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Earthquakes at the Karymskiy Volcanic Center and their Relation to Tectonics

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This paper examines earthquake generation in the Karymskiy seismic region, situated in the middle of the Karymskiy ring structure. It is shown that the earthquake generation may be related to crustal magma bodies in the region and to the movement of magma along comparatively old northeast faults which were reactivated during recent time.

INTRODUCTION

Volcanic earthquakes are interpreted by many investigators as a brittle response to pressure changes in the magma systems of volcanoes. They provide information on the magma system and processes that are going on in it [26], [29], [30], [31]. This paper is not concerned with shallow (H<=2 km) earthquakes of the Minakami's B-type (Tokarev П- and Ill-types) nor with explosion earthquakes. Such earthquake usually occur within a short time interval just before eruptions or are related to volcanic explosions. Background seismicity in volcanic areas consists of deeper (2 to 70 km) events of type A whose wave patterns are similar to those of tectonic earthquakes occurring in the Benioff zone and were classified by G. S. Gorshkov as volcanotectonic earthquakes. P. I. Tokarev defined them type A earthquakes. He believes that they characterize the microtectonics of a volcano and its environs and reveal changes in the state of stress of the uppermost crust caused by pressure fluctuations in the conduit and upper chamber, but does not rule out their relation to displacements on tectonic faults [17].

A good target area to study volcanic earthquakes in Kamchatka is the central portion of the Karymskiy ring structure. This comparatively small area (30 by 30 km) contains an active andesite volcano (Karymskiy), a permanent source region of crustal earthquakes, a mature hydrothermal system, and an active zone of recent crustal movements. Recurring earthquake swarms and surface deformation are generally typical of andesite and dacite volcanoes with their highly viscous magma [4], [18], [29], [30], [31].

A base seismograph station was installed in May 1970 in the Karymskiy caldera at a distance of 3.5 km from the crater. In 1989 it began radio transmission of seismic information. All earthquakes of energy class greater than $K_S^F=8.5$ around Karymskiy Volcano are recorded by the stations of the Kamchatkan network. The epicenter location uncertainty is 20 km. A temporary local tripartite array was operated on the volcano in 1985; it revealed a systematic bias in local epicenter locations as given by the regional network [26]. Applying the resulting epicentral corrections improves the interpretation of seismic data.

BRIEF DESCRIPTION OF KARYMSKIY VOLCANO

The volcano is about 6000 years old. It is situated in a Holocene caldera superimposed on the middle and late Pleistocene Dvor and Pra-Karymskiy volcanoes. South of the Karymskiy caldera is the Akademii Nauk caldera of late Pleistocene age (about 40 000 years); at present it is occupied by Lake Karymskiy. The Karymskiy Center includes another active volcano (Malyi Semyachik), 18 extinct volcanoes, and more than twenty monogenetic structures. The center of the Karymskiy ring structure where Karymskiy Volcano is located, is considered to be an energy source generating melts in the country rocks: the rocks show maximum concentrations of silica, sodium and potassium oxides there. The Karymskiy andesites contain 60% silica [13]. Mostly Vulcanian-type eruptions occur on Karymskiy; lava flow is usually preceded by the growth of a volcanic dome in the crater. The last eruption terminated in 1982 [17], [18], [20], [23]. A magnetic and a gravity anomaly, both positive, occur above the Karymskiy caldera. They are thought to be due to a subvolcanic intrusion or a shallow magma chamber, whose center of gravity lies at 4-5 km depth, the top, at about 1.5 km. Assuming a spherical shape and a reasonable density excess, one gets 2.3 to 3.5 km for the radius of the chamber [5]. Judging by geodetic and photogrammetric data, the top of this inferred magma chamber is 1 to 5 km below the surface. It might be a sphere or a cylinder of radius 0.5-0.8 km [11].

SEISMICITY

The earthquakes recorded by the tripartite array in 1985 were located in a spherical half-layer about 5 km thick which surrounds on the southeast an aseismic sphere of radius ~2.5 km centered at 6.5 km depth under the Karymskiy summit {26]. This corroborates the existence of a shallow magma chamber beneath the volcano. In map view, most of the earthquakes lie within a NE-trending 7 X 9 km ellipse. The center of this seismic volume is about 3 km south of the crater (Fig. 1).

The seismicity of the Karymskiy volcanic center for the observation period of 1962 to 1992 was examined by sampling data sets from the regional Karymskiy catalog of earthquakes that were of energy class K,>8.5 and occurred within a square of 53.65-54.35°N and 159-160°E. The epicenters were then displaced by 8 km northward and 2 km eastward in order to compensate for the systematic bias. The corrections were borrowed from [26]. As a result the epicenter uncertainty was improved from 10-15 to

