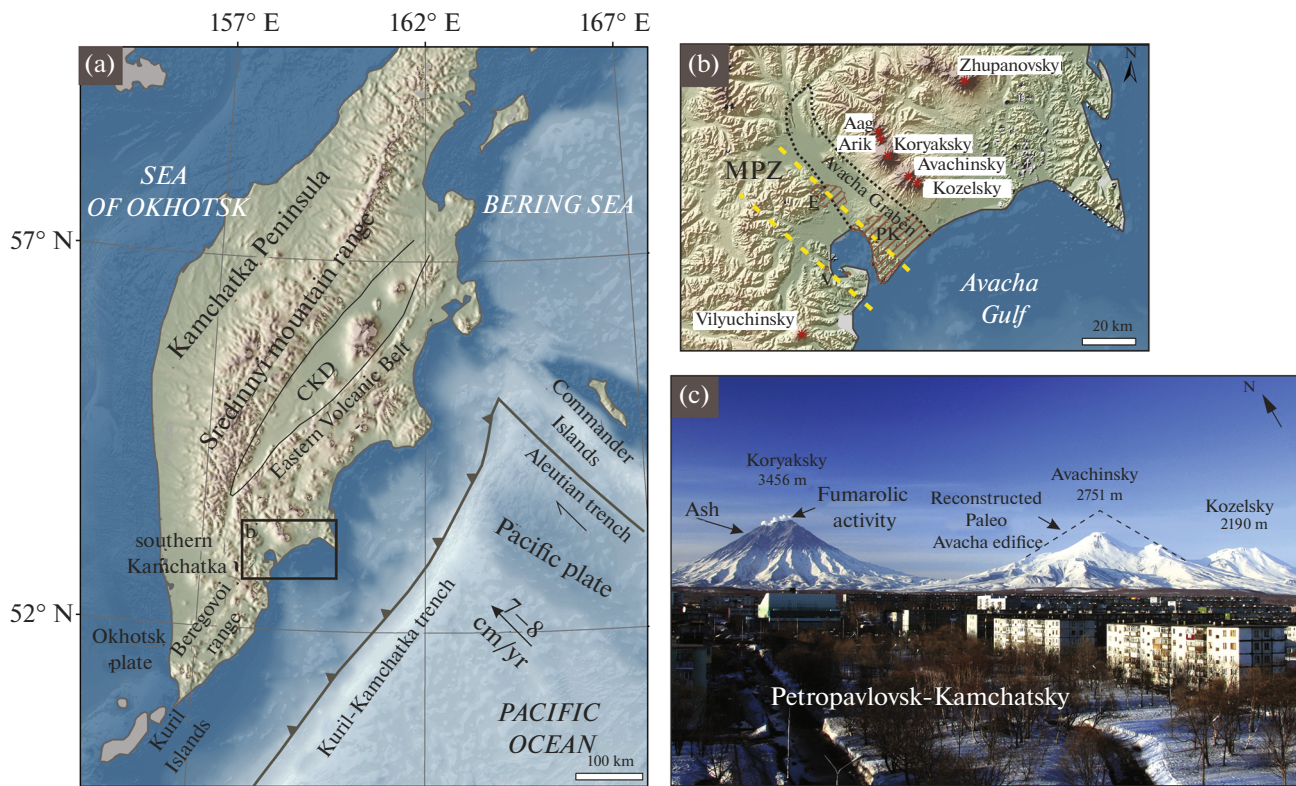


Fig. 1. Kamchatka (a), area of the Avacha Gulf (b), and the Avachinsky volcanic cluster as viewed from Petropavlovsk-Kamchatsky (c). CKD Central Kamchatka Depression; PK town of Petropavlovsk-Kamchatsky, E town of Elizovo, V town of Vilyuchinsky; MPZ Malko–Petropavlovsk zone of transverse dislocations. Photographed by A.V. Sokorenko on April 26, 2009. The heights of volcanoes are after (Masurenkov et al., 1991). The height of the Paleo Avacha edifice might be around 3700 m as estimated (personal communication of M.Yu. Puzankov, IVS FEB RAS, 2022). The boundary of the Avacha Graben (Avacha Depression) is after (Pozdeev, 2003).

THE GEOLOGICAL STRUCTURE OF THE AVACHINSKY–KORYAKSKY VOLCANIC CLUSTER

The Avachinsky–Koryaksky volcanic cluster is situated in the south of the Kamchatka Eastern volcanic belt (Fig. 1b). The region has a complex geological structure because of the accretionary boundary of the Kronotsky paleo arc (Avdeiko and Bergal-Kuvikas, 2015; Lander and Shapiro, 2007) and of the long-lived system of southern Kamchatka, including the Beregovoi range (Bergal-Kuvikas and Rogozin, 2023). The boundary has surface expression as the Avachinsky transform fault on the slab (Andreev, 1993) confirmed by mantle tomography (Bushenkova et al., 2023). The results of electrical prospecting and gravity surveys provide evidence of an anomalous zone, the Avacha Graben, which is complicated by volcano-tectonic depressions of the Avachinsky–Koryaksky volcanic cluster (Moroz and Gontovaya, 2003; Nurmukhamedov, 2016). The ground surface of central Kamchatka shows numerous tectonic discontinuities of the Malko-Petropavlovsk zone of transverse dislocations with associated monogenic cones and hydrothermal magmatic systems (Agibalov et al., 2023).

The Avachinsky–Koryaksky volcanic cluster is a linear row of volcanoes oriented northwest, that is, across the Eastern volcanic belt (see Fig. 1). The cluster consists of the following volcanoes (from west to east): Aag (2319 m), Arik (2166 m), Koryaksky (3456 m), Avachinsky (2751 m), and Kozelsky (2190 m). The total area of the deposits discharged by these volcanoes is ~ 2000 km². The volcanoes do not appear as individual edifices up to a height of 1000 m, the deposits of their bases make an isometric accumulative pedestal 40–50 km in diameter (Masurenkov et al., 1985). According to the State Geological Map (2000), the Avachinsky–Koryaksky volcanic cluster belongs to the Pleistocene–Holocene andesite formation. Koryaksky Volcano stands at a distance of 230 km from the trench, and the isotope geochemical characteristics of its lavas classify it as belonging to the backarc part of the volcanic belt (Bergal-Kuvikas et al., 2022). The results of magnetotelluric sounding surveys show that the volcanoes of the Avachinsky–Koryaksky volcanic cluster receive recharge along the faults of the Malko–Petropavlovsk zone of transverse dislocations (Moroz and Loginov, 2019), and that the area of the Avacha Graben is saturated with fluids (Moroz and Gonto-

