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Ground Surface Breaks Produced by an Earthquake and Volcanic Eruptions in the Karymsky Volcanic Center on January 1-2, 1996

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This paper presents the first results of an investigation of the ground-surface ruptures caused by a magnitude 7.0 earthquake and eruptions in the Karymsky volcanic center over the period January 1-2, 1996. The propagation and structure of the ruptures, the character of displacements, and the structural setting are discussed.

INTRODUCTION

The Karymsky earthquake of January 1, 1996, was a shallow event and had a magnitude of 7.0. It was the largest earthquake recorded beneath the Kamchatkan volcanoes over nearly 50 years of seismological observation [5]. The Kamchatkan Experimental Seismological Team, Geophysical Service, Russian Academy of Sciences, reported its epicenter to be about 17 km south of Karymsky Volcano (Figs 1 and 2). The earthquake was immediately followed by volcanic eruptions that occurred simultaneously along a north-south line: at Karymsky, one of the most active volcanoes in Kamchatka, and several eruptive vents in Lake Karymskoe where no historic eruptions had been recorded.

The surface effects of the Karymsky earthquake were investigated over the period July 29 to August 12, 1996. The first areas were investigated south of Lake Kaiymskoe (the catchment area of Karymsky Creek and the upper reaches of the Polovinka River), because the instrumental epicenter was situated nearby. Nevertheless, no traces of a large

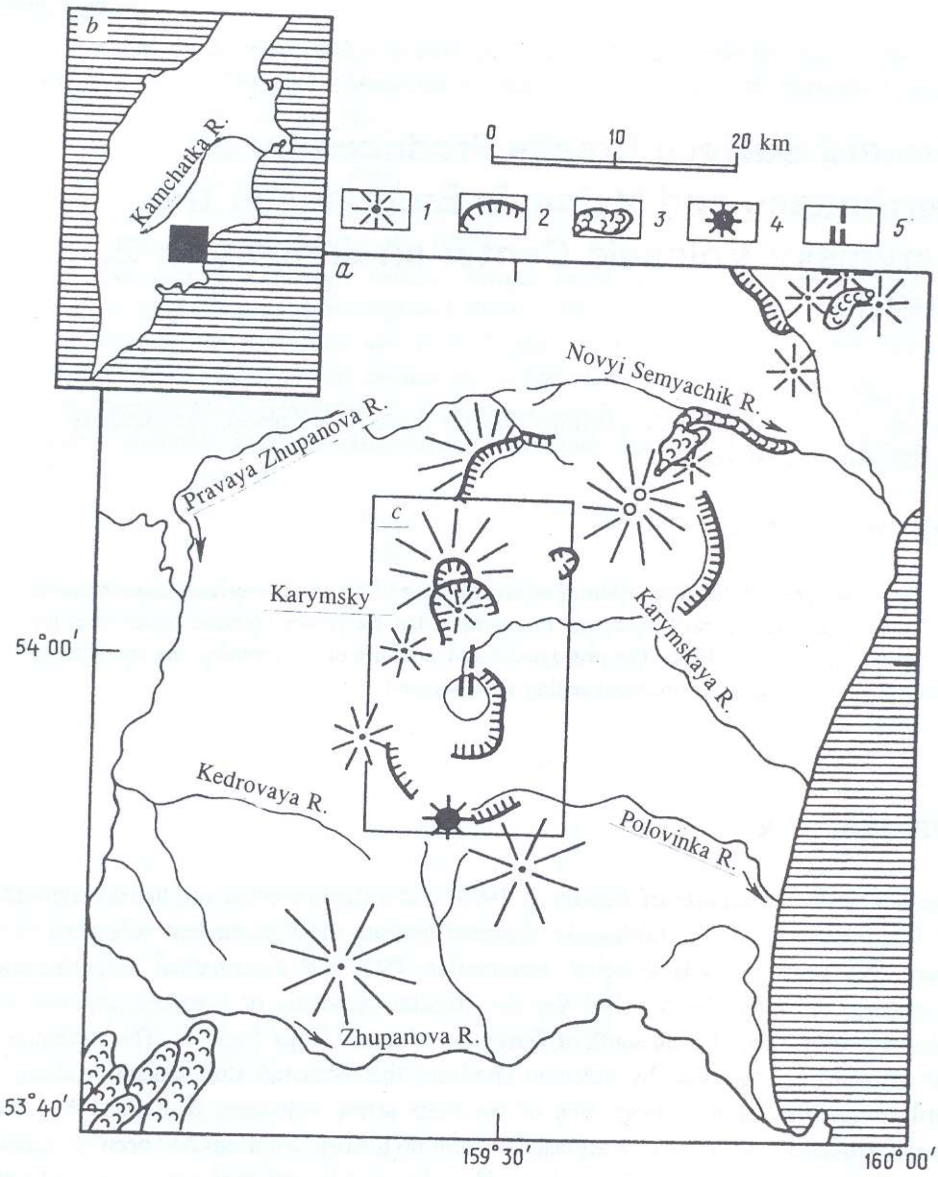


Figure 1 Schematic map *(a)* of the January 1, 1996, earthquake area;1 - volcano; 2 - caldera; *3* - large Holocene lava flow; *4* - main shock epicenter; 5 - zone of large ruptures due to this earthquake; *b* - location of the study area; *c* - see Fig. 2.

