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Lineaments, Tectonic Fractures, and Mechanical Behavior of Klyuchevskoi Volcano

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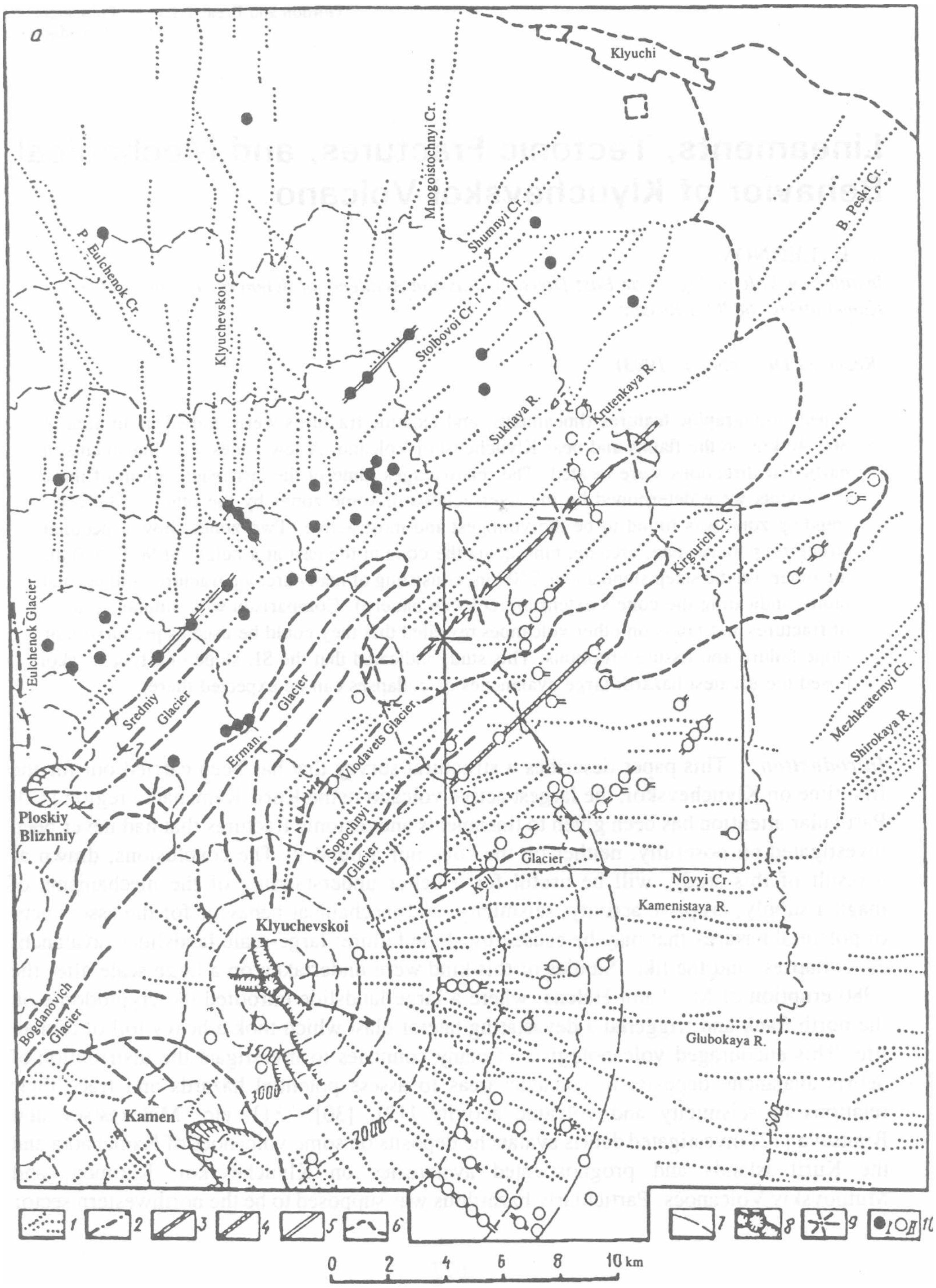
Linear topographic features (lineaments) and tectonic fractures were studied in an area of 30x40 km on the flanks and near Klyuchevskoi Volcano. A few zones with lineaments of particular directions were located. The relative ages (time of the last reactivation) of these lineaments were determined by the intersections of some zones by the others. The NW-trending zone was found to be the youngest and most active. Two zones show a peculiar structural pattern: one, arcuate, embracing the cone in the east at a height of 900-2500 m, the other, on the steep slope above 2500 m, consisting of many arcuate fractures and normal faults, indicating the cone's extension (cobweb pattern). Comparison with similar systems of fractures and faults on other volcanoes revealed that they could be used as precursors of slope failure and fissure eruptions. This study indicated that the SE slope of Klyuchevskoi posed the greatest hazard: large avalanches or collapses can be expected there.

Introduction. This paper describes a structural survey that has been carried out for the first time on Klyuchevskoi, the largest active volcano in the Kuril-Kamchatka region [17]. Particular attention has been given to lineaments and tectonic fractures that had never been investigated purposefully, neither on the cone nor around it. The conclusions, drawn as a result of this study, will be useful for a better understanding of the mechanisms of magma supply, eruptive activity, seismicity, and mechanical behavior for the assessment of potential hazards that may be caused by slope failure: large-scale landslides, avalanch-es, collapses, and^the like. Studies of this kind were undertaken on a large scale after the 1980 eruption of Mt. Saint Helens, where a large landslide unroofed the cryptodome on the north flank and triggered a devastating lateral blast which took a heavy toll of human life. This encouraged volcanologists of many countries to investigate the distribution of debris avalanche deposits in volcanic areas to assess potential hazards and trace their relations to seismicity and volcanic activity [12], [30], [31], etc. Melekestsev and Braitseva [12] investigated debris avalanche deposits on some volcanoes of Kamchatka and the Kuril Islands and prognosticated avalanches on Klyuchevskoi, Kizimen, and Mutnovskiy Volcanoes. Particularly hazardous was supposed to be the northwestern sector


a
Klyuchi
Mnogoistochnyi Cr.
B. Peski Cr.
Shumnyi Cr.
P. Eulchenok Cr.
Klyuchevskoi Cr.
Stolbovoi Cr.
Krutenkaya R.
Sukhaya R.
Kirgurich Cr.
Eulchenok Glacier
Srednity
Glacier
Erman
Glacier
Vlodavets Glacier
Mezhkraternyi Cr.
Shirokaya R.
Ploskiy
Blizhniy
Sopochnyi
Glacier
Kell
Glacier
Novyi Cr.
Kamenistaya R.
Klyuchevskoi
Bogdanovich
Glacier
Glubokaya R.
3500
3000
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500
Kamen
1
2
3
4
5
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8
9
10
0 2 4 6 8 10 km

of the Klyuchevskoi cone. The probability of an avalanche there was noted by Fedotov *et* ***al.*** [16]. Another circumstance that stimulated our study were the events of the late 1980s, when a large portion of the cone, from the height of 2000 m to the summit was intensely broken by numerous fractures [7]. Khrenov *et al.* [17] prophesied that a possible pattern of further developments on Klyuchevskoi are large avalanches and the destruction of its cone as happened on Kamen and Ostryi Tolbachik volcanoes located nearby. Large landslides and volcanic eruptions pose a threat to the city of Klyuchi situated at the foot of Klyuchevskoi. In this context the study of the mechanical behavior of its cone is an urgent task. In the present paper this problem is considered in structural terms.