Table 1. Information on the historical activity of Koryaksky Volcano

Year of activity	Type of activity		Supplementary information	Source
	fumaroles	Ash ejections		
1827	+			(Melekestsev, 1996)
1855	+			(Melekestsev, 1996)
1890s?			Fissure	(Melekestsev, 1996)
1897	+			(Melekestsev, 1996)
1904	+			(Melekestsev, 1996)
1926	+	+		(Melekestsev, 1996)
1931	+			(Melekestsev, 1996)
1945	+		“Very violent”	(Melekestsev, 1996)
1952	+			(Melekestsev, 1996)
1954	+		“Violent”	(Melekestsev, 1996)
1956–1957	+	+	Lahar, fissure	(Gordeev et al., 2011; Melekestsev, 1996)
1962	+			(Melekestsev, 1996)
1983	+			(Taran, 1985)
1984	+			(Gordeev et al., 2011)
2008–2009	+	+		(Gordeev et al., 2011)

vaya, 2001). Mantle tomography gave the depth to the magma chamber beneath Koryaksky as 7 km (Bushenkova et al., 2019).

Koryaksky is a typical stratovolcano with alternating lava flows and pyroclastic sequences (Masurenkov et al., 1991). The volcano has a regular conical shape 3456 m in height with steep slopes: up to 35° at the summit and up to 20° in mid-slope. The diameter of the base is about 20 km, the relative height above the southern pedestal is 3200 m and that above the northern is 2399 m. The slope surface is dissected by deep barrancos. The base of the volcano has an area over 300 km² (*Gosudarstvennaya ...*, 2000). In the western part of the volcano is a crater about 200 m across and as deep as 30 m. The crater is open southward. There are active fumarole patches in the crater and at a height of 3 km on the volcano’s western slope (Masurenkov et al., 1991). Simulation of the equilibrium shape for the Koryaksky edifice showed that, in addition to ring structures, there are sectors in the edifice where a gravity-stable slope profile has been achieved over time (Delemen et al., 2004).

The Koryaksky edifice has been going through two phases in its evolution: the earlier, Late Pleistocene phase and the later, Holocene phase (*Gosudarstvennaya ...*, 2000). Koryaksky Volcano was highly active in the early Holocene, with about 60 events being recorded as can be inferred from tephrostratigraphic data (Krashennnikov et al., 2020). The age of some lava flows discharged by Koryaksky is estimated as

8000–8200, 7800, 7150, and 6700 calendar years (Bazanov et al., 2012) (Fig. 2).

During the last 200 years Koryaksky showed 15 bursts of activity dominated by phreatic eruptions (Melekestsev, 1996). The last cycle of activity took place in 2008–2009 when high fumarolic activity and ashfalls were observed (Gordeev et al., 2011) (Table 1, see Fig. 1c). Satellite-based radar interferometry techniques based on images of the Japanese ALOS-1 satellite were used to determine displacements for the Koryaksky slopes, which were found to reach 25 cm during the last burst of activity (Mikhailov et al., 2021). The most likely factor causing the recorded displacements must have been, in the opinion of these authors, the emplacement of magmatic material into the volcanic edifice, producing a fissure whose lower rim was 0.5 km above sea level. Its dimensions are 1.0 km along strike, 2.4 km along dip, and its angle of dip is between 45° and 60° (Mikhailov et al., 2021).

Avachinsky has the Somma-Vesuvius shape. It consists of alternating lava flows and pyroclastics (Zavaritsky, 1977). The existing young cone of Avachinsky volcano has grown in the place of Paleo Avacha, which was ~3700 m high, according to some estimates (the personal communication of M.Yu. Puzanov, IVS FEB RAS, 2022), and which was partially destroyed in the Pleistocene by several eruptions. Melekestsev et al. (1991, p. 9) showed that “the evolution of Avachinsky Volcano during Late Pleistocene time involved at least two episodes of considerable damage done to its edifice related to catastrophic eruptions of the directed explosion type occurring at

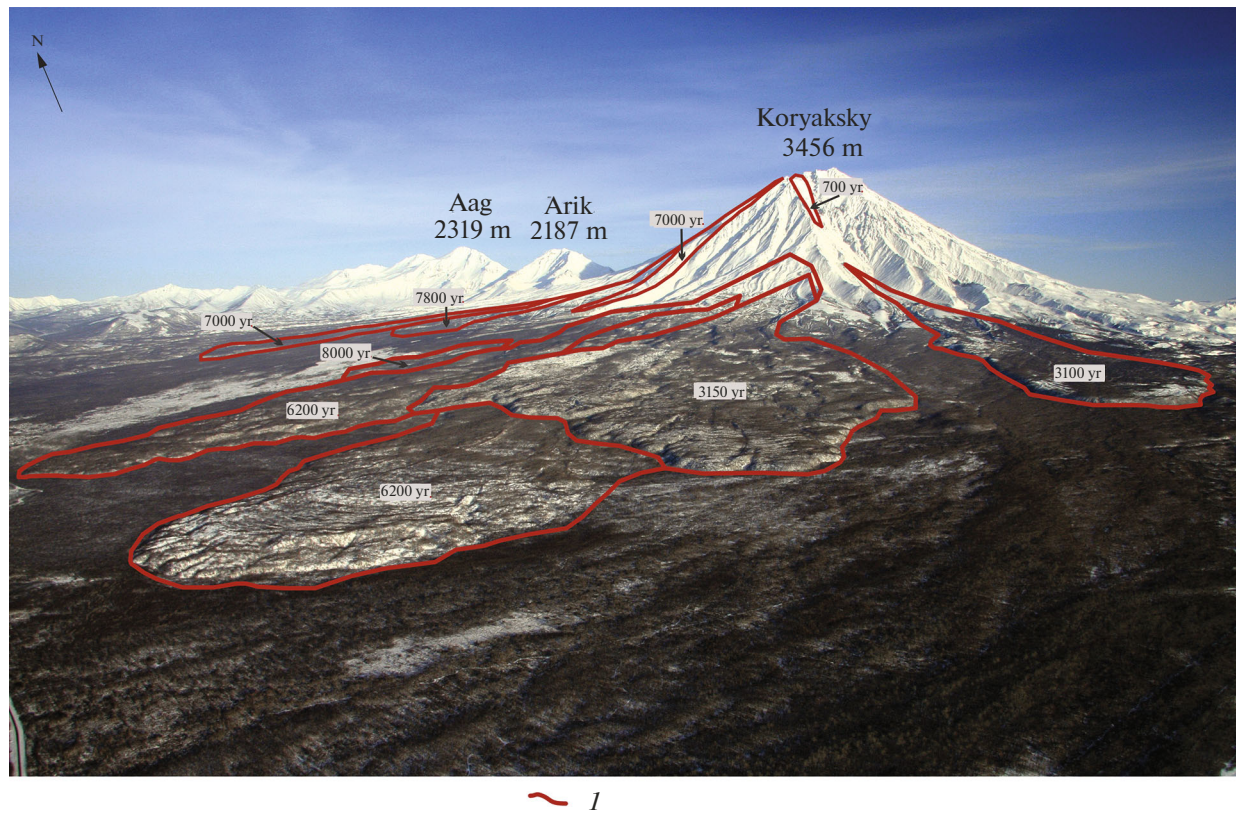


Fig. 2. Lava flows of Koryaksky Volcano. Heights of volcanoes are after (Masurenkov et al., 1991). The contours and ages (in calendar years) for lava flows are after (Ponomareva et al., 2016; Golotsenovi ..., 2023). Photographed by A.V. Sokorenko. Note: (1) contours of lava flows.

