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The Faults That Appeared near Karymskii Volcano, Kamchatka on January 1–2, 1996: The Geometry and Mechanism of Generation

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Abstract—Unusual (for this location) events occurred near Karymskii Volcano, Kamchatka in early January of 1996: a magnitude 6.9 earthquake, the simultaneous eruptions of two volcanoes, and the generation of extensive ground breakage. This paper is concerned with the breaks, specifically, their positions, structure, and the character of the displacements. The breaks were studied with the help of trenches that were dug across them to expose their internal structure. Crosswise profiles were constructed on some of the breaks to analyze the variation of their geometry along the strike. This work revealed the specific features of the displacement episodes and whether these episodes were multiple ones, established their sequence, and suggested a mechanism of their generation and the overall mechanism responsible for the deformation observed.

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INTRODUCTION

A swarm of crustal earthquakes occurred near Karymskii Volcano, Kamchatka in early January of 1996, including the largest earthquake ever to have been recorded in the volcanic areas of Kamchatka (M = 6.9) [3, 18]. Nearly simultaneously with these earthquakes, two volcanoes 6 km apart began to erupt: Karymskii Volcano, whose last eruption occurred in 1982, and the Akademii Nauk caldera, where no eruptions have been observed during historical time [14, 18]. The eruption in the caldera (which is about 5 km across and filled with a lake) was phreatomagmatic and terminated ~18 hours after its beginning. Karymskii Volcano has continually erupted until the present time (2008) over a period of 12 years. A survey of the area carried out in the summer of 1996 showed that the January events produced numerous cracks and faults on the surface, with different areas being dominated either by reverse displacements and cracks with compression occurring across these or by gaping breaks and normal-displacement faults [8]. Some faults show a complex geometry, viz., a progressively varying angle of dip for the fault surface along the strike, combinations of reverse and gaping fissures, the variation of morphologic characteristics along the fault strike, etc. Making an inference about the mechanism of generation for these breaks required more detailed surveying and this was done during the summer periods of 1997–2002. Many cracks and faults were opened by trenches dug across them. The displacements were studied in cross-sections on trench walls to reveal multiple displacements at a number of locations and to determine the sequence of events. This work provided the data to judge the mechanisms of breakage and the possible causes that produced the observed deformations. Below we report the results of this work.

A General Description of the Study Area and the Breakage of Early January 1996. The area where the events to be described occurred is situated at the center of an extensive (40 by 60 km) volcanic upland that is part of the East Kamchatka Volcanic Belt (Fig. 1). The upland is composed of over 20 large volcanoes and numerous minor ones, mostly of Quaternary age, including two active volcanoes, viz., Malyi Semyachik and Karymskii, which is one of the more active Kamchatkan volcanoes. The name of the last volcano is also applied to the entire upland, which is sometimes called the Karymskii group of volcanoes or the Karymskii Volcanic Center [1, 16, etc.]. Along the upland axis are several Late Quaternary calderas surrounded by extensive fields of pumice and ignimbrite deposits. Being contiguous, these calderas make an uninterrupted zone of subsidence extending northeast for 35 km (Fig. 1).

One conspicuous element in the structure of the area, as is also the case for the entire East Kamchatka Volcanic Belt, is a network of young, mostly Late Pleistocene to Holocene, faults. These mostly occur in the axial zone of the volcanic belt, strike north-northeast (20°–25° NNE) and form a row of isolated groups in an en echelon arrangement. The Karymskii Volcanic Center contains two sets of such faults, the Zhupanova–Karymskii and the Malyi–Bol'shoi Semyachik [20].

The surface breakage that formed near Karymskii Volcano in early January 1996 is shown in Fig. 2. Its main characteristics are given in Table 1. Some map-

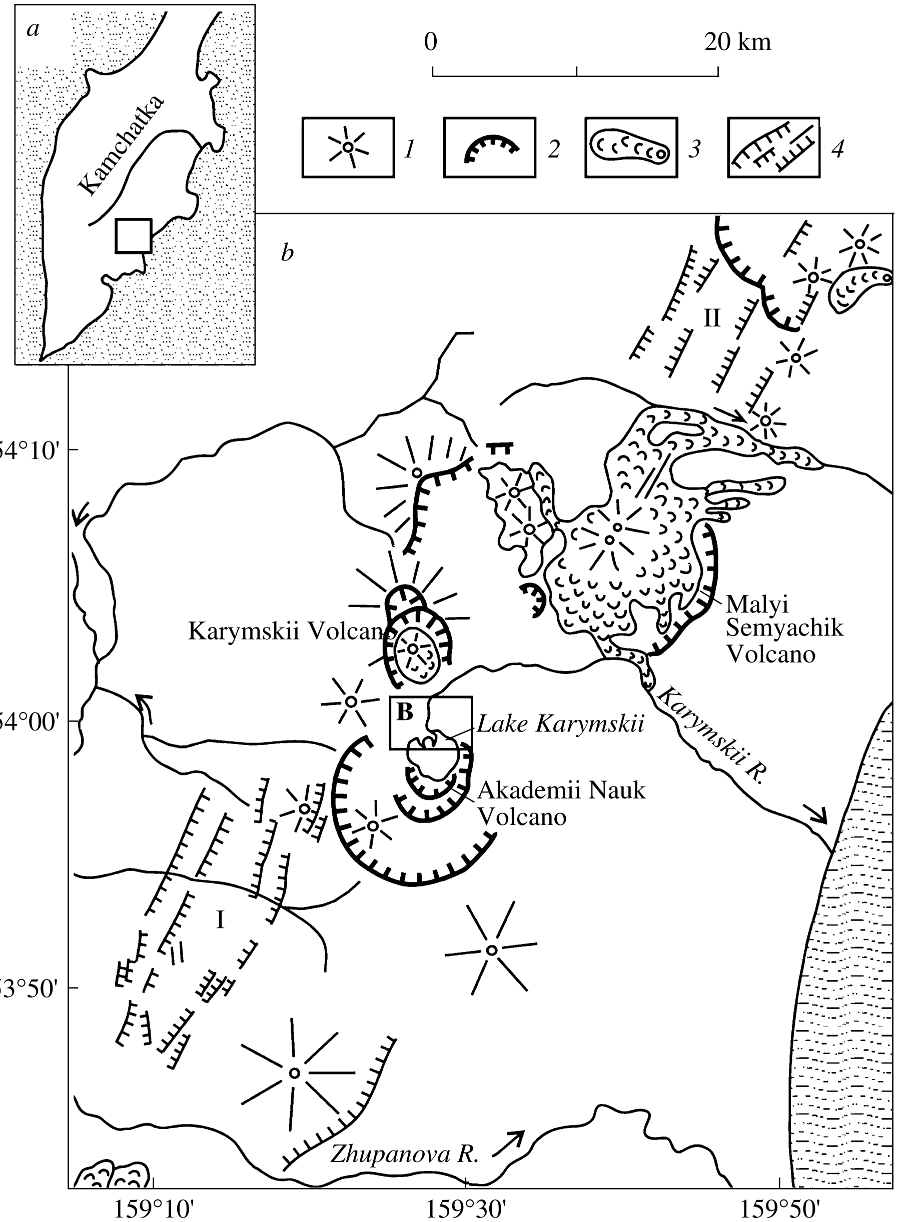


Fig. 1. General maps (*a*, *b*) of the study area: (*1*) volcanoes, (*2*) calderas, (*3*) Late Pleistocene/Holocene lava flows, (*4*) Late Pleistocene/Holocene surface breaks (I, II isolated sets of breaks: I Zhupanova–Karymskii, II Malyi–Bol'shoi Semyachik). The rectangle at the center (**B**) shows the area displayed in Fig. 2.

ping of these breaks was done by this author in 1996 [8] for the faults designated as I to VII. Another set of faults was detected in 1997 (denoted as VIII to XII). Ushakov and Fazlullin [17] also report hypothetical faults in the bottom of Lake Karymskii. Most of the breaks identified by now have experienced reverse displacements. Normal and gaping breaks were identified in a north–south, narrow (1.5 by 5 km) band situated in the upper reaches of the Karymskii River in the middle of the study area. Also in this north–south zone, the largest horizontal and vertical displacements were recorded [8]. It should be noted that these data on the character and amplitudes of the displacements observed on the identified faults are completely identical with the horizontal and vertical deformations measured instrumentally by direct geodetic observation [11, 12]. The uplifted areas identified from geodetic surveys coincide with those containing reverse faults. The area of ground extension and subsidence, as detected by geodetic techniques, is completely identical with the north–south zone mentioned above where normal and gaping breaks were found. The deformation amplitudes are similar as well. Geodetic observation has revealed the maximum extension to have been on an east–west line across the