Network of lineaments on the slope and around the Klyuchevskoi cone. During the early stage of our structural survey we followed the instructions for a conventional morphostructural analysis given in [9]. After the interpretation of air photographs and the work with topographic maps we located rectilinear topographic features and classified them as lineaments representing a pattern of faults in the area. Chains of lava domes, extensional eruptive fissures, fractures followed by the outcrops of similar lavas, and some other features were interpreted as lineaments. Various types of lineaments from volcanic areas have been described comprehensively by Shantser [29].

The basis of this work were topographic maps and air photographs, scale 1:50 000, the latter being more informative. We also used maps of other scales and the photographic products of space missions. As mentioned in [9], maps and photographs of different scales represent tectonic features of different extent and different depth. The first step therefore was to locate lineaments ranging in length from hundreds of meters to a few kilometers, the next, to locate zones dominated by lineaments of certain directions and having a length of tens to hundreds of kilometers, identified in photographs and maps of a smaller scale.

We located 1028 lineaments in the study are of 30x40 km; the largest of them are shown in Fig. 1, ***a***. One can see distinct zones of lineaments. The N-S oriented lineaments predominate in the northwest of the area, in the drainage areas of Klyuchevskoi, Mnogoistochnyi, and Pravyi Eulchenok Creeks. Southeastward, the areas of the Stolbovaya, Sukhaya, Krutenkaya, and Kirgurich Rivers exhibit NE-trending lineaments that stretch SW as far as the foots of Ploskiy Blizhniy and Klyuchevskoi cones. In the southeast, the areas of the Glubokaya and Kamenistaya Rivers are obviously dominated by W-E lineaments. Closer to Klyuchevskoi Volcano, the structural pattern changes markedly. An arcuate zone occurs at elevations of 900 to 2500 m; it rounds the cone from the east and is distinguished by a notably larger number of lineaments and also by a roughly uniform

Figure 1, ***a*** Schematic map of lineaments in the Klyuchevskoi area: 1 **-** morpholineaments (straight segments of rivers, creeks, valleys, and scarps on the slopes); 2 - inferred buried zones of fissures and normal faults, traced by glaciers; 3 - axes of lava dome chains; 4 - lineaments traced by compositionally uniform lavas [18]; 5 - extension fractures on cinder cones, eruptive fissures; 6 - area covered by Klyuchevskoi eruptive deposits; 7 - boundary of an arcuate zone showing its own structural pattern; 8 - cauldron scarps on the steep-sided portion of the cone; 9 - lava domes of the Lavovyi Shish type; 10 - cinder cones and sites of flank eruptions: I - Late Pleistocene, II - Holocene and modern. The boxed area is shown in Fig. 3, *b* on a larger scale.

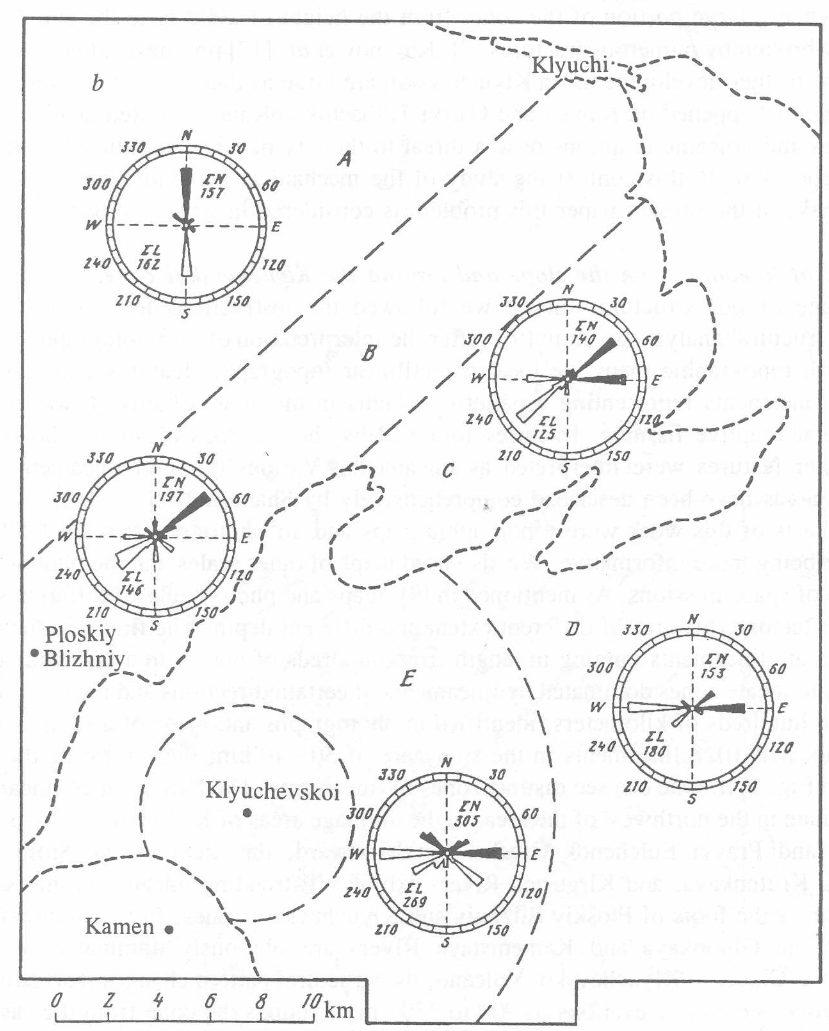

Figure 1, *b* Rose diagrams of the distribution frequency and total lengths of lineaments in zones *A, B, C, D,* and *E*.

distribution of lineaments trending in different directions. A peculiar structural pattern was found on the steep portion of the cone from a height of 2500 to the summit, where a network of arcuate fractures and faults produces a cobweb pattern.

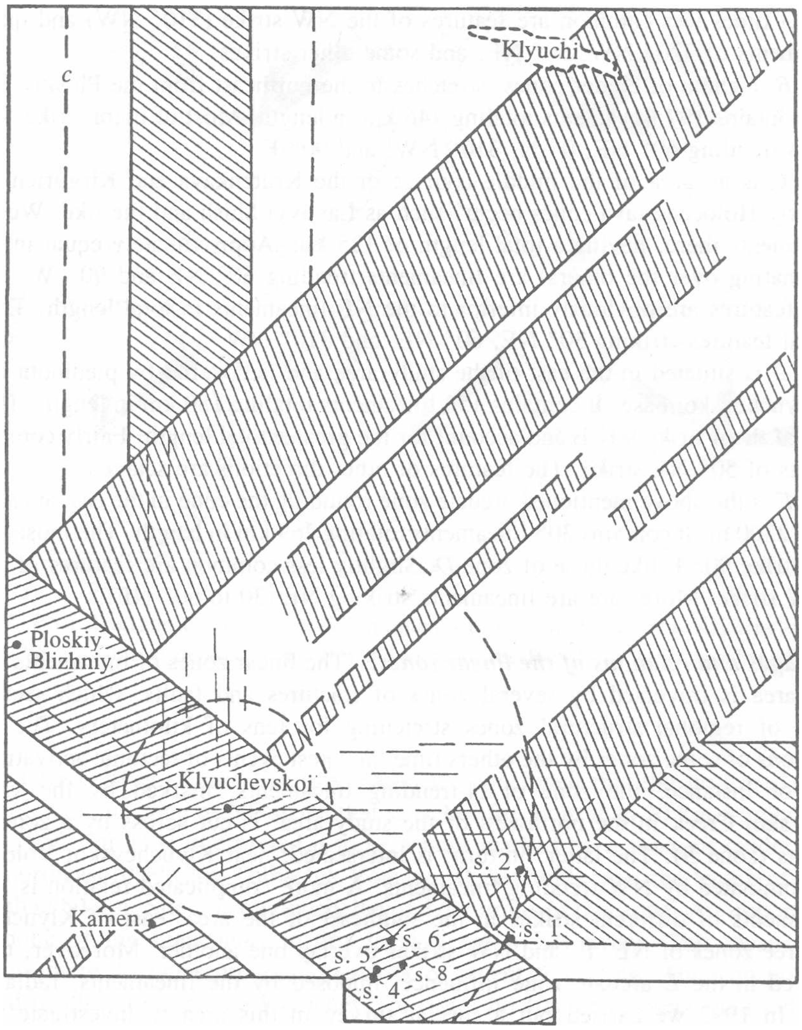

Figure 1, *c* Schematic pattern of relations between the major zones of closely spaced lineaments (hatched).