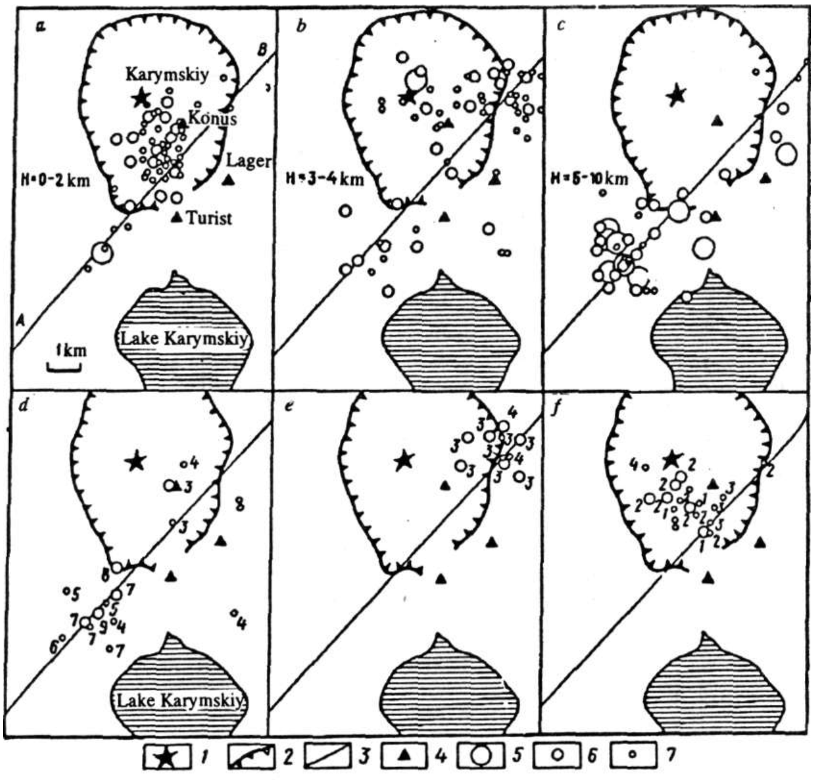

Figure 1 Spatio-temporal distribution of earthquakes in the Karymskiy seismic region in 1985 based on local network data [26]: *a, b, c* - maps of epicenters for the depth ranges 0-2, 3-4, and 5-10 km, respectively; *d, e, f* - distribution of earthquake epicenters for three time intervals from May 14 to June 8, 1985: 1 - Karymskiy crater; 2 - caldera wall; 3 - fault; 4 - seismic stations; 5, 6, 7 - epicenters of energy class 8-10, 6-7, and 4-5, respectively The depths (km) are indicated near epicenters (circles).

5 km for the events recorded since 1970. The uncertainty for the pre-1970 earthquakes was 20 km. The depth uncertainty remained the same, 10 km.

The Karymskiy seismic region is shown in Fig. 2 for the depth ranges 0-5, 6-15, and 16-25 km. The earthquakes concentrated in the middle of the Karymskiy ring structure where most of the Pleistocene volcanoes of this volcanic center are situated (volcanoes are marked by stars in Fig. 2). The hypocenters tend to lie deeper in the south of the seismic region than in the north. The positions of the events in the short high-energy swarm of January-February 1978 were updated using the corrections referred to above. The largest Kj = 12.7 event took place at 21 h 51 min GMT on January 29, 1978, in the area of Lake Karymskiy. The other five largest events whose source mechanisms can be found in [4] occurred within 7 km from the main shock, in the area between Polovinka, Krainiy, and Dvor volcanoes.

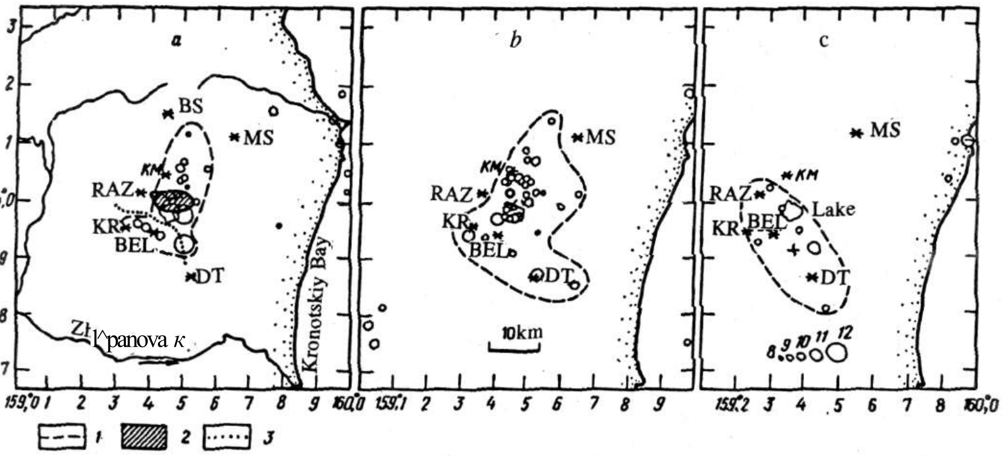

Figure 2 Distribution of earthquakes of class $K_S^F \geq 8.5$) in the Karymskiy volcanic center based on the data of the regional seismic network for the period 1962-1992 in the depth ranges: *a* - 0-5, *b* - 6-15, *c* - 16-25 km; 1 - extension area; 2 - spreading center; 3 - line of strain reversal (extension replaced by compression contraction, after M. A. Maguskin). Volcanoes: KM - Karymskiy, MS - Malyi Semyachik, RAZ - Razlatyi, KR - Krainiy, BEL - Belyankin, DT - Ditmar, BS - Bolshoi Semyachik.

Figure 3 shows the projections of the 1962-1992 earthquake epicenters in the region 53.65-54.35°N, 159-160°E, $0<H<200$ km on to a vertical plane across the Benioff zone. The zone is dipping under the continent at an angle of about 60° in the segment of the volcanic arc including the Karymskiy volcanic center within the depth range 80-200 km. It is 110-180 km deep beneath Karymskiy Volcano and 100-160 km beneath Malyi Semyachik. Because no earthquakes have been recorded under the Karymskiy seismic region at depths of 20 to 100 km, the region is spatially separated from the Benioff zone.

