Volc. Seis., 2000, Vol. 22, pp. 161-178
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Holocene Faults (Inferred Paleoseismic Dislocations) and the Assessment of Earthquake Hazard for the Koryak Autonomous District, Northeast Russia

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(Received November 19, 1997)

Areal interpretation of air photographs was carried out for the Koryak Autonomous District (KAD) which includes the northern part of Kamchatka and the southern Koryak Highlands (ca. 240 000 km^2) to locate young (Holocene) faults, fissures, and their combinations as hypothetical paleoseismic scarps (or traces of old large ($M > 6.5$) earthquakes). In all, 410 features were located, their abundance and density were mapped, and the variability of their strikes was analyzed. Also located were hypothetical seismogravitational features, such as landslides, rockfalls, and soil liquefaction sites. This paper is concerned with the problems related to earthquake hazard assessment for the region of study and with the location of areas differing in structure and in the number and dominant trends of paleoseismic ruptures. It is shown that the distribution of the latter is generally consistent with the disposition of major structural zones in the area.

INTRODUCTION

The territory of the Koryak Autonomous District embraces the northern part of the Kamchatka Peninsula and the southern part of the Koryak Highlands (Fig. 1). Based on the poor seismicity recorded there during a period of instrumental measurements, until recently this territory was classified as an area of M = 5-6 shaking [28], [29]. However an earthquake of M = 7, known as the Khailinskii event, occurred there in March 1991 with shaking in the epicentral area amounting to M = 8 [12], [16]. This stimulated efforts

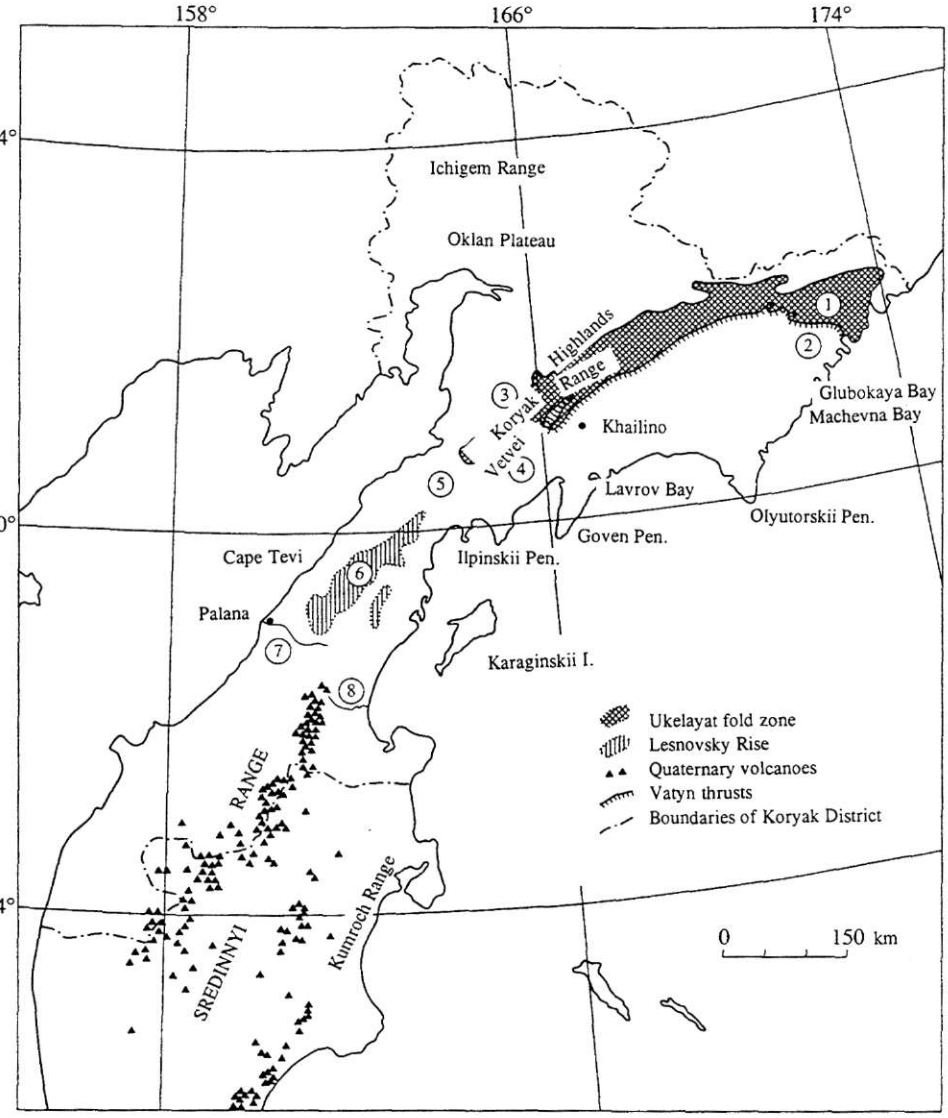

Figure 1 Location map of the Koryak Autonomous District and its structural and orographic features. Numbers in circles: *1-3* - Ukelayat, Snegovoi, and Unnei-Tunup ranges, respectively; *4* - Khetapkhaen Mountains; 5 - Kamchatka Isthmus; *6* - Lesnovsky Rise; 7 - Palana River; *8* - Khailyulya River.

for refining a map of seismic zonation for the area of the Koryak Autonomous District. This work was done in 1992-1995 [4], [5], [6], [9]. Because of the small number of recorded earthquakes, great hopes were pinned on the method of paleoseismology, that is, on the estimation of the parameters of large earthquakes of the past using the traces left by these events in the form of seismic scarps [31], [32]. Some foreign seismologists use the terms "seismic scars" [21] or "seismites" [43] for these traces. Recently the term "seismodislocation" was used meaning a common rupture of tectonic origin expressed in the topography as linear forms such as scarps, systems of narrow long sinks, and the like [26], [36].