We distinguished five zones ***(A, B, C, D,*** and ***E*** in Fig. 1, *b)* on the basis of the predominance of some or other structural pattern and the geologic structure of the Klyuchevskoi foot. We countered the overall number of lineaments on strike and measured

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their total length for each zone using 10° sectors. Zone *A* in the northwest contains 157 lineaments, totaling 162 km in length. As mentioned above, most of them strike N. Roughly 3 times less common are features of the NW strike (310° NW) and quite rare are lineaments of 320° NW, 50° NE, and some other strikes.

Zone *B,* a chain of cinder cones, stretches to the northeast from the Ploskiy Blizhniy cone. It contains 197 lineaments totaling 146 km in length. Most of them strike 50° NE, much less trending 60° NE, 0° N, 310° NW, and 90° E.

Zone *C* is an area of the middle courses of the Krutenkaya and Kirgurich Rivers, where early Holocene lava cones occur, such as Lavovyi Shish and the like. We located 140 lineaments there, having a total length of 125 km. Approximately equal in number (predominating over the others) are lineaments trending 50° NE and 90° W. The W-trending features are obviously inferior to the NE lineaments in total length. There are occasional features striking 30° NE, 60° NE, and 310° NW.

Zone *D* is situated in the east of the study area and is covered by piedmont deposits of the Klyuchevskoi base. It contains 153 lineaments totaling 180 km in length. The most frequent of them strike 90° E and account for the greater total length. Fairly common are lineaments of 50° NE strike. The features of other directions are scarce.

Zone *E* is the above mentioned arcuate zone rounding the cone in the east at elevations of 900 to 2500 m. It contains 305 lineaments totaling 269 km in length. The most frequent of them strike 90° E like those of zone *D.* Slightly less common are features of 310 and 320° NW strike. More rare are lineaments striking NE (30 to 60° NE).

Relative ages and relations of the linear zones. The linear zones of lineaments indicate that the area is traversed by several zones of fractures and faults, which seem to be segments of regional structural zones stretching for tens of kilometers. The distinct intersections of some zones by the others time the latest events of tectonic activation (Fig. 1, c). For instance, the zone of N-trending lineaments, marked by the valley of Klyuchevskoi Creek in the northwest of the study area, is cut across by a zone of NE lineaments (zone *B).* The latter, in turn, is intersected, near Klyuchevskoi Volcano, by a zone dominated by NW-trending lineaments. A more complicated relation is between the lineaments of different strikes in the southeast of the area, east of Klyuchevskoi, where three zones of NE, E, and NW strikes overlap one another. Moreover, this area is involved in the *E* arcuate zone influence, imposed by the lineaments, radial to the volcano. In 1993 we carried out a special survey in this area to investigate tectonic fractures. We measured the dips, strikes, and the extent of openness and healing of all fractures located within the outcropping flat surfaces of lava flows that have been polished by temporary streams. The sites of measurements are shown in Fig. 1, *c.* In spite of a limited number of fractures (114) we could discern a distinct trend: five of the seven sites examined yielded fractures of 50° NE strike (Fig. 2). The planes of most of them were found to dip 60 to 80° NW. The exceptions were Site 1 with the dominant fractures of 80-90° E and 290-300° NW and Site 4 (Obruchev Cone), where a few fractures showed 320-335° NW strikes.

The locality where these measurements were made is situated on the continuation of the closely spaced NE-trending lineaments in the area of Mezhkraternyi Creek and the

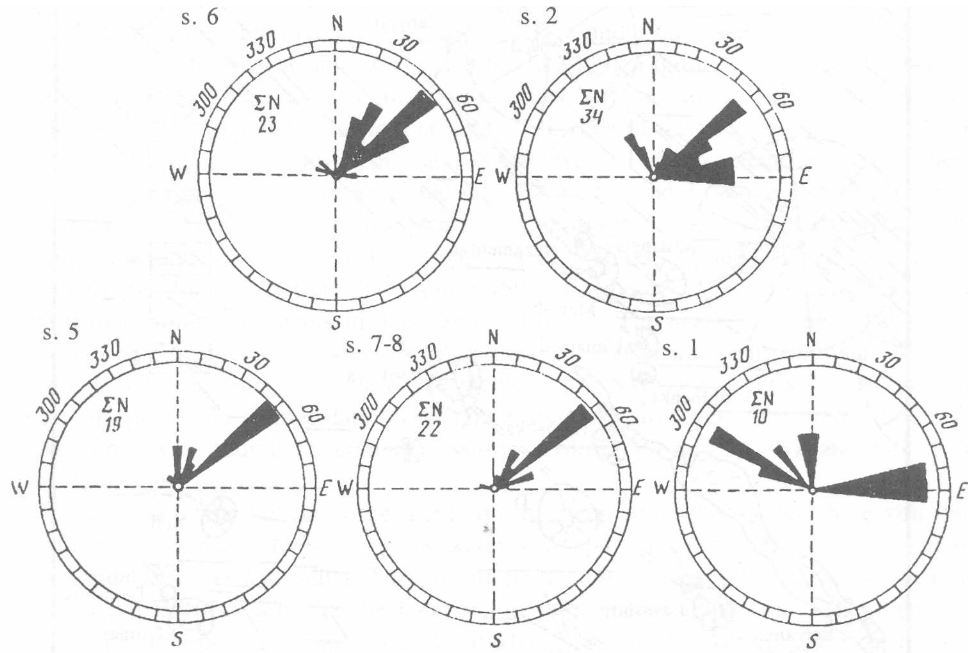
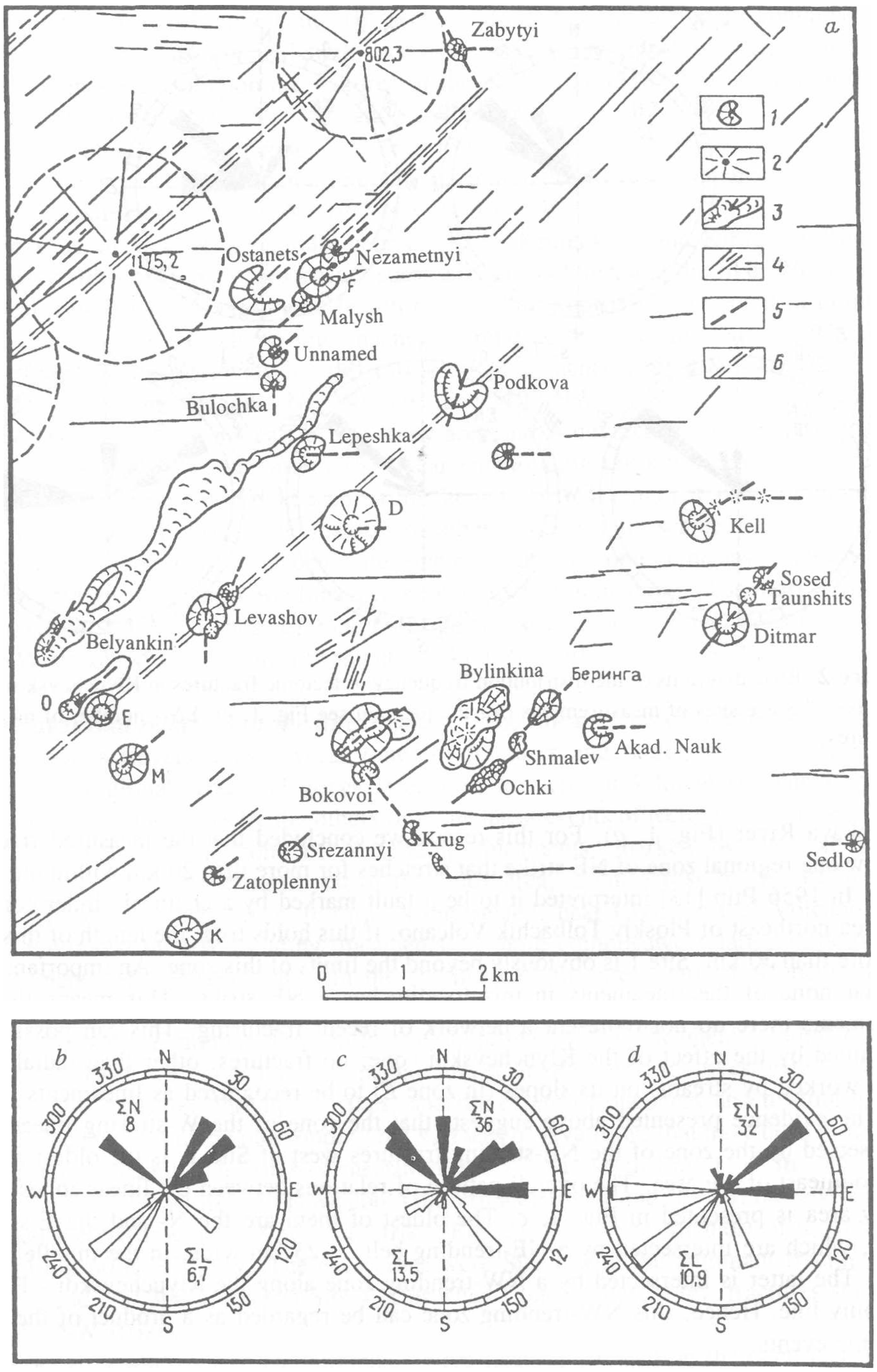