intervals of a few (?) thousand years. Material was ejected southwestward and southward both times.” Radio carbon technique was used to determine the ages of these catastrophic eruptions, namely, 29–30 and 35–40 ka (Melekestsev et al., 1991). The ruda-ceous explosive and collapse deposits covered an area of about 400 km² at first, their volume was 16–20 km³ (Melekestsev et al., 1991). According to Delemen et al. (1985), the deposits of these directed explosions at Avachinsky lay in an area of about 150 km², reaching a thickness of about 300 m at the pedestal of the Avachinsky–Koryaksky volcanic cluster. The eruptions have cardinally restructured the relief south of Avachinsky volcano, with the lower reaches of the Avacha River bed being displaced by 6–10 km (Melekestsev et al., 1991). The existing town of Petropavlovsk-Kamchatsky and adjacent population centers are situated on explosion-related collapse deposits of Avachinsky volcano whose maximum measured thickness is 170 m (Fig. 3).

The Avachinsky–Koryaksky volcanic cluster contains thermal mineral springs (Koryakskie Narzany, Izotovskiy, and Pinachevskiy springs, see Fig. 3), which are hydraulically connected to the zone where magma is emplaced to feed Avachinsky and Koryaksky volcanoes (Kirjukhin et al., 2015).

METHODS OF STUDY

The problems that we are going to address in this study require the use of a set of approaches and models based on recent advances, including those in the area of geoinformation technologies.

SAR Interferometry

Satellites equipped with Synthetic Aperture Radar (SAR) acquire images of the ground surface by emitting radio signals and analyzing the reflected signal. In contrast to visible or infrared light, radio waves can pass through most clouds, and are equally effective both in day and in night time (Hanssen, 2001). Radio signals are characterized by amplitude and phase. Amplitude is related to the energy of the back scattered signal. Phase is related to the distance between the sensor and the target, and is used to estimate displacements in interferometric applications.

Interferometric Synthetic Aperture Radar, InSAR or SAR interferometry, is a method for measuring the change in signal phase between two images obtained for the same terrain at different times. When a point at the ground surface is displaced, the distance between the sensor and the point changes, affecting the phase of the signal recorded by the sensor. An interferogram

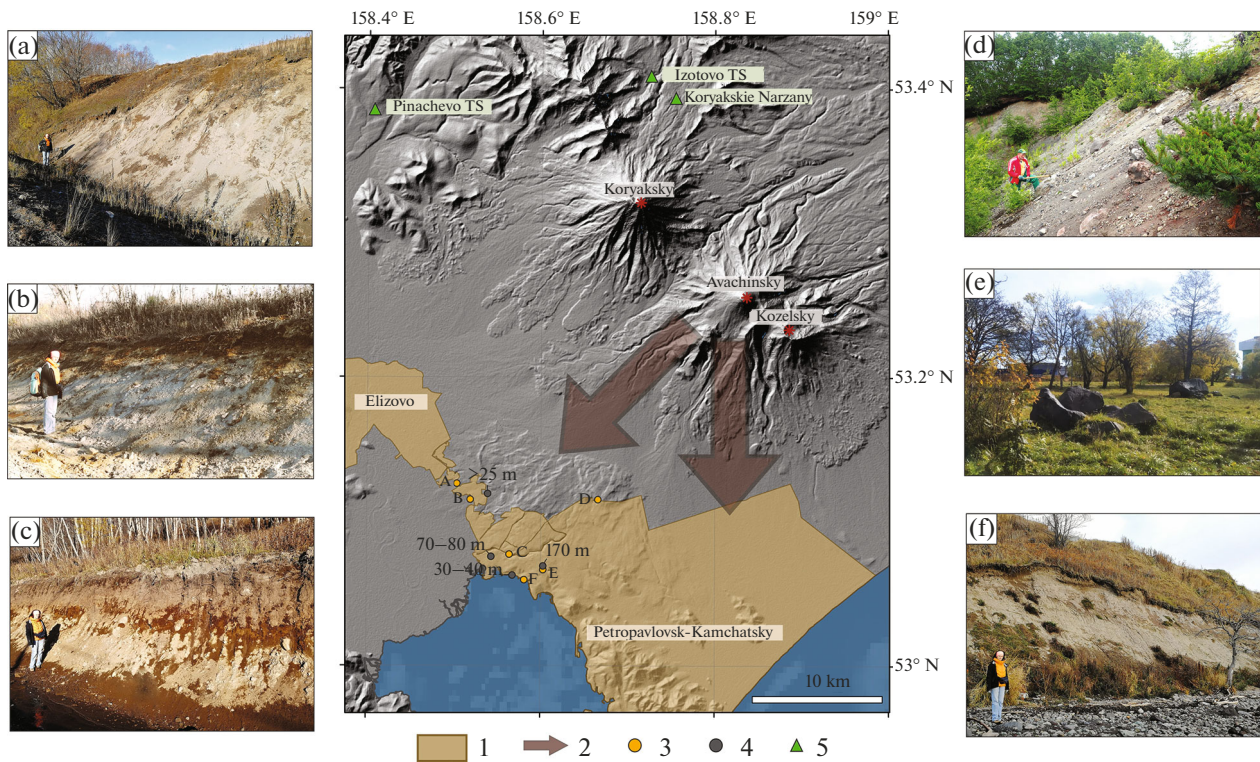


Fig. 3. Directions of propagation for landslide deposits due to Pleistocene eruptions of Avachinsky Volcano and photographs of representative exposures. Photographed by these authors. (1) areas of population centers in the Elizovo–Petropavlovsk agglomeration; (2) directions of propagation for landslide deposits due to Late Pleistocene catastrophic eruptions of Avachinsky Volcano (after Melekestsev et al., 1991); (3) sites where exposures were photographed: (a) v. Krasnyi, (b) v. Nagorny, (c) v. Krutobergovyi, (d) Mt. Lagernaya, (e) park near the building of IVS FEB RAS, (f) Mokhovaya Bay; (4) sites where thicknesses of debris avalanches were measured (after Grib et al., 1985; Melekestsev et al., 1991); (5) thermal springs (TS).

is a digital representation of changes in ground surface displacements.