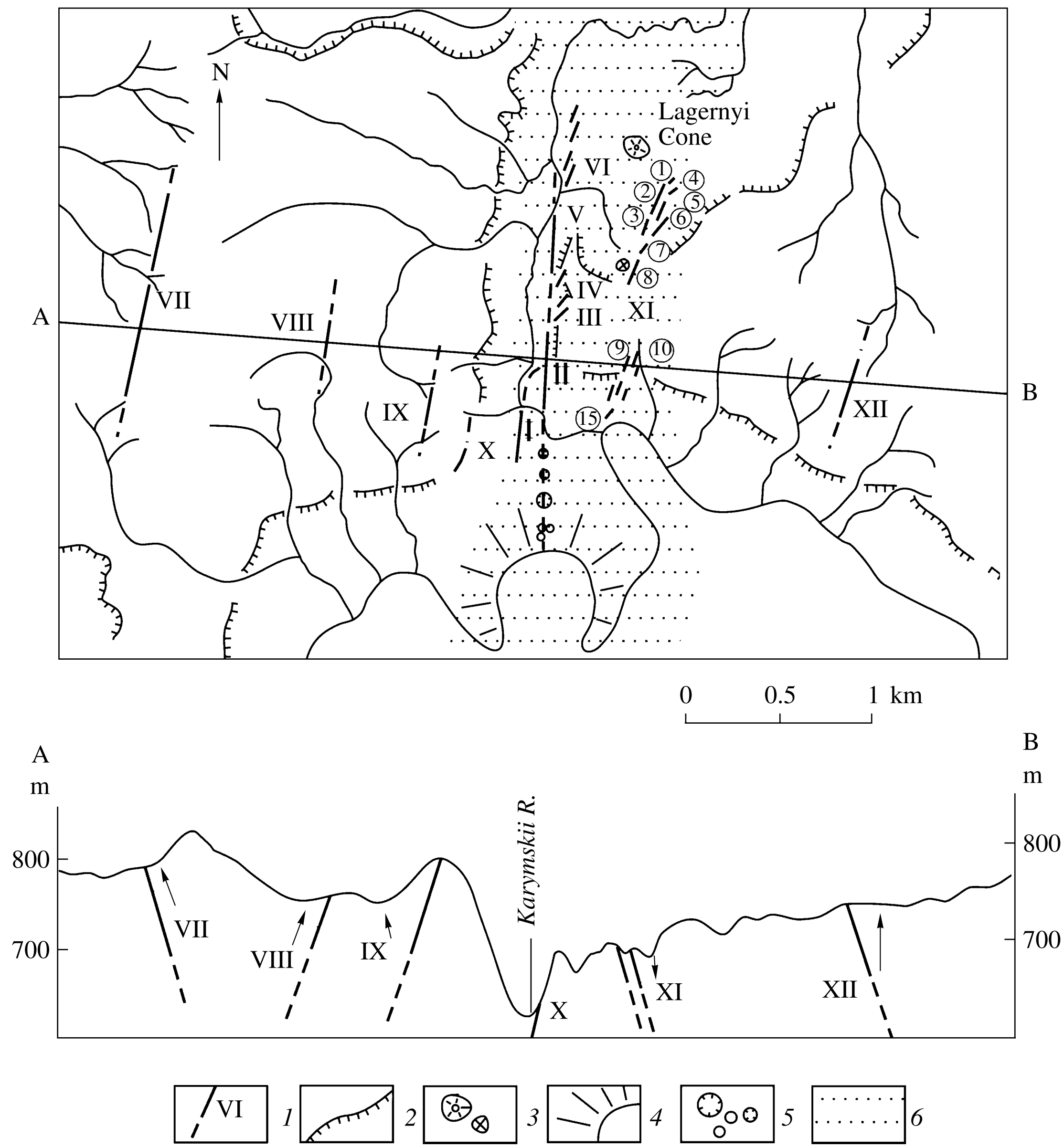


Fig. 2. The area of the largest surface breaks generated in early January 1996: (*1*) fault and its identification number (the larger faults are characterized in Table 1, smaller breaks in zone XI are marked by numerals in circles and are characterized in Table 2), (*2*) erosion scarps that bound the calderas (from above and from below) and the Karymskii River valley (at the center), (*3*) cinder cones and necks, (*4*) the main center of the eruption occurring in Lake Karymskii January 2–3, 1996, (*5*) minor explosive and collapse pits forming near the main center of lake Karymskii eruption, (*6*) north–south zone of extension and subsidence (for explanation see main text).

north–south tension zone. The displacement was 2.3 m on a 3.6 km baseline [11]. The largest extensional displacement, which we measured on fault II, is 2.5 m [8]. The maximum amplitude of vertical displacement for fault I is 1.37 m as measured by geodetic techniques and 1.5 m as measured by this writer in 1996; a displacement of about 1 m was recorded in the southern part of fault II [8]. At the same time, a more careful study of the breakage showed that the amplitude of vertical displacement was much larger and that of horizontal displacement smaller than that measured in 1996 for some segments, especially along fault II. We now discuss the results of this work in more detail.

The Geometry and Generation Conditions of the Breakage in the Upper Reaches of the Karymskii River (along the West Boundary of the North–South Subsidence Zone). The breaks found in the upper reaches of the Karymskii River are the largest among the recent surface breakage (Table 1). They extend north–south, are as long as 0.5–1.0 km, and extend as a whole for 2.5–3.0 km [8]. Further south, on the extension of these breaks, is a chain of explosive craters and

Table 1. Characteristics of the larger faults that formed near Karymskii Volcano in January 1996

Fault identification number	Strike, deg.	Length, m	Amplitude of vertical movement, cm	Dip angle of fault plane		Displacement type	Extensional component, cm
				descriptive direction	angle, deg.		
I	0–10 25–30*	400	85	E	80	normal	20–50
II	0	700 1800***	80–375	W* E**	80–82	reverse* normal**	up to 250
III	30–70	40	20	SE	80	normal	up to 60
IV	20–45	60	10* 40–50**	SE	63–80	normal	up to 60
V	0	400	130	W	75–82	reverse	up to 100
VI	25–30	100	30	NW	76	reverse	up to 50
VII	10–15	1200	16–20	E	70–75	reverse	up to 50
VIII	15–17	170	3–4	W	70–80	reverse	–
IX	20	250	40–50	W	70–80	reverse	–
X	20–25 40**	200	50–70 20**	SE	70	reverse	–
XI****							
XII	20	150	10	E	81	reverse	–

Notes: * denotes data on the fault in its northern part,
** denotes data on the fault in its southern part,
*** fault length incorporates its supposed southward extension, toward the eruption center in Lake Karymskii,
**** zone of minor faults (Table 2).

collapse sinks produced by the January 2–3, 1996 eruptions in the lake (Fig. 2). The transverse profiles, which were constructed in the summer of 1997 on faults I, II, and V, made it possible to calculate the amplitudes of vertical and horizontal displacements with greater accuracy (Fig. 3).

The east wall has been displaced downward on fault I situated on the left bank of the Karymskii River; the fault surface dips east at an angle of 80°. My previous estimate of the vertical displacement amplitude on the fault was 1.5 m [8], but the true amplitude found from this transverse profile taking into account the ground dip turned out to be considerably lower (85 cm) (Fig. 3). It should also be noted that the plane of fault I is arcuate, with the strike being 0° in the south, then 10° NNE where it traverses the Karymskii River, and 25°–30° NNE still farther, at the northern end of the fault.

Transverse profiles on fault II were constructed at five sites (sites 2–6, Fig. 3). Comparison of the profiles shows that the morphology of fault II varies considerably along the strike. At the southernmost site 2 the fault surface dips east. The east side is downthrown, the amplitude of vertical displacement is 1.6 m. Further north, at sites 3–6, it is the east side also which is downthrown and the west side is upthrown, but the fault surface dips west at these sites. The dip angle is 80°–82°, both in the south and in the north. The amplitude of vertical displacement is the greatest (3.75 m) at site 4. The amplitude drops to 2 m at distances of 100–150 m only to the north and south of the site (sites 3 and 5). Farther north beyond site 5, the fault is rapidly wedging out, with the amplitude of vertical displacement decreasing to reach 0.8 m just 100 m farther, at site 6, and the break disappears altogether going 100 m more.