Figure 2 Rose diagrams of the distribution frequency of tectonic fractures in Klyuchevskoi lavas s. 1 to s. 7-8 are sites of measurements (for the location see Fig. 1, *c*). ΣN - number of measure fractures.

Shirokaya River (Fig. 1, a). For this reason we concluded that the measured fractures follow one regional zone of NE strike that stretches for more than 20 km within the study area. In 1956 Piip [13] interpreted it to be a fault marked by a chain of cinder cones in an area northeast of Ploskiy Tolbachik Volcano. If this holds true, the length of this zone is more than 50 km. Site 1 is obviously beyond the limits of this zone. An important point is that none of the lineaments in this locality has a NE strike. This means that the lineaments there do not represent a network of recent fracturing. This can possibly be explained by the effect of the Klyuchevskoi cone: no fractures, other than radial, have been worked by streams on its slopes (in zone *E)* to be recognized as lineaments.

The evidence presented above suggests that the zone of the W-striking lineaments, intersected by the zone of the NE-striking fractures west of Site 1, is the oldest zone in the southeast of the area. The overall pattern of relations between the linear zones of the study area is presented in Fig. 1, *c.* The oldest of them are the N- and the E-striking zone, which are intersected by a NE-trending belt, ~23 km wide, in the middle of the area. The latter is intersected by a NW-trending zone along the Klyuchevskoi - Ploskiy Blizhniy line. Hence, this NW-trending zone can be regarded as a product of the latest tectonic events.


a
Zabytyi
802,3
1175,2
1
2
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4
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6
Ostanets
Nezametnyi
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Malysh
Unnamed
Bulochka
Podkova
Lepeshka
D
Kell
Sosed
Taunshits
Ditmar
Levashov
Belyankin
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Bokovoi
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ΣN 8
ΣL 6,7
ΣN 36
ΣL 13,5
ΣN 32
ΣL 10,9
330
30
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240
120
210
150

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Volcanic lineaments and the structure of the cone's steep-sided portion. By volcanic lineaments we mean eruptive fissures, rows of lava and cinder cones, chains of craters and erosion cirques on volcanic cones, and the like [29]. Figure 3, *a* shows examples of these land forms. We classified them into zones, as we did in the case of tectonic lineaments: two zones of the far foot (C and *D),* a zone of the near foot (*E*), and a zone of the steep-sided cone (above 2500 above sea level). The lineaments located in these zones are listed in Tables 1 (zones C and D), 2 (zone *E),* and 3 (above 2500 m). Figures 3, *b, c,* and *d* show rose diagrams of the distribution frequency and total length of the volcanic lineaments (in 10° sectors). The far-foot zones, C and *D* (Fig. 3, *d),* are dominated by NE and E trending features (50° NE and 90° E). This agrees with the pattern of tectonic lineaments in these zones (Fig. 1). The near-foot zone (£) does not show volcanic lineaments of some or other direction that would be predominant (Fig. 3, c). As to the total length, the NW lineaments (320° NW) are slightly longer than the others. In spite of the limited data (only eight eruptive fissures were measured), the steep-sided cone was found to contain fissures striking 30 and 50° NE and 310° NW (Fig. 3*, b).*

In addition to the volcanic lineaments on the steep cone, we located three volpano-tectonic trenches there (Krestovskiy, Kozyrevskiy, and Apakhonchich) and a number of large arcuate fissures and faults. Their locations relative to the summit are shown in Fig. 4. It is of interest to consider the locations of the trenches relative to a plane passing through the summit and having a bearing of 310° NW: the Krestovskiy and Kozyrevskiy trenches (340° and 280°) are arranged symmetrically at an angle of 30° to this plane, whereas the Apakhonchich trench is parallel to it. The arcuate fissures and normal faults also show a regular arrangement relative to this plane. This pattern is especially pronounced on the southwestern slopes of the cone (Fig. 4). At least three fault scarps were located there south of the Apakhonchich trench; we called them southwestern walls 1, 2, and 3. The scarps amount to 30-40 m in height and were traced for 1-1.5 km in length. The steep sides of all scarps look NE, to the axis of the Apakhonchich trench. This suggests a zone of large cauldrons having a width of more than 3 km.

Another system of arcuate fissures was located to the northeast of the Apakhonchich trench, but their scarps look SW and are much lower. This is perhaps because the northern and northeastern slopes are covered by a thick snow and ice cap. More field work need be done in this locality to survey the structural details of these fissures and faults.