The differential InSAR, or DInSAR, differs from InSAR in that the topographic effects in acquired interferograms are compensated by using a digital model of topography for the area of study, producing differential interferograms. DInSAR is not a method for accurate measurements of ground surface displacements, since as a matter of fact one measures the projection of displacement at a target point along the satellite line of sight, but the method is nevertheless useful for monitoring of natural occurrences accompanied by intensive crustal movements such as earthquakes and volcanic eruptions (Atzori et al., 2019; Ji et al., 2013; Sreejith et al., 2020; Wang et al., 2018; Xiong et al., 2022).

InSAR data are indispensable in cases in which the other techniques for the study of natural objects are inapplicable or have limited applicability because the objects of study are remote, or because of complex logistics or unfavorable weather conditions in the area of study. One remarkable example is furnished by the program of research in the volcanoes of the Aleutian Islands using SAR interferometry where important data have been acquired relating to ground surface dis-

placements that accompanied various phases in the precursory periods before eruptions on volcanoes such as Okmok, Westdale, Akutan, and others (Lu and Dzurisin, 2014).

In this study we analyzed SAR interferograms obtained by using the SF DAAC HyP3 2022 software and the GAMMA software product. We used the request service to retrieve InSAR data accessing the Vertex portal created at the Alaska Satellite Facility, University of Alaska, Fairbanks (Kristenson, 2022). The data contain processed data of Copernicus Sentinel 2022 provided by the European Space Agency (ESA). The creation of InSAR and DInSAR data was based on the Copernicus GLO-30 Public DEM digital topographic model with 1-s resolution (~30 m).

In order to remove the effects of atmospheric inhomogeneities and other factors that add noise to the resulting maps of deformation distribution, the interferograms were processed by the method of small baselines (SBAS—Small Baseline Subset). The principle of the method is that pairs of SAR images that are involved in the generation of interferograms are chosen so as to minimize the spatial and temporal separation (baseline) between the orbits of data acquisition, thus reducing decorrelation phenomena (Berardino

et al., 2002; Lanari et al., 2007). The SBAS method yields maps of mean deformation rate and time-dependent maps of deformation for each selected area in the territory under study.

We estimated crustal deformation using the Vertex service based on the SBAS procedures to analyze 18 pairs of images for the area of study acquired by the Sentinel-1 satellite in summer months from 2016 to 2022 inclusive. For this analysis we chose pairs of images with the shortest spatial separation (below 20 m) and a time interval of one year. All images involved in this analysis were recorded at the descending orbit. We analyzed three interferograms for each one-year interval (2016–2017, 2017–2018, and so on). The final map of relative vertical displacements is the result of averaging over all interferograms.

The Energy Cone Model

We assessed the hazard related to the descent of debris avalanches on Koryaksky using the Energy cone model. The model was first formulated by Malin and Sheridan (1982). It is a 3D-extrapolation of the energy line model (Heim, 1882). The model was based on the idea that the mobility of a volcanic gravity flow is controlled by the angle of the energy line. The angle is found as the ratio of relative height (H) to the distance of lateral movement of a volcanic gravity flow (L). As an example, if an avalanche starts at height 4 km and descends down the slope to reach a height of 1 km, having traversed a distance of 10 km, then we have $H/L = (4 - 1)/10 = 0.3$. The longer distance travelled by the flow, the smaller is the H/L ratio.

It thus appears that the assessment of the hazard of a debris avalanche using the energy cone model requires two parameters: the H/L ratio and the height of the block that goes down (H_c). The Energy cone model is used to describe various kinds of volcanic gravity flows, including pyroclastic flows, debris avalanches, and lahars.

Hayashi and Self (1992) and Sosio et al. (2012) give the distribution of various kinds of slide processes on volcanoes (volcanic collapse, pyroclastic flows, rock avalanches, etc.) in relation to the parameter H/L and avalanche volume. It was noted that debris avalanches on volcanoes involve greater volumes of rock compared with other, nonvolcanic, avalanches, as well as covering larger areas.

Ponomareva et al. (2006) used the H/L parameter, along with other characteristics, to describe debris avalanches on various volcanoes in Kamchatka. One can follow the diversity of observed values of that parameter (between 0.09 and 0.8) for different debris avalanches.

The parameter H/L is being used not only to describe past events, but also for simulation of possible future events. Such research has been done, e.g., for the following volcanoes: Merapi, Indonesia (Yulianto

et al., 2015), Changbaishan (at the border between North Korea and China) (Wan et al., 2012), and Vesuvius and the Phlegraean Fields, Italy (Tierz et al., 2016).

Our modeling of various scenarios for the descent of debris avalanches relied on the Energy Cone Simulation tool, which is part of the software product for the Volcanic Hazards Assessment Support System (VHASS) (Takarada, 2017). This system features a remarkable graphical interface, in which the point where an avalanche is about to start can be determined by a simple mouse click. Inputting the height of the block about to collapse (H_c), the lowest and greatest values, and the step at which the H/L parameter is varied, we can make the system generate a map with different scenarios for the descent of a gravity flow in relation to these parameters.

Further processing and visualization for the map was done using the ArcGIS and Google Earth software products.

RESULTS AND DISCUSSION

The final map showing the distribution of ground surface displacements (Fig. 4) clearly reveals areas of positive deformation along the Avachinsky–Koryaksky volcanic cluster on the north side of the area of study, which agrees with paleotectonic reconstructions and with the uplift of a considerable area in the Avachinsky and Vostochny ranges (*Karta ...*, 1977; Bergal-Kuvikas et al., 2019). The surface is experiencing negative deformation southeast of the volcanic cluster (see Fig. 4). These data provide evidence of a heterogeneous basement beneath Koryaksky Volcano, possibly standing on a northwest striking fault (Marenina et al., 1962). Geophysical observations corroborate the presence of the Avacha Graben at the basement of the Avachinsky volcanic cluster (Bushenkova et al., 2023).