According to A. A. Nikonov [27], the practical use of the paleoseismological method is often confronted with serious restraints and difficulties: it is impossible to locate and estimate the parameters of earthquakes with $M < 6$-6.5; not all large earthquakes ($M > 6.5$) produce dislocations on the ground surface, and part of them might have been obliterated; as a rule, the focal depths of crustal earthquakes cannot be determined, and intermediate- and deep-focus earthquakes elude locating. T. Matsuda [21] noted that in Japan ruptures emerged at the ground surface only in ca. 40 % of large earthquakes ($M > 6.5$), and the remaining 60% of events did not produce any traces on the surface. Nevertheless, taking merely shallow-focus seismicity in Japan, K. Mogi [24] proved that faults and rock deformations associated with earthquakes had been produced by all large events. He concluded that the distribution of active faults provided an important reference material demonstrating the zones of seismic movements in the Earth's crust. Moreover, S. G. Wesnousky *et al.* [44] demonstrated that generally the level of intraplate seismicity in Japan showed a positive correlation with the concentration of Quaternary faults. They proved that data on the focal mechanisms of earthquakes were consistent with the character of displacements on the surface ruptures that had been produced by large intraplate earthquakes, and also that the total displacement documented by Quaternary faults was the ultimate effect of many events that had occurred on these faults in Quaternary time. An example supporting this view are the events that were observed in 1996 in the area of Karymsky Volcano in Kamchatka. After a series of large earthquakes ($M = 6.1$-6.9) that occurred there on January 1-2, 1996, several detachment faults arose on the surface in a N-S zone 2.5-3 km long, which suggested the reactivation of some segment of an old N-S fault [17].

Based on the above evidence a decision was made to carry out the areal interpretation of air photographs available for the whole territory of the Koryak Autonomous District for locating inferred seismogenic structures (traces of past earthquakes), analyzing their distribution, and estimating on this basis seismic hazard for the given territory. The main attention was given (1) to locating recent faults and fissures (inferred seismotectonic dislocations) and (2) to locating large landslides, collapses, debris avalanches, and the like (inferred seimogravitational dislocations).

METHODS OF STUDY

The main method of study was a method of structural airphoto deciphering [33]. We dealt mainly with air photographs of scales ranging between 1:30 000 and 1:65 000. The located faults had lengths ranging between 1-2 and 10-20 km. To avoid possible interpretation errors, a few of the same segments were interpreted by different workers. This test showed that the inferred seismogravitational dislocations (landslides, collapses, debris avalanches, and the like) had been interpreted identically. Significant disagreements were found to be associated with different datings of the faults. In this context we carried out a special study to compare the deciphering patterns of recent faults, to group them by ages, and to assess the possibility of interpreting them as paleoseismic dislocations. The main bases for this work were relations among different groups of faults, their relations with moraine deposits produced during the second phase of the Late Pleistocene glaciation, and relations between the faults and dated volcanic formations (in areas of recent volcanism). This study showed that the Holocene faults, a few meters wide and 3-4 km long, looked in the airphotographs as thin, threadlike lines. They were easily identifiable; the main difficulty was to classify them as single-event features or as features produced by several displacements. In some cases several displacements were discovered through the location of uncontemporaneous landslides, collapses, or areas of soil liquefaction, adjacent to the faults. In most cases the located faults were interpreted as single-event features formed as a result of one large earthquake.

The results of this work were plotted on topographic maps of scale 1:100 000 which was sufficient to show the structural details of fault zones or of landslide and avalanche bodies, measure their characteristics and estimate their areas and potential volumes. The next step was to transfer these data onto topographic maps of scale 1:1 000 000. Details were certainly lost, but we were able to show the areal distribution of various formations. The third step was to plot maps of the density of dislocation distribution. We used a square with a side of 10 km as an area unit.

RESULTS

This work was done for an area of ca. 240 000 km^2, from 62°20' in the north to 55°00' in the south. Our group of the inferred seismotectonic dislocations included 410 separate faults (or their isolated groups) (Fig. 2). All of them were dated Holocene. Each dislocation was given its own number, its coordinates and brief characteristics being given in a catalog (Table 1). Below we will discuss some of their examples.

Figure 3, *a* shows an inferred paleoseismic dislocation mapped in the area of the Kamchatka Isthmus. It consists of several parallel faults, presumably of Early Holocene

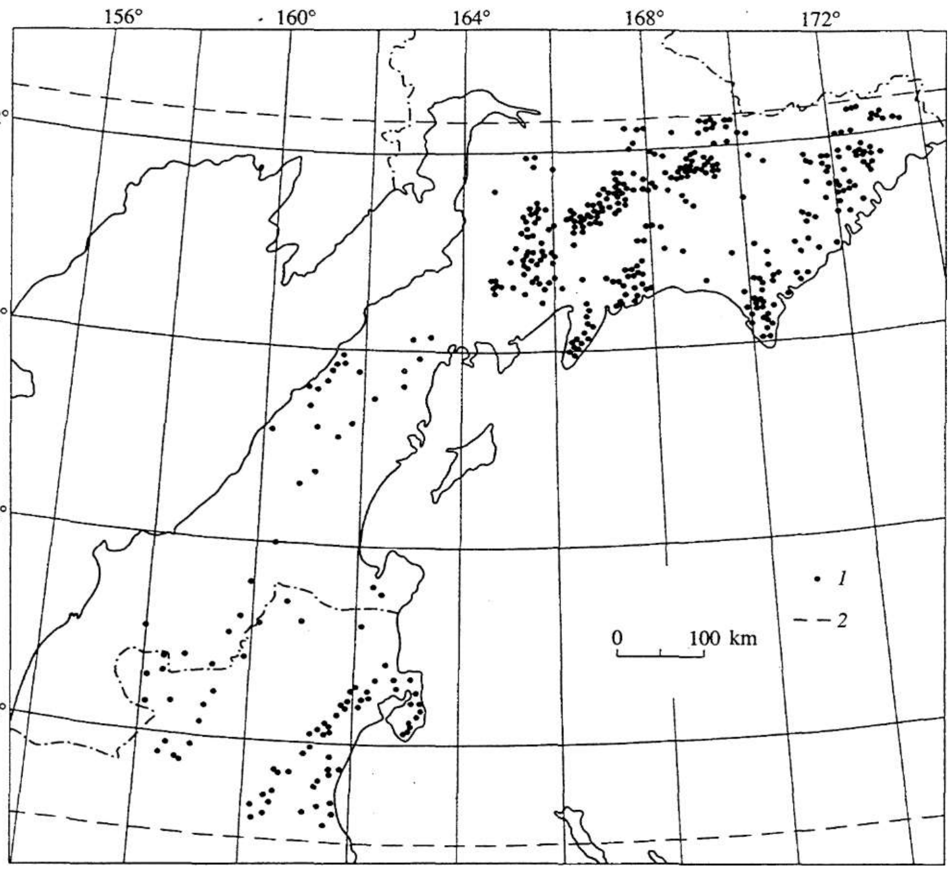

Figure 2 Map of Holocene faults and fissures (inferred paleoseismic dislocations) located as a result of interpreting air photographs for the Koryak District and the adjacent areas of Kamchatka (from 62°20' in the north to 55°00' in the south): 1 - fault shown as a dot denoting its middle; 2 - parallels restricting the interpretation area.

age, which form a graben ca. 3 km long and 400 m wide. The magnitude of displacement is 2-3 m. The faults and graben strike roughly 25° NE. Adjacent to the fault are a few large landslides and also localities of soil liquefaction. The rocks had been displaced in the same (eastward) direction in the main fault and in most of the landslides (Fig. *3, a).*

Very characteristic seismic dislocations are seismic trenches and "broken peaks" usually restricted to the water divides and to the crests of the ridges [15]. Similar dislocations are known to have been formed during many large modern earthquakes: Khait [19]. Gobi-Altai [7], East Siberia [10], California [42], to name but a few. It is believed that such forms arise in epicentral zones during shakings of M = 10-11 [15]. They are

Table 1 Coordinates and main characteristics of Holocene faults, fissures and their systems as inferred paleoseismic dislocations with features not less than 3 km long.