Comparison with the geodetic data given in [12] shows that the geometrical center of the Karymskiy seismic region, somewhere in Lake Karymskiy, coincides with the center of the extensional strain area (Fig. 2). The northern part of the region is under extension and the southern under slight compression (see the line of the strain reversal in Fig. 2).

The orientations of the local stress axes in the middle of the Karymskiy volcanic center were discussed by Zobin *et al.* [4]. They studied six of the largest events of a swarm at depths of 0 to 10 km. Three of them took place in the north of the area. The planes of the least compressive stresses had the following strikes: 50° for the event in the Karymskiy caldera and 10-15° for those in the area of Lake Karymskiy. The other three events which occurred in the south had the planes of the least compressive stresses striking 310° to 350°. It is thus inferred that the fissures better suited for opening and upward magma transport are those in the caldera and Lake Karymskiy with azimuths 10-50° and fissures with azimuths of 310° to 350° in the area of Krainiy, Belyankin, and Polovinka volcanoes.

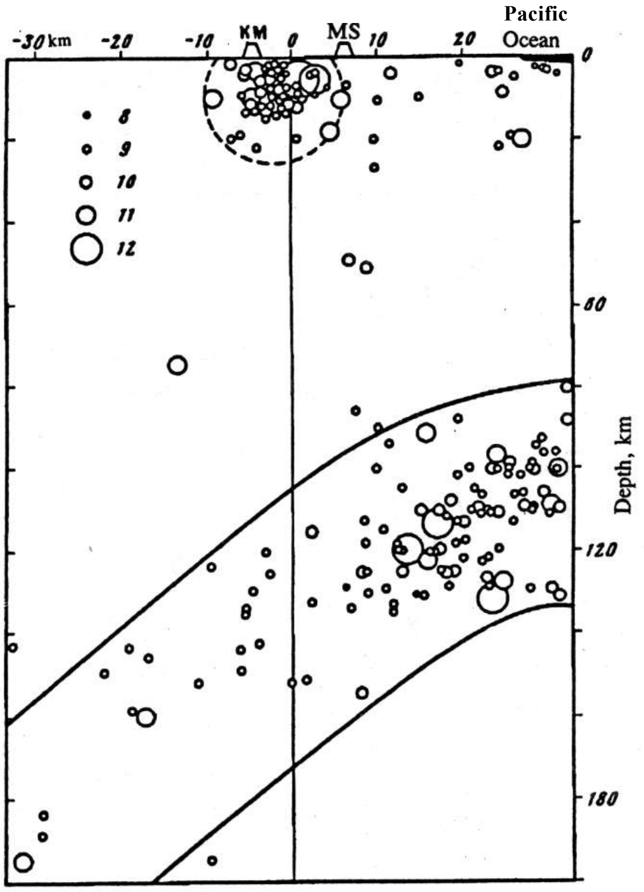

Figure 3 Benioff zone in the volcanic arc segment of the Karymskiy volcanic center, and the Karymskiy seismic region in cross section. The data are for 1962-1992, $K_S^F \geq 8.5$. This map was obtained by projecting the hypocenters contained within the cube 53.65°-54.35°N, 159°-160°E, $0 \leq H \leq 200$ km onto a vertical plane across the Benioff zone. The vertical scale is twofold compressed. KM - Karymskiy, MS - Malyi Semyachik.

Figure 4 compares the maximum energy classes K_{max} of earthquakes in the Benioff zone, in the 53.65-54.35°N band at depths ranges $H \leq 70$ km and $H > 70$ km, vertical displacements in the Karymskiy caldera, and the maximum energy classes K_{max} of earthquakes in the Karymskiy seismic region. Arrows mark the episodes of lava outflow at Karymskiy. It is obvious that the seismotectonic processes in the Benioff zone are not synchronous with the deformation and seismicity in the Karymskiy seismic region, hence, there is no direct relation between them. However, all lava discharges on the volcano were preceded by increases of seismotectonic activity in the Karymskiy seismic region, even though seismicity increases in 1985-1986, 1989, and 1992 were followed by eruptions.

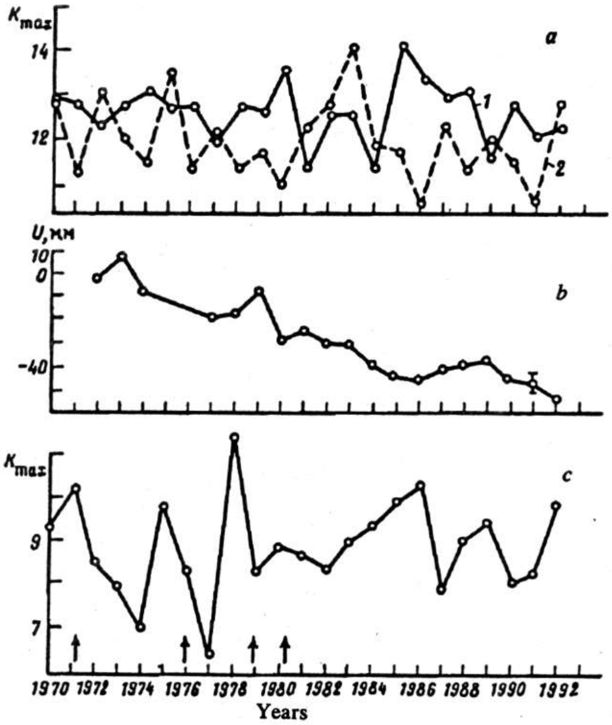

Figure 4 Comparison of maximum energy classes K_{max} of tectonic earthquakes in the Benioff zone (*a*), vertical displacements (U) in the Karymskiy caldera (*b*), and maximum energy classes (K_{max}) of earthquakes in the Karymskiy seismic region (*c*) for the period 1970-1992. Arrows mark the times of lava flow at Karymskiy. The vertical displacements were measured by Maguskin *et al.* [12]; 1 - H < 70 km, 2 - H > 70 km.