An analysis of volcanic activity for the period of historical observation (Fig. 5) showed a dominant fumarolic activity with periodic ejections of ash. The ashes mostly consisted of resurgent material (Gordeev et al., 2011; Ponomareva et al., 2012). Absolute dating of some phenocrystals consisting of the ash discharged during the 2009 burst of activity showed that the magma is contaminated with heterogeneous detrital components of sedimentary rocks, and that the basement rocks beneath Koryaksky volcano have a wide time range, between the Archean and the Cenozoic (Bindeman et al., 2016). Geophysical observations on Koryaksky in 1966–2009 provide evidence of periodic activation of the faults and the penetration of meteoric water provoking occurrences of fumarolic activity on Koryaksky (Senyukov and Nuzhdina, 2010). An analysis of the seismic events beneath the volcano during the 2008–2009 eruption conducted by Kiryukhin (2020) showed that earthquake clusters were recorded at absolute heights of up to 2 km above sea level. That

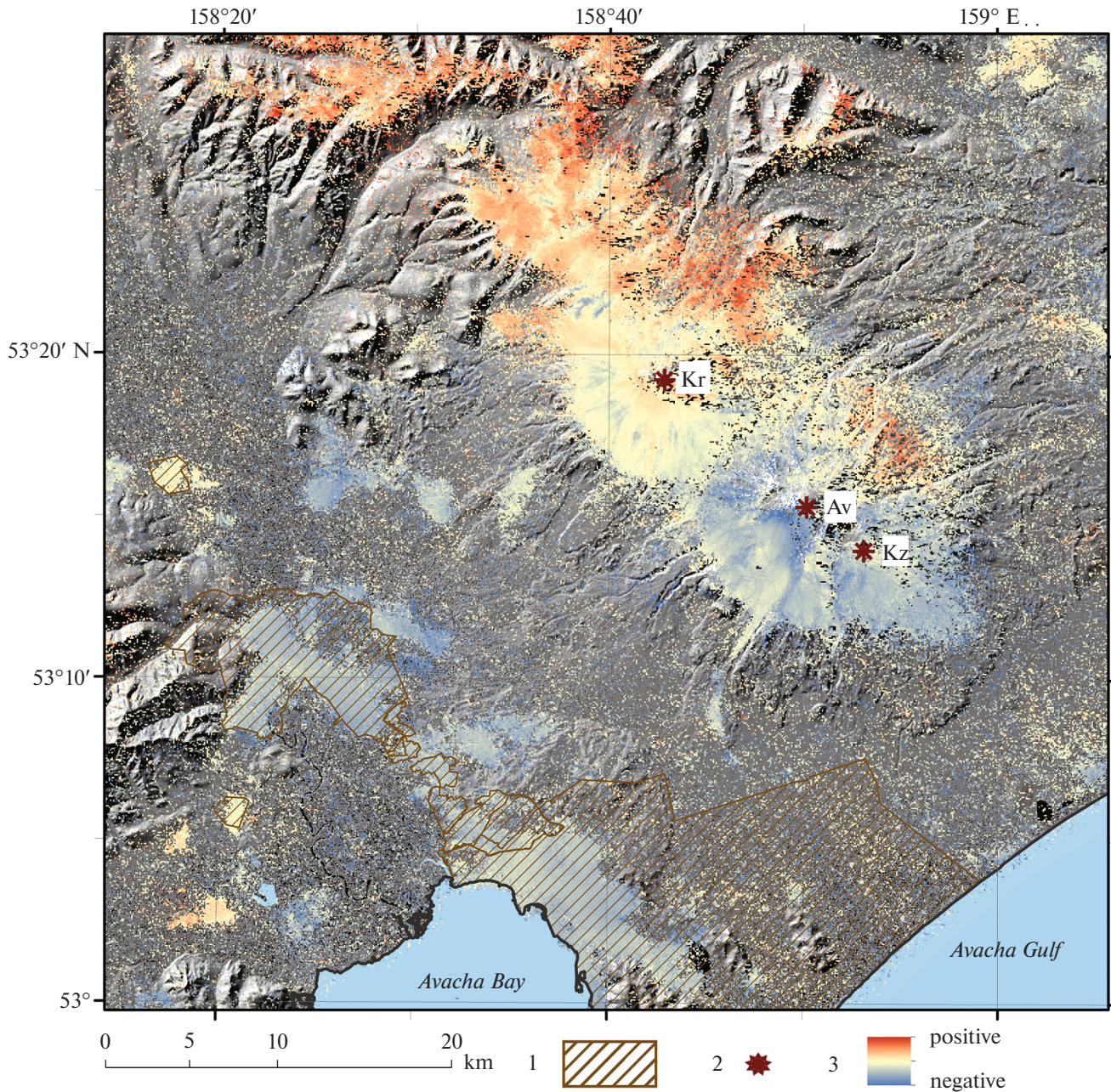


Fig. 4. Relative deformations of ground surface as recorded by the SBAS method from InSAR data. Positive deformation is interpreted as uplift, negative one as subsidence. (1) areas of population centers in the Elizovo–Petropavlovsk agglomeration; (2) volcanoes: Kr Koryaksky, Av Avachinsky, Kz Kozelsky; (3) relative deformation.

fact may provide evidence of an accumulating inhomogeneity of the volcanic edifice due to intensive heating of the rocks by fumaroles.

Numerous studies of stratovolcanoes provide evidence that hydrothermal alterations can produce collapses in volcanic edifices and give rise to landslide deposits (Kereszturi et al., 2021). Landslide deposits have been recorded on most volcanoes of the Avachinsky–Koryaksky cluster (Ponomareva et al., 2006), while for Koryaksky there are signs of destabilization

in the edifice and of fumarolic activity that is heating the entire edifice. These data were used to simulate the potential hazard due to landslide deposits on Koryaksky.

Figure 6 shows the results of simulation for different scenarios that can take place in the evolution of a potential landslide on Koryaksky volcano with surface relief incorporated. We have used various parameters to find the distances to which debris avalanches could travel. The lowest values (the height of the collapsed block 5 m, $H/L \sim 0.3$) were used, because Ponomareva