Catalog No	Coordinates, deg.		Strike, deg.	Length, km	Catalog No	Coordinates, deg.		Strike, deg.	Length, km	Catalog No	Coordinates, deg.		Strike, deg.	Length, km
	N lat.	E long.				N lat.	E long.				N lat.	E long.		
1	61.97	165.33	307	5.0	74	61.61	167.53	70	4.5	141	60.97	165.67	304	4.0
2	61.97	165.50	307	3.0	78	61.55	167.08	30	5.5	148	60.68	165.48	315	3.0
3	61.92	165.50	307	6.0	79	61.50	167.22	30	4.0	155	60.63	164.77	30	4.0
4	61.83	165.92	307	5.0	80	61.50	167.32	30	11.0	159	60.60	164.87	40	3.0
5	61.58	164.67	295	3.0	81	61.58	167.32	290	6.0	160	60.65	165.03	47	5.0
8	62.20	167.83	0	3.0	82	61.52	167.45	55	3.0	162	60.61	166.00	47	3.0
10	62.03	167.58	58	5.0	84	61.53	167.52	315	4.0	163	60.55	165.78	40	3.5
11	62.17	168.50	40	4.0	85	61.48	167.30	310	3.0	165	60.42	165.67	30	3.0
13	62.25	169.33	20	4.0	87	61.35	166.92	310	4.0	166	60.67	166.50	38	5.0
14	62.25	169.50	15	4.0	88	61.50	166.83	28	3.5	167	61.48	168.77	312	3.0
15	62.25	169.52	17	4.5	89	61.47	166.87	30	6.0	168	61.43	168.85	335	3.0
16	62.20	169.53	20	5.0	90	61.43	166.67	33	4.0	169	61.37	169.00	32	9.0
17	62.17	169.17	18	3.0	91	61.47	166.72	27	3.0	171	61.13	168.45	17	6.0
19	62.23	169.78	10	4.5	92	61.40	166.78	307	3.5	172	16.15	168.20	18	3.0
20	62.25	169.92	14	5.0	93	61.38	166.87	40	3.0	173	61.02	167.88	324	4.0
21	62.18	169.80	10	5.0	94	61.40	166.90	34	4.0	174	61.02	167.77	0	5.5
22	62.13	170.12	8	3.0	95	61.38	166.97	35	7.0	178	60.75	167.77	318	5.5
23	62.13	170.25	8	4.0	96	61.40	166.28	310	4.0	183	60.73	167.50	70	5.0
27	61.92	168.97	342	3.0	97	61.35	166.33	28	4.5	185	60.68	167.05	30	4.0
28	61.92	168.95	338	4.0	98	61.35	166.28	30	5.5	186	60.67	16717	50	3.0
30	61.98	168.08	28	3.0	100	61.30	166.30	27	6.0	188	60.63	167.37	90	4.0
32	61.93	168.37	301	3.5	101	61.30	166.43	23	4.0	191	60.58	167.85	25	3.5
33	61.78	168.25	312	5.5	103	61.25	166.60	18	5.0	192	60.58	167.92	310	6.0
34	61.70	168.50	70	3.0	106	61.30	166.67	17	3.0	197	60.37	167.25	313	4.0
36	61.71	168.63	78	4.5	108	61.30	166.72	12	4.0	198	60.42	166.60	90	3.0
37	61.75	168.78	300	4.0	109	61.30	166.83	18	4.0	201	60.20	166.65	40	4.0
38	61.75	168.85	300	3.0	110	61.30	166.92	26	3.0	203	60.13	166.55	40	9.5
42	61.72	168.92	287	4.0	112	61.27	166.92	20	4.0	204	60.10	166.63	40	3.0
44	61.75	169.08	35	3.5	113	61.15	166.58	35	7.0	205	60.08	166.43	90	6.0
47	61.83	169.37	308	5.0	116	61.37	165.42	26	3.0	206	60.03	166.33	340	3.0
50	61.80	169.50	308	6.0	117	61.38	165.53	297	7.0	210	59.98	166.38	53	5.5
51	61.80	169.48	308	5.5	118	61.38	165.63	17	6.0	211	59.90	166.33	64	7.0
52	61.80	169.47	308	4.5	121	61.28	165.40	0	3.0	215	62.17	173.05	297	3.5
53	61.85	169.72	90	3.0	122	61.27	165.47	18	6.0	216	62.17	173.13	297	3.0
56	61.77	167.27	315	4.0	123	61.20	165.25	18	13.0	217	62.16	173.05	62	3.0
59	61.77	167.23	0	3.0	126	61.15	165.45	0	3.0	219	62.12	173.23	69	4.0
64	61.57	168.00	300	4.0	127	61.25	165.81	18	5.2	222	62.02	177.22	302	3.0
68	61.65	167.33	30	3.0	130	61.07	165.61	47	4.5	224	62.03	172.50	288	3.5
69	61.63	167.30	70	4.0	131	61.03	165.05	305	3.0	225	61.83	171.35	50	4.5
70	61.61	167.25	30	4.0	132	60.95	165.28	18	8.0	226	61.83	171.42	303	3.0
71	61.60	167.20	80	4.0	133	60.95	165.30	90	7.0	227	61.80	171.83	75	7.0
72	61.63	167.45	25	3.0	138	60.90	165.28	20	3.0	230	61.70	171.88	307	5.0

Table 1 (continued).