FAULTS IN THE KARYMSKIY VOLCANIC CENTER

The largest faults in the center of eastern Kamchatka, where the Karymskiy volcanic center is situated, strike NNE 20-30°. This was reported by Gusev [2], Erlikh [28], and Svyatlovskiy [15], the most detailed description of these faults was by Legler [8]. The dense network of the NNE, mostly normal faults marks a large extension zone whose surface expression is a wide (up to 20 km) graben. This graben was described by Masurenkov [13], [14], Florenskiy and Trifonov [22], Kozhurin [7], and Leonov [9], [17]. Masurenkov, Florenskiy and Trifonov divided this fault zone into several segments: Zhupanovo-Karymskiy, Malyi and Bolshoi Semyachik, Bolshoi Semyachik-Uzon, Uzon-Krasheninnikov, Krasheninnikov-Kronotskiy. The segments form an en echelon pattern. The largest offsets were observed in the Karymskiy volcanic center (Fig. 5).

In addition to these NNE faults, there are northwest, northeast (NE 45°), east-west, north-south, arcuate and ring faults. Investigators differ as to their relative importance.

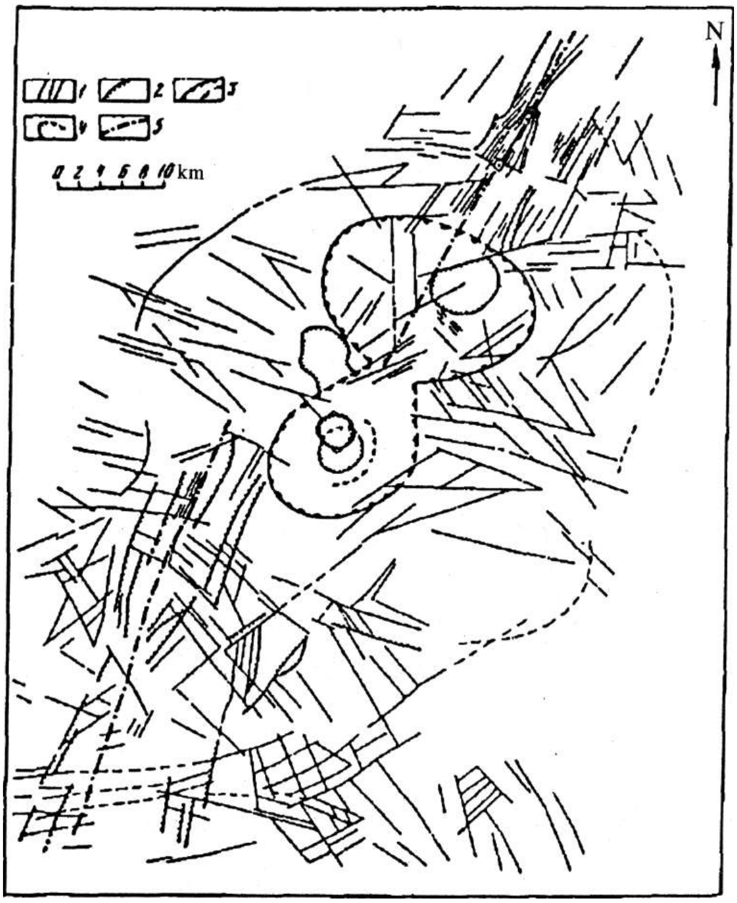

Figure 5 Faults in the Karymskiy volcanic center [13]. Linear faults: 1 - without visible displacement, 2 - with displacement. Ring caldera faults: 3 - middle Pleistocene, 4 - late Pleistocene; 5 - spreading axis.

For instance, Erlikh [28] emphasized the contribution of the northwest, northeast, and east-west. A later, more detailed description of these faults was given by Shantser [24]. In particular, he identified the major east-west Karymskiy-Ganaly fault expressed at the surface as chains of Holocene and late Pleistocene basaltic cinder and lava cones. Masurenkov [13] discussed this fault in great detail, stressing its WNW direction, and thought it to be the main transverse structural feature. He believed that the intersection of this fault and the longitudinal NNE fault zone had controlled the structural evolution of the area. Large east-west fault zones were identified also by Ermakov *et al.* [3], Shilin *et al.* [27], Kozhurin [7], and other workers. Many investigators consider these faults to be right lateral strike-slip faults with displacements of up to 10-15 km.

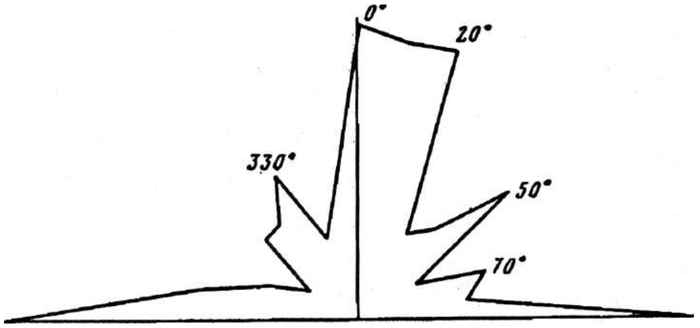

Figure 6 Summary rose diagram indicating the strikes of fractures measured in the area of the Karymskiy seismic region (1374 fractures).