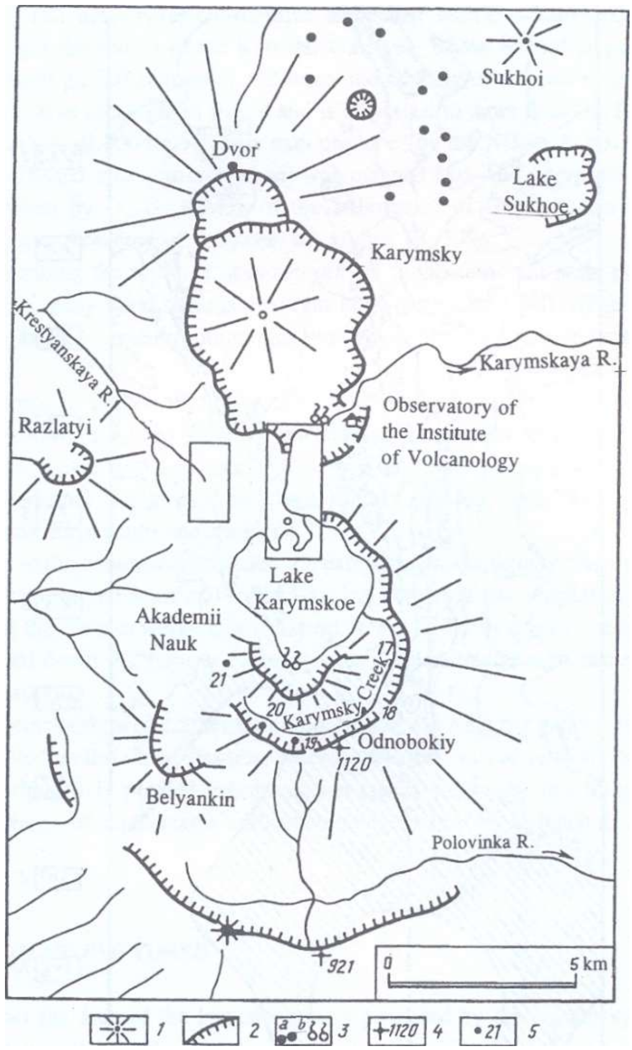
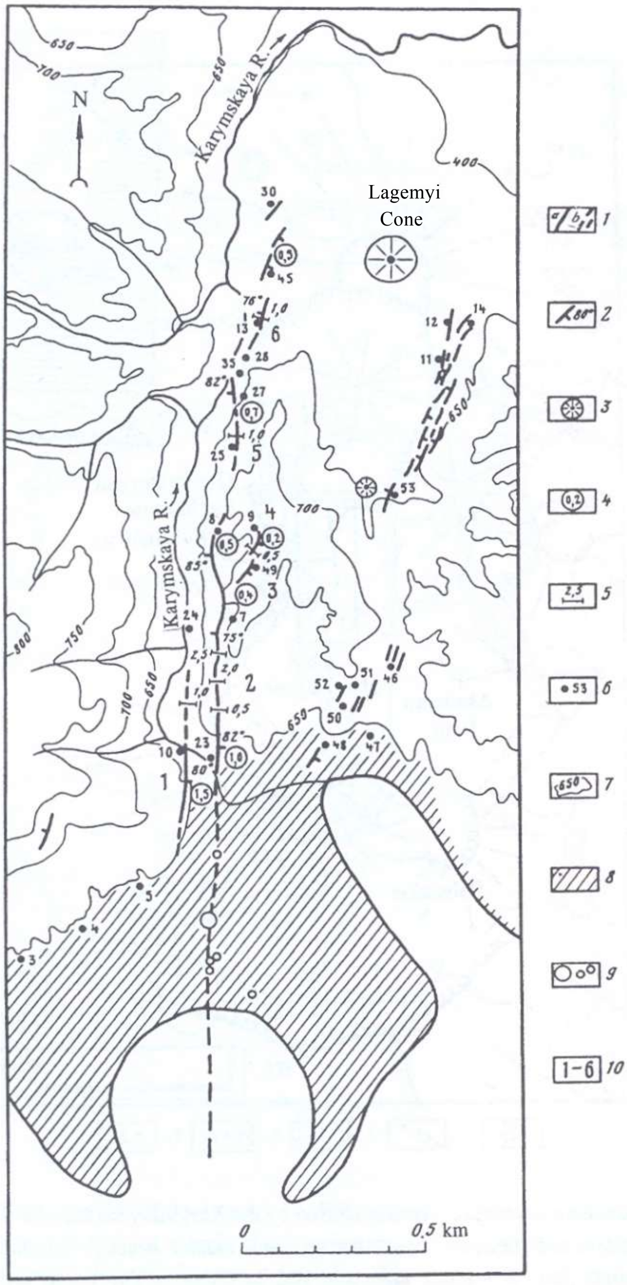


