On the Focal Layer, Seismicity and Volcanicity of the Kurile-Kamchatka Zone *

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Abstract

The general relationships of the structure of the Kurile-Kamchatka zone are examined. The chain of volcanoes forms a true arc with the radius of 1884 km. The focal layer of earthquakes along the whole arc extends to depth with an angle of $48^{\circ} \pm 5^{\circ}$, and is a part of the surface of a circular cone. The energy of earthquakes at intervals of depth 0-100 km, 101-300 km, and 301-650 km is on the average distributed equally along the whole arc and in time. The activity of volcanoes of the whole zone in time is also rather evenly distributed. The energy lost from the earth's interior during the volcanic eruptions is not less than the energy emitted as elastic waves during tectonic earthquakes.

Introduction

The focal layer, seismicity and volcanicity of the Kurile-Kamchatka zone have been studied by many investigators. But in most of the studies the main attention was given to some specific aspects of this problem. In this paper, the author tries to show the more general phenomena of the Kurile-Kamchatka geostructural arc with regard to the distribution of seismicity and volcanicity in time and space.

All the tectonic earthquakes with a focal depth more than 70 km (1118 earthquakes) and the strongest earthquakes ($M \geq 6{,}5$) with focal

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depth $H \leq 70$ km (124 earthquakes) for the period 1911-1966 were used in this paper (1).

The energetic class scale K ($K = \lg E_{erg} - 7$, where E = earthquake energy) and magnitude scale M were used for the energy characteristics of earthquakes. The relationship $\lg E = 11.8 + 1.5\,M$ was used for the inversion from M to K, from which it follows that $K = 4.4 + 1.5\,M$.

As most of the energy escapes during strong earthquakes, strong earthquakes for the period 1911-1966 were registered without omission, and earthquake energy was used for the determination of a seismicity zone characteristic.

The Form of the Kurile-Kamchatka Geostructural Arc

The main elements of the Kurile-Kamchatka geostructural arc clearly marked at the earth's surface, are the topography of the surface and of the Pacific ocean floor, and the location of the active volcanoes. For the calculation of the arc form it is necessary to use the formula of spherical trigonometry, which determines the relationship of the distance between two points M_i and M_j at the earth's surface from the coordinates of these points φ_i, λ_i, φ_j and λ_j. $\cos \Delta_{ij} = \cos \theta_i \cdot \cos \theta_j + \sin \theta_i \cdot \sin \theta_j \cdot \cos (\lambda_i - \lambda_j)$ where $\theta = 90^\circ - \varphi$.

The active volcanoes were used for the calculation of the volcanic arc form. The determination errors of volcano coordinates do not exceed 1′. Seventy-one volcanoes were used in the calculation: 5 in Hokkaido Is., 39 in the Kurile Islands and 27 in Kamchatka. For the calculation of the arc form of the deep-sea trench, the points of the most deep places of the trench were used, taken according to the charts. The determination error of the coordinates of the most deep places of the trench is equal to 6′. For the calculation 42 points of the deep sea trench were chosen which are distributed more or less uniformly along the arc.

As the volcanoes and the points of the greatest depths along the arc are not distributed uniformly, then weighting equal to $W_i = \frac{l_i}{100}$

(1) The data about these earthquakes are published in *Earthquake Atlas of the USSR*, *Bulletin of seismic stations in the USSR* for 1957-1961, and in the publication *Earthquakes in the USSR* for the period 1962-1966.

Data about volcanoes and their eruptions were taken from the *Catologue of active volcanoes of the world* (parts 7, 8 and 11) and later publications.

km was added to each point in order to reduce the errors, where l_i is the half distance between projection of the points $i - 1$ and $i + 1$ on the arc axis, expressed in km.

The calculation of arc centers and radii was done by the least-squares method. The volcanic arc has the radius $16° 57' \pm 1'$ or 1884 km $\pm$ 2 km with the center in the point: $\varphi = 58° 01' \pm 1'$ North latitude; $\lambda = 129° 52' \pm 1'$ East longitude. The standard deviation of the volcanoes from the arc is equal to $12' 0$ or 22.2 km. The arc center of the deep-sea trench is at the point: $\varphi = 58° 06' \pm 3'$ N, $\lambda = 127° 23' \pm 6'$ E, and its radius is equal to $20° 04' \pm 3'$ or 2233 km $\pm$ 6 km. The standard deviation of the points from the arc is $7' 1$ or 13.3 km. The center of the deep-sea trench is shifted 147 km to the west relative to the center of the volcanic arc. The distance between the two arcs gradually changes from 200-205 km in the Kamchatka region to 250 km in Hokkaido region.