Catalog No	Coordinates, deg.		Strike, deg.	Length, km	Catalog No	Coordinates, deg.		Strike, deg.	Length, km	Catalog No	Coordinates, deg.		Strike, deg.	Length, km
	N lat.	E long.				N lat.	E long.				N lat.	E long.		
231	61.72	171.88	310	3.0	299	60.30	170.58	70	8.0	359	56.48	162.18	50	5.0
232	61.67	171.87	40	3.5	300	60.22	170.13	307	3.0	360	56.45	162.25	45	10.0
233	61.83	172.13	325	3.0	301	60.27	170.25	75	12.0	361	56.40	162.18	40	4.0
235	61.83	172.35	47	3.0	302	60.13	170.33	40	3.0	363	56.37	162.15	20	12.0
236	61.85	172.72	77	5.0	303	60.13	170.42	17	4.0	364	56.30	161.70	20	14.0
238	61.81	172.73	297	5.0	305	60.00	170.25	50	5.0	365	56.28	161383	20	24.0
239	61.81	172.72	297	3.5	306	60.00	170.33	30	4.0	366	56.18	161.65	30	6.0
240	61.81	172.65	290	6.0	308	61.83	170.25	56	8.0	367	56.15	161.55	15	4.5
241	61.81	172.88	296	3.5	309	61.73	170.52	55	4.0	368	56.12	161.45	28	6.5
242	61.80	173.13	10	3.0	310	61.42	170.02	30	5.0	369	56.10	161.48	0	3.5
245	61.68	172.92	315	3.5	311	60.08	162.83	28	4.0	372	56.08	161.60	20	3.0
246	61.65	172.85	0	4.5	312	60.05	163.22	40	4.0	373	56.05	161.38	25	3.5
248	61.55	171.50	302	4.0	313	59.85	168.08	45	6.0	374	56.05	161.38	25	3.5
250	61.61	172.23	60	5.5	314	59.73	162.67	45	4.0	375	55.83	161.10	35	26.0
251	61.52	172.08	27	5.0	319	59.83	161.80	90	3.0	377	55.65	161.70	63	4.5
254	61.43	172.33	290	8.0	320	59.77	161.83	45	4.0	378	55.63	161.60	305	10.0
255	61.43	172.23	295	6.0	321	59.80	161.38	30	3.0	379	55.61	161.53	305	15.0
258	61.33	171.88	300	3.5	322	59.63	161.19	45	3.0	380	55.53	161.37	10	3.0
259	61.32	172.50	310	3.0	324	59.55	160.83	320	5.0	381	55.48	161.35	25	5.0
260	61.30	172.10	310	5.0	325	59.35	160.92	45	5.0	382	55.63	160.61	30	5.0
261	61.20	172.27	325	3.0	326	59.10	160.02	54	6.0	383	55.60	160.66	45	6.0
266	61.10	171.33	33	3.0	327	59.17	160.98	45	4.0	384	55.63	160.81	45	20.0
267	60.97	171.37	310	4.0	331	58.55	160.73	45	7.0	385	55.48	160.55	20	10.0
269	60.87	171.97	45	4.5	333	57.55	160.03	50	6.0	386	55.45	160.42	20	3.0
271	60.83	171.17	45	4.5	334	57.40	160.81	45	5.0	387	55.35	160.50	25	12.0
274	60.83	170.42	310	4.0	338	57.03	157.93	40	10.0	388	55.25	160.25	60	25.0
276	60.61	169.20	65	6.0	340	56.78	158.85	305	3.0	389	55.25	160.43	30	15.0
277	60.47	169.92	47	3.0	341	56.73	159.27	90	3.0	390	55.17	160.33	65	20.0
278	60.60	170.10	297	3.0	342	57.12	159.50	315	3.0	392	55.30	161.37	0	3.0
279	60.57	170.25	80	6.5	343	57.18	159.78	45	20.0	393	55.28	161.61	20	8.5
280	60.53	170.38	90	3.0	344	57.13	160.02	45	14.0	394	55.17	161.72	70	7.0
281	60.63	170.55	300	9.0	345	56.75	159.80	53	10.0	395	55.07	161.52	0	3.0
282	60.60	170.53	60	6.0	346	57.17	160.95	45	3.0	396	56.63	162.72	330	8.0
284	60.61	171.03	50	3.0	348	56.77	162.57	65	7.5	397	56.50	162.81	310	7.0
286	60.53	170.83	90	4.0	349	56.50	158.03	45	4.0	399	56.55	163.17	310	4.5
287	60.45	170.80	40	3.0	350	56.60	158.33	10	3.0	400	56.50	163.15	30	4.0
293	60.33	170.25	45	3.0	351	56.22	158.15	310	23.0	401	56.23	163.32	70	9.5
294	60.30	170.33	90	3.0	352	56.27	158.62	315	3.0	402	56.20	163.22	70	17.0
295	60.25	170.20	60	3.0	353	56.40	159.18	50	20.0	403	56.15	163.07	0	5.0
296	60.25	170.25	60	3.0	354	56.27	159.12	55	5.0	405	56.02	162.97	315	3.5
297	60.23	170.17	65	3.0	357	56.55	162.03	20	3.0	409	55.66	158.83	50	3.0
298	60.28	170.45	70	8.0	358	56.50	162.00	0	4.0	410	55.85	158.97	45	3.0

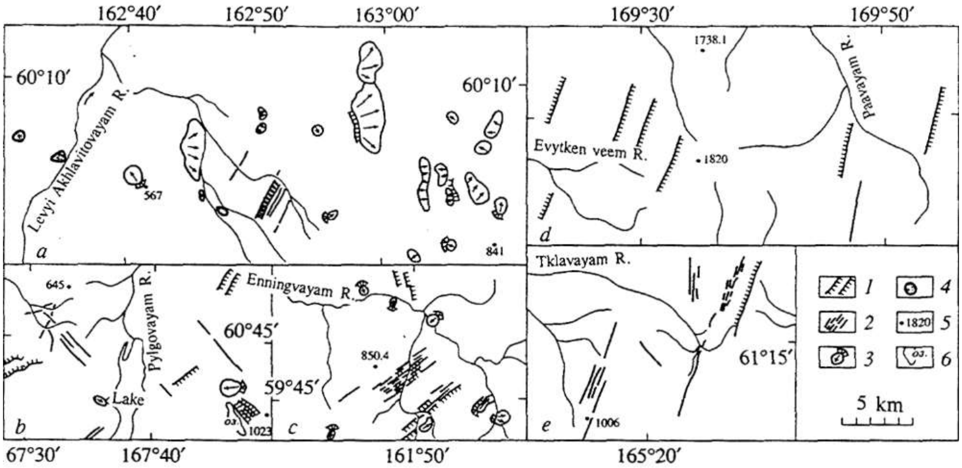

Figure 3 Examples of inferred paleoseismic dislocations located in different areas of the Koryak Autonomous District: *a* - Kamchatka Isthmus (Catalog N 311 in Table 1); *b* - Lake Khai-Gytkhyn area (N 177-184); *c* - Lesnovsky Rise (N 319, 320); *d* - upper reaches of the Evytkenveem and Paavayam Rivers (13-21); e - upper reaches of the Tklavayam River (121-124); 1 - Holocene faults with one side upthrown relative to the other (hatchures indicating the lowered side); 2 - Holocene fissures (without visible displacements); *3* - landslides (arrows indicate landslide directions); *4* - areas of soil liquifaction; 5 - isolated highs and their altitudes; *6* - lakes.