Figure 2 Area where the surface fissures caused by the Karymsky earthquake were studied: 1 - volcano; 2 - caldera and maar; *3* - small monogenetic volcanic structure (*a*) and hot springs (*b*); *4* - absolute height (m); 5 - observation site and its number. The boxed areas are the sites containing the largest ruptures (see Figs 3 and 11).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earthquake were detected there, except for the upper reaches of Karymsky Creek where a few small (shorter than 50 m) fractures were discovered; they will be described later in this paper. The best-expressed ruptures associated with the Karymsky earthquake developed around the source of the Karymskaya river, where several large ruptures cut across the bedrock (a tuff sequence) and were undoubtedly of tectonic origin. This area is outlined as a large rectangle in Fig. 2 and is displayed in more detail in Fig. 3. Figure 3 was based on a 1:10,000 topographic map produced by the NIIGAiK institute in 1975. The recently affected area (cross-hatched) was mapped from the interpretation of aerial photographs taken by O. G. Korkin of the Laboratory of Geodesy, Institute of Volcanology, Russian Academy of Sciences, on August 13, 1996.

Before describing the ruptures, it is appropriate to mention their main morphological types (typical of many other regions of recent large earthquakes [4]): ridge-like ruptures (compression cracks), open ruptures (extension cracks), and closed ruptures (shear cracks).

The compression cracks developed as narrow, bulging earth rolls. It could be seen locally that the earth had been squeezed out from the cracks like toothpaste from a tube, forming narrow ridges 3-5 cm wide and as high as 20 cm. Trenches dug across these features showed that the cracks had been tightly pressed, with the opposite sides sometimes being forced into one another.

In contrast to the compression cracks, the extension cracks usually had well-developed edges which were pulled apart and formed gaping fissures a few centimeters to 2-2.5 m wide. Some of the fissures were visibly as deep as 7-8 m. Many cracks disrupted the turf, which collapsed down the fissures together with rock fragments and bushes, filling the tops of the cracks.

The shear cracks showed neither bulging squeezed-out rolls nor gaping troughs. These cracks resembled well-defined fissures, whose walls had moved relative to one another while remaining closely pressed together. Such cracks were very few in number. They had the appearance of small scarps with smooth edges offset by as much as 2-3 to 20-30 cm.

DESCRIPTION OF RUPTURES

Figure 3 shows the area of the largest ruptures produced by the Karymsky earthquake. Some of them are numbered.

Figure 3 Area of the largest surface ruptures due to the Karymsky earthquake of January 1,1996; *1* - ruptures (a - certain, *b* - inferred); 2 - direction and angle of dip of rupture planes, in degrees; *3* - cinder and lava cones, necks; *4* - amount of vertical displacement (m) (figures in circles denote downthrown walls); 5 - width of gaping fissures (m); 6 - observation site and its number; 7 - contour line (m); *8* - area covered by the pyroclastic material ejected during the January 2-3, 1996, eruption; *9* - explosion craters of the January 2-3, 1996, eruption; *10* - numbers of larger ruptures.

Figure 4 Rupture 1, view from the north. The foreground is the Karymskaya River. This and the other photographs were taken by V. L. Leonov.

Rupture 1 is the best developed fissure on the western bank of the Karymskaya River some 400 m from its source (Fig. 4). This is a normal fault with the eastern side downthrown. The vertical displacement is 1.5 m. The fault plane dips east at an angle of 80°. The footwall is dissected by numerous joints parallel to the main fault. In some places near the fault the rocks were broken into blocks, some of which were lowered to form a small graben (Fig. 5). The new rupture partly followed an older, healed fissure which now is a 40-cm-thick neptunian dyke striking 0°, but deviated eastward in the lowest 5 m close to water table, making an angle of about 10 degrees with the dyke. Another rupture situated 10 m east of the main rupture also followed an older, healed joint. It has a bearing of 10°, the rupture plane dips west at 74°; the older rupture, which had been healed with sandy material, is 10 cm wide, while the new gaping fissure is 2 cm wide.

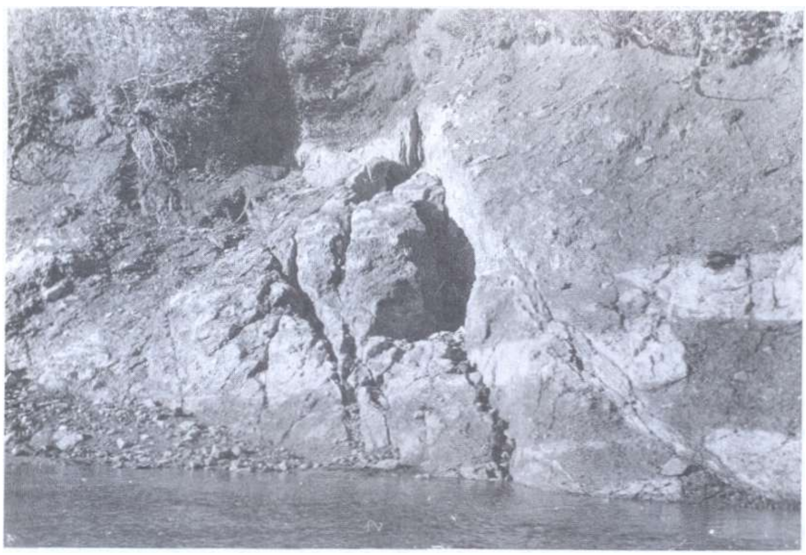

Figure 5 Rupture 1, a detail at the water-line. For explanations see the text.