Thus the axes of the volcanic arc and deep-sea trench are well approximated by the parts of the circular arc. Volcanoes are situated within a narrow linear zone along the volcanic arc. 75 % of the volcanoes are in a zone 45 km wide ($\pm$ 22,5 km). From the considered points of the greatest depths of the Kurile-Kamchatka deep-sea trench, 93 % of the points are in a zone 45 km wide ($\pm$ 22,5 km) along the axis of the deep-sea trench. Variations of the volcanic chain in some places from the regular arc (Fig. 1) have an irregular character and may be a result of some non-uniformities in the arc structure. The length of the volcanic arc from Sheveluch volcano in the North to the intersection with Japanese volcanic arc in the South (Usu volcano) is 2300 km.

Since the Kurile-Kamchatka geostructural arc has a regular form, the zone was divided into 6 belts concentric to the volcanic arc, and into 30 sectors for studying the arc seismicity (Fig. 1). Width of each belt on the earth's surface is equal to 100 km. The zone was divided into belts in the following way: the second belt coincides with the intersection of the focal layer with the earth surface. All the sectors are of the same dimension. Each of them occupies a length of the volcanic arc equal to 90 km. The position and dimension of the sectors are chosen so that such structural elements of Kamchatka as Kamchatsky and Kronotsky peninsulas and Kamchatsky and Kronotsky bays are included in the same sector. It is necessary to note that the above mentioned division of the zone into belts and sectors differs from previous divisions (TOKAREV, 1958).