In general, the Apakhonchich trench and the zones of fissures and faults fringing it is a wide zone of extension, the transverse profile of which resembles the profiles of broad

Figure 3 Volcanic lineaments: *a* - example of distribution (for the location see the boxed area in Fig. 1, *a)\ b, c, d* - rose diagrams of the distribution frequency and total lengths by zones: *b* - steep-sided cone, c - near-foot area, *d* - far-foot area; 1 - cinder cones produced by flank eruptions; 2 - lava domes of the Lavovyi Shish type; 3 - modern fissure eruptions and their lava flows; 4 - morpholineaments (straight segments of valleys, rivers, creeks, and scarps on the slopes); 5 - volcanic lineaments (chains of craters, scours, and gullies on volcanic slopes); 6 - volcanic lineaments traced by chains of volcanic edifices with uniform lava composition.

Table 1 Volcanic lineaments in zones *C* and *D*.

Crater, eruptive fissure	*Strike, deg.*	*Length, km*
Tuila	30	0.5
Atlasov	335	2.0
Sizmos	90	0.2
Zabytyi	50	0.1
Nezametnyi	50	0.3
Crater	50	0.2
Malysh	50	0.2
Unnamed	0	0.1
Bulochka	90	0.3
Lepeshka	25	0.5
Podkova	320	0.2
Crater	90	0.5
	0	0.2
Kell	55	0.7
	90	0.5
Ditmar, Taushits, Sosed	45	1.0
Akad. Nauk	90	0.3
Bering	50	0.5
Shmalev	90	0.1
Ochki	55	0.7
Sedlo	90	0.2
228.2	90	0.5
260.5	50	0.1
373.5	50	0.3
Ostanets	50	0.5
Cone *E* - Podkova lineament	50	7.0
Lavovyi Shish - Mt. Zabytaya chain	50	10.0

graben-like structures that have formed in recent extension zones of the crust (Iceland, Afar depression, etc.). At the same time the Apakhonchich trench is markedly different from the other volcano-tectonic trenches (Krestovskiy and Kozyrevskiy) which do not have broad extension zones but are typically V-shaped, narrowing toward the cone base.

The interpretation of the air photographs of the northwestern slopes revealed another system of arcuate fractures and faults that produced a structural pattern symmetrical about the 310° NW trending plane (Fig. 4). So, the NW trend, which is accompanied by obvious extension features of the cone, is the main structural line that controls many structural forms of the volcano.

Lineaments located from seismic events preceding Klyuchevskoi fissure eruptions. Seismic data sometimes help locate seismo-tectonic lines and axes which add to the general pattern of lineaments [26]. Some earthquake swarms that occurred in the area showed obviously extended epicentral zones. For instance, the swarm that preceded the 1987 flank eruption (Predvidennyi) stretched from NW to SE, the line along which earthquake epicenters propagated on February 20-22 before the first eruptive fissure

Table 2 Volcanic lineaments of zone *E*.

Crater, eruptive fissure	*Strike, deg*	*Length, km*
Krug	320	1.5
Bokovoi	90	0.2
Crater	90	0.5
	60	0.5
Srezannyi	60	0.1
Zatoplennyi	55	0.2
Crater *K* (Novyi)	60	0.1
Crater *M*	50	0.2
Crater *O*	50	0.5
Levashov	0	0.2
	20	0.2
Lesnoi	90	0.5
Crater Otkrytyi	30	0.4
Gorshok	90	0.2
Steller	310	0.5
Karpinskiy	310	0.5
Peshchernyi	310 (?)	-
Malenkiy	90 (?)	-
Pribrezhnyi	310	0.2
Yubileinyi	317	2.0
Kozei Group	90	1.0
Nevidimka	90	0.2
Tiranus	64	0.2
Bilyukai	60	0.2
	20	0.2
Apakhonchich	310	0.1
Pogrebennyi	315	0.2
Unnamed	0	0.5
Slyunin	0	0.2
Vernadskiy	320 (?)	-
Belyankin	30	0.5
Piip	15	0.3
	45	0.1
Holm	315	0.3
March	59	1.0

developed on February 23 [16]. Fedotov *et al.* [16] reported a similar NW epicentral • lineation before'the 1980 fissure eruption. Zharinov *et al.* [7] reported that the earthquake swarms had been elongated in the same NW direction before two fissure eruptions of 1989.

Zobin [8] carried out a comprehensive analysis of stresses that had operated in the Klyuchevskoi area prior to the 1974 flank eruption. Two earthquake swarms were recorded in April and August. The fissure eruption took place immediately after the August events. Approximately 70% of measurements yielded compressional axis stresses directed within a range of 0-90° during the April swarm, whereas most of the stress axes

Table 3 Volcanic lineaments on the upper steep-sided portion of the cone (above 2500 m).

Fissure eruption	*Strike, deg.*	*Length, km*
4th VVS*, 1974	60	0.5
Predskazannyi, 1983	70	0.4
Predvidennyi, 1987	30 (?)	1.0
25 years IV**, 1988	30	1.0
	45	0.3
Small fissure eruptions of Dec	50	2.0
1988, March and Feb 1989	310	0.5
Skuridin, 1989-1990	310	1.0

VVS - Vsesoyuzn. Vulkanol. Sovesh. (National Conference on Volcanology).
IV - Institute of Volcanology.

were directed within a range of 79-170° during the precursory August swarm, and fissures developed in the main, northwestern direction under extensional conditions. So, the seismic data are fully consistent with the pattern of lineament distribution and prove that the NW-trending zone passing through Klyuchevskoi, which has been located as a result of our study, is the main structural trend of modern activity. This zone accommodates the sources of earthquakes that precede fissure eruptions. Cauldrons and broad graben-shaped troughs are formed on the cone slopes within it. Most of the volcano-tectonic trenches and eruptive fissures are symmetric about the axis of this zone. This suggests that the cone is structurally anisotropic, an important observation that need be considered in interpreting the volcano's eruptive mechanisms, modeling the magma plumbing system, and predicting potential slope failure. Let us consider the principal structural factors that control the mechanical behavior of volcanoes and the conditions that favor the occurrence of landslides, avalanches, cauldrons, and other destructive events on Klyuchevskoi.

Mechanism of the structural localization of landslide and explosion cirques. In the area of the Klyuchevskoi volcanic group, landslides and avalanches are known to have occurred on Krestovskiy (Mt. Ploskiy Blizhniy), Kamen, Mt. Ovalnaya Zimina, Ostryi Tolbachik, and Ploskiy Tolbachik [12]. Very large avalanches took place on Kamen and Ostryi Tolbachik. On both volcanoes they were directed SE. The resulting cirques are oriented in the same direction. The cirque on the Kamen cone is 4x7 km in size and has steep, locally vertical, walls 2500 m high [12]. An avalanche on Krestovskiy Volcano (Mt. Ploskiy Blizhniy) produced a cirque oriented in a W-E direction (Fig. 1). A large avalanche on Mt. Ovalnaya Zimina formed a 3 x7 km cirque, elongated in a NE direction and having, as does the cirque on Kamen, steep, locally vertical walls. Extensive cirques and eruptive craters were formed as a result of explosive activity on Bezymyannyi, Zarechnyi, Staryi Shiveluch, and Molodoi Shiveluch Volcanoes. The cirques produced by explosions on the first three volcanoes are open SE, the cirque on Molodoi Shiveluch, SSW.