quite numerous in the study area. Near the Khai-Gytkhyn lake the faults had broken both the crest and the slopes of a ridge located east of the lake (Fig. 3, *b).* In the crest area the magnitudes of vertical displacements in the faults are as great as 40-50 m. The total height of the collapse appears to be not less than 100 m. In this respect the resulting form resembles a structure that had been formed during the Gobi-Altai earthquake of December 4, 1957 [7], [10].

In some areas the Holocene faults occur as a dense network where dozens of faults, often intersecting, were mapped in a relatively small area (20-25 km^2) with many ridges looking as "broken crests". Such dislocations might have been produced by one earthquake, as is the case of the 28 June 1992 Landers earthquake in California [39], where deformations had been produced not by one fault but by a broad shear zone. At the same time such deformations may result from several events. These cases require a more detailed study with necessary field measurements.

We also discovered localities where numerous Holocene faults and fissures intersected at right angles producing a peculiar network resembling a peculiar "planetary fracture pattern" described in [38]. It remains to be clarified whether these areas can be treated as the traces of large earthquakes of the past, and whether they had been produced by one or several earthquakes. Again, this calls for further studies.

A general remark is that most of the inferred paleoseismic dislocations were located for the first time and were not examined comprehensively. It is not unlikely that some faults were erroneously interpreted as paleoseismic dislocations. In this context the faults and fissures listed in the catalog (Table 1) and plotted in Fig. 2 should be treated as the inferred traces of paleoearthquakes. Their further study and detailed examination in a field work will help to establish their origin as seismogenic formations and refine their dating.

General distribution patterns of Holocene faults (inferred paleoseismic dislocations) in the study area. The maps of Figs 2 and 4 show the distribution and density of Holocene faults and fissures in the Area of the Koryak Autonomous District. Bellow we list the main features of their distribution.

1. Most of them are concentrated on the Vetvei and Ukelayat ranges in the Koryak Highlands and in the axial zone of the Sredinnyi Range in Kamchatka. They are also rather numerous on the Goven and Olyutorsky peninsulas, and also northeast of Palana Town (Cape Tevi area).

2. The Holocene faults and fissures are much more numerous in the Koryak Highlands than on the Sredinnyi Range of Kamchatka. Much less of them occur in the southern part of Koryak Autonomous District, where the region of Quaternary volcanism begins.

3. The areal distribution of dislocations has a mosaic pattern even on the ranges where the absolute heights are roughly identical: localities with their highest concentrations are separated by localities where dislocations are few or absent.

In addition to these general distribution patterns of Holocene faults and fissures, there are areas where dislocations of some or other strikes are developed. For instance, in the area of the Lesnovsky Rise (Kamchatka Isthmus), 21 dislocations were mapped, 15 of them being faults, or groups of fissures and faults, striking 40-45°NE. A zone of their concentration, extending for 220 km along the axis of the rise, has the same general strike. An example of one of the inferred seismogenic structures, located in this area, is shown in Fig. 3, c.

Most of the inferred seismic dislocations mapped in the Koryak Autonomous District occur in the area of the Vetvei Range in the Koryak Highlands (Fig. 4). Their predominant strike is NNE. Figure 5, *a* shows an area between the Imlanvayam and Lulovayam Rivers, where 49 inferred seismogenic features are concentrated. This figure also shows a diagram of their strikes, which shows that the bulk of them strike 20-30°NNE. The other areas of the Vetvei Range are also dominated by NNE-striking dislocations (see Fig. 3, *d* and *e).*

A quite different pattern was observed in the eastern part of the Koryak Highlands, on the Ukelayat and Snegovoi ranges (Fig. 5, *b).* This area is dominated by faults and fissures striking 290-300°WNW, the faults of the NE and NNE strikes being almost completely absent: merely 3 of them strike NE out of the 40 faults mapped.

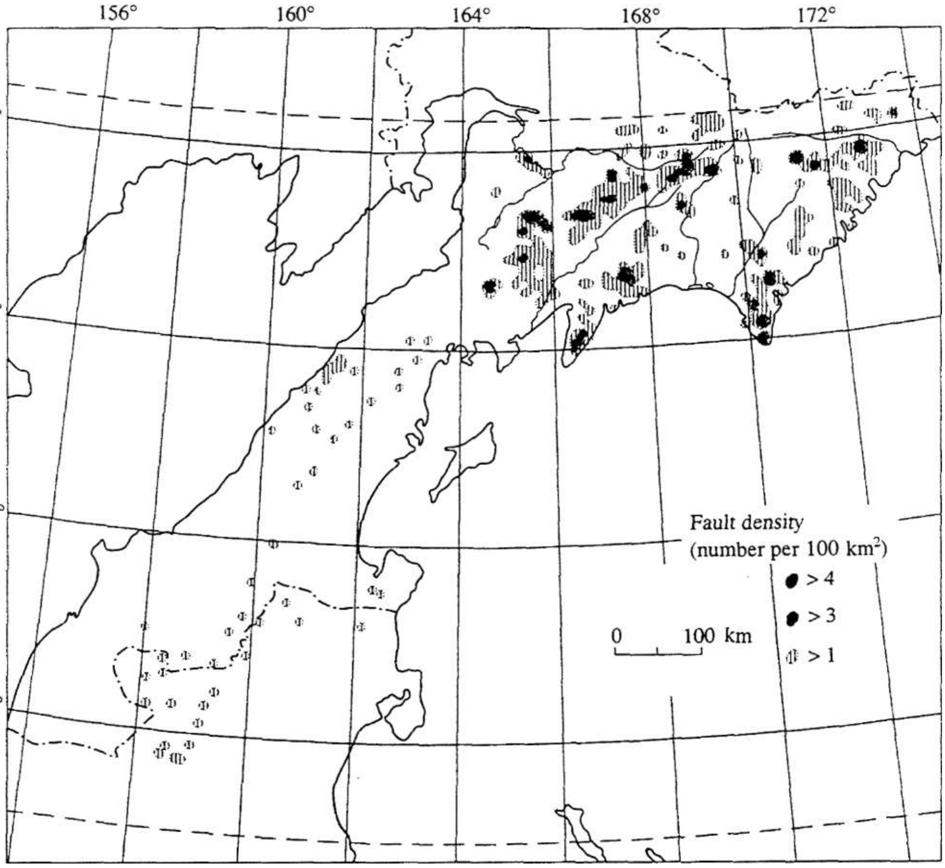

Figure 4 Distribution density of Holocene faults and fissures on the territory of the Koryak Autonomous District (not shown for the Kumroch Range, Kamchatka).