The main rupture can clearly be followed across the river as a straight transverse scarp with the west side upthrown, which can be seen underwater on the riverbed. On the eastern bank of the river, the rupture is partially overlain by boulders deposited by the river after the lake was breached in May-June. In two localities the rupture was discovered on the eastern sloping bank in a dwarf alder grove. It forms a trench up to 1 m wide which had broken up the turf. Further north the rupture crosses the river, but is not visible in the river bed.

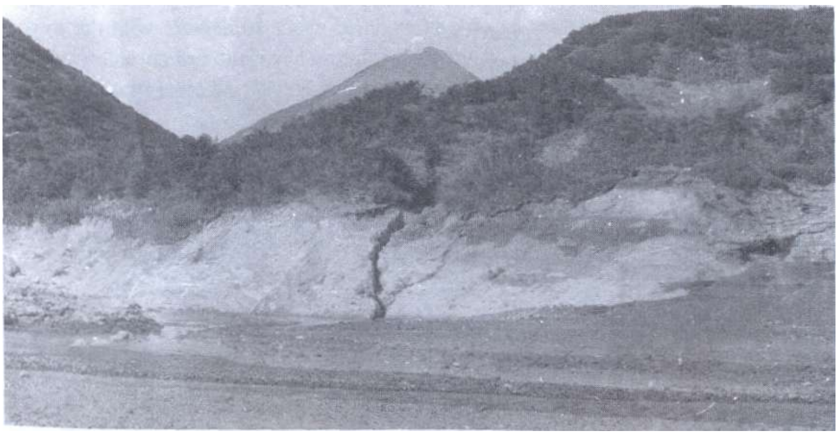

Figure 6 Rupture 2, view from the south. Karymsky Volcano can be seen in the background and pyroclastic material in the foreground; the latter was ejected by the January 2-3, 1996, eruption and masked the rupture.

South of the river, the scarp could be traced for about 200 m; it could be seen on the plateau and is covered with the turf that had been displaced by the earthquake and mixed with dwarf vegetation, but it could not be located beyond the plateau. The total length of the rupture is thus about 400 m.

Rupture 2 is situated on the eastern bank of the Karymskaya River. It starts 300 m from its source (Fig. 6). As with rupture 1, it is a normal fault with the eastern side downthrown. The vertical displacement is 1 m. The fault plane dips east at 82° in the southern segment of the rupture. The rupture extends northwards for about 700 m. Over all of its length it forms a trench, a gaping fissure that splits apart the turf and the bedrock. The fissure is filled with turf and soil blocks and alder bushes that fell into it. The width of the fissure varies between 50 cm and 2.5 m, its depth is 7-8 m. The fault plane dips west at 75-80° in the northern segment of the rupture (sites 7 and 8). The upthrown block is again western side, as with the southern segment. The upthrow amplitude is 50 cm at site 8. North of this site the rupture consists of a sequence of thin cracks appearing as small squeezed-out ridges that are convex eastwards.

Figure 7 Rupture 4 at site 9 (see Fig. 3). View from the south.

Ruptures 3 and 4 were discovered east of rupture 2, near its north end. Both of these ruptures are arcs that are convex south-eastwards. Their strikes vary from 70° in the southern part of rupture 3 to 50-40° in the north, and from 40-45° in the south of rupture 4 to 25-30° in the north. The ruptures are a few tens of meters long. Both have their north-western sides upthrown. The displacement is 30-40 cm. It decreases north-eastward, and the ruptures gradually disappear (Fig. 7). In the south the ruptures are gaping fissures 50-60 cm wide with turf collapsed into them.

Rupture 5 is located north of rupture 2 right on its continuation. However, no cracks were found between them over a distance of about 200 m. The southern segment of rupture 5 consists of two fissures striking 10 and 14°. Both of them are gaping fissures, 8 and 35 cm wide. They are 1.2 m apart. Further northward there is a vertical crack with a 0° strike (Fig. 8). Its width varies between 20 cm and 1 m, its depth is 8 m. The western side is raised, the eastern side downthrown. The vertical displacement is 70-80 cm. Further northwards, at a distance of about 150 m, this rupture is a trench in the turf and has a 1-1.5-m width and depth (site 27), and becomes a series of gaping fissures in the bedrock 50 m farther north (site 35). It has a strike of 0° in this northern segment, its rupture plane dipping west at an angle of 75 to 82°. The fissures extend further north to the river and are clearly seen in its steep eastern bank (Fig. 9), where minor fissures striking 45° were discovered at the northern end of this rupture (sites 35 and 28). At site 35 a gaping fissure 10 cm wide was traced in both the soil and the bedrock. At site 28 there are small cracks 1-2 cm wide.

Figure 8 Rupture 5 at site 25 (see Fig. 3). View from the south.

Figure 9 Area of die upper waterfall on the Karymskaya River (site 35 in Fig. 3). View from the north. The hardrock bluffs of the right bank show gaping fissures with an azimuth = 0°; their rupture planes dip west at 75-82°.