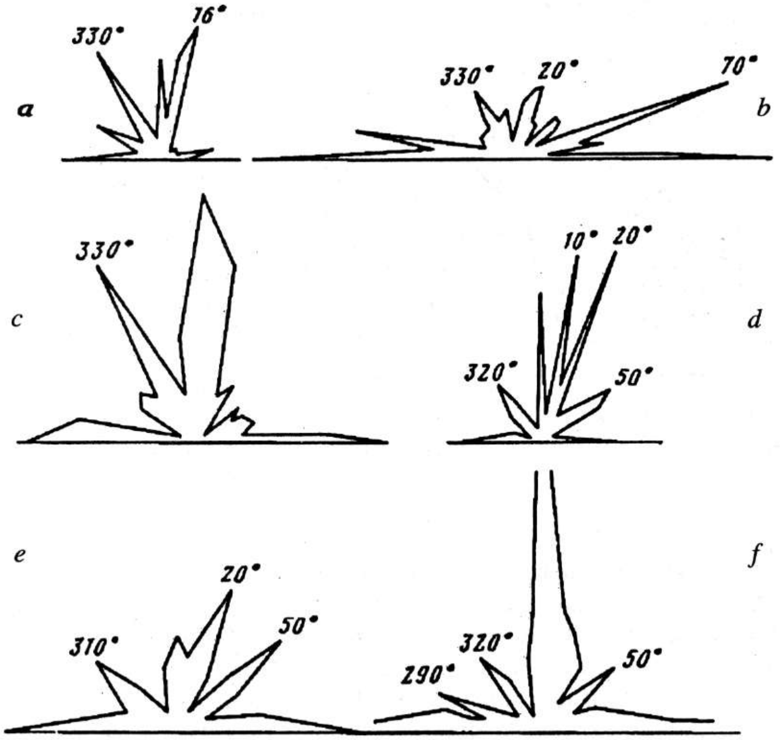

Figure 7 Rose diagrams of fracture orientations in various localities of the Karymskiy area: *a* - area of the second and third waterfalls (53 measurements); *b* - western part of the Klyuchevaya Valley (244 measurements); *c* - source of the Karymskiy River (278 measurements); *d* - area of the fourth and fifth waterfalls (185 measurements); *e* - Lake Karymskiy surroundings (140 measurements); *f* - walls of Karymskiy caldera (280 measurements).

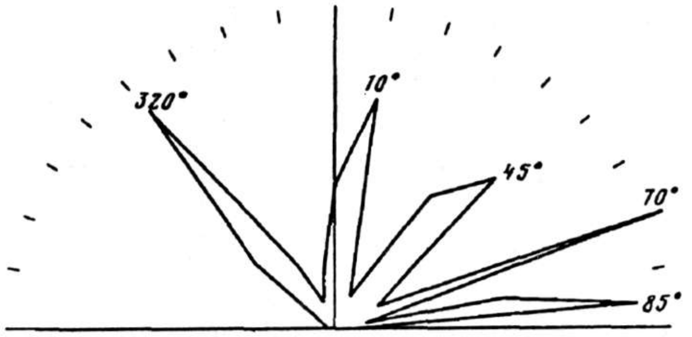

Figure 8 Summary rose diagram of fracture separation (75 measurements).

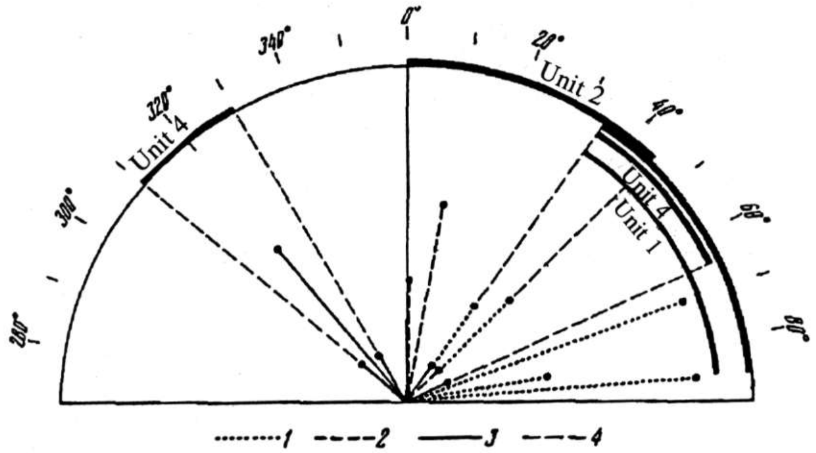

Figure 9 Diagram of fracture separation in units of different age: 1 - Unit 1; 2 - Unit 2; 3 - Unit 4; 4 - boundaries between units.

The north-south faults were also treated in several different ways. For example, Shteinberg *et al.* [27] identified from airborne magnetic data a large north-south fault passing through Sobolinyi, Dvor, Karymskiy, and Akademii Nauk volcanoes. Later Ivanov [6] mapped it as three large, closely spaced north-south faults that had controlled volcanic activity. According to Masurenkov [13], the north-south faults are few in the Karymskiy volcanic center, and their structural role is negligible.

Generally, the east-west and north-south faults were best identified by geophysical techniques [1], [3], [16], [27]. Interpretation of aerial photographs and ground-based data were more effective for tracing the NNW, arcuate, and ring faults. This situation is similar to the pattern reported from southern Kamchatka [10], where the faults were divided into three groups: the older faults (mostly striking east-west, north-south, and northwest), the Pleistocene faults (striking northeast), and the late Pleistocene/Holocene faults (striking NNE). Likewise, the east-west and north-south faults of the Karymskiy volcanic center seem to be the oldest. They were identified reliably by geophysical methods. A special study was carried out in the area to investigate tectonic fracturing in more detail. The results are presented below.