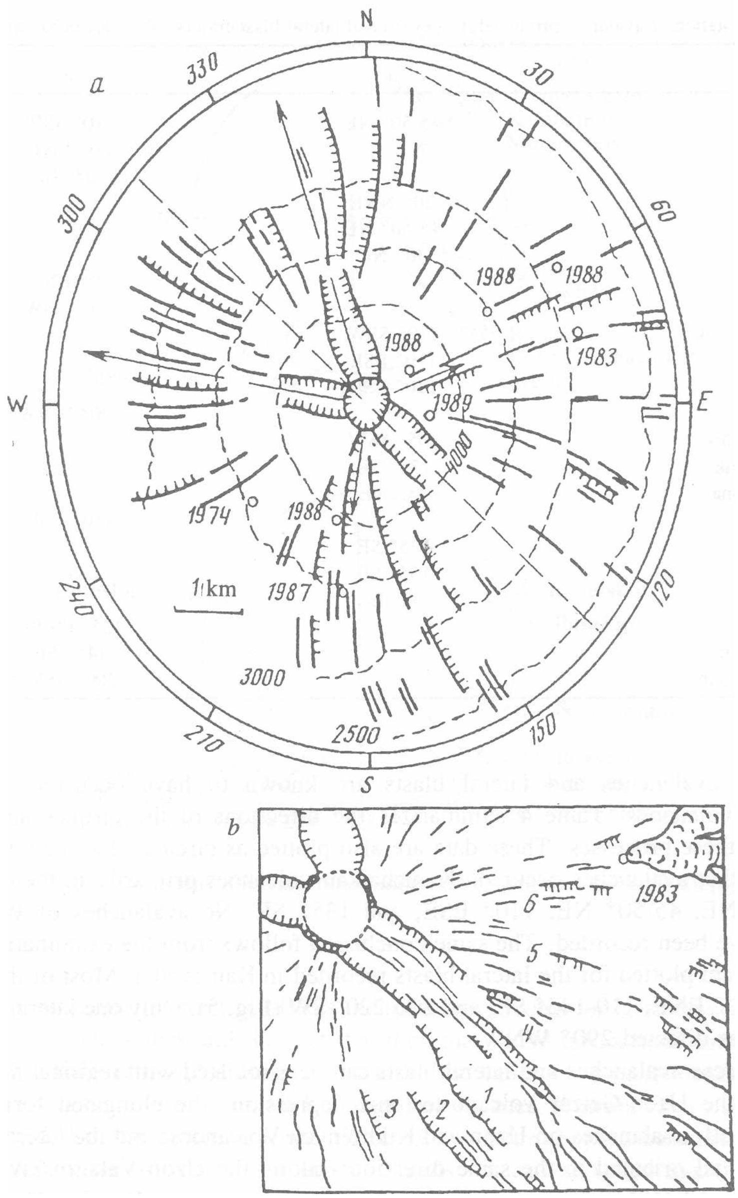

Figure *4 a* - Schematic map showing the cobweb pattern of arcuate fissures, normal faults, and flank eruptions of the Klyuchevskoi summit steep-sided portion (above 2500 m). The dashed line is the axis of the cobweb network, the arrows indicate the orientations of volcano-tectonic trenches and the directions to the concentrations of fissure eruptions, *b* - Interpretation of an air photograph of the SE foot of the volcano, taken on October 21, 1984. The figures indicate: 1, 2, 3 - SW walls 1, 2, and 3; 4, 5, 6 - NE walls 1, 2, and 3, respectively.

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Table 4 Orientation of avalanch-produced cirques (*a*) and lateral blast craters (*b*) on Kamchatkan volcanoes.

Volcano	*a*	*b*
Kambalnyi	45-50° NE	210° SSW
Iliinskiy	-	80° ENE
Zheltovskiy	-	135° SE
Khodutka	20° NNE	-
Mutnovskiy	45-50° NE	-
Vilyuchinskiy	30° NE	-
Kozelskiy	-	70° ENE
Avacha	-	220° SSW
Bolshoi Semyachik	210° SSW	-
Kikhpinych	110° ESE	-
Uzon	110° ESE	-
Taunshits	-	290° WNW
Ploskiy Tolbachik	205° SSW	-
Ostryi Tolbachik	135° SE	-
Ovalnaya Zimina	45° NE	-
Bezymyannyi	-	110° ESE
Kamen	135° SE	-
Sredniy	135° SE	-
Krestovskiy	90° E-	-
Zarechnyi	-	135° (?) SE
Staryi Shiveluch	-	145° SE
Molodoi Shiveluch	-	200° SSW

Rockslide avalanches and lateral blasts are known to have occurred on many Kamchatkan volcanoes. Table 4 summarizes the directions of the cirques and craters produced by these processes. These data are also plotted as circular diagrams in Fig. 5. One can see that avalanches occur on Kamchatkan volcanoes primarily in the directions of 20-30° NNE, 45-50° NE, 110° ESE, and 135° SE. No avalanches of W or NW directions have been recorded. The same conclusion follows from the examination of the circular diagram plotted for the lateral blasts recorded in Kamchatka. Most of them were directed 70-80° ENE, 110-145° SE, and 200-220° SW (Fig. 5). Only one lateral blast (on Taunshits) was directed 290° WNW.

In many areas avalanches and lateral blasts can be associated with regional faults. For example, in the Uzon-Geizer volcano-tectonic depression, the elongated form of the depression itself, avalanches on Uzon and Kikhpinych Volcanoes, and the lateral blast of Taunshits are all oriented in the same direction - along the Uzon-Valaginskiy Fault of 290° WNW trend [10]. The cinder cones and explosion crater of Iliinskiy Volcano are restricted to the large W-E oriented Ozemovskiy Fault [10]. The arrangement of the largest avalanches on Mutnovskiy Volcano is controlled by a wide linear fault zone of NE strike traversing the volcano [11]. These and other examples indicate that the faults that were responsible for the origin and eruptive activity of the volcanoes control the orientation of avalanches and lateral blasts that occur on their cones.