Rupture 6 occurs north of rupture 5 on the eastern bank of the river; it crosses the valley of a creek (the right-hand eastern tributary of the river) as a transverse trench 1-1.2 m wide and 2 m deep, where the rupture strikes 25° NE. The north-west side is upthrown, with a vertical displacement of 30 cm. The rupture plane dips west at 76°. The rupture extends further NNE where many turf cave-ins were found on the plateau among the bushes, some with the western side upthrown and locally as wide as 50 cm. Some 200 m NNE of site 13 there is a crack with Az = 45°, and another still farther, at site 30, looking as a squeezed-out ridge with Az = 40-45°.

Ruptures at sites 46-52. About ten cracks, mostly striking NNE, were found in an area 300 m NNE of the Karymskaya River source. Nearly all the cracks resemble squeezed-out ridges. Three cracks spaced 15-20 m apart were found at site 46. Two of these strike 10°, and the third 20°. The cracks are perfectly straight, can be followed for 30-40 m, and then disappear (cannot be traced) on slopes overgrown with grass and bushes. All cracks are seen on the surface as small ridges of an unconsolidated squeezed-out material. The ridges are occasionally as high as 10-15 cm. The eastern side of one crack is downthrown (3-4 cm). Another crack, striking 10°, was found at site 47 as a gaping fissure 2-3 cm wide. At site 48 there is a straight crack 30 m long with Az = 45°. Its width is 5-10 cm, the south-eastern side is downthrown (10-20 cm).

Figure 10 Squeezed-out ridges above cracks at site 50 (see Fig. 3).

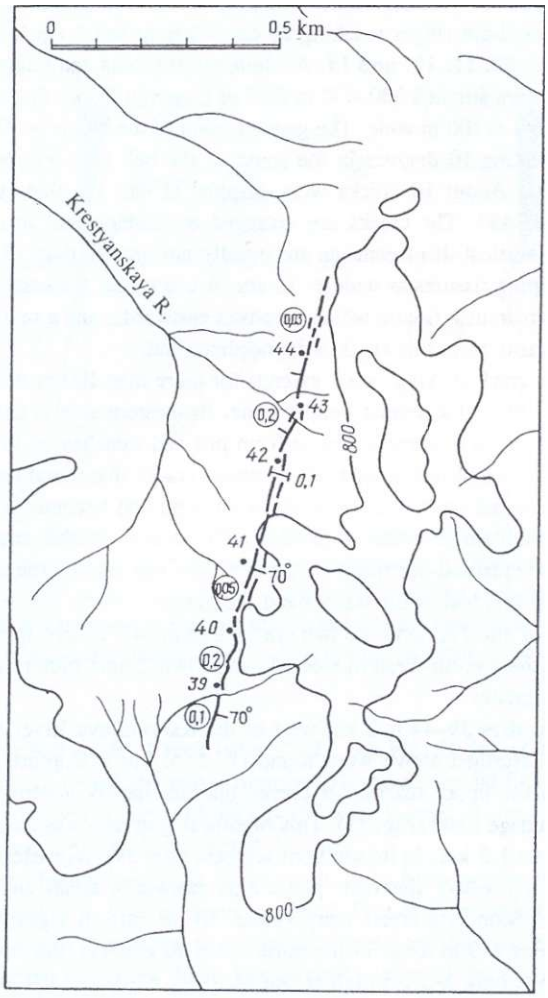

Figure 11 Positions and parameters of rupture 7. Notation as in Fig. 3.

Four cracks were found at site 50, one striking 45°, two 15°, and one at 10°. All cracks are expressed on the surface as squeezed-out ridges (Fig. 10). At site 51, 100 m north of site 50, a glade showed four cracks: three straight, longer than 20 m, striking 10°, and one a broken line consisting of connected segments striking 0-5° and 50-60°. An overall view of this glade (site 51) showed that the 0-10° cracks formed the main set, while those striking 50-60° connected with the production of L-shaped segments. All of the cracks are squeezed-out ridges reaching 20 cm in height and 5 cm in width.

Ruptures at sites 53,11,12, and 14. A whole set of cracks and minor normal faults was mapped in this area situated 300-400 m SSE of Lagernyi Cone; they form a narrow belt —700 m long and ~ 100 m wide. The general trend of the belt is ~30° (see Fig. 3). There is a crack striking 10 degrees in the south of the belt (site 53), with the downthrown western side. About 10 cracks were mapped at site 11, their strikes varying between 15-25° and 45°. The cracks are arranged en echelon and form a system of micrograbens. The vertical displacements are usually not greater than 15-25 cm. Some of the cracks are gaping fissures as wide as 10 cm. A crack near the eastern boundary of the rupture zone is an arcuate fissure which is convex eastwards, and a small squeezed-out ridge extends eastwards from this crack at its northern end.

A clearly visible crack striking ~20° extends for more than 100 m at site 12 near the northern end of the above-mentioned rupture zone. Its western side is upthrown (10-20 cm). The ground caved in in some places to form pits and trenches up to 1 m wide and deep. The crack zigzags and is accompanied by minor cracks that round the ground cave-ins. Near its northern end the crack has a westward bend and becomes a small (as high as 10 cm) squeezed-out ridge. Some 10 m west of it, there is another crack, which also has the shape of a squeezed-out ridge 10-20 cm high; this crack extends for a further 50 m. Further north it is lost in the bushes and the grass.