Fault II is open for much of its length; its sides have separated, producing a long gaping crevasse on the left bank of the Karymskii River. My previous publication reported a figure of 2.5 m for the separation of fault II sides [8], but I came to the conclusion that it was much less, considering the vertical displacements described above and using the profiles constructed (Fig. 3). The greatest discrepancy is observed at site 4 where it is about 1.7 m when the above facts have been taken into account (the actual distance between the opposite sides of the crevasse is 2.5 m). South and north of site 4 the amplitude of horizontal separation gradually becomes smaller and equals 1.6 m at site 3 and 0.2 m at site 2 in the south; it is 0.6 m at site 5 in the north. Farther north, the fault sides converge, it is a typical reverse fault at site 6; the west side is tightly pressed against the east side and upthrown by 0.8 m relative to the latter (Fig. 4). Reverse faulting was accompanied by the upper part of the section penetrated in the west side (including the turf and the vegetative cover) being overthrown onto the east side; this seems to have been due

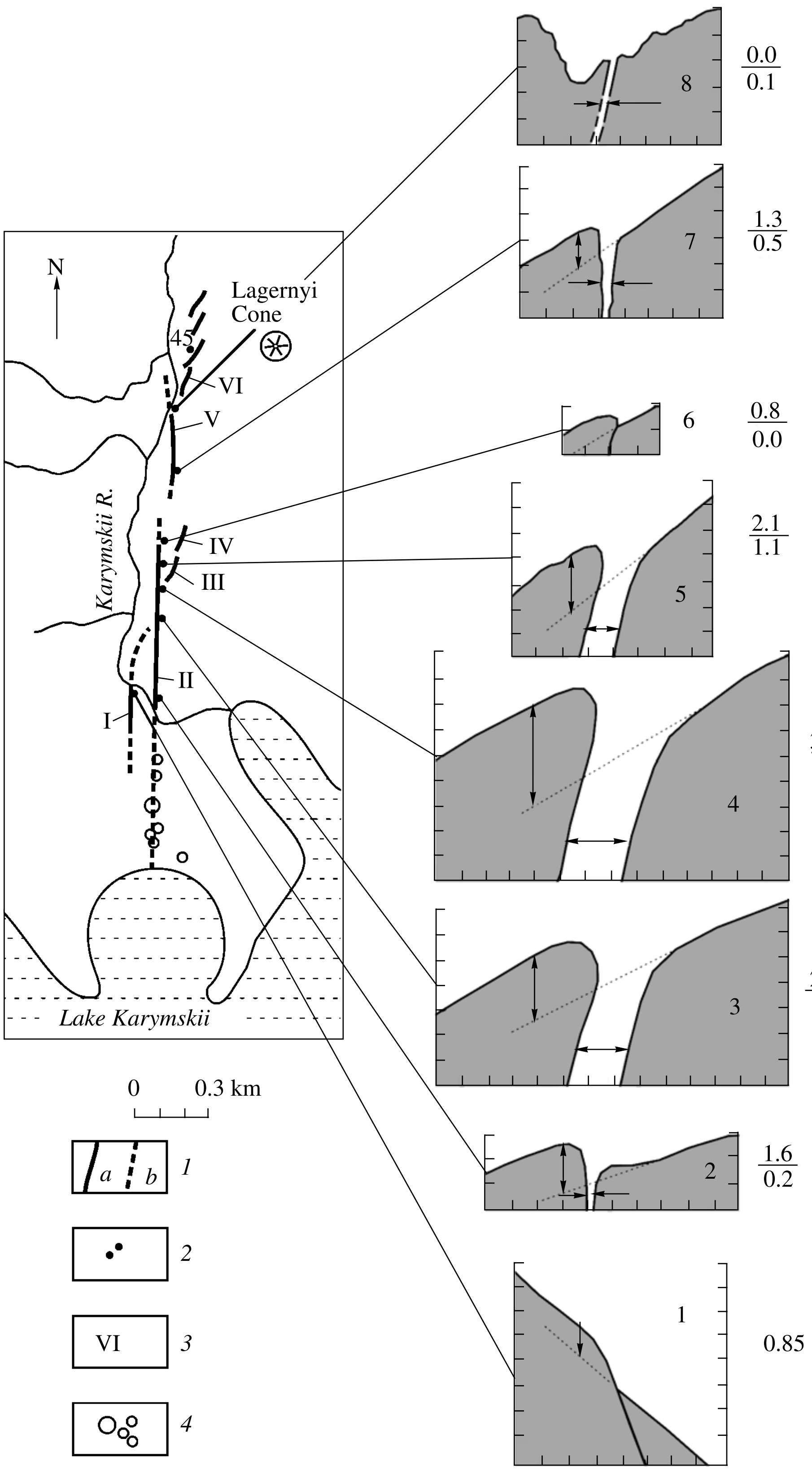


Fig. 3. Transverse profiles constructed on faults I, II, and V. (*1*) faults (*a* certain, *b* inferred), (*2*) sites where trenches were dug and transverse profiles constructed, (*3*) identification numbers of faults, (*4*) explosive and collapse pits forming on the probable southward extension of fault II. Arrows on profiles and numerals by them denote calculated amplitudes of vertical and horizontal fault displacements. The distance between the ticks in the profiles corresponds to 1 m.

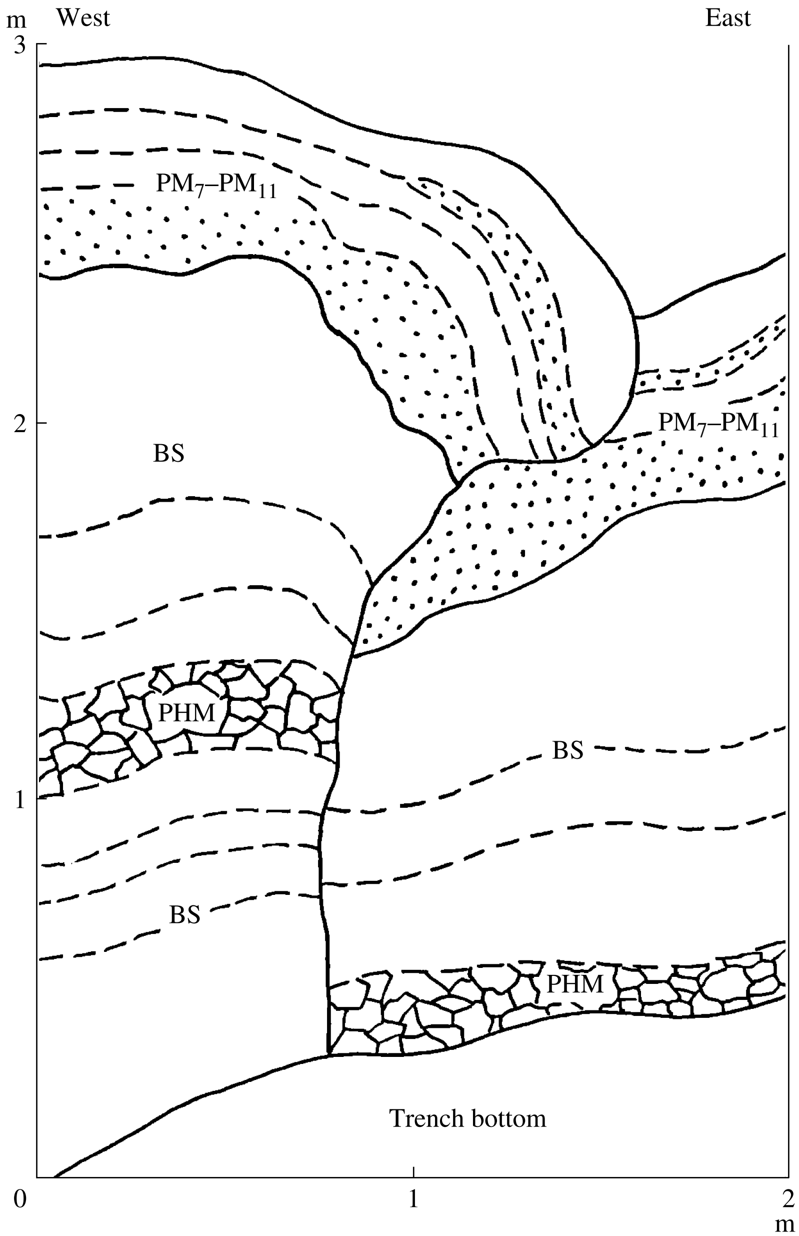


Fig. 4. View of the north wall of the trench dug across fault II at site 6 (Fig. 3). Letter designations: PM_7–PM_{11} are pumice horizons deposited during the last phase of activity of Karymskii Volcano (age 0–500 years), after [1]; BS stands for buried soils that record a decreased activity of Karymskii Volcano (age 500–3000 years), after [1]; PHM stands for a layer of dense sandstone and green gravelite (phreatomagmatic deposits apparently due to an Upper Holocene eruption in Lake Karymskii).

to considerable compression across the fault strike in the area.

It can be seen in the two profiles across fault V (sites 7 and 8 in Fig. 3) that the fault surface also becomes slightly curved, being subvertical in the south and dipping west at an angle of 75°–82° in the north. For much of the fault length, the west side is also upthrown. The amplitude of vertical displacement is 1.3 m at site 7 (Fig. 3), with the amplitude of horizontal displacement varying from 0.1 to 0.5 m.