Also different in strike are the groups of faults and fissures located on the Olyutorsky and Goven peninsulas. The former is dominated by dislocations ranging in strike from 45-50°NE to 70-80°ENE, the largest of them having the latter strike. The Goven peninsula is dominated by dislocations striking 40°NE.

General distribution pattern of landslides, collapses, and other slope formations in the study area. Figure 6 shows the distribution of these formations (hereafter called landslides because of their predominance) studied in the area between 55°00' in the south and 62°20' in the north. We mapped 3026 landslides (plus ca. 240 landslides had been located by O. N. Egorov in the north of the Koryak Autonomous District, on the Ichigem Range and Oklansky Plateau, which are also shown in Fig. 6). One can see that the

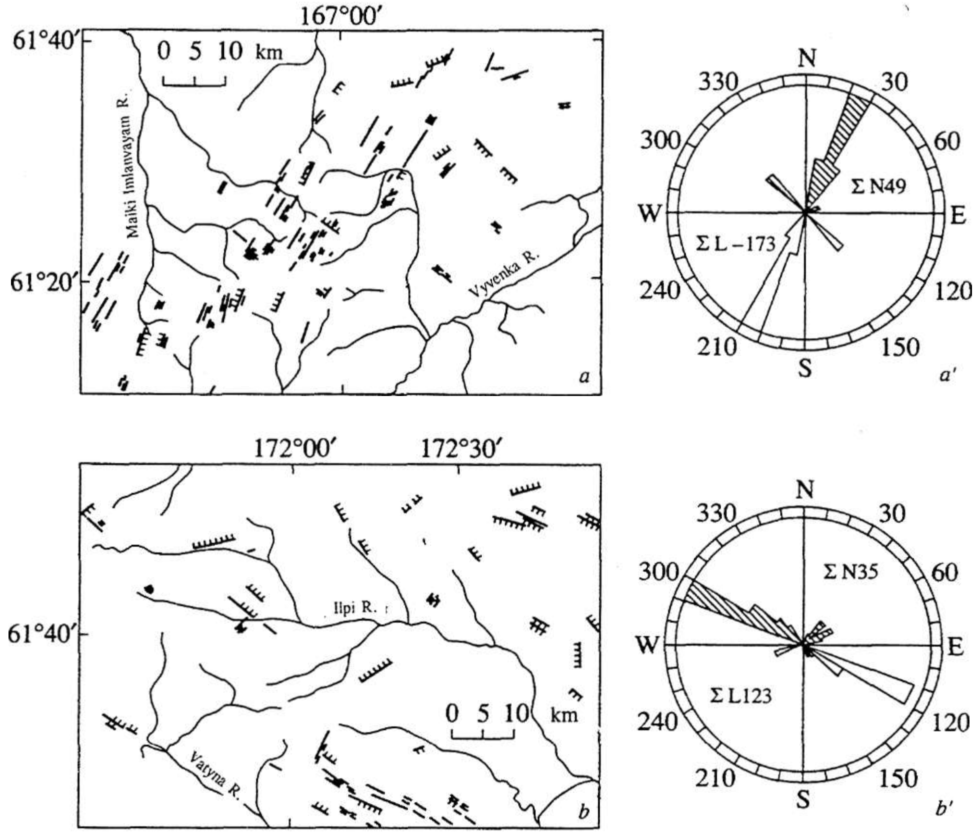

Figure 5 Distribution of Holocene faults and fissures (*a* and *b*) and rose diagrams for the frequency and total length (*a′* and *b′*) between the Imlanvayam and Lulovayam Rivers (*a* and *a* and on the Ukelayat and Snegovoi ranges (*b* and *b′*); ΣN – number of located faults and fissure ΣL – their total length, km. The other symbols are as in Figure 3.

landslides are distributed highly nonuniformly. They are much more numerous on the Kamchatka peninsula than on the Koryak Highlands. The largest number of landslides were found in the area of the Lesnovsky Rise extending from the Kamchatka isthmus in the north to the Palana and Khailyula Rivers in the south. Southward a zone of their concentrations extends NNE as a narrow belt along the axis of the Sredinnyi Range. Landslides are much less numerous in the central segment of the range, where the products of Quaternary volcanism are widely developed, which are absent in the north and south.