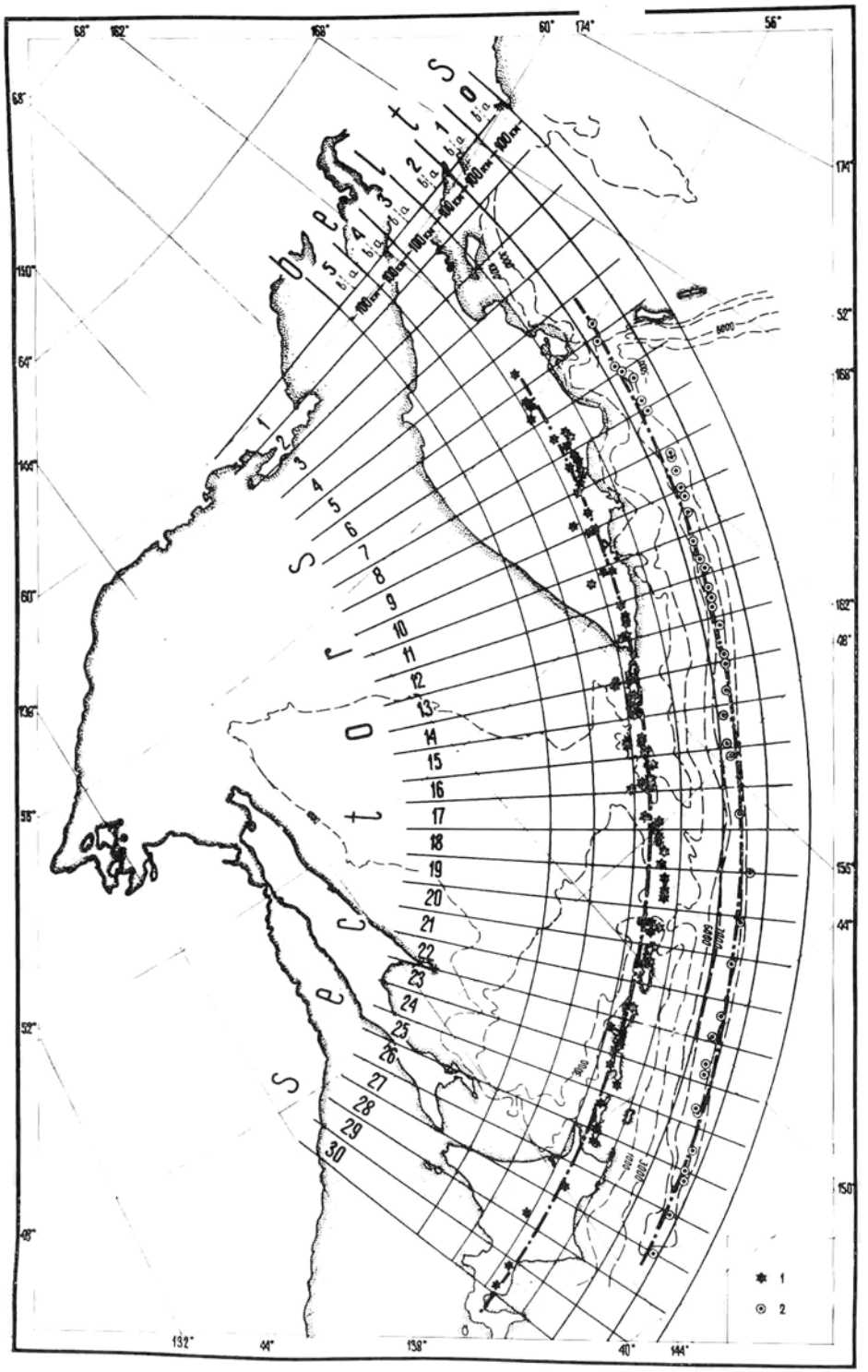

FIG. 1 - Chart of the division of the Kurile-Kamchatka zone into belts and sectors: 1) active volcanoes; 2) points of maximum depths of the trench.

Distribution of Seismic Foci and Energy by Depth and Form of the Focal Layer

All the available data about the earthquakes for the period 1911-1966 were used in order to get a detailed view about earthquake foci distribution by depth.

Deep-seated sections of the earthquake foci in the whole zone for 1911-1966 and in the Kamchatka region (5-14 sectors) for 1962-1967 according to the results of detailed seismic obsevations are shown in Fig. 2. The sections are projection of the earthquake foci on a vertical plane passing through the center of the volcanic arc. The sections of the earth's crust and relief of the earth surface are also given ([2]).

Inclination angle of the focal layer in sectors 6-21 is equal to 50° and in sectors 22-30 it gradually decreases from 50° to 38°. Average value of inclination angle of the focal layer for the whole zone is equal to 48° $\pm$ 5°. Considering the deep-seated foci in some separate sectors it is difficult to establish a continuos fracture of the focal layer. Therefore it is possible to think in the first approximation that the focal layer goes deeply down under continent without a continuous fracture. The whole zone is divided into 6 belts (Fig. 1). Every belt is a layer 74 km in thickness, going deeply down beneath the continent at an angle of 48° (Fig. 2). The surface, coming through the middle of the second belt and dipping down at the angle 48°, is the focal surface. It crosses the earth's surface at a distance 125 km from the volcanic arc and forms an arc with radius 2010 km, concentric to the volcanic arc. Proceeding from this arc radius and inclination of the focal layer it is easy to show that the focal surface is part of the surface of a right circular cone, the symmetry axis of which goes through the center of the Earth and the pole of the volcanic arc, and the apex is at a depth of 1560 km from the earth's surface. The angle between the axis and generating line is equal to 60°.

Fig. 3*f* shows the projection of earthquake foci on a vertical surface, running along the volcanic arc, and Fig. 3*g* shows a projection of earthquake foci on the focal surface, unfolded to a plane. In the both figures a lower boundary is marked by dotted lines. From the sections of Fig. 3*f* and 3*g* it follows that the most deep earthquakes

([2]) Data taken from a collective monograph « *Earth crust structure in the transition region from the Asian continent to the Pacific ocean* » (edition « Nauka », 1964).

