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A double-planed seismic zone in Kamchatka from local and teleseismic data

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Abstract. The fine structure of a double-planed deep seismic zone is studied over a wide area of the Kamchatka peninsula. This prominent feature of deep seismic zone configuration is ascertained through the analysis of microearthquake hypocenters from the local seismic network of the Institute of Volcanology of Kamchatka and 22 focal mechanism solutions from the formal inversion of long-period P and SH waves for events with $m_h>5.5$. Additionally, 11 focal mechanism solutions estimated from the first motion of P-waves and 12 centroid moment tensor solutions of Harvard University are used. The maximum depth of the double seismic zone is 170-180 km. The two planes of seismicity are separated by 40 km at a depth of 50 km, and by 10-15 km at 180 km depth. The focal mechanism solutions of shallow earthquakes show an abrupt change from the thrust events to down-dip compressional events at approximately 60 km depth at the upper boundary of the descending slab. Within the descending slab, the earthquakes with down-dip tensional axis form the lower plane of the double-planed deep seismic zone. Several earthquakes with down-dip tensional axis are discovered in a narrow area of the upper seismic zone at the depth of about 50 km. The double seismic zone is revealed clearly in the area between ~52°N to ~54^{W}N and probably extends up to ~56°N.

Introduction

The first indication for the presence of a possible double seismic zone in Kamchatka was reported by *Fedotov* [1968]. Later, *Zobin* [1990] discussed the average stress distribution in Kamchatka based on focal mechanism solutions determined with P-wave first motion data from local earthquakes. Although the results are not conclusive, his data suggest the presence of a double seismic zone. Recently *Kao and Chen* [1994] using the results of waveform inversion of teleseismic recorded events with $m_b>5.5$ demonstrated that the double seismic zone can be traced in the central part of Kamchatka, and it turns into a regular Wadati-Benioff zone with down-dip compression in the northeastern part of Kamchatka trench. The purpose of this paper is to reexamine the seismicity beneath the Kamchatka peninsula in order to perform detailed analysis of the spatial distribution of earthquakes, both using the local catalog and focal mechanism solutions of accurately located hypocenters estimated from teleseismic data. Those data allow us to infer the fine morphology of a double seismic zone under the Kamchatka peninsula.

Hypocentral distribution

The seismic network of the Institute of Volcanology of Kamchatka (IVK) consists of twenty permanent, short-period (T_s=1.2s) seismic stations, and covers most of the Kamchatka peninsula (Figure 1). The catalog of local seismicity of Kamchatka includes epicenters, depths and magnitudes of the events and errors of their determination [*Fedotov et al.,* 1964; *(Gusew* 1979] from 1962 to 1990. For the analysis of hypocentral distribution, only the earthquakes with reported depth errors of less than 10 km were selected. The distribution of seismicity shows that the dip of the descending slab beneath the Kamchatka peninsula remains constant from ~51°N to ~55°N. Between ~55°N to ~56°N, it sharply changes and becomes shallower *[Gorbatov et al.,* 1993]. Cross-sections A-A' and B-B' (see insert in Figure 2) are selected according to the configuration of the descending slab to represent the general characteristics of the subduction process in Kamchatka.

The separation of the intermediate-depth seismicity into two planes is clearly seen on cross-section A-A' (Figure 3a). The hypocenter estimates for the region of this cross-section are more accurate because of the denser coverage of the seismic stations (Figure 1). The distance between two planes of seismicity is ~40 km at a depth of 50 km, and it decreases gradually to about 10-15 km at a depth of ~180 km. The dip of the upper plane is about 55°. The lower seismic sheet has a dip ~20° less than the upper sheet.

In cross-section B-B' (Figure 3b) the separation of the two planes of seismicity is not as clear as on A-A' (Figure 3a). This is probably because of a less dense distribution of seismic stations in northern Kamchatka resulting in less accurate hypocentral locations than in the central part of the peninsula (Figure 1).