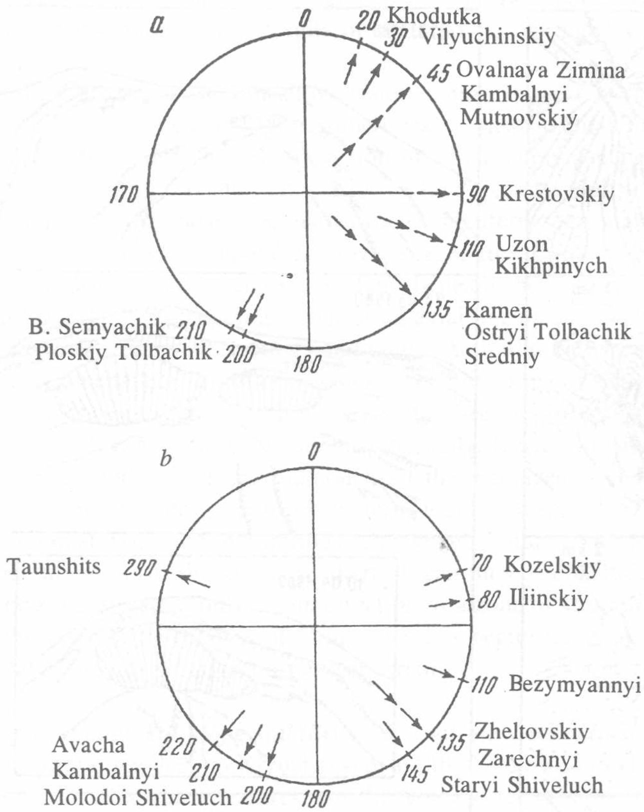
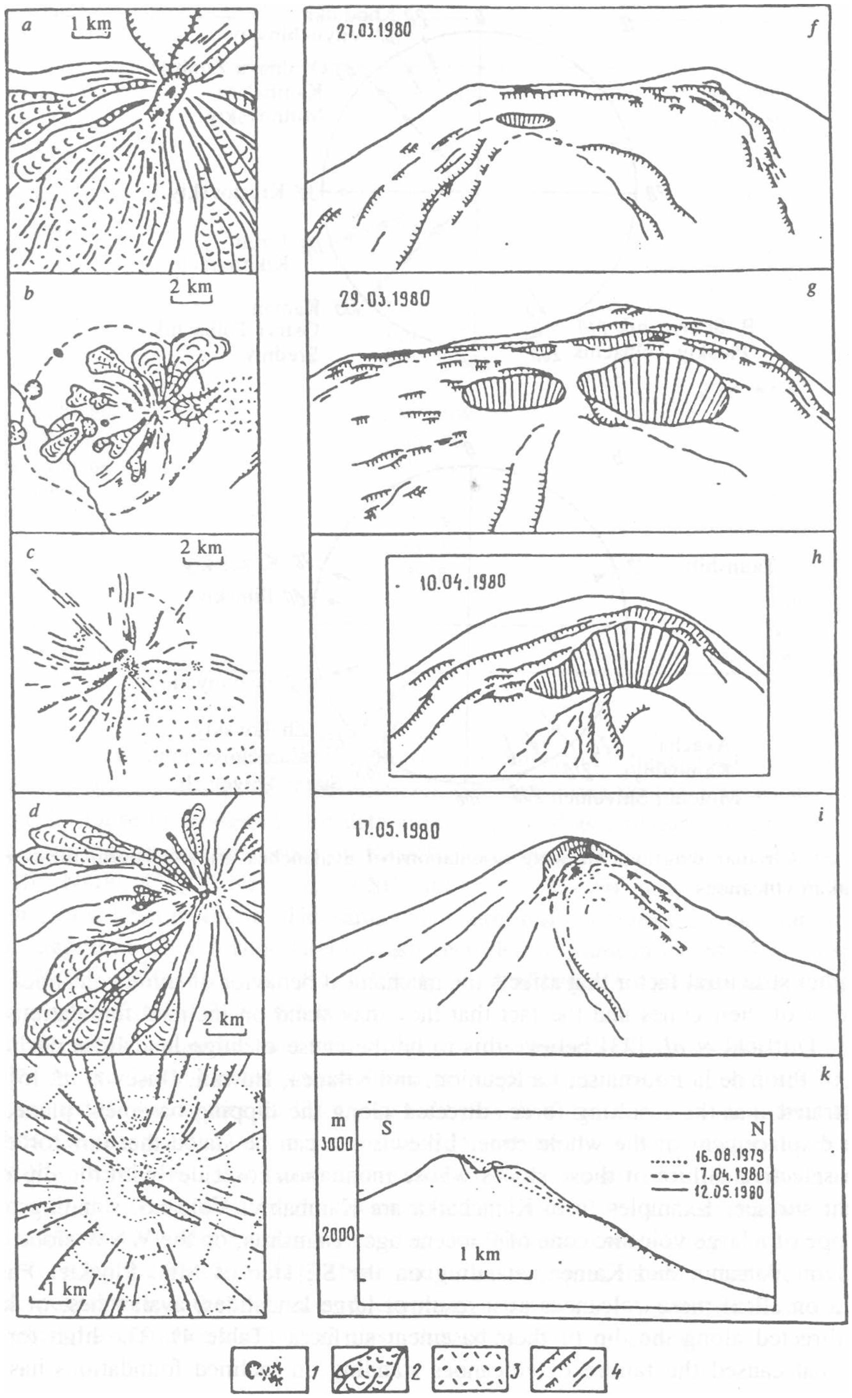


Figure 5 Circular diagrams showing orientations of avalanches (*a*) and lateral blasts (*b*) on Kamchatkan volcanoes.

Another structural factor that affects the mechanical behavior of some volcanoes is the asymmetry of their cones and the fact that they may stand on inclined foundations. For instance, Duffield *et al.* [23] believe this to be the cause of huge landslides during the growth of Piton de la Fournaise, La Reunion, and Kilauea, Hawaii. Gusev *et al.* [5] have demonstrated that the resulting force, directed along the dipping basement plane, may cause a displacement of the whole cone. Likewise, it can be stated that this force may cause a selective failure of those slopes whose inclination coincides with the dip of the basement surface. Examples from Kamchatka are Kambalnyi Volcano, standing on the SSW slope of a large volcanic cone of Pliocene age; Taunshits, on the WNW slope of the older Uzon volcano; and Kamen, standing on the SE side of Mts. Ploskie. Failures occurred on all of these volcanoes as a result of large landslides, avalanches, or lateral blasts, directed along the dip of their basement surfaces (Table 4). The high force of gravity that caused the failure of volcanoes standing on inclined foundations has been


a
1 km
b
2 km
c
2 km
d
2 km
e
1 km
27.03.1980
f
29.03.1980
g
10.04.1980
h
17.05.1980
i
k
m
S
N
3000
2000
16.08.1979
7.04.1980
12.05.1980
1 km
1
2
3
4

mentioned in many reviews on volcanology (R. W. Van Bemmelen, H. Williams, I. V. Luchitskiy, and many others). The results of our study is one more evidence in support of this conclusion.

The structural factors considered above (faults controlling the birth of volcanoes and the inclination of their basements) can sometimes be instrumental for the fairly exact location of a potential failure and the direction in which an avalanche or a lateral blast may take place. Also helpful is the examination of fractures and faults on the cone slopes.

As has been mentioned above, the main structural pattern determining the structure of the Klyuchevskoi cone is a broad zone of closely spaced lineaments of the NW trend. This zone obviously follows a large deep-seated fault beneath the volcano. The trend of this fault can be followed in the steep-sided cone as an axial line of a cobweb structural pattern formed by a network of arcuate fractures and faults. A similar pattern can be reconstructed on many of Kamchatkan volcanoes: Kambalnyi, Iliinskiy, Zheltovskiy, Koryakskiy, etc. (Fig. 6). Evidence of such structural patterns has been reported from other volcanoes of the world [22], [23], Mt. Saint Helens included [24]. During the period preceding the rockslide avalanche and catastrophic lateral blast that occurred on Mt. Saint Helens in 1980, many fractures forming a cobweb pattern were rejuvenated by vertical displacements (Fig. 6). On all volcanoes exhibiting such cobweb features their axes coincided with the axes of the lateral blasts that occurred there. It can thus be concluded that the cobweb pattern may be suggestive not only of the direction of a zone of structural weakness under the volcano but also of the process of failure that has begun (or is already operating) in its cone. This is likely to be an important precursor.