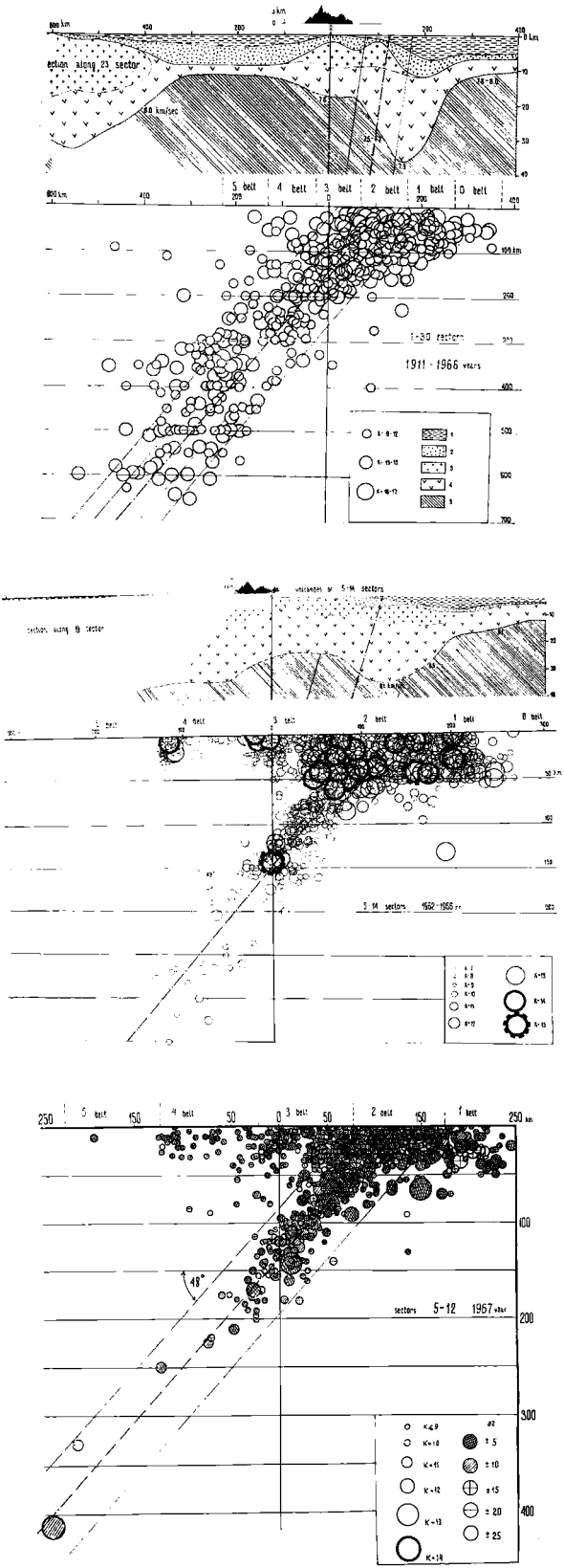

FIG. 2 - Vertical sections of the earth's crust and earthquake foci for 1911-1967. 1) water; 2) sedimentary layer; 3) « granitic » layer; 4) « basaltic » layer; 5) upper mantle.