STUDY OF TECTONIC FRACTURING IN THE KARYMSKIY SEISMIC REGION

This work was conducted in the area of the Karymskiy caldera and Lake Karymskiy for the first time. The aims were to locate fractured rock masses, measure the orientation, separation, displacement, and filling of fractures, and determine their age.

The first of these tasks was made easier by previous studies (e.g., [6], [13]). Using their results and our field observations, we identified five rock units that are most severely fractured (in the order from old to recent): (1) "wild" tuff - a sequence of hydrothermally altered, bedded tuff, supposedly of middle Pleistocene age; (2) ignimbrites in the calderas of Stena-Sobolinyi and Polovinka volcanoes, possibly 150 000-180 000 years old; (3) the lava-pyroclastic sequences of Odnobokiy, Dvor, and Pra-Karymskiy volcanoes; 4 "noble" tuff of pumice flows in the calderas of Odnobokiy and Akademii Nauk volcanoes, supposed to be 40 00-100 000 years old; and (5) pumiceous tuff of pyroclastic flows in the Karymskiy caldera, phreatomagmatic deposits, and the lava-pyroclastic sequence of Karymskiy Volcano, ranging in age from recent to 8 000 years.

We disagree with some of the previous conclusions [13]. We believe that the "wild" tuff exposed at the source of the Karymskiy River cannot be classed as young lacustrine deposits enclosed in the calderas of Stena-Sobolinyi and Polovinka volcanoes. The high degree of the hydrothermal alteration and fracturing of the rocks suggest them to be among the oldest deposits of the area that were involved in tectonic uplift. Our measurements of the dips and strikes of the bedded tuffs revealed their azimuths and angles of dip to be 7-32, 40-20, 55-40, 60-15, 105-27, 120-35, 120-40, 170-28, 190-24, 275-24, 290-9, and so on, respectively. The dip is vertical in some places. This shows that the rock sequence has been crushed and consists of individual, frequently steeply dipping and randomly oriented blocks. This is improbable for Quaternary deposits. We believe the "wild" tuff to have been produced in one of the oldest historical periods of the area.

The other comment concerns the phreatomagmatic deposits 5500-6000 years old. They were not previously identified as a separate unit [13], but recent observations revealed them to be widespread in the sides of the Klyuchevaya Valley. They attracted us as the most fractured rocks among the Holocene deposits. They consist of alternating thin layers of greenish sandstone and siltstone, averaging 20 to 50 cm in total thickness and draping the underlying relief. We classified the deposits as phreatomagmatic after consulting with O. A. Braitseva who had recently arrived at the same conclusion.

General description of the fractures, their orientation and separation. 1374 fractures iii our field work. Their usual frequency is 1 or 2 per square meter. They spaced 1.5 to 2 m apart in the "noble" tuff. The greatest frequency of fractures was recorded in the "wild" tuff (as many as 10-15 per sq.m.). Figure 6 presents a diagram of fracture strikes which shows the most frequent strikes to be north-south (NNE 10-20°) and east-west. The northeast (NE 40-50°) and northwest (NW 310-330°) strikes are fewer by a factor of two. The orientation varies widely over the area (Fig. 7). However, the pairs of orthogonal (east-west and north-south) and diagonal (NE 50° and NW 320°) fractures occur almost everywhere. They represent a ubiquitous fracture system. Nearly all areas exhibit NNE 10-20° fractures set which characterize the neotectonic fault system of the East Kamchatka volcanic belt [10]. Occasionally encountered are perpendicular, WNW 280-290° fracture sets. The "wild" tuff shows a peculiar set of ENE 70° fractures which are not found in the other deposits of the area.

Separation and filling vary from 0.3-1 m zones filled with thin-bedded silty psammite to hairbreadth joints with no filling at all. Fractures 1 to 6 cm wide filled with brown sandstone are frequent in the "noble" tuff. There are fractures filled with bleached pumice sand and gravels. The separation diagram in Fig. 8 clearly shows the greatest separation in all fractures striking northeast (ENE 85, 70°, NE 45°, NNE 10°) and northwest (NW 320°). Diagrams of fracture openness in the rocks of different ages (Fig. 9) show that the orientation of the open fractures varies progressively from ENE 85-70° and NE 35-45° typical of Unit 1 ("wild" tuff) to north-south and NNE 10° typical of Unit 2 (ignimbrites) to mostly northwest (NW 320°) typical of Unit 4 ("noble" tuff). As will be shown below, this orientation (NW 320°) is also common in the youngest rocks of the area, both in the Karymskiy caldera deposits and in the lavas of the volcano.

Movements parallel to the fracture plane, either vertical or horizontal, are uncommon. Horizontal displacement (strike slip) has not been found at all, vertical displacement (normal faulting) occurs merely in two cases: at site 69 in agglomerate pumiceous tuff along a zone 18 cm wide striking 330° where the northeastern side is downthrown by 60 cm, and at site 90 on a narrow east-west fracture with a northward downthrow of 20 cm. Smaller northward downthrow displacements were observed on some other fractures at this site.

Fractures in rock units of different ages. Let us examine the variation pattern of fracture strikes in the five stratigraphic units identified above (Fig. 10). We measured 36 fractures in the youngest deposits (Unit 5). Most of them strike NE 330°; fewer but well developed fractures are of the NNE 10-20° strike.