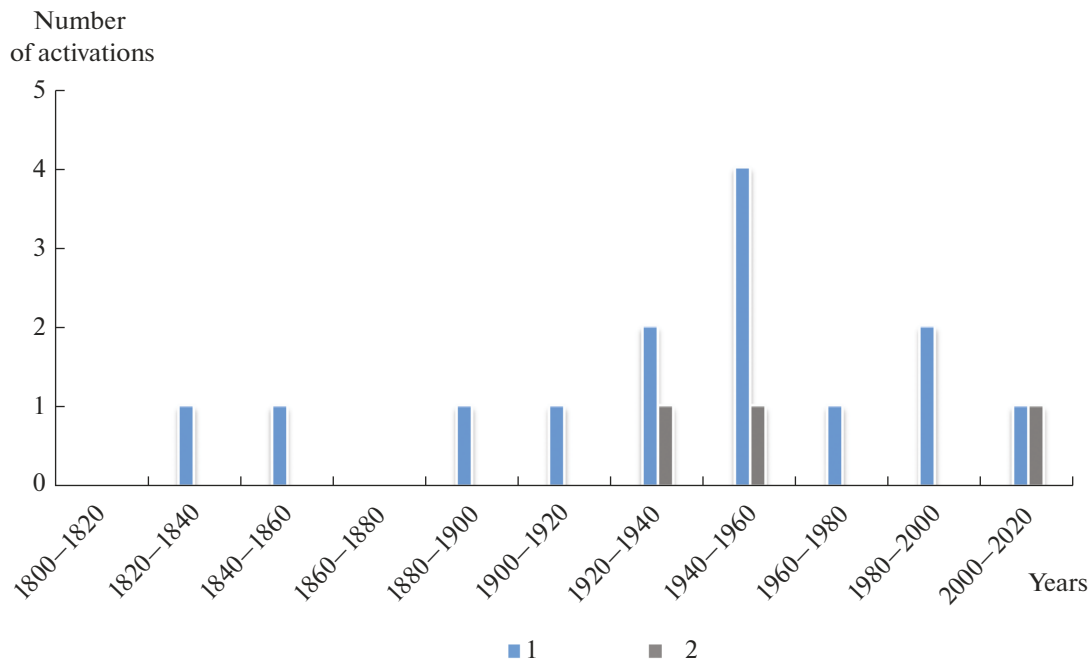


Fig. 5. A histogram of activity for Koryaksky Volcano during historical time (based on Table 1). (1) fumarolic activity, (2) ash ejections.

et al. (2006) have found out that such avalanches have occurred on Koryaksky volcano in the past. The greatest values (the height of the collapsed block 100 m, $H/L \geq 0.1$) were based on the debris avalanches on Avachinsky as reported by Ponomareva et al. (2006). We used the parameters of the avalanches that have taken place on Avachinsky as the model values for Koryaksky, since both of these volcanoes are confined to the same tectonic structure, have similar ages and rock compositions, as well as having similar morphologies and absolute heights (Melekestsev et al., 1991).

The results show that a potential landslide can trigger a debris avalanche that can travel at least 10 km from the volcanic edifice (see Figs. 6a, 6c). If the scenario of Avachinsky debris avalanches repeats on Koryaksky, the situation can attain catastrophic dimensions and affect much larger areas (see Figs. 6b, 6d). Recalling the existence of uplifts with great height contrasts (Avachinsky and Kozelsky volcanoes), the propagation of debris avalanches southeast is somewhat limited (see Fig. 6).

Since the Koryaksky edifice is heterogeneous, and its northeastern part is uplifted, while the debris avalanches on Avachinsky traveled south and southwest, we hypothesize that the dominant direction of travel for debris avalanches would be southwest (Fig. 7). Supposing that the next collapse on the volcano would be on the same scale as the known historical event (Ponomareva et al., 2006), that is, would have a volume on the order of 0.1 km^3 and would travel through

a distance of 10 km, the area under hazard would correspond with the parameter values $H/L \sim 0.3$ (see Fig. 7, the green area). The landslide deposits would then have a thickness reaching 1 m. When this relatively “favorable” case occurs, the greatest hazard would affect the summer cottages near the southwestern slopes of the volcano, as well as probably the buildings and infrastructure lying along the road toward the pass between Koryaksky and Avachinsky.

Adushkin et al. (1995) examined a mechanism of failure in a volcanic edifice due to nearly horizontal emplacement of magmatic material to propose the most likely scenario of landslide in the southwestern direction and with the distance of propagation for avalanches equal to 30–50 km and the area of avalanche deposits 80–1500 km^2 ; the volume of a possible avalanche collapse was $\sim 8 \text{ km}^3$. Such parameters of a debris avalanche correspond with values of H/L near 0.1, that is, with the blue area in Fig. 7. This is the worst scenario of those considered in this study, because the hazard zone covers densely populated areas and military facilities which are situated, e.g., in the village of Radygina, as well as infrastructure objects (the airport and the seaport, roads, electricity lines, etc.).

According to the Federal Statistical Service for Kamchatka Region, there were 288 730 residents in Kamchatka as of January 1 2023 (Baza ..., 2023), of whom 56% lived in the capital of the Region, and 21% more in the Elizovo Municipal District (Fig. 8a),