Smaller feather fractures showing a general northeast trend were generated near the north ends of faults II and V. Many of these fractures have typical arcuate shapes, with the convex side being toward the southeast. The breaks situated near the north end of fault II were previously described by myself as faults III and IV, and a break diverging from the north end of fault V as fault VI [8]. All the feather breaks have their northwest sides upthrown and the southeast downthrown; the amplitude of vertical displacement varies between a few centimeters and 40–50 cm. In some cases, similarly

Fig. 5. Two nearby faults with different types of movement (*a* general view, *b* view of the southwest wall of the trench dug across the faults). The positions of the fault planes are shown by arrows. For explanation see main text.

to the main faults, the slip surfaces were found to have a gradually varying dip like the shape of a propeller, with the dip being southeast in the south and northwest in the north. The slip surface of fault IV uniformly dips southeast, but the angle of dip varies from 63° in the southwest to 80° in the northeast.

Important features have been identified in the surface breakage situated in the northernmost part of the area, features that allow the sequence of displacement episodes to be determined. For example, two closely situated slip planes have been identified (Figs. 5*a*, 5*b*) in trenches dug across the breakage zone at site 45, which is 300 m west of Lagernyi Cone (Fig. 3). The respective displacements were reverse on one plane (the fault plane dips northwest, the northwest side is upthrown relative to the southeast side) and normal and extensional on the other (the fault plane dips southeast, the southeast side is downthrown, an open fissure as wide as 6–7 cm passes along the fault plane). A typical ridge of squeezed-out earth has formed on the ground above the former plane, which is a common occurrence for fissures under compression [8]. Subsidences and collapses have occurred above the latter plane and the open fissure that was generated along it (Fig. 5*a*). One can see in places that the latter plane dips at a very low angle (as low as 27°) near the ground surface and cuts across the earth ridge that formed above the former plane (Fig. 5*b*). This suggests two deformation phases for the area under discussion; the first of these involves compression and reverse faulting, while the second was extensional and generated normal faults and gaping fissures. The fact that the fault planes that were active during the second phase dip at very low angles also suggests that the deformation of the second phase was subhorizontal and involved southeastward displacement of the southeast fault sides.

We sought to determine the relative horizontal displacements of the fault sides to greater accuracy by a purposeful search for markers that would be visible on both walls of the crevasses. These were detected at two sites on fault II (sites 4 and 5, Fig. 3). At site 4 the fault cuts across a vertical neptunic dike 50 cm thick. The dike can be clearly seen both on the west and on the east wall of the crevasse, there is no horizontal displacement of the dike along the fault plane. This case therefore involves pure extensional faulting, with the east side being displaced eastward. The marker at site 5 (Fig. 3) was a characteristic locality where a horizontal contact between two differently colored pumice tuff layers is intersected by a vertical neptunic dike 3 cm thick. The intersection was found on both walls of the crevasse, and is 2.1 m lower and 0.4 m farther north in the east side than the other. It thus appears that fault II also experienced a small left lateral horizontal displacement along the fault plane in this locality, apart from vertical slip and extension.

The Geometry and Generation Conditions for the Breakage Situated Southeast of Lagernyi Cone (along the East Boundary of the North–South Subsidence Zone). The surface breakage in this area was previously described briefly in [8]. Trenches were dug in 1997 across the breaks there. This enabled us to estimate the vertical displacement amplitudes, the direction of dip, and the angles of dip for the fault planes more accurately. The larger breaks in the area are characterized in Table 2 and their locations are shown in Fig. 2. The breaks are at the base of a steep slope that is part of the south wall of the Karymskii Volcano caldera. Both the caldera wall and the breakage zone strike 20°–25° NNE. Individual breaks also mainly strike 20° NNE (Table 2). As to the character of slip, normal faults with a downthrown northeast side are dominant. There are also several normal faults at the center of the area with the fault plane dipping southeast. The result was the production of a small graben about 200 m long and 10–15 m wide. Viewed as a whole, the breakage zone in the area has a length of 500 m and is 50–60 m wide (Fig. 2).

The character of displacement on individual faults in the area is rather complicated. The combination of cracks shown in Fig. 6 was opened by a trench at the location where faults 2 and 5 are the closest at the northern termination of the graben described above. One can see in the trench wall that both of these faults are gaping fissures as wide as 5–6 cm. The fault planes dip differently: the fault situated to the west dips northwest (at an angle of about 60°) and that situated to the east dips northeast (at an angle of about 80°). One can see when looking at the ground surface that the central block between the faults has subsided by 7–8 cm, so that the resulting structure can be regarded as a graben bounded by reverse faults, or the so-called ramp valley. At the same time one can see in the trench wall (Figs. 6*a*, 6*b*) that the northwest side of this structure experienced horizontal displacement and subsidence after it had been upthrown by reverse movement, with the edge of the hanging wall collapsing. The horizontal deformation of the second phase also produced the result that both of these faults became tension faults; their sides moved away from each other and formed gaping crevasses. These two hypothetical phases of deformation, which have produced the structure, are shown in the insets (Fig. 6*b*, I, II).

It was found that the geometry of the faults rapidly varies along the strike. For example, the plane of fault 2 situated 2 meters south of the site described above dips northwest there at an angle of about 70°, but dips southeast 10 m farther south at an angle of about 60°. The result is that fault 2 in its northern part in the area described has a propeller-like curved fault surface, similarly to the faults in the upper reaches of the Karymskii River. The same can be said about fault 5 in the area. While in the north it is a reverse fault and the fault plane dips steeply southeast, moving 2 meters south we find the plane dipping northwest, with the fault becoming normal and persisting in this structure for more than 100 m.

The faults situated in the east of the area described have a simpler structure. Fault 6 is normal for all of its length with the northwest side downthrown by 15–20 cm. The fault strike is found to vary, 20° NNE in the north and 50° NE in the south. Fault 7, situated somewhat to the south (Fig. 2), is normal as well; its northwest side has been downthrown by 20–30 cm, and it strikes about 45° NE. A characteristic bend in the layers of the downthrown northwest side can be seen in a trench dug in the northern part of fault 6 (Fig. 7). This bend, and the fact that the fault sides are tightly pressed to each other, show that the extension and generation of the normal fault was followed by an across strike there.

Overall, the peculiar features of fault structure in the area also suggest at least two deformation phases. The presence of normal faults and of the ramp structure detected in the northern part of faults 2 and 5 indicate compression preceding the general extension there, similarly to the area in the upper reaches of the Karymskii River.

Table 2. Characteristics of faults that formed south of Lagernyi Cone in January 1996 (zone of fault XI, Fig. 2)

Fault identification number (Fig. 2)	Strike, deg	Length, m	Amplitude of vertical movement, cm	Dip angle of fault plane		Displacement type
				descriptive direction	angle, deg.	
1	20	25–30	2	–	90	reverse (?)
2	20–35	100	12	NW* SE**	70	reverse* normal**
3	20	50	8	SE	57	normal
4	45	10	3–5	NW	70 (?)	normal
5	20	100	10–20	NW SE*	77	normal reverse
6	20 50**	100	15–20	NW	60	normal
7	45	100	20–30	NW	67	normal
8	20	10	7	–	90	normal (?)
9	10	30	–	SE	80	(?)
10	10	20	3	SE	70	normal
11	20	20	3	SE	80	normal
12	20	20	–	NW	73	(?)
13	15	20	–	NW	80	(?)
14	20	20	–	NW	66	(?)
15	45	30	10–20	SE	80	normal

Notes: * data on the fault in its northern part,
** data on the fault in its southern part.