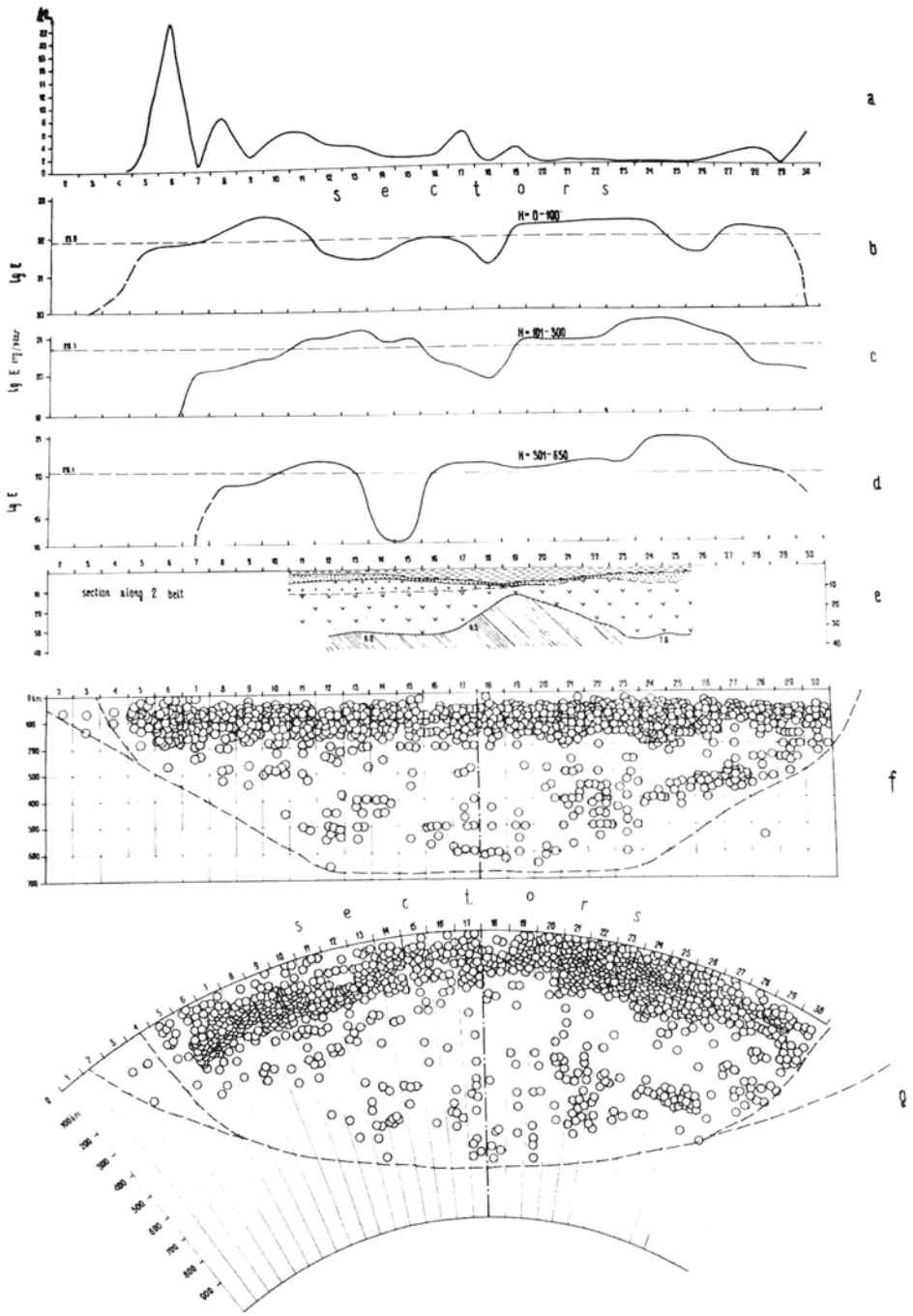

FIG. 3 - Distribution along the arc: *a*) number of eruptions for 1901-1967; *b, c, d*) earthquake energy for 1911-1966; *e*) vertical sections of the earth crust; *f*) vertical sections of the earthquake foci; *g*) projection of earthquake foci on the focal surface, unfolded to a plane. Section « *e* » has the same legend as Fig. 2.

take place in sectors 12-23, and depth of foci gradually decreases to the ends of the arc. In the sections of Fig. 3 of the focal layer there are only relatively small parts which are not covered by foci and this indicates that the whole focal layer is seismic. The lower boundary of the focal layer is symmetric with respect to the axis line, between the boundary of sectors 17 and 18. The axis of symmetry comes to the thin place of the earth's crust in the middle part of the Kurile region (Fig. 3*e*).

Distribution charts of average-annual earthquake energy of the zone for 1911-1966 according to sectors for depth 0-100 km, 101-300 km and 301-650 km are shown in Fig. 3*b*, 3*c* and 3*d*. As the foci of strong earthquakes are situated along the arc and have lengths of