The number of fractures measured in the "noble" tuff (Unit 4) was 319. Most of them strike NE 40-50° and W 270°, some sets, NNE 20° and NW 310-320°. We measured 315 fractures in the lavas of Pra-Karymskiy and Dvor volcanoes (Unit 3). These are mostly east-west and north-south fractures, all other directions being less frequent (Fig. 10, III). This can apparently be explained by the fact that the measurements were made in the walls of the Karymskiy caldera which subsided along older weakened zones trending east-west and north-south.

The ignimbrites of the Stena-Sobolinyi and Polovinka calderas (Unit 2) are obviously dominated by the fractures striking NNE 10-20° and north-south. Also well developed are fracture sets striking NE 40-50° and NW 310-320°. The other directions are much less frequent.

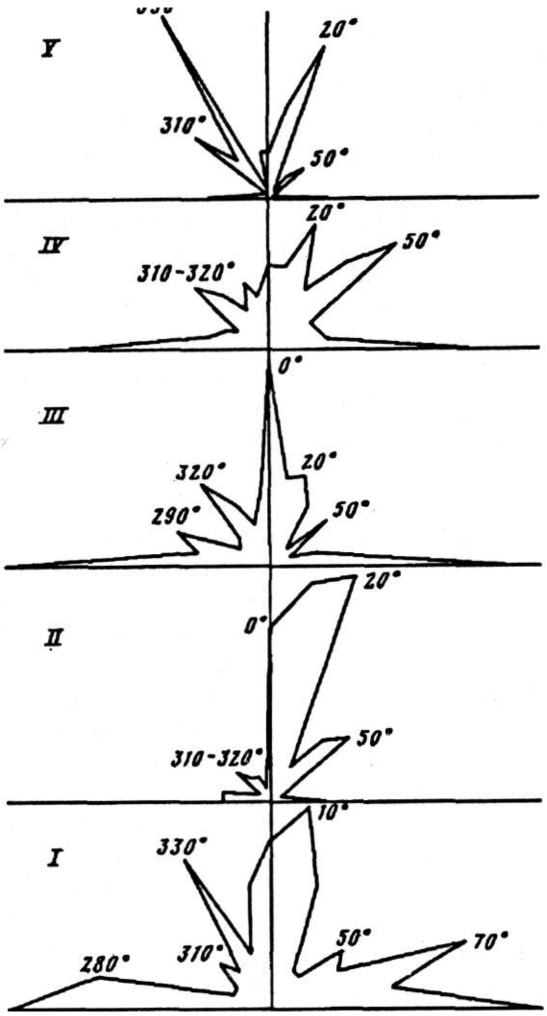

Figure 10 Rose diagrams of fracture strikes for Units I-V (see the text): I - 443, II - 248, III - 315, IV - 319, and V - 36 measurements.

The predominant fractures in the "wild" tuff (Unit 1) strike W (270-280°) and ~N (NNE 10-20°); there are also ENE 70° and NW 330° fractures. We measured 443 fractures in this unit.

The predominance of the NNE 10-20° fractures in the study area is because that most of the faults in eastern Kamchatka strike NNE. They have been studied in various areas of the volcanic belt. These faults and fractures were formed in the Late Pleistocene during the formation of the largest calderas in eastern Kamchatka. As one can see in Fig. 10, V, fractures of this strike were active also during Holocene time.

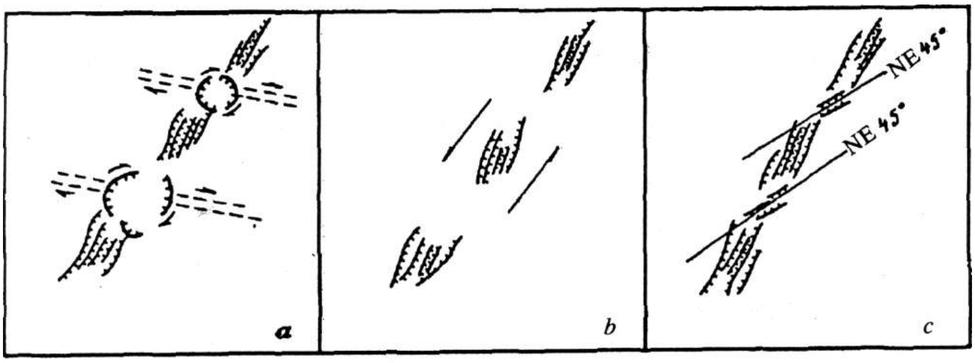

Figure 11 Dynamic interpretations of Karymskiy faults after: *a* - [13]; *b* - [22]; *c* - [10].

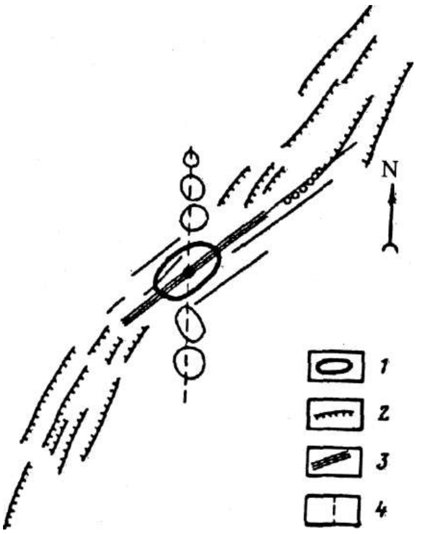

Figure 12 Structural setting of the Karymskiy seismic region: 1 - Karymskiy seismic region; 2 - network of neotectonic faults; 3 - activated segment of an old fault; 4 - deep-seated north-south fault which controlled the location of late Pleistocene volcanoes.