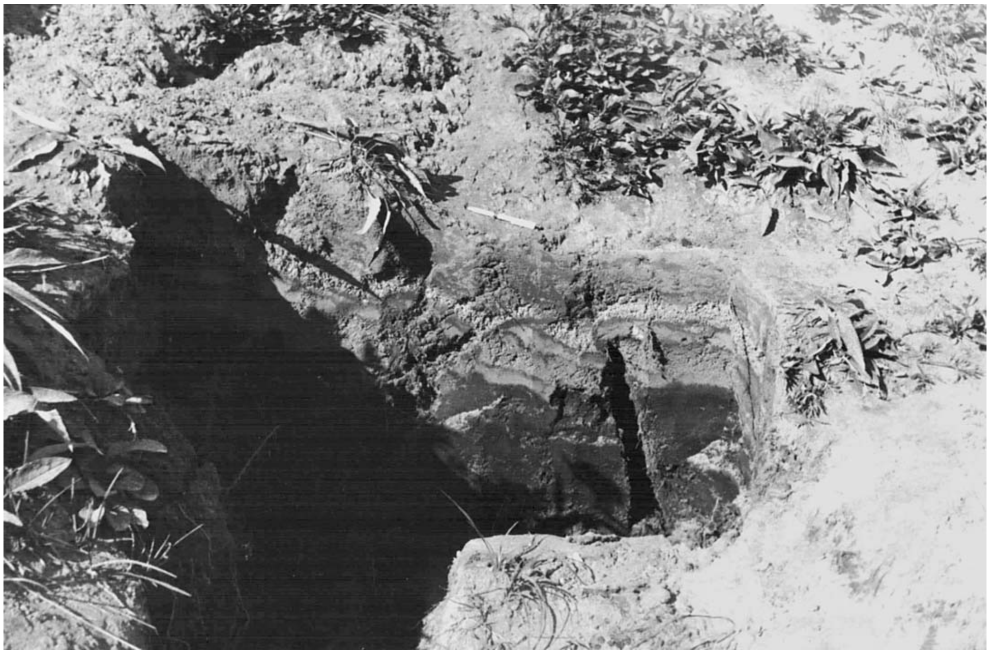
The first phase generated reverse faults (faults 1, 2, and the northern part of fault 5), while the second produced normal faults and open fissures. The compression found for the last phase in the generation of fault 6 may have been due to a subhorizontal southeastward displacement of the blocks also occurring there (which has been found for the preceding area). This displacement may have given rise to a local transverse compression in the southeasternmost breaks.

The Fault Geometry in Uplifted Areas. The areas situated west and east of the above-mentioned north–south subsidence zone have experienced uplift. Geodetic data show the uplift amplitude to have been 60–70 cm in the west and 20–30 cm in the east [11]. My 1996 survey west of the Karymskii River revealed a single fault identified as VII in [8]. The fault strikes 10°–15° NNE, is 1.2 km long, and shows reverse displacement with an upthrown east side and a downthrown west for most of its length. The fault plane dips east at an angle of 70°–75°. The amplitude of vertical displacement varies from 16–20 cm in the south to 3–4 cm in the north. Three more surface breaks were detected east of fault VII in 1997 with identification numbers VIII, IX, and X assigned to them (Fig. 2). All of these show reverse movement as well, with the fault plane dipping west in faults VIII and IX and east in fault X. The fault planes dip at 70°–80° in all these cases. Fault VIII strikes 15°–17° NNE, its west side is upthrown relative to the east by 3–4 cm, and it has been followed for 170 m. Fault IX strikes 20° NNE, the upthrow amplitude for the west side reaches 40–50 cm at the center of the fault; the fault has been followed for 250 m. Fault X strikes 20°–25° NNE (the strike being 40° NE in the south), the east side is upthrown, with the upthrow amplitude being 20 cm in the south to 50–70 cm in the north. Fault X has been followed for 200 m.

One fault only (XII, Fig. 2) has been identified in the areas (uplifted as well) east of the abovementioned north–south subsidence zone (by 20–30 cm after [11]). The displacement is also reverse. It strikes 20° NNE, the east side is upthrown, and the upthrow amplitude is 10 cm. The fault plane dips east at an angle of 81°. The fault can be followed for 150 m.

The Abundance and Structural Occurrence of Faults of Various Strikes. The above description of surface breaks generated near Karymskii Volcano in early January 1996 shows that most of these persistently strike north–northeast (10°–20° NNE). Faults with other directions are much less frequent, and have primarily north–south and northeast strikes (30°–70° NE). Breaks striking east–west or southeast–northwest are nearly nonexistent (it is only in the south of the area, in the upper reaches of Karymskii Brook, that three minor cracks striking 115°–120° SE were found [8]).

a



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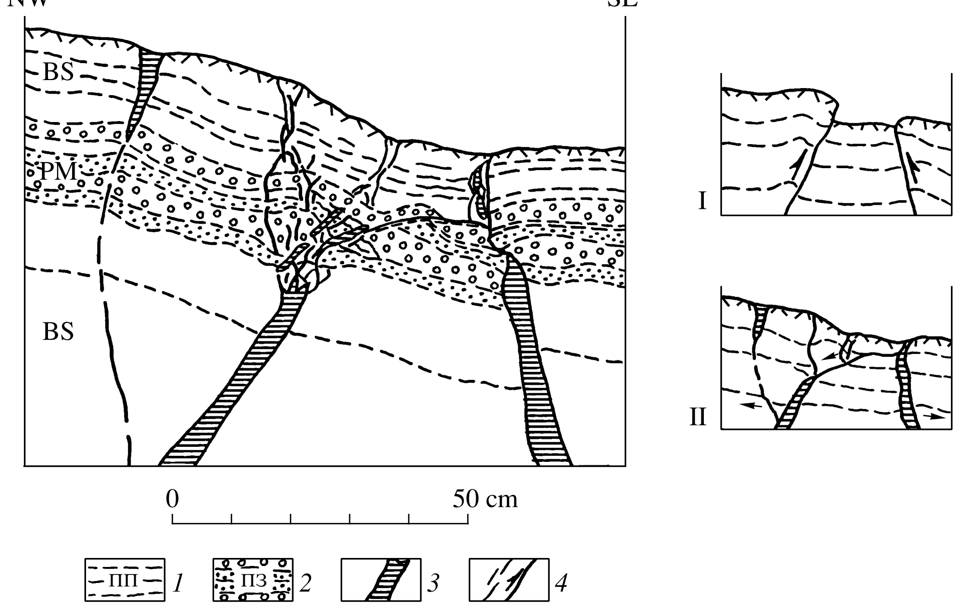

Fig. 6. View of the north wall of the trench dug across faults 2 and 5 near their northern ends (Fig. 2). Photograph (*a*) and the figure (*b*) clearly show the fault planes forming a characteristic ramp structure. The insets (I, II) show the two phases of deformation that are supposed to have produced the structure. (*1*, *2*) horizons of buried soil (*1*) and of pumice volcanic gravel and sand (*2*), (*3*) gaping fissures produced along the fault planes, (*4*) faults and the character of displacement in their sides.

An analysis of the abundance of identified breaks over the area shows that all north–south and northeast breaks concentrate in a small north–south band in the middle of the area. As shown in [8], the north–south breaks having the greatest amplitudes of vertical and horizontal displacement are confined to the zone of a comparatively old north–south fault, which bounds the uplifted crustal block from the east. New breaks were generated by resumed movement in the zone of that fault. The character of the movement is inherited also, all the new breaks in that zone have their west sides upthrown [8].

The northeast faults (30°–70° NE) are the most numerous near the northern ends of the north–south

Fig. 7. View of the northern wall of the trench dug across fault 6 (Fig. 2). For explanation see main text.

faults (Fig. 2). They are much shorter, many have arcuate shapes (convex southeastward), and the west side is upthrown, similarly to the north–south faults. The above features in the positions and structure of the northeast breaks suggest that these are feather faults with respect to the north–south ones. According to [22], such breaks at the ends of main faults, where stress concentration occurs, are structures of the second rank. The overall resulting pattern resembles a horsetail structure (Fig. 2). The generation of the northeast breaks may have been influenced by older faults with the same strike. That such faults are present is indicated by the straight valleys of the Karymskii River and its tributaries extending northeast, as well as by the northeast trend of the southern boundaries of the Karymskii Volcano caldera. Most of the new breaks striking in this direction are situated on the extensions of these lineaments (Fig. 2).

The northwest striking breaks are found, as mentioned above, in a single location, in the upper reaches of Karymskii Brook in the south of the area [8]. Apart from these, the valley of that brook also contains breaks of other directions; their strikes generally vary in accordance with that of the brook valley [8]. Since the brook seems to have originated along an arcuate fault passing along the inner edge of the Odnobokii Volcano caldera (Fig. 2 in [8]), the appearance of cracks that extend along the edge may indicate increased movements in the zone of that fault. At the same time, no large displacements have occurred on the fault considering the shortness of the new cracks (40–50 cm) and the absence of noticeable vertical displacements.

To sum up, the common feature to note for the new north–south, northeast, and northwest breaks seems to be that all of these were generated by increased movements in the zones of older faults. No such pattern occurs for the northeast faults, these being abundant all over the area and failing to show unambiguous relationships to any older faults.

On the Blocky Character of the Movements. Morphostructural considerations were previously used to identify several blocks situated between the Karymskii caldera and the Akademii Nauk caldera, among these are blocks 1 and 2 situated west and east of the Karymskii River, respectively [8]. It was shown that multiple episodes of movement have occurred on the north–south fault that separates the two blocks. The amplitude of uplift for block 1 relative to block 2 is about 100 m at present. The movements that occurred in the zone of that fault in early January 1996 showed that the west side of the fault (block 1) experienced an uplift again and the east side (block 2) subsided [8, 11]. The evidence available at present on the new breakage (see above) and geodetic data [11, 12] enable a broader reconsideration of these block movements with the additional hypothesis of two deformation phases involving significantly different displacements (Fig. 8).