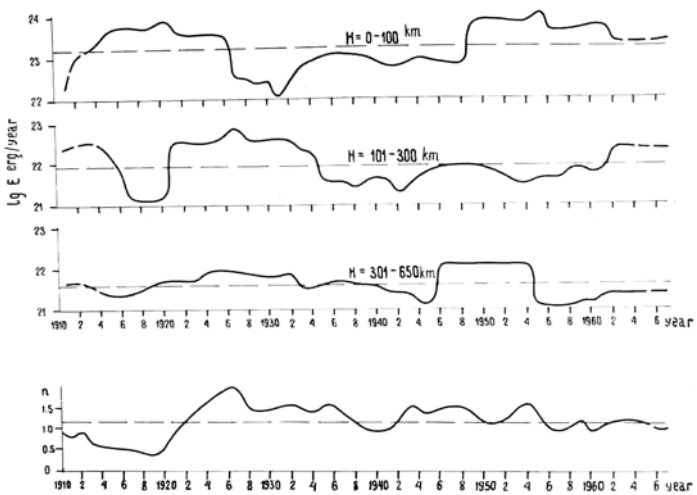

FIG. 4 - Distribution in time of earthquake energy of the Kurile-Kamchatka zone for 1911-1966 (E) and of volcanic activity (n) for 1901-1967.
n - weighted number of eruptions.

about 300 km, and sector width of about 100 km, the data were smoothed with average value of 3 sectors. The average value lg E erg/year in sectors 5-29 at the depth 0-100 km is equal to $21.9 \pm 0{,}5$; in sectors 7-29 at the depth 101-300 km $- 20.7 \pm 0.5$; in sectors 8-29 at the depth 301-650 km $- 20.1 \pm 0.8$. With an increase in the time interval of observations the graphs are more and more smoothed. From the graphs of Fig. 3 it follows that the energy of the earthquakes is distributed rather uniformly along the arc. Some decrease in

average annual energy in the middle part of the arc at the depth 0-300 km and a considerable decrease in sectors 14-15 at the depth 301-650 km are possibly caused by the short time interval of observations (56 years).

Fig. 4 shows the graphs of earthquake energy distribution of the whole zone in time for depths 0-100 km, 101-300 km and 301-650 km. The graphs are smoothed with average values of 7 year time intervals. It follows from the graphs that earthquake energy of the whole zone at each depth interval escapes rather uniformly in time. Energy deviations from average value are small and have transient features. Emission of seismic energy at different intervals of depths for the period 1911-1966 can be expressed by the equation $E = at \pm b$, where time is expressed in years. For the depth 0-100 km, $E = 2.8 \cdot 10^{23} t \pm 1.3 \cdot 10^{23}$ erg; for the depth 101-300 km, $E = 1.8 \cdot 10^{22} t \pm 1.5 \cdot 10^{22}$ erg; and for the depth 301-650 km $E = 4.9 \cdot 10^{21} t \pm 3.7 \cdot 10^{21}$ erg. Decrease in energy below the value $E = at - b$ will indicate the possibility of a strong earthquake forthcoming.

Energy distribution and distribution of average rate of seismic energy emission ϱ (1) according to depth with 100 km interval in different belts are shown in Table 1 (2). It follows that 1) the main part of the seismic energy (more than 92 %) escapes at the depth 0-100 km; 2) rate of seismic energy emission at the depth 200-600 km is 2 orders lower than at the depth 0-100 km; 3) the predominant number of earthquakes is in a comparatively thin focal layer of the second belt, and in this layer 74 km thick, 2/3 of the seismic energy of the whole zone escapes, and 93 % of the whole zone energy escapes in the layer 150 km thick (belts Ib, 2 and 3a). It is necessary to take into consideration a great scattering caused by large mistakes in the coordinate determination of earthquake foci from 1911 to 1950. In the Kamchatka region for the period 1961-1967 the focal layer is considerably thinner (Fig. 2).

The analysis of earthquake foci distribution and earthquake energy allow us to draw the conclusion that seismicity of the Kurile-Kamchatka zone is related to the relative movements of continental and oceanic blocks of the earth's crust and upper mantle. Superficial earthquakes $H \leq 50$ km of the inner parts of the arc (Sredinny ridge

(1) ϱ is a ratio of average-annual energy for 1911-1966 to volume of focal region where it escaped.

(2) In the calculation, the 1st and the 3rd belts were in addition divided into two equal parts each marked as Ia, Ib, 3a and 3b (Fig. 1).

TABLE 1 - Distribution of average annual energy E and average rate of energy emission ρ in Kurile-Kamchatka zone for the period 1911-1966. Earthquake energy E is expressed in units 10^{20} erg/year and ρ in erg/cm^3 year.