At site 14, east of site 12, there are two cracks striking 45°. They form small scarps 3-5 cm high, with their north-western sides downthrown. Some minor subsidences can be seen along these cracks.

Rupture 7 near sites 39-44 is 2 km west of the Karymskaya River segment where the main ruptures described above were found (1, 2, 5, etc.). Rupture 7 occurs on a drainage divide, in the upper reaches of creeks that are mostly confined to the Krestyanskaya River drainage basin (Fig. 11). This rupture is generally straight, strikes at 10°, and extends for about 1.2 km. In its southern segment (site 39), its eastern side is thrust over its western side, where the fault plane dips eastwards at an angle of 70°. Its morphological expression is a small scarp (about 10-20 cm). It zigzags along strike, producing undulations 7-8 m long. In the north (sites 40 and 41), the rupture looks the same, but the scarp is only 3-5 cm high at site 41.

This rupture is slightly different in its northern segment. At site 42, it is a gaping fissure, 10 cm wide, with no appreciable vertical displacement. The rupture abruptly changes its strike from 30° (as it ascends a hill) to 0° (as it descends the slope); the overall dip of the rupture plane is westward. At site 43, the rupture again becomes a scarp as high as 15-20 cm (the eastern side is upthrown and the western side is downthrown). Further north (at site 44) the vertical displacement decreases to 3-4 cm, and the rupture is split into several smaller (3-5 m long) en echelon cracks. The rupture plane again dips westwards at an angle of about 70°. Some 100 m north of site 44, the rupture was no longer visible.

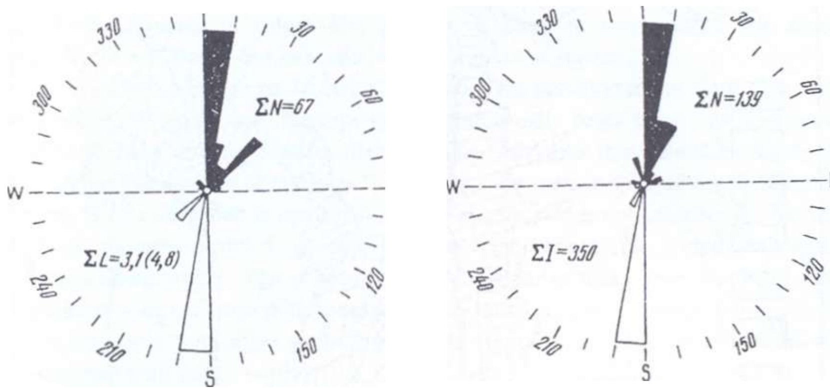

Figure 12 Rose diagrams showing the number (N), total length (L), and opening (I) of the ruptures: *a* - for those due to the January 1, 1996, earthquake; *b* - for older ruptures surveyed at sites 2-5, 10, 23 and 24 (see Fig. 3); *N* - number of measured ruptures; *L* - total length of measured ruptures (the figure in the parentheses includes the southward extension of rupture 2 across the area of explosion craters), km; *I* - total opening of ruptures, cm.

Ruptures at Karymsky Creek (sites 17-21, see Fig. 2). Inspection of the Karymsky Creek basin did not reveal any major ruptures. However, we did find a few small cracks. A series of small open cracks striking 45-50° were located at site 17, on the right-hand bank of the creek. The cracks disrupted the turf.

At site 18 on the northern bank of the creek, three fissures were found, each about 50 m long at a height of ~ 1120 m above sea-level. One of them strikes 70° and is an open fissure (with a width 2 cm); the two others strike 60 and 50° and have small ridges of loose soil squeezed out along them. The overall pattern of the fissures is an arc that is convex northwards.

Two arcuate fissures, each 40-50 m long and striking 70°, were found at site 19, 1 km west of the 1120 m site. Two more fissures striking 115-120° were discovered at site 20, 500 m further westward. They are marked by ridges of squeezed-out material and form an arc that is convex northward. A similar fissure was found at site 21, west of Akademii Nauk Volcano. It is also marked by a small ridge of squeezed-out soil and has the shape of an arc convex toward the lake.

No vertical displacements were detected for any of these fissures.