Block 1, previously identified by myself, [8] is situated between the Karymskii caldera and the Lake Karymskii caldera, west of the upper reaches of the Karymskii River. It is bounded on the east by the north–south fault described above, while its western boundary seems to pass near fault VII (Figs. 2, 8). The northern and the southern boundaries of the block pass along the edges of the Karymskii and the Akademii Nauk calderas, respectively. The block is thus about 3–4 km wide and as long as 7–8 km. All the breaks generated within the block show reverse displacements and provide evidence of the block being uplifted. This is also borne out by geodetic data, which shows that all the observation sites within the block have risen [11]. It was found that the uplift amplitude was the greatest (66 cm) near the southern boundary of that block and gradually decreased northward (Fig. 8). The displacements on the faults that bound the block on the east and west also show a general pattern of increasing amplitude from north to south [8]. These data suggest that block 1 was not only uniformly uplifted but also has experienced a northward tilt. The source of deformation was in the south, where the greatest fault displacements have occurred, in addition to the greatest uplifts of geodetic sites. All the geodetic sites within block 1 have experienced west–northwestward horizontal displacements; the displacement amplitude decreases from south to north from 120–150 cm to 40–60 cm [12].

Block 2 (Fig. 8) is to the east of block 1 and is much smaller (approximately 0.5 by 1.5 km). Previously the block was identified from morphostructural considerations [8] and was clearly detected by geodetic measurements [11, 12]. To the west it is bounded by the north–south fault that bounds block 1 from the east. The northern and the southern boundaries coincide with the boundaries of the Karymskii caldera and of the Akademii Nauk caldera. The eastern boundary passes near the zone of breaks situated south of Lagernyi Cone (these were described in detail above). Most of the faults situated within and along the boundaries of that block have experienced extension. The type of movement is mostly normal and extensional. The geodetic sites situated near the eastern margin of the block have subsided by 70–71 cm [11]. The block seems to have undergone a much greater subsidence near the western boundary. Faults II and V situated there have amplitudes of vertical displacement in the range 1.5–2.0 m; the figure is 3.75 m at site 4 of fault II. Since that amount consists of the uplift amplitude for block 1 and the subsidence amplitude for block 2, it can be inferred that the net subsidence of block 2 at its western boundary is 1.0–1.5 m on the average (the maximum was at site 4, up to 3 m). Therefore, considered as a whole, block 2 experienced a subsidence and a northwestward tilt. Geodetic evidence also suggests its southward horizontal displacement, since site 63 situated on the top of Lagernyi Cone has been displaced southward by 45 cm [12].

The area east of blocks 1 and 2 should apparently be considered as an individual block or a set of uniformly deformed blocks (block 3 in Fig. 8). The area has experienced a slight uplift based on geodetic data (up to 23 cm) [11]. A single break has been detected there showing reverse displacement. The character of vertical deformation for this area thus seems to be identical with that for block 1. At the same time, the horizontal displacement of the block was in the opposite sense, east–southeast, as shown by geodetic measurements [12]. The displacement amplitude is 35 to 95 cm, increasing from north to south, similarly to block 1. The structural boundaries of that block in the north and in the south seem to pass along the boundaries of the Karymskii and Akademii Nauk calderas, similarly to block 1 again. The block under discussion has a common boundary with block 2 in the west, while the eastern boundary is not clear.

As to other possible blocks in the area of study, the relevant data are scantier, hence our knowledge is less definite. The extensive area of subsidence southeast of Karymskii Volcano can be considered as a separate block 4 (Fig. 8). The geodetic stations within that block have experienced horizontal displacements in different directions [12]. The western boundary to block 4 should more likely be fixed between geodetic stations 20 and 47, where the direction of horizontal displacement changes abruptly. The eastern and the southern boundaries of the block seem to pass along the faults that bound the Karymskii caldera from the southeast. The northern boundary remains indeterminate.

The above data on surface breaks generated in the Karymskii Brook valley suggest another hypothetical block (block 5, Fig. 8) composed by the edifice of Akademii Nauk Volcano. To the east, south, and southwest the block is bounded by an arcuate fault passing along the edge of the Odnobokii caldera (Fig. 8). The northern boundary is hidden under Lake Karymskii. The block seems to be isometric in shape and to be approximately 4 by 5 km in size. The block must have moved very slightly, considering that no vertical or horizontal displacements on the faults identified along its boundaries have been detected. The movements of the geodetic stations set up in the summit part of Akademii Nauk Volcano suggest that the block has moved horizontally eastward by about 30 cm [12].

The whole of this evidence definitely points to the fact that the deformation that occurred near Karymskii Volcano in early January 1996 was blocky in character. The individual blocks are usually 1 to 4–5 km across and have experienced very diverse displacements, uplift, subsidence, tilt, or horizontal movements. Faults were usually the block boundaries, with many of the faults being generated in zones of older breaks, which seem to have moved repeatedly, both during the Holocene and before that time. The above data on the breaks and on the variable movements of these also suggest two phases for block movements. The first phase mostly involved vertical movements (uplift and, to a much lesser degree, subsidence) (Fig. 8a), while the second was dominated by subsidence and horizontal displacements (Fig. 8b).

DISCUSSION OF RESULTS.

The Hypothetical Mechanism of the Deformation. The above description of the breaks and the con-