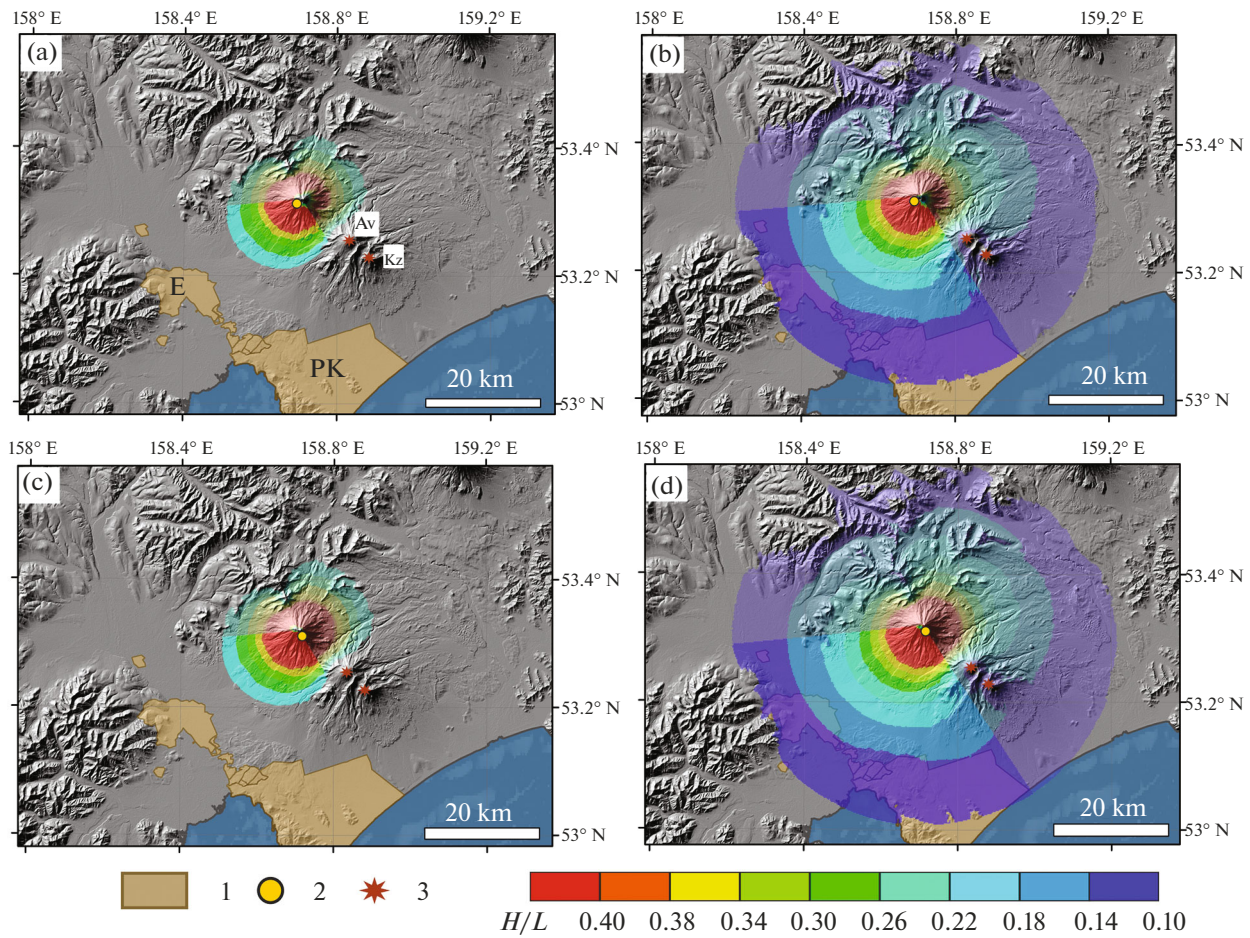


Fig. 6. Simulating the distribution of the H/L parameter which controls debris avalanche mobility on Koryaksky Volcano. (a, b) avalanche starts on the southwestern slope; (c, d) avalanche starts on the southeastern slope ((a, c) the height of the collapsing block is 5 m, $H/L \sim 0.3$; (b, d) the height of the collapsing block is 100 m, $H/L \geq 0.1$). (1) areas of population centers: PK Petropavlovsk-Kamchatsky, E Elizovo; (2) location where the debris avalanche started moving; (3) volcanoes: Av Avachinsky, Kz Kozelsky.

which includes two other towns of Kamchatka, viz., Elizovo and Vilyuchinsk. We thus see that more than half of the Kamchatka population live in immediate vicinity of Koryaksky Volcano, and is in the zone of risk due to potential rockfalls.

The Elizovo–Petropavlovsk agglomeration, which includes the towns of Elizovo, Petropavlovsk-Kamchatsky, and the population centers of the Elizovo District between them, is also the most developed area of Kamchatka in economic terms with over 60% of the income due to all facilities in the Region (see Fig. 8b). In the context of the problem discussed in the present paper, it is especially important that a considerable proportion of the economy of the Elizovo District is due to enterprises of agriculture, hunting, fisheries, extraction of mineral deposits, manufacturing enterprises, resource supply (water disposal, production of electrical energy and gas). The key role for these is played by, firstly,) reliable infrastructure (roads, elec-

trical lines, logistic points, etc.); and, secondly, exploitation of developed land. In this connection the impact of a debris avalanche from Koryaksky Volcano on the scale shown in Fig. 7 would be catastrophic for the economy of the whole Kamchatka Region. It is therefore all the more important to conduct continuous monitoring of the Koryaksky edifice in order to have enough time for preparation and for reducing, as much as possible, the negative impact due to potential avalanches and subsequent economic loss.

CONCLUSIONS

Satellite interferometry was used to show that the northeastern slopes of the Koryaksky edifice are subject to positive deformation relative to the subsiding southwestern slopes. Periodic fumarolic activity and ejection of resurgent ashes imply circulating meteoric waters in the volcanic edifice. This can favor the for-