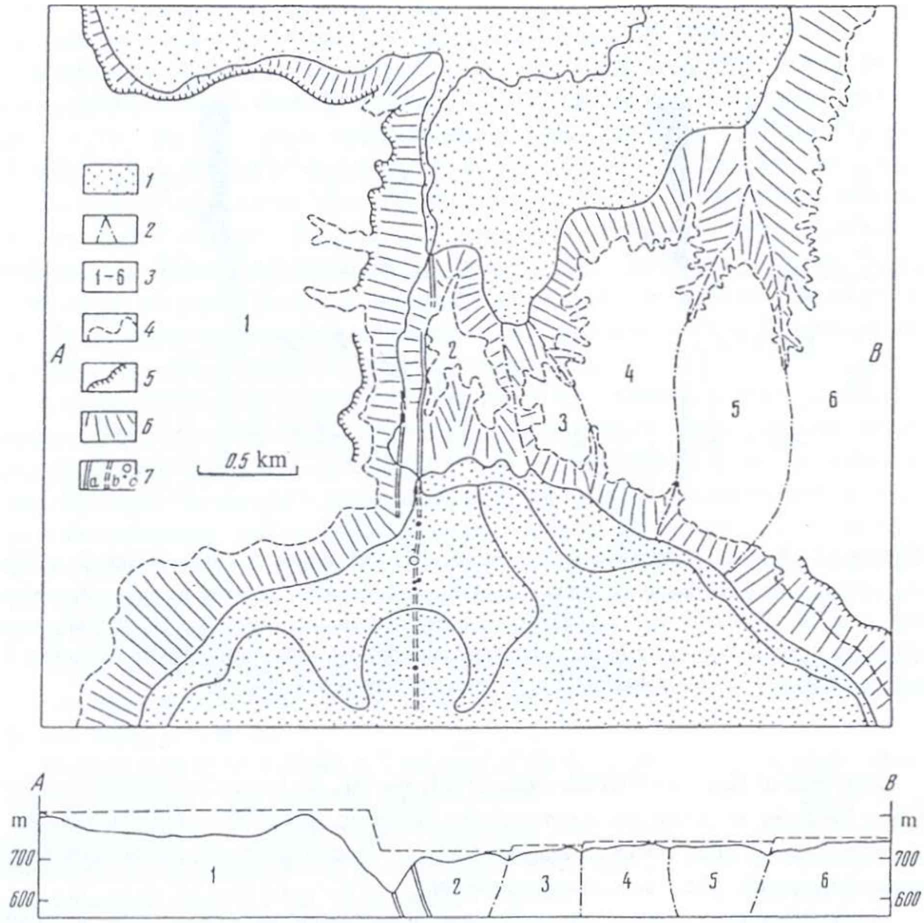

Figure 13 Overall morphostructural map of the upstream area of the Karymskaya River: 1 - relatively low-lying areas (the top is the caldera of Karymsky Volcano, the bottom is the caldera of Lake Karymskoe); 2 - boundaries of morphostructural blocks; *3* - block number; *4* - 700 m contour line (based on a 1:10,000 topographic map prepared by V. N. Dvigalo); 5 - scarps with a morphological expression; 6 - steep slopes bordering plateau-like uplands; 7 - main ruptures caused by the January 1, 1996, earthquake: *a* - certain, *b* - inferred; *c* - explosion craters.

STRUCTURE OF RUPTURE ZONES

The morphology of the larger faults is characterized, over nearly all of their lengths, by extension fractures: uneven edges of scarps, gaping subsidence, and, south of the Lagernyi cone, numerous small grabens. Evidence of compression was found at the southern end of rupture 7, in the upper reaches of the Krestyanskaya River (sites 39 and 40), where one clearly see that the eastern side of the fault is thrust over the western side. Some smaller cracks and squeezed-out ridges also provide evidence of compression. No obvious indications of horizontal displacement were found at the surface.

A characteristic feature of the larger ruptures is the variation in the plane dips of their planes along the strike, with the dips in the south usually being to the east and the dips in the north being directed towards the west. The fault plane thus resembles a propeller. At the same time the type of slip on a fault remains the same in spite of this variation. For example, the western side is upthrown and the eastern side is downthrown for the whole lengths of ruptures 2 and 5, while in rupture 7 the eastern side is upthrown and the western is downthrown. The morphology of the ruptures thus varies along the strike. Rupture 2 is a normal fault with some pull-apart movement in the south, but is a reverse fault in the north, with some spreading as well. Rupture 7 is an overthrust in the south and a normal fault in the north.

Figure *12, a* demonstrates the strike variation of the ruptures. Most of the ruptures strike 0-10°. Ruptures with strikes of 30-45° are also numerous. The other strikes are rare. The distribution of the ruptures with different strikes within the area of study shows that the feature we noticed at site 51 is general: the ruptures striking at 0-10° form the main system, while those striking north-east are secondary; they serve to connect the north-south ruptures, producing Z-shaped features.

STRUCTURAL SETTING OF THE ZONE OF THE MAIN RUPTURES

The distribution of displacements over the area shows that the larger displacements, both the vertical (normal) and the lateral (pull-apart) faults, are confined to the upper reaches of the Karymskaya River. The associated ruptures form a narrow zone stretching north-south. This zone extends roughly along a major, previously inferred fault which is marked by the Dvor, Karymsky and Akademii Nauk volcanoes [1], [2]. The cliffs around Lake Karymskoe, near the Karymskaya River source showed extensive continuous tuff exposures after the January 2-3, 1996, eruption and a subsequent decrease in the water level, compared with 1992, when tectonic joints were studied [3]. Renewed examination of the cliffs showed an absolute preponderance of north-south trending (0-10°) ruptures (Fig. 12, *b)* around source of the Karymskaya River (sites 2-5, 10, 23 and 24). These same ruptures showed the largest extension: the total thickness of the associated neptunian dykes was 4.4 m. The widest gaping fissures are concentrated in the Karymskaya River segment, around sites 10,23 and 24. Some of these fissures are infilled with vertical clay, sand, and gravel beds forming neptunian dykes as thick as 1.2 m.