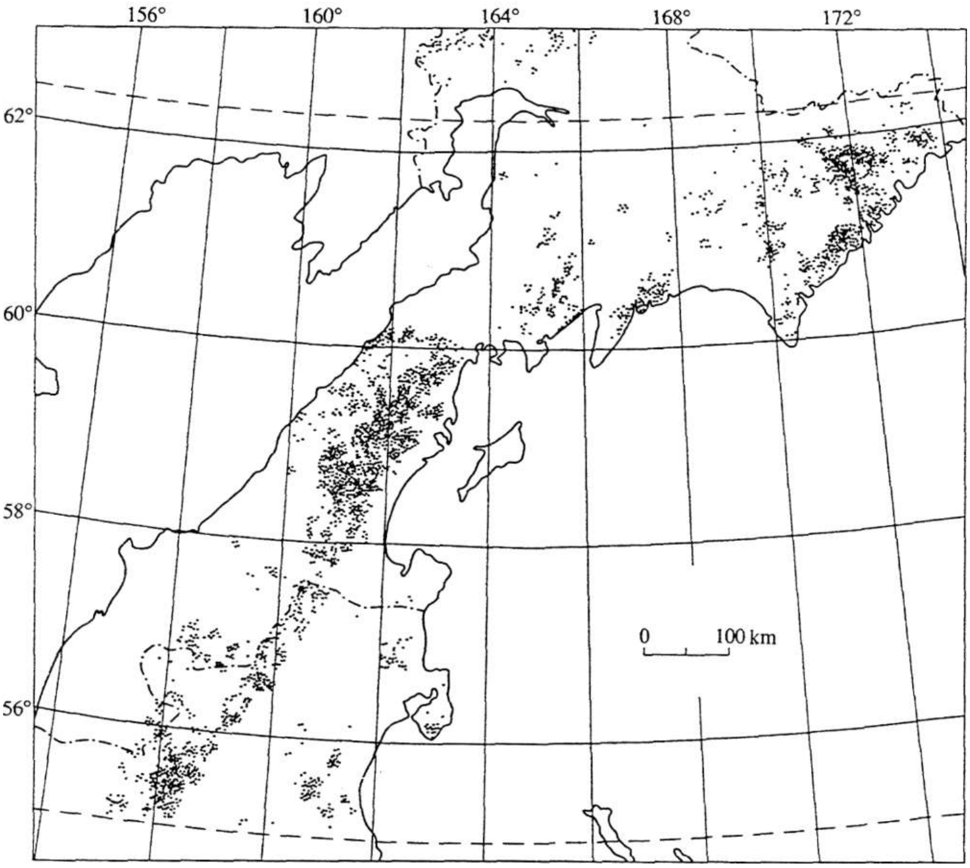

Figure 6 Map showing the distribution of landslides, collapses, debris avalanches, and other slope formations located as a result of interpreting air photographs for the territory of the Koryak Autonomous District and adjacent areas of Kamchatka (between 62°20' in the north and 55°00' in the south). Landslides and collapses are shown as dots denoting their middles.

We located several areas of landslide concentration on the Koryak Highlands. They are most numerous in the east, in the drainage area of the Ilpa River and in the coastal areas (Machevna, Glubokaya, and other bays). A significant number of landslides are concentrated in a small area NE of the Goven peninsula (Lavrov Bay), and also in the southern segment of the Vetvei Range (on the Unnei-Tunup Range and in the Khetapkhaen Mountains).

Considering the general distribution of landslides on the territory of the Koryak Autonomous District, it should be noted that it is poorly correlated with the geology or topography. In the northern part of the Kamchatka peninsula, most of the landslides are associated with the domal uplift of the Sredinnyi Range, especially with its relatively elevated northern and southern segments. In Koryakiya, no correlation can be traced with the Koryak uplift [35]. Moreover, as seen in Fig. 6, there are almost no landslides on its SW and W slopes, their elevations being as great as 1700-1800 m. Our comprehensive analysis of the factors contributing to landslide formation in this area revealed that landslide had been formed on steep slopes produced by the last Late Pleistocene glacial [18]. No landslides were found where glaciation had been absent.

Comparison of Fig. 2, showing the distribution of Holocene faults (inferred seismotectonic dislocations), with Fig. 6, showing the distribution of landslides (some inferred to be seismogenic), shows that there is little in common between them. The number of landslides is insignificant in areas of the maximum concentration of Holocene faults (Kumroch Range in East Kamchatka and Vetvei Range in Koryakiya). On the contrary, Holocene faults are scarce in areas of the greatest concentration of landslides (southern and northern segments of the Kamchatkan Sredinnyi Range, Lavrov and Machevna bays, and the eastern Koryak Highlands). The exceptions are the Ukelayat and Snegovoi ranges in the east of the Koryak Highlands where the maximum concentrations of landslides and Holocene faults coincide. This implies that landslides can hardly be used as a paleoseismicity indicator in this area.

This conclusion contradicts the rules of a new paleoseismological technique proposed in [2], [3], where swarms of large gravitational dislocations are advised to be used as indicators of old earthquake epicenters. In the context of our study, caution must be used in applying this technique. The data reported here suggest that landslide swarms do not always indicate the epicenters of old earthquakes. They might have been produced by other mechanisms.

DISCUSSION OF RESULTS

Seismic hazard assessment. Limitations and difficulties in the use of paleoseismology have been mentioned in the beginning of this paper. Even a detailed study of the discovered seismic dislocations does not ensure that the results obtained contain information of all, or even of the majority of, earthquakes that had occurred in some or other area. Earthquakes that occur at depths of 15-20 km remain undetected. Besides, some researchers believe that the seismicity level remained variable even during the Holocene, and that it is lower in the recent epoch than, for example, during the Early Holocene [25]. If this is the case the assessment of seismic hazard using paleoseismic dislocations (without their exact dating) will inevitably lead to its overestimation.

Our attempt to assess seismic activity on the territory of the Koryak Autonomous District using Holocene faults (inferred paleoseismic dislocations) also posed numerous questions which for the time being have no answers. Can all of the Holocene faults be taken as the traces of paleoearthquakes? How can we correlate their fairly great number with the very poor modern seismicity? What criteria can be used as a basis for the seismic zonation of this territory? What is the maximum possible magnitude and frequency of large earthquakes?

Nevertheless, some estimates can be derived even at this stage of the work. The above figures show that the located faults and fissures (inferred paleoseismic dislocations) are surprisingly similar in size: their average length is 3.5-4 km, merely a few faults being as long as 8-12 km (see Table 1). We did not find faults as long as 20-30 km, similar to those known, for example, from the Kumroch Range in East Kamchatka, and also from North Kamchatka and the Koryak Highlands. We recorded only single cases of old fault reactivation, those reactivated during the Holocene also having restricted lengths (4-5 to 8-9 km). This evidence suggests that the area of study can be interpreted to be similar to Japan and different from the regions such as California or China (distinctive features of these regions can be found in [24]). The distribution pattern of faults in these regions is very complicated, and their sizes not large. This state of the earth is characterized by numerous "particular spots" [24] where stress is concentrated.

At the same time the analysis of the areal distribution of Holocene faults shows that the areas of their maximum concentration in Koryakiya are arranged as a north-facing arc along the Vetvei and Ukelayat ranges (see Figs 2 and 4). This arc generally coincides in strike with the main structural zones of the southern Koryak Highlands, with the Ukelayat fold zone [14], [34] and with the Vatyn thrust fault system [23]. S. D. Sokolov *et al.* [30] showed that these structural zones belonged to the outer frontal zone of a large fold system arched to the northwest. This system has a complex nappe-fold structure with widely developed slabs, wedges, and large nappes. Most of the located Holocene faults (inferred paleoseismic dislocations) occur in the outer zone of this fold system. It can be postulated that the earthquakes that had occurred on the Koryak Range had been restricted to the upper structural level, like in the other regions of a similar tectonic setting, e.g., in the eastern Caucasus [1]. They might have been associated with motions along the faults that had originated at greater depths, e.g., in the basement, but had not reached the ground surface or are hidden beneath an "alpine cover". As mentioned in [1], tectonic analysis often reveals different strikes of structural features in the basement and in the sedimentary cover and a relative independence of tectonic processes in the sedimentary cover upon the processes in the basement.