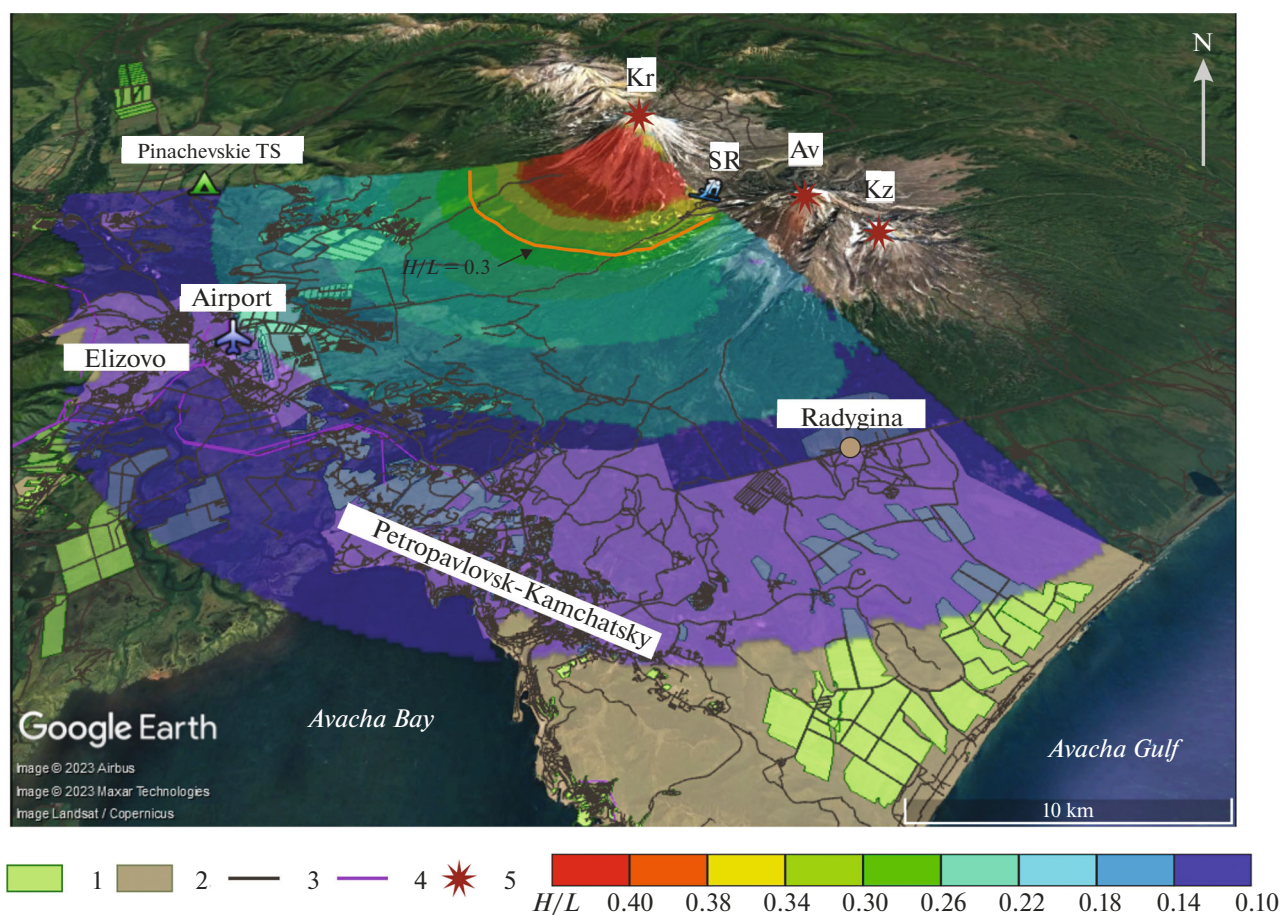


Fig. 7. A map showing the hazard of potential debris avalanches on Koryaksky Volcano. Onto a 3D scene we have superposed areas of the distribution of H/L , shown in Fig. 6a and Fig. 6b. (1) agricultural areas (pastures, farms, horticultural associations, etc.); (2) areas of population centers; (3) roads, passageways; (4) electricity lines; (5) volcanoes: Kr Koryaksky, Av Avachinsky, Kz Kozelsky. SR ski resort, TS thermal springs. (1–4) according to the OpenStreetMap project (2022).

mation of fields of altered rocks, hence disturbances in the strength of the edifice, creating conditions for collapse on the volcano resulting in the generation of landslide deposits. Bearing in mind the scale of landslide deposits on the adjacent Avachinsky Volcano, we did a simulation of collapse for a part of the Koryaksky edifice, and demonstrated the sector of this collapse. The zone affected by the movement of a potential debris avalanche covers nearly all of the Elizovo–Petropavlovsk agglomeration, which poses very high risks for human lives and for the economy of Kamchatka Region. The reduction of the impact due to processes occurring on Koryaksky Volcano requires the implementation of several measures that should include, at the minimum, installation of precision GPS stations near the Koryaksky summit, as well as a network of seismometers. Should considerable deformation occur in the volcanic edifice, this monitoring would enable the emergency services to carry out several rescue operations, including evacuation of the people concerned.

ABBREVIATIONS AND NOTATION

IVS	Institute of Volcanology and Seismology
FEB	Far East Branch
RAS	Russian Academy of Sciences

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

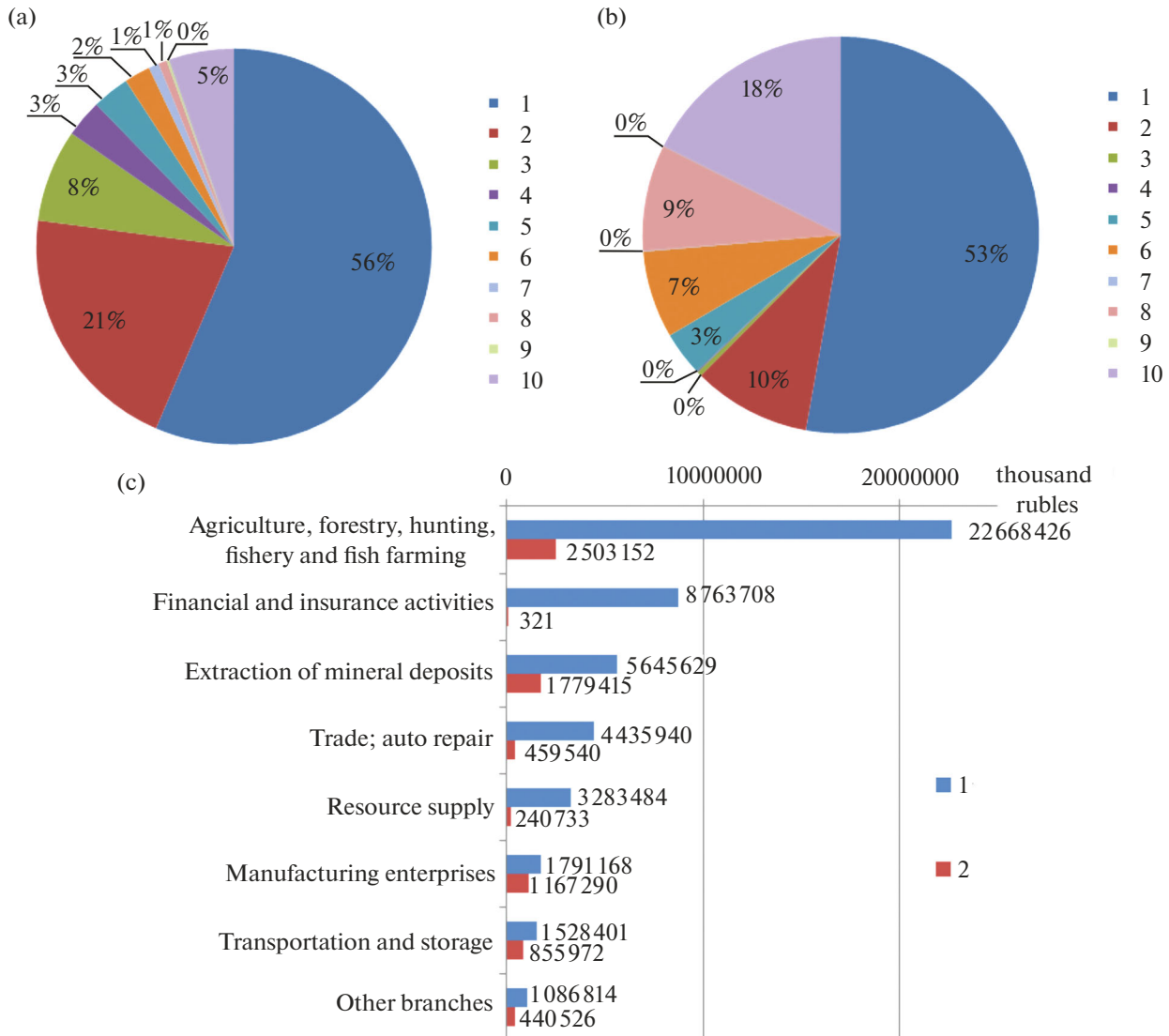


Fig. 8. Social and economic parameters for districts of Kamchatka Region, after (Baza ..., 2023). (a) percent distribution of population as of January 1, 2023, (b) percent distribution of income for organizations based on accounting data for 2021, (c) income distribution for organizations in Petropavlovsk-Kamchatsky District and in Elizovo District in various branches of industry for 2021. (1) Petropavlovsk-Kamchatsky city district, (2) Elizovo municipal area (MA), (3) Vilyuchinsk, (4) Milkovo MA, (5) Ust-Kamchatsk MA, (6) Ust-Bolsheretsk MA, (7) Bystrinsky MA, (8) Sobolevo MA, (9) Aleutian Municipal District, (10) Koryaksky District.

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