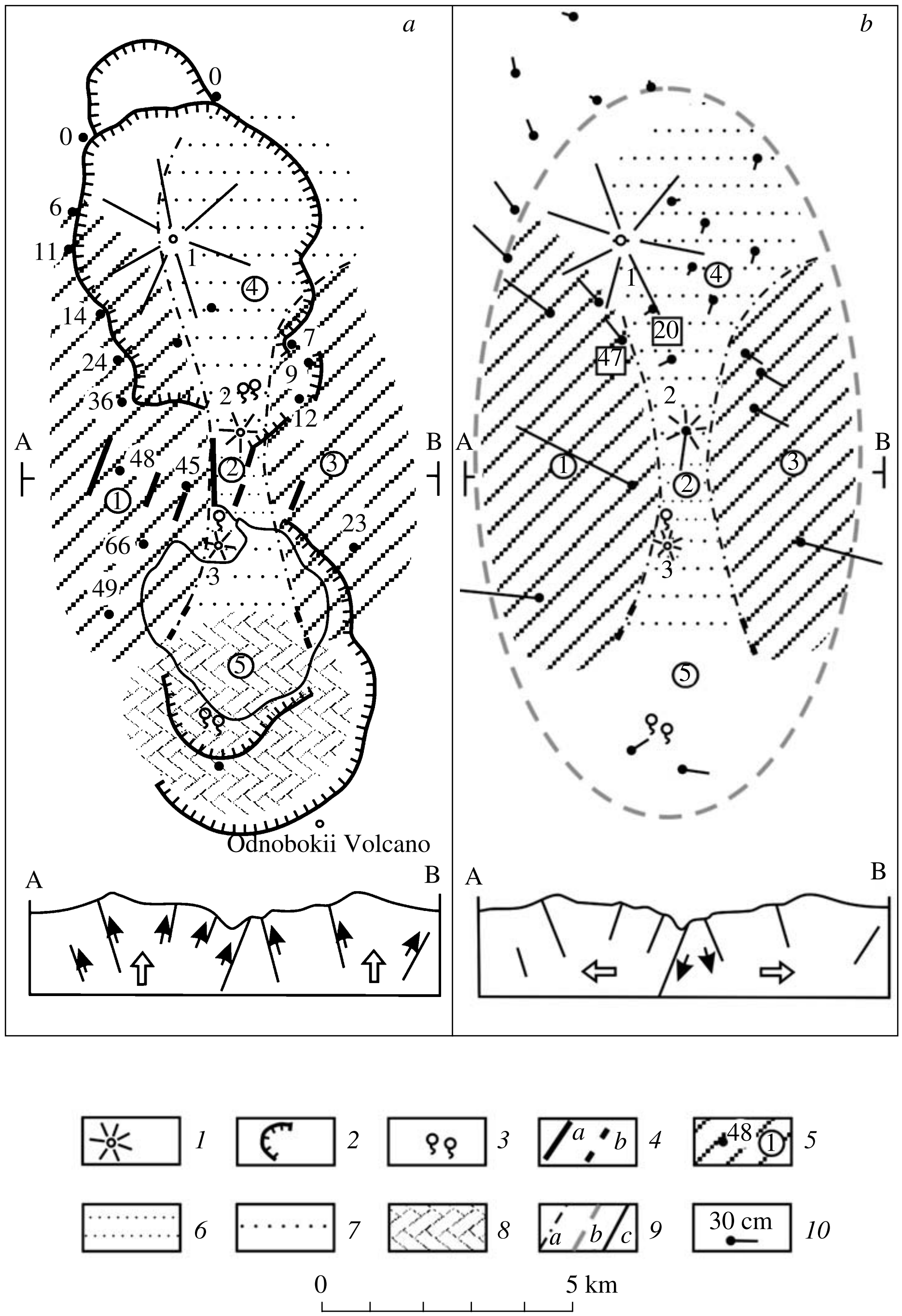

Fig. 8. Block movements near Karymskii Volcano in early January 1996 (*a* uplifts and subsidences during the first phase of deformation; *b* horizontal displacements occurring during the second phase of deformation). (*1*) Holocene volcanoes: (*1*) Karymskii, (*2*) Lagernyi, (*3*) main center of the 1996 eruption in Lake Karymskii); (*2*) calderas, (*3*) thermal springs, (*4*) faults : *a* certain, *b* inferred (incorporating the data listed in [17]), (*5–8*) areas where block movements have been identified: (*5*) uplifts and northward tilts (a dot and a numeral indicate the observation site and the associated uplift amplitude in cm after [11], a numeral in a circle denotes the identification number of a block, numerals in squares on the right of the figure are identification numbers of observation sites referred to in the text), (*6*) subsidences with amplitudes of up to 1.5–2.0 m and westward tilts, (*7*) subsidences with amplitudes of below 15 cm [11], (*8*) block of Akademii Nauk Volcano (a series of arcuate cracks formed along its boundaries [8], data on vertical movements are not available), (*9*) lines that bound: (*a*) uplifted and subsided areas after [11], (*b*) area where block movements have been identified (in outline), (*c*) faults in cross-sections (arrows indicate the sense of movement on the faults), (*10*) direction and amplitude of horizontal movements after [12]. Large arrows in the cross-sections indicate the hypothetical block displacements during the first (*a*) and second (*b*) phases of deformation.

ditions of their generation, as well as geodetic data in the area [11, 12], suggest several features for the deformation. We note some of these.

(1) The deformations occurred in an extensive area of at least 14 by 7 km; they were not restricted by any local surface structures like volcanic edifices or calderas, but were, as it were, superimposed on these and involved both these structures and the space between them.

(2) These events gave rise, not just to a single fault, but to numerous minor breaks dispersed throughout a large area.

(3) The breaks did not have radial orientations with respect to any volcanoes or to the Karymskii Volcanic Center as a whole. Most of the breaks are parallel to one another and strike north-northeast (about 20° NNE).

(4) The deformation was blocky in character; the resulting blocks are not new formations, but had formed previously, mostly in relation to caldera generation processes. Most block boundaries were, accordingly, caldera boundaries or older faults that started moving again as a result of the deformation.

(5) The block movements were not uniform. Some blocks have subsided and normal faults formed at their boundaries. Other blocks have been uplifted and reverse faults formed at their boundaries and in the blocks themselves. Some blocks have experienced significant horizontal displacements: block 1, which is situated in the west of the study area, has moved west–northwest, block 3 which is situated in the east has moved east–southeast.

As shown above, one must identify two phases of the deformation. The first mostly involved the generation of uplifts and reverse faults, while the second mostly gave rise to subsidence, normal faults, and horizontal displacements. The compression which occurred during the first phase was oriented in the vertical upward direction. Judging by the tilts of the uplifted blocks (with the greatest uplift occurring in the south with the amplitude of displacement gradually diminishing northward), the principal source of pressure that has given rise to the deformation of the first phase was situated in the south, in the area of Lake Karymskii. An unusual occurrence was observed in the same area after this deformation, viz., a simultaneous discharge of basaltic and rhyolite lavas [14]. These phenomena were undoubtedly related; in conjunction with the fact that they occurred at the center of an area that has been one of the greatest extension based on long-term geodetic observations [13]; this suggests that all these phenomena have direct relationships to magmatism. One likely mechanism for the relationship was discussed by S.A. Fedotov [18], who showed that the ultimate cause of these events may have been increased pressure in the intermediate magma chamber situated at a depth of 13–23 km. The subsequent emplacement of magma in the upper crust must have produced an additional excess pressure that gradually increased to reach 300 bars at a depth of 5 km [18]. In Fedotov's opinion, the emplacement of magma from the deeper chamber occurred along a crack (dike) whose thickness and horizontal extent were 2.5 m and 2900 m, respectively, in the depth range 0–5 km.

What caused the numerous breaks and block movements on the surface? The magma chamber at 13–23 km depth could not, taken by itself, have served as the source of deformation for the small area concerned (14 by 7 km). The responsible deformation source must have been much shallower. Could the dike be the source of deformation? This option was discussed in [6]. These authors have reconstructed the sources of elastic deformation using relative displacements of geodetic stations on the surface. It was inferred that the bulk of the displacement occurred in the area due to dike emplacement, which has extended and pulled apart fault sides on the ground surface with amplitudes of 3.2 m [6]. Experimental research shows that dike emplacement in the upper crust may produce subsidences, grabens, tension cracks and normal faults [25, 27, 28]. However, a field study of Icelandic dikes has shown that the stresses associated with their emplacement are too small to generate large faults or grabens on the surface [24]. Keating et al. [26] report results from a study of the plumbing systems of small-volume basaltic volcanoes and associated dikes to come to the conclusion that the zone of influence of a dike is no more than 110 m at depths shallower than 50 m (across the dike strike). The results of these field studies thus provide unambiguous evidence that basaltic dikes cannot cause surface deformation in an extensive area having transverse dimensions of 10 km or greater, as is the case in the Karymskii Volcano area.

Detailed surveys of ground deformation were carried out in the 1970s in the area of the Great Tolbachik Fissure Eruption (GTFE) [19]. During the initial explosive period in the activity of Pervyi Cone of the GTFE, an extensive area (at least 6–7 km across) experienced a relative uplift of a few meters. Where the bocche were opened, the uplift was replaced with subsidence. It was concluded that these deformations were most likely to have been due to a sill emplacement of magma occurring at a few kilometers depth [19].

Uplifts of extensive areas and reverse faulting are ordinary occurrences in those cases where dome uplifts or transverse folding are simulated above extensive lens-like sources [2, 10, 15]. It is pointed out in [15] that normal faults are being expanded downward on the hinges of folds and reverse faults grow upward on the limbs of folds. The latter are oriented like a fan and across the layer, they arise near the edges of the die (the area that produced the pressure). A decreasing thickness of the deformed layer and an increasing die area must have produced a double stress maximum on the hinge.

As was shown above and one can see in Figs. 2 and 8, the breaks that appeared near Karymskii Volcano in

1996 contain two special sets of reverse faults that are diverging fanlike upward and are situated west and east of Lake Karymskii. Comparison of these data with experimental results [15] suggests that the deformation near Karymskii Volcano may have been due to a pressure increase in an extensive sill body (a flattened magma chamber). The top of that body lay at 3–4 km depth (this estimate is based on average block size and the distribution of earthquake hypocenters [3, 21]). It may be hypothesized that in this case, similarly to the Yellowstone and Long Valley calderas [23], a basaltic magma has been emplaced at the base of a partially molten acidic magma reservoir situated at a shallow depth beneath the Lake Karymskii caldera. It is also possible that it was the existence of this reservoir that was the cause of two more pressure sources appearing along the edges of the lake. An accumulating basaltic magma and increasing pressure ultimately resulted in a breakthrough of the chamber top, producing the block movements observed on the surface.

However, these ideas do not provide the answer to the question of why the surface breaks did not propagate in an axisymmetric manner. This should have been the case if the breaks had only been due to the action of the excess pressure in the chamber. However, as has been shown above, most of the new breaks show persistent north–northeast strikes, and this is likely to be related to the regional stress field, whose axis of maximum horizontal compression has a north–northeast strike in Kamchatka [7]. This suggests that the stress field that had existed during the first deformation phase was as follows: the axis of maximum stress (σ_1) was vertical, with its sense being controlled by the excess magma pressure; the axes of intermediate and least stress (σ_2 and σ_3) were horizontal; the axis of greatest horizontal stress (σH_{max}) corresponds to σ_2 striking north–northeast (about 20° NNE).

The second deformation phase seems to have involved a reorientation of the principal stress axes. The subsidence episodes occurring during that phase show that the excess magma pressure in the chamber disappeared. Judging from the fact that horizontal displacements clearly occurred during that phase producing low-angle normal faults and extensional fissures, the axis of maximum stress seems to have become horizontal at that time (thus corresponding to σH_{max}). These novel conditions in which the horizontal compression was greater than the vertical stress must have stopped the upward propagation of magma and facilitated its emplacement in horizontal directions. Moreover, since the axis of maximum pressure was striking north–northeast (about 20° NNE), the horizontal emplacements must have occurred in the direction perpendicular to that axis.