Most of the Holocene faults (inferred paleoseismic dislocations) located in the Koryak Highlands have a NNE strike (20-30°NNE). In the eastern part of the highlands, namely, on the Ukelayat and Snegovoi ranges, the dominant strikes of the faults are WNW (290-300°WNW). These two groups of faults are arranged at right angles and seem to form one system, similar to what is known as a regmatic planetary fault system [38]. It is possible that the persistence of these fault orientations had been related to some regional stress field controlled by the kinematics and dynamics of lithospheric plates and by the processes that had operated at their boundaries [20]. The mechanism responsible for the stability of the Holocene fault strikes in the study area is yet to be established. It seems obvious that this must have been some common mechanism that had operated over a sufficiently large territory. Apparently this mechanism continues to operate in the present time: during the Khailinskii earthquake of March 8, 1991, the main rupture (instrumentally determined main fault) had the same strike (18-20°NNE) and was not associated with any old fault; it was a newly generated dislocation [16]. At the same time both the Khailinskii earthquake and the other events that had occurred there previously might have been generated by deep basement faults that had not emerged to the ground surface but had remained to be hidden beneath the sedimentary cover of the outer zone of the Koryak fold system. Judging by the general outline of the aftershock swarm, the fault responsible for the Khailinskii earthquake had a NW strike [16].

On the Goven and Olyutorsky peninsulas the Holocene faults have strikes different from the strikes of faults elsewhere. Apparently these peninsulas can be interpreted as separate crustal blocks where their own local stress systems had operated. This mechanism remains to be clarified as well.

Similarly, some special conditions seem to have controlled the development of Holocene faults striking 40-45°NE on the Lesnovsky Rise. Here, the effect of old NE-striking faults can be postulated. Apparently different segments of these faults had been reactivated during different intervals of time. The almost rectilinear zone of closely spaced Holocene faults, extending along the axis of the rise for a distance of 220 km, can be interpreted as a signature of a large seismogenic fault or a zone of faults similar to those that were mapped by I. E. Gubin in the Garm region of Tadjikistan [8] or by R. N. Ibragimov in Eastern Uzbekistan [13]. In contrast to the other concentrations of Holocene faults on the Koryak Highlands described above, the Lesnovsky zone of faults is marked by numerous landslides and debris avalanches, some of them being very large [18]. This evidence suggests that the mechanisms of earthquakes in the Lesnovsky zone had been substantially different from those of earthquakes that had occurred elsewhere in the study region. The significant length of the seismogenic zone here may be indicative (in accordance with the law of seismic tectonics [11]) of the significant magnitudes of its earthquakes. At the same time, judging by the number of the located inferred paleoseismic dislocations there, the frequency of seismic events in this zone had been much lower than on the Koryak Highlands.

Still less Holocene faults were located southward in that part of the study area where volcanism had occurred during the Quaternary (see Figs 2 and 4). This fact can be used as evidence in support of the recently advanced view that magma overpressure suppresses tectonic stresses: magma pressure counteracts the tectonic stress, and the risk of large earthquakes is lower in volcanic areas [41]. This view was recently confirmed by the evidence reported by Japanese researchers [40] suggesting a close correlation between seismicity and temperature: seismicity is much lower in areas underlain by shallow low-velocity zones (potential magma sources).

To sum up, the studied territory of the Koryak Autonomous District can be subdivided into three regions differing substantially in the operation conditions of seismic activity. These are the region of Quaternary volcanism in the south, the area of the Lesnovsky Rise in the middle, and the region of the Koryak Highlands in the north. Based on the character of the inferred paleoseismic dislocations, their number and distribution, it can be concluded that large earthquakes are significantly less frequent in the southern region of Quaternary volcanism than in the other regions. Apparently they are inferior to them in strength, even though the estimation of the maximum magnitudes of earthquakes from paleoseismic dislocations is veiy difficult, because most of the located Holocene faults have lengths of 3-12 km, and their combination to larger zones is often problematic. The central region (Lesnovsky Rise area) yielded more seismic dislocations and more landslides and other collapses. This suggests the existence of long seismic zones. The paleoseismic dislocations located there, some of which have been described above, indicate a significant strength of old earthquakes. Based on the number (21) of the inferred paleoseismic dislocations there and on the time interval during which they had been generated (10-12 thousand years), the recurrence interval of large earthquakes in this area is 500-600 years. This interval is comparable with an estimate based on the study of tsunami traces in the coastal zone east of the Lesnovsky Rise. According to I. V. Melekestsev and A. V. Kurbatov [22], the dating of these traces suggests that earthquakes with $M > 7.5$ occurred there during the last 2000 years with an interval of a few hundred years (averagely with an interval of 320 years).

The largest number of Holocene faults located in the northern region, on the Koryak Highlands, suggests that this region experienced the greatest seismic activity in Holocene time. At the same time the fact that the faults (inferred paleoseismic dislocations) are distributed there in a mosaic pattern and are not associated directly with any large faults, and also the fact that the strikes of these faults are invariable and they can be interpreted as a network of planetary, regmatic faults, suggest some specific conditions of the development of Holocene faults and, accordingly, of paleoseismicity there. As has been mentioned above, these conditions might have been produced by the wide development of thrust faults and nappes there, although seismicity in this particular case can be interpreted in terms of the self-organization of the earth, as has been proposed by N. V. Shebalin [37]. The repetition of large earthquakes in this region can be estimated on the basis that ca. 300 paleoseismic dislocations were located there. The time of their development is 10-12 thousand years. Accordingly, the recurrence of large earthquakes can be taken to be 30 years (on the condition of the uniform distribution of Holocene events). It can be postulated in this context that the next earthquake, similar to the 1991 Khailinskii event ($M = 6.6$-7), is likely to occur on the Koryak Highlands after 25-30 years. However, this forecast is hardly reliable, because it remains unknown whether Holocene earthquakes had occurred after uniform intervals of time, and how many of them had not left any traces. Answers to these questions require more detailed work, the study of particular seismogenic faults, the knowledge of faulting history based on the study of surface faults, location of active basement faults, estimation of the thickness of the seismically active layer, and the like. Hopefully, this work will be done in future.

This work was supported by the Administration of the Koryak Autonomous District in the framework of the Project "Refinement of the Map of Seismic Zonation of the Koryak Autonomous District" headed by A. V. Vikulin.

I am grateful to A. V. Vikulin, O. N. Egorov, I. V. Melekestsev, L. S. Shumilina, O. V. Potapova, and G. V. Chernysheva for their interest and help in this work.

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