This suggests that the upper segment of the Karymskaya River follows a major north-south extension zone which is repeatedly rejuvenated. The ruptures caused by the earthquake and eruptions of January 1996 are again situated along that zone. As has been pointed out, they partially renewed some of the older ruptures, but mostly formed a new series of open fissures which are traceable for about 1.5 km.

The vents that were active during the January 2-3, 1996, eruption continued a chain of new rupture zones. It is most likely that they mark the southward trend of these zones (see Fig. 3). It can thus be concluded that the total length of the main rupture zone is at least 3 km.

Figure 13 shows a topographic sketch of the area of study. Several isolated flat plateau-like blocks (steps) can be seen between the calderas of Karymsky Volcano and Lake Karymskoe. Block 1 west of the Karymskaya River is seen to be relatively elevated, while block 2 immediately east of the river is the lowest lying. The dip slip of block 2 relative to block 1 is about 100 m, as is clearly seen in the cross-section of Fig. 13. The eastern boundary of block 1 is nearly straight and extends north-south. As has been demonstrated above, it was along this boundary that the extension joints were repeatedly generated, many of them being exposed as neptunian dykes around sites 10, 23 and 24. The new ruptures produced by the January 1, 1996, earthquake rejuvenated the eastern boundary of block 1: the main rupture intersected the western slopes of block 2, making the outline of block 1 nearly straight (see Fig. 13).

The structural setting of the main ruptures that developed in early January in the Karymsky volcanic center is therefore obvious: the ruptures were formed along an old boundary between the two blocks, a zone of repeated movements in the past, and the new displacements mainly repeated the sense of the old block movements, namely that block 2 subsided relative to block 1. It should be noted that block 1 was not involved in the collapse that took place during the formation of the Karymsky caldera at about 8000 B.P. This block formed a noticeable ridge near the southern edge of the caldera, thus strongly distorting its regular outline (see Figs 2 and 13). This seems to indicate that block 1 is a rigid monolith, which was and continues to be an important element in the structure of the study area. The general conclusion is that the north-south fault passing along the eastern boundary of block 1, which was reactivated during the January 1, 1996, earthquake had a long history. It was active throughout the Holocene, with its recent reactivation being one of the episodes in its continuing evolution.

DISCUSSION OF RESULTS

The ruptures caused by the Karymsky earthquake in many respects resemble the tectonic pattern in eastern California and Nevada, i.e. the region known as the Basin and Range Province [4], which is dominated by normal and pull-apart faults, where the faults that separate subsiding basins and rising ranges are repeatedly active. The fractures produced by the historic earthquakes that occurred in the Basin and Range Province had uneven edges and were accompanied by gaping subsidences and numerous small grabens. Being generally straight, they showed a zigzag pattern, constantly deviating to one or the other side. The individual fissures were fairly short, but new fissures developed nearby and grew rapidly in amplitude as the previous cracks were attenuated [4]. This pattern is typical of the main rupture system that developed during the Karymsky earthquake. In both cases the dominant movement was extension across the trend of the ruptures. However, there are some features of the Karymsky ruptures that suggest a more complex mechanism of origin. These features do not fit the simple extension model. The features include the propeller-like shapes of the main rupture planes, the bends in some of them (for instance, in ruptures 3 and 4) towards the south-east, the subsidence of the eastern blocks of the rupture as their rupture planes dipped west, and the presence of reverse displacements, etc. More detailed studies are necessary to explain these features and to reconstruct the histories of the ruptures.

CONCLUSIONS

1. The study of the areas situated north of the January 1, 1996, epicenter revealed a network of new ruptures, which are supposed to have resulted from the earthquake source reaching the surface.

The fact that the eruptive centers that were active in January 2-3, 1996, are situated on an extension of these ruptures indicates the close relationship of the ruptures with igneous activity and the ascent of magma.

2. The main rupture zone is situated in the upper reaches of the Karymskaya River, and consists of several ruptures, each of which is 0.5-1 km long. The ruptures strike north-south, their western sides being upthrown and their eastern sides downthrown throughout their lengths. The vertical displacements range between 0.5 and 1.5 m. Maximum displacements were recorded near the southern end of the rupture zone and were gradually attenuated northward.

3. All of the larger ruptures in the main zone show unmistakable signs of extension across the strike; the surface expression of a particular rupture usually consists of gaping fissures, trenches, and ground subsidences. The fissures are sometimes as wide as 2-2.5 m. In contrast, the ruptures and zones of smaller cracks that developed to the west and east of the main zone mostly indicate compression. Their surface expressions are small overthrusts or bulging rolls of loosened and squeezed-out earth.

4. An analysis of the structural setting of the main rupture zone revealed that it was confined to an old fracture zone that had been repeatedly active (during Holocene time), and formed the eastern boundary of the relatively stable upthrown block. The areas east of the block were downthrown to a depth of about 100 m. The new ruptures rejuvenated the eastern boundary of the block, making it nearly straight. The earthquake and subsequent eruptions seem to have activated the old north-south fault, producing new fissures along it over a distance of 2.5-3 km.

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