The events that took place in the area of Karymskii Volcano in early January 1996 are consistent with these ideas. The eruptions in Lake Karymskii, which began in the fault zone produced by the first phase of deformation, were soon to cease [14], while the horizontal displacements occurring immediately afterward, during the second phase of deformation, mostly were in the east–southeastward and west–northwestward directions [12].

Karymskii Volcano is under special conditions, since its eruption, which began during the first phase of deformation, also continued after the reorientation of the overall stress system (and continues until now). These conditions may be due to the presence of a magma chamber beneath it at a depth of ~1.5 km below sea level [5, 21]. The chamber seems to create a local stress system of its own which transforms the regional field.

Local changes in the regional stress field can also be invoked to explain the appearance of feather breaks around the ends of the north–south faults due to the deformation described in this paper. Since the trend of these faults does not coincide with the orientation of the maximum horizontal compression axis (σH_{max}), it follows that definitely oriented breaks of the second rank must appear around the ends of the north–south faults (Fig. 9) as shown by simulation of such structures [15, 22]. The observed feather faults completely coincide with those simulated, which shows that the mechanism suggested here is viable.

The influence of local stress fields seems to be also felt near the new eruption center in Lake Karymskii. It has been shown above that the fault planes of the north–south faults generated around the head of the Karymskii River dip west throughout nearly all of their length, while the displacement is reverse in sense. At the same time, the fault plane rotates like a propeller around the south ends of these faults near the new eruption center in Lake Karymskii; all the faults found there are normal. Obviously, this curvature in fault plane is related to some special conditions that existed near the new eruption center. It is most likely that the discharge of magma at this location was accompanied by a local tension, and it was this which transformed the regional stress field.

Taking a review of the deformation as a whole, we can see that it can be satisfactorily explained when related to magmatism and treated as resulting from increased pressure in the set of magma chambers existing in the interior of the area. Attempts at explaining the deformation by different causes, in particular, treating the main event to have been purely tectonic [3] seem to be less fruitful, considering that the origin of these tectonic movements remains unclear. If one assumes the main cause to have been a regional horizontal transverse tension as hypothesized in [4, 20], that hypothesis is contradicted by the mostly reverse displacement that has occurred in the area of study. There is also no reason to consider the deformation as resulting from left lateral shear, as could be inferred from an analysis of the mechanism for the M=6.9 earthquake that occurred simultaneously with this deformation [3]. No strike-slip move-

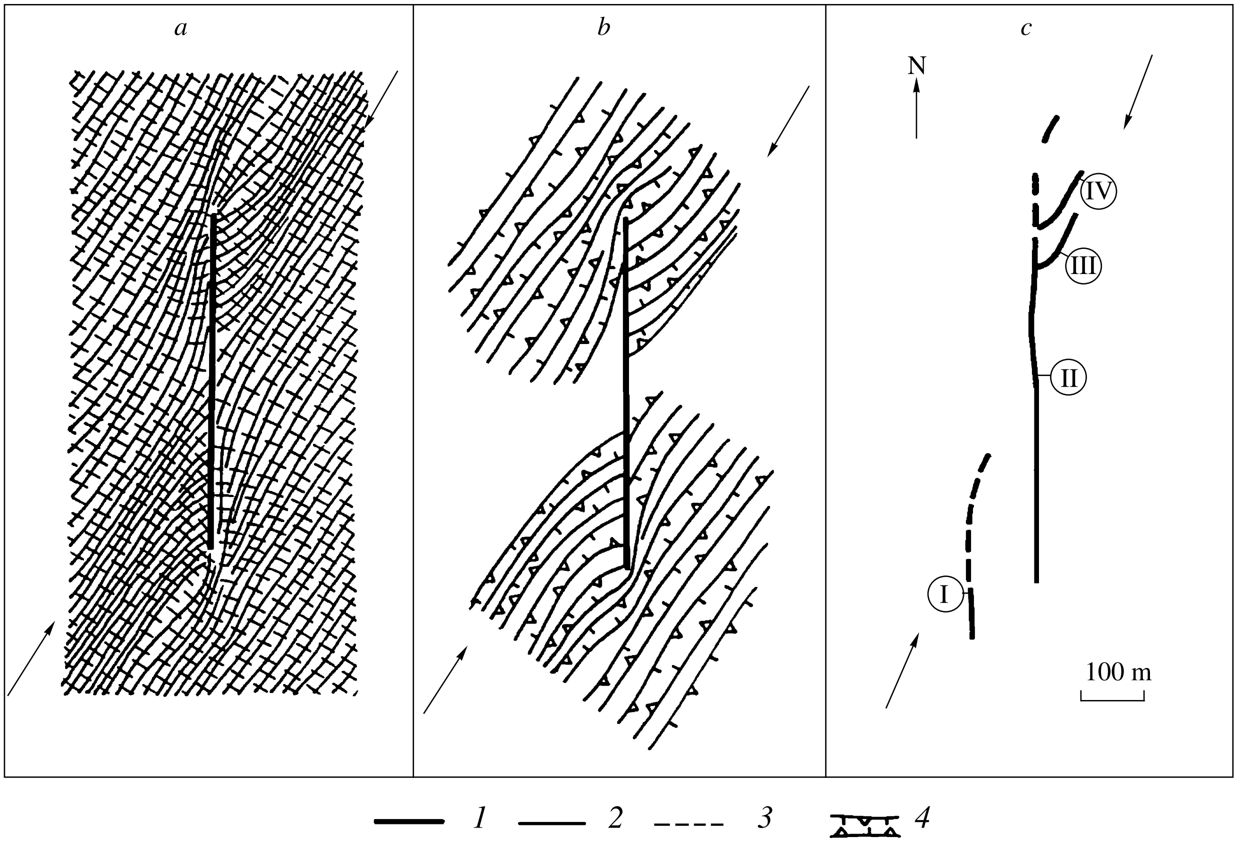

Fig. 9. Comparing the stress field and the faults as predicted by simulation and theoretical analysis, and those identified by field work: (*a*) two-dimensional local stress field in the vicinity of a plane fault oriented at an angle of $\alpha = 30°$ relative to the axis of greatest compression in the original field after [15, 22], (*b*) map of predicted secondary breaks in the massif that surrounds the fault shown in the left in this figure, after [15], (*c*) map of faults identified in the upper reaches of the Karymskii River, encircled numerals indicating their identification numbers: (II) main fault, I, III, IV faults of the second rank (feather breaks). (*1*) fault, (*2*) σ_{min}, (*3*) σ_{max}, (*4*) type of movement on secondary faults. Arrows indicate the direction of the axis of greatest compression in the original stress field (σ_1).

ments have been detected in the area of study, either on older or more recent breaks [8, 9]. The deformation as described here does not suggest a single extended fault that could have been produced by the large earthquake. All the faults are no longer than 1.5 km on the ground surface and these were dispersed over a large area.

CONCLUSIONS

(1) Most breaks that appeared near Karymskii Volcano in early January 1996 are reverse faults, the relevant movements frequently combining reverse and extensional displacements. Of lesser importance are the faults with normal displacements, all of these being confined to a narrow north–south zone in the center of the area that has experienced the deformation.

(2) The breaks mostly have north–northeast orientations (about 20° NNE). Faults with other directions (north–south, northeast, and northwest) are less frequent and occur only in the zones of older faults that have been called to life by the deformation.

(3) The movements are blocky, the blocks (mostly 1 to 4–5 km across) were not new formations; all of these were formed during the preceding phases in the evolution of the area. The block movements were not uniform: some of these were uplifting, some subsiding, and still others moved horizontally.

(4) It has been found that the faulting occurred in two phases in the area of study. The first phase was to produce reverse faults upon the background of a general uplift in the area. The second phase involved a subsidence of some territory in the middle of the study area and some horizontal displacements; the resulting faults were reverse and extensional.

(5) A likely mechanism has been suggested to explain the deformation. The fractures and block movements in the upper 3–4-km crustal layer are supposed to have occurred as a result of the top of a shallow magma chamber (which had a large area and a flat, sill-like shape) being broken through. The breakthrough, which was occasioned by increased pressure inside the chamber, was accompanied by eruptions and large earth-

quakes (with magnitudes as large as 6.9). After the breakthrough in the chamber top the axes of principal stresses were reoriented and conditions arose to favor magma emplacement in horizontal directions. The orientation of the new faults is supposed to be controlled by the regional stress field that exists in the upper crust of Kamchatka.

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