Depth interval km	Measuring value	Belts and their thickness							The whole zone
		0	1a	1b	2	3a	3b	4	
		74 km	37 km	37 km	74 km	37 km	37 km	74 km	
0-100	E	36	124	680	1910	23	29	1.8	2804
	%	1.2	4.1	22.40	62.9	0.8	1.0	0.06	92.5
	ρ	0.12	0.89	5.1	7.3	0.18	0.24	0.08	—
101-200	E	0.4	21	21	111	20	0.2	—	173,6
	%	0.01	0.7	0.7	3.7	0.7	0.01	—	5.8
	ρ	0.001	0.14	0.15	0.42	0.16	0.001	—	—
201-300	E	—	—	2	3.8	3.8	0.64	—	9.6
	%	—	—	0.07	0.13	0.13	0.001	—	0.3
	ρ	—	—	0.016	0.016	0.033	0.003	—	—
301-400	E	—	—	1.8	19	5.8	1.8	—	28.4
	%	—	—	0.06	0.6	0.2	0.06	—	1.0
	ρ	—	—	0.017	0.091	0.042	0.018	—	—
401-500	E	—	—	2.4	2	0.2	0.2	—	4.8
	%	—	—	0.08	0.07	0.01	0.01	—	0.2
	ρ	—	—	0.031	0.031	0.003	0.003	—	—
501-600	E	—	0.2	3.8	5.6	3.8	—	1.8	15
	%	—	0.01	0.13	0.2	0.13	—	0.06	0.5
	ρ	—	0.003	0.054	0.043	0.054	—	—	—
601-650	E	—	—	0.06	—	—	—	—	0.06
	%	—	—	0.002	—	—	—	—	0.002
0-650	E	36	145	711	2051	57	31	4.1	3035
	%	1.2	4.8	23.4	67.5	1.9	1.0	0.1	100
101-650	E	0.4	21.2	31	141.4	33.6	2.2	1.8	231
	%	0.01	0.71	1.04	4.7	1.17	0.08	0.06	7.7

of Kamchatka and central part of Okhotsk sea) are apparently connected with tectonic movements of the earth crust in these regions and with orogenic processes. The share in earthquake energy of the zone is negligible. Volcanic earthquake energy of the zone is also negligible and amounts to an average value about 10^{19} erg/year, *i.e.* about 0,01 % of tectonic earthquake energy.

In Fig. 2 one can see rather well that the areas adjacent to the focal layer in oceanic and continental blocks at the depth more 50 km is negligibly seismic. This condition would be the natural result of relative displacement of blocks along the focal surface. But many investigators explain the region of weak seismicity in the space between the earth's crust and the focal layer in the continental block by an assumption about reduction of material viscosity in this place or about existence of liquid magma chambers. To my mind there are no grounds for such assumptions.

Distribution of Volcanic Activity along the Arc and in Time

Energy measurement of volcanic eruptions have been made only recently. That is why a number of eruptions from 1901 to 1966 are estimated from their characteristic activity. As the force of eruptions greatly changes, a different weight was given to each eruption. Weight equal to 1 was given to great eruptions with material outburst more than 10^8 m^3; weight equal to 0.3 was given to average eruptions, and weight equal to 0.1 was given to weak eruptions.

Fig. 3*a* shows the irregular distribution of volcanic activity along the arc. In Kamchatka it is considerably higher than in the Kurile Islands and in Hokkaido Island. Maximum activity is in sector 6, where the Kliuchevskaya group of volcanoes (Kliuchevsky, Bezymyanny and Plosky Tolbachick) is situated; 1/3 of all the eruptions of the Kurile-Kamchatka arc are related to this group. Activity of the middle part of the Kurile Islands is slightly higher than the average level of the arc activity.

Distribution in time of volcanic activity of the whole Kurile-Kamchatka zone is shown in Fig. 4 (n is the weighted number of eruptions). The graph is smoothed with average values of 7-year interval. It is seen from the graph that volcanic activity takes place fairly uniformly in time ($n = 1.2 \pm 0.4$ eruptions/year).