Fractures striking northeast (NE 50°) and northwest (NW 310-330°) also occur in all units. One notes a surprisingly great frequency of 330° fractures in the youngest deposits. When these data are compared with the separation diagram, where the youngest joints strike NW 330°, and with the overall elongation of the Karymskiy caldera in the same direction, one comes to the conclusion that this direction was an important, probably leading direction during the neotectonic history of the surface structure in the area.

The east-west and north-south fractures are most widespread in the older units and less frequent in the younger. As has been mentioned, they played an important part in the caldera formation: even though these faults seem to be of the oldest they were reactivated in some segments. The same applies to the fractures striking ENE 70°, in the "wild" tuff, which are apparently the oldest in the area. Such fractures are nearly absent in the other units. This fact is very important, because one can infer therefrom that the "wild" tuff is the oldest rock in the area and that the ENE 70° fractures were of particular importance. They do not occur in any of the later deposits.

DISCUSSION OF RESULTS

This study of tectonic fragmentation revised some of the existing views on the faults in the area and improved their dynamic interpretation.

One of the three main views was offered by Masurenkov [13] who ascribed a special significance to the intersections of the longitudinal NNE faults and the transverse WNW faults (Fig. 11, *a),* the latter being right lateral strike-slip faults. This view was supported by Kozhurin [7], who is ready to admit some clockwise rotation of the longitudinal extensional zone accommodated by the east-west faults, in addition to right lateral strike slip displacement, with the centers of rotation in the late Pleistocene calderas.

Florenskiy and Trifonov [22] are of a different opinion. Admitting the same longitudinal extensional zone trending NNE and noting the en echelon pattern of the fault zones in it, they suggested a left lateral strike slip along the axis of the zone. No transverse faults with right lateral strike slip along them have been mentioned in contrast to [7] and [13] (Fig. 11, *b).*

The third view was suggested by Leonov [10], who stressed the role of the relatively old northeast faults (NE 40-50°). The neotectonic faults striking north-northeast (NNE 20-30°) in some segments of the East Kamchatka volcanic belt were relieved through the older northeast faults, thereby activating them. This produced the en echelon pattern of the neotectonic faults (Fig. 11, c).

Our study of tectonic fractures demonstrated that neither the east-west fractures nor those striking northeast or north-northeast showed lateral displacement. Most of them are open and filled with sandy and clayey material or tuff, some exhibit downdip displacement. This indicates that the upper crust in the area is under extension. Accordingly, the first and second viewpoints outlined above are unacceptable. Neither can we agree with Masurenkov [13] who thinks that north-south faults are rare in the Karymskiy volcanic center and that their structural control was negligible. One can clearly see in the summary diagram of Fig. 6 that the north-south fractures are not only fairly numerous but predominate over the fractures of other directions.

Let us examine the third viewpoint. One can see in the separation diagram for the rocks of different ages (Fig. 9) that the northeast (NE 35-45°) fractures are the only features that remained open during all phases of the geological evolution. This fact shows that they were active and operated in a geodynamic environment that favored magma emplacement. This is in complete agreement with the third viewpoint: the most active or repeatedly reactivated features were the fractures and faults of the northeast strike.

The above evidence suggests that the structural environment of the Karymskiy volcanic center is likely to be as shown in Fig. 12. This part of the seismic region is located at the intersection of a comparatively old northeast fault, which was activated during late Pleistocene time when a neotectonic network of NNE fractures was developed, and an older north-south fault that controlled the origin of Odnobokiy, Akademii Nauk, Karymskiy, and Sobolinyi volcanoes (marked by circles in Fig. 12).

As seen in Fig. 2 the seismic region broadens and shifts southward with depth. Geological evidence shows that the volcanoes are arranged in the order of older age in the same direction (from north to south): recent Karymskiy, Akademii Nauk, Odnobokiy, and the old Polovinka caldera. The deep roots of these volcanoes, which are situated along the same major north-south fault, are likely to be connected. Each new volcano was born north of the preceding one and inherited part of its magma system. The structure and state of stress of the Karymskiy seismic region are consistent with the relevant geological evidence and indicate a complex magma system of Karymskiy Volcano, which shifts southward and turns northwest in the area of Krainiy, Belyankin, and Polovinka volcanoes.

CONCLUSION

1. As indicated by earthquake data recorded in 1962-1992 crustal seismicity within the Karymskiy ring structure was concentrated under its middle in a depth range of 0 to 20 km and spatially separated from the Benioff zone. The geometrical center of the region is situated in Lake Karymskiy. The region is not more than 20x30 km in map view. The earthquakes in the south of the region are deeper than in the north. The size of the region may be slightly overestimated because of random epicenter scatter.

2. The northern part of the seismic region is under extensional strain and contains a spreading center, the southern is undergoing slight compression.

3. The local stress system down to 10 km depth is such that the most favorable conditions for opening and magma transport exist in the fractures striking 10-15° in the Karymskiy caldera and Lake Karymskiy and in those striking 310 to 350° in the area of Krainiy, Belyankin, and Polovinka volcanoes.

4. The study of tectonic fractures in the area of the Karymskiy caldera and Lake Karymskiy showed that the area had been under extension since the middle Pleistocene (?). No horizontal displacements were found in the area. The northeast (NE 40-50°) fractures which were active during all phases of structural evolution.

5. The structural setting of the seismic region was determined by its location at the intersection of the north-south and northeast faults. The latter were responsible for the northeast elongation of the region.

6. The structure of the Karymskiy seismic region is in good agreement with geological data, suggesting that the magma system of Karymskiy Volcano shifts southward with depth and turns acquiring a northwest direction.

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