Evaluation of Klyuchevskoi slope stability. We will now see which of the surface and deep-seated structural features on Klyuchevskoi are likely to cause the failure of its slopes. The most pronounced surface features are the volcano-tectonic trenches: Krestovskiy, Kozyrevskiy, and Apakhonchich. They are believed to have been formed as a result of downward movement of large rock masses on slopes by the force of gravity, like the rockslide that occurred on December 2, 1985 (the volume of the debris deposited in the Krestovskiy trench has been estimated at 6 million m^3 [6]). Some investigators believe that the NW sector of the volcano, where the Krestovskiy and Kozyrevskiy trenches are situated, poses the greatest hazard of avalanches [12], [16]. Is it really so? Although a deep cleft of NW strike had existed on Mt. Saint Helens before the huge rockslide avalan-

Figure 6 Examples of cobweb structural patterns on some of Kamchatkan volcanoes: *a* - Kambalnyi, *b* - Iliinskiy, *c* - Zheltovskiy, *d* - Koryakskiy, *e* - Mt. Saint Helens; 1 - explosion craters and lava domes; 2 - lava flows; 3 - pyroclastic deposits of lateral blasts; 4 - faults and fissures; *e* to *k* are topographic elements that existed before the 1980 eruption of Mt. Saint Helens [24], The dashed lines show faults and fractures that developed from March 27 (onset of eruption) to May 18 (devastating lateral blast). The drawings were traced from photographs [24]. One can see how a system of fissures and faults on the N slope of Mt. Saint Helens was developing and becoming more and more complex before the rockslide avalanche and lateral blast. The N-S section across the northern slope of the volcano *(Ik)* shows changes in the topography that occurred during the same period of time.

che that triggered a devastating lateral blast in 1980, the landslide and the blast occurred at an angle of 45° to it [24], Another example is the Bezymyannyi Volcano, where a deep W-E oriented trough existed before the catastrophic eruption of 1956, whereas the lateral blast was directed SE at an angle of 20° to the trough [2], [3], These examples demonstrate that even though clefts, fissures, and trenches on volcanic slopes may be of large sizes, they are actually surface features. There may occur small rockslides and debris avalanches in them, but not catastrophic rockslide avalanches or lateral blasts. The location of the latter is controlled by deep magma channeling zones, whose orientation may be different from that of the surface features.

On Klyuchevskoi, such a deep-seated zone of structural weakness has a NW strike. Large NW-trending faults have been reported there by many investigators. For instance, Yarotskiy [21] examined geophysical data on the crustal structure of Kamchatka and located a number of crustal faults of the Aleutian (NW) trend, the largest of them being the Tigil-Klyuchevskoi Fault. Gusev *et al.* [4], [5] interpreted the photographs of space missions for Kamchatka and found a wide development of NW faults there, especially southeast and northwest of the Klyuchevskoi volcanic group. They classified them as crustal faults. Shantser [19] distinguished a broad zone of NW faults and named it Kronotsko-Tigilskiy. He believed its faults to be relicts of older (Mesozoic) faults which were rejuvenated periodically up to the Quaternary. The NW fault passing through Klyuchevskoi Volcano was reported by Balesta *et al.* [1]. It was interpreted as a normal fault with the downthrown NE side.

Our study of the network of lineaments revealed that the NW fault on which Klyuchevskoi is sitting was marked by a distinct zone of closely spaced lineaments. This is a broad zone of extension in the upper crust. Judging by the location of epicenters of earthquakes that preceded the fissure eruptions of the last years, movements along this fault continue, and presently this is the most active tectonic feature of the area.

Proceeding from the fact that Klyuchevskoi stands on the southeastern slope of a large shield volcano, Ushkovskiy (also known as Ploskiy) [17], [20], and from the main structural line trending to the northwest, potential failure may occur on the southeastern slope. This may be a deep sag, cauldron, or large landslide, similar to those that occurred on Mt. Etna, Piton de la Fournaise, or on the nearby Kamen volcano. A sag may occur in a slowly developed or a sudden manner. The onset of its formation may be manifested in the reactivation of the arcuate fissures and faults, as it happened before the avalanche on Mt. Saint Helens [24], Are there indications of such activity on Klyuchevskoi? All previous fissure eruptions (Predskazannyi, Predvidennyi, Skuridin, etc.) occurred on the fissures that had been interpreted as radial. At the same time, they are elements of an arcuate zone, symmetric about the NW structural line. This suggests that the fissure eruptions that occurred on the volcano in the 1980s indicate the beginning of the formation of an arcuate break-off zone along which a sag or an avalanche of the NE portion of the cone may take place. An example of such a sag is the Valle del Bove depression on Mt. Etna [25], Recent investigations [27] revealed that the location and orientation of historical eruptive fissures and feeder-dikes on Mt. Etna had been controlled by gravitational forces. The fact that dikes were injected along the edge of the Valle del Bove depression indicates that it continues to spread [28],

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The possibility of large landslides or avalanches, leading to the cone failure, on the NW slopes of Klyuchevskoi, suggested by Melekestsev and Braitseva [12] and Fedotov *et al.* [16], is hardly realistic. First, as I have mentioned above, the volcano stands on the inclined basement, which suggests a potential SE slope failure. Secondly, the analysis of rockslides and avalanches on many Kamchatkan volcanoes revealed that not a single large avalanche had occurred on their N, NW, or W slopes. Thirdly, as I have demonstrated above, surface features (and the trenches referred to in [12] and [16] are surface features) do not play a significant part in volcanic slope failure. This may happen only if a surface and a deep-seated structural feature have the same trend. Such a coincidence has been found in the Apakhonchich trench alone.

Conclusions. 1. The most frequent lineaments of the study area are restricted to linear and arcuate zones. The linear zones are interpreted as zones of tectonic fractures representing the existence of regional linear structural features (large faults, extension areas, buried grabens); the arcuate zone, as areas dominated by volcanic factors. The latter are superimposed on the linear features, inasking their effects. The sites where some linear zones are intersected by other zones can be used to determine the time of their last reactivation. The N and E trending features are the oldest. They are cut across by the NE trending features which are in turn intersected by the NW, youngest features.

2. The lineaments restricted to the arcuate zone are mostly radial fissures produced by the cracking of the cone. The regional linear features can be identified in the network of this zone where they coincide with the radial directions. The measurements of tectonic fractures carried out in this zone revealed a zone of NE fractures which have not been identified in the network of lineaments, whereas the tectonic fractures located outside of this zone coincide with the latter.

3. The distribution pattern of the volcanic lineaments at the foot and on the slopes of the volcano is generally consistent with the pattern of nonvolcanic lineaments: their directions correspond with the regional structural trend in the far-foot zones, and with the strike of the radial fissures, in the near-foot zones. Of particular importance is the structural zone of the upper steep-sided portion of the cone (above 2500 m), where volcanic lineaments and volcano-tectonic trenches produce a structural pattern, symmetrical about the NW-trending (310° NW) axial plane. The interpretation of air photographs revealed a cobweb pattern of arcuate and radial fractures and faults, indicative of the gravitational sagging and extension of the cone, oriented across the main NW structural line.

4. The location of the epicentral areas of the earthquakes that preceded the fissure eruptions of 1980, 1987, 1988, and 1989 shows that all of them were elongated in a NW direction. The sources of these earthquakes moved along the same direction. These data support the conclusion based on the network of lineaments that the NW zone passing through the volcano is the main structural zone of the area, and that it continues to be active in the present time.

5. The analysis of the structural positions of the avalanche- and explosion-produced cirques known on Kamchatkan volcanoes revealed that most of them were oriented to the east; none of them was directed W or NW. The main factors that are likely to control the

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direction of large rockslides, avalanches, and lateral blasts are the regional faults and the asymmetry of the volcanic cones standing on the inclined basements.

6. More exact forecasts of potential slope failure require a distinction between surface and deep-seated structural features. The former show a more distinct topographic expression but do not cause or determine the character of catastrophic events on volcanoes (large rockslide avalanches and lateral blasts). Such events are controlled by deep-seated structural features that may be manifested on the surface as systems of arcuate fractures and normal faults of a cobweb pattern.

7. The mechanical behavior of Klyuchevskoi Volcano is controlled by its location on the SE slope of the old large Ushkovskiy (Ploskiy) volcano and on the regional NW fault that has been recently reactivated repeatedly. Potential failure is likely to occur as a deep sag or an avalanche in the SE sector of the cone, where a network of arcuate fissures and normal faults has recently begun to form as indicated by the fissure eruptions of the last ten years.

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