For the period 1901-1967, 211 eruptions of different force took place in the whole zone (3.1 ± 2.1 eruptions/year according to unsmoothed data) or 77 weighted eruptions (1.2 ± 1.0 eruptions/year according to the unsmoothed data). The average rate of material emitted to the earth's surface along the whole zone is equal to $3 \cdot 10^8 \pm 1 \cdot 10^8$ ton/year. The mean thermal energy, lost from the interior part of the earth during eruptions is about $4 \cdot 10^{24}$ erg/year. The thermal energy of volcanic eruptions in the Kurile-Kamchatka zone is 13 times more than the seismic energy. Even taking into consideration the possible errors in determination of absolute values of earthquake energy, it is possible to say that energy losses from the Kurile-Kamchatka zone in volcanic eruptions is not less than energy losses from earthquakes.

Formerly the author (TOKAREV, 1959) considered the problem of correlation in time of volcanic and seismic activity in the Kurile-Kamchatka zone. It was determined that the correlation coefficient in time of volcanic eruptions with earthquake energy for the depth 0-70 km is equal to 0; for the depth 71-300 km : $r = 0.55$ and for the depth 301-650 km : $r = 0.24$. But a more careful analysis of the data for the period 1911-1966 shows that the correlation coefficients greatly depend on the smoothing interval and time interval for which the calculation is made. Positive correlation coefficients for the depth 101-650 km ($r = 0.31$ for $H = 0$-100 km; $r = 0.38$ for $H = 101$-300 km and $r = 0.48$ for $H = 301$-650 km) were obtained. However, note should be taken that the calculation was made for the whole zone, whereas maximum activity of volcanoes is at the northern end of the geostructural arc, where seismic activity at these depths is weak. An attempt to make a correlation analysis for some sectors did not succeed as there were too few data about eruptions and earthquakes for each sector. However, it was noticed that at the time of the gigantic eruption of Sheveluch volcano in 1964 a sharp increase in seismic activity at the 80-200 km depth was observed in the area of the northern group of Kamchatka volcanoes (TOKAREV, 1967).

Conclusion

Seismic activity of the Kurile-Kamchatka zone is connected with relative movement of continental and oceanic blocks of the earth's crust and upper mantle. The boundary of the opposite-directed move-

ment of the blocks is along the focal surface. The focal layer is in an especially stressed condition, where great shifts are taking place; the thickness of the focal layer is about 150 km (± 75 km from the focal surface). The movement takes place rather uniformly in time at each depth interval along the whole focal layer. The share of tectonic earthquakes whose foci are in the earth's crust outside the limits of the focal layer, and the share of volcanic earthquakes to the total energy of earthquakes of the zone is negligible.

The focal layer of earthquakes indicates a gigantic fracture, the length of which on the earth's surface is about 2500 km. It goes down to a depth of 650 km, *i.e.* at the depth more than 0.1 of the earth radius. Area of the focal surface is equal to $1.5 \cdot 10^6$ km^2, and volume of the focal layer at 150 km thickness is equal to $2.2 \cdot 10^8$ km^3. This fracture can be called global. It divides oceanic and continental blocks of the earth's crust and upper mantle. Apparently the greatest depth of the focal layer (650 km) can be taken as a measure of the thickness of the blocks. The earth's crust, accounting for less 5 % of this block thickness is a structure of the second order and it cannot considerably affect the distribution of seismic activity along the focal layer.

Structure differences between continental and oceanic blocks of the earth's crust are well known. The earth's crust in oceanic areas is thinner, containing no granitic layer.

At the base of the earth's crust in oceanic areas the velocity of seismic waves is more than under the crust of the continental block (FEDOTOV and SLAVINA, 1968). According to magnetometric and gravimetric data the difference in blocks is traced to a depth up to 125 km (GAINANOV, 1964; TUEZOV *et al.*, 1967; GORSHKOV, 1967). There is no doubt, that differences in physical condition and perhaps in chemical composition of blocks exist at greater depths.

The focal layer intersects the earth's surface at 125 km distance from the volcanic arc, and it shows a connection of volcanicity with the focal layer. However, there are no grounds to confirm that volcanicity is directly connected with the focal layer. Perharps movement along the focal layer forms structures which generate volcanicity.

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