Stress distribution from teleseismic data

The determination of focal mechanisms is based on a least square inversion of long-period P and SH waveforms *[Ndbelek,* 1984]. In total, 22 teleseismicaly recorded events

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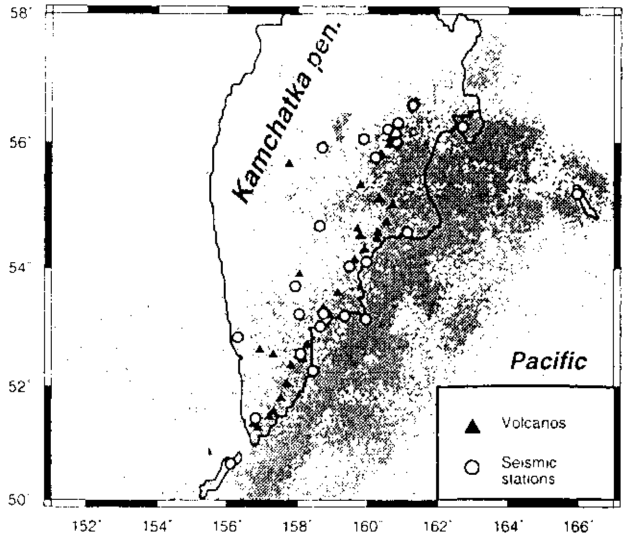

Figure 1. Location of earthquakes (1962-1990) registered by the local seismic network of the Institute of Volcanology of Kamchatka (IVK).

(m_b>5.5) were modeled (Gorbatov et al., manuscript in preparation, 1994) (Figure 2), using the data from the National Earthquake Information Center (NEIC) World-Wide Standardized Seismograph Network (WWSSN) dataset. Additionally, twelve centroid moment tensor solutions reported by Harvard University (HCMTS) *[Dziewonski et al.,* 1981; *Dziewonski and Woodhouse,* 1983) were included together with eleven focal mechanism solutions (Gorbatov et al., manuscript in preparation, 1994) estimated from the P-wave first motion arrivals reported by the International Seismological Center (ISC) bulletin (Figure 2).

Some part of those focal mechanism solutions are presented in Table 1. It should be noticed that our set of the modelled events extends further to the north than the data set of *Kao and Chen* (1994] (which is limited by 54°N) and only four events are the same in the both sets. These mutual events have practically similar focal mechanisms but the hypocentral depth systematically differs by 10-20 km, probably because we used for the inversion the local velocity model of *Balesta et al.* 11985], while *Kao and Chen* [1994] applied an averaged modification of the whole Earth velocity model *[Kennett and Engdahl,* 1991].

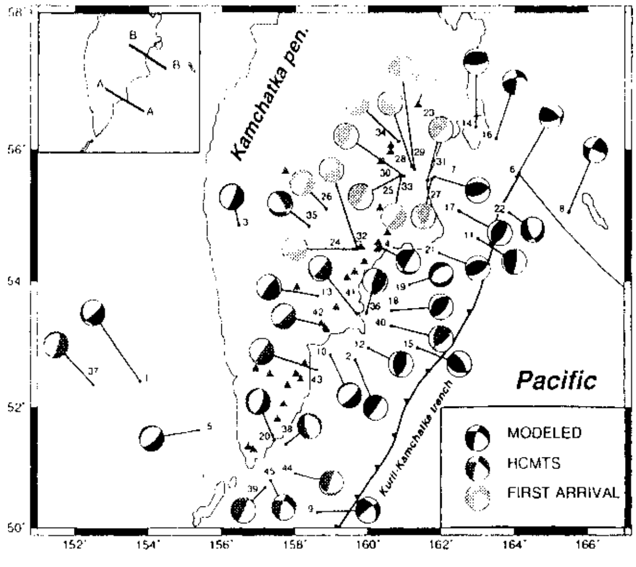

Figure 2. Lower hemisphere earthquake mechanisms. From wave form inversion (black compressional quadrant): centroid moment tensor solutions reported by Harvard University (HCMTS) *[Dziewonski et al.,* 1981; *Dziewonski and Woodhouse,* 1983] (dark gray compressional quadrant); from first arrivals (light gray compressional quadrant). The numbers identify the events in Figure 3 and Table 1. Black triangles are active volcanos. Insert shows the location of cross-sections A-A' and B-B'.

The homogeneous structure of the Wadati-Benioff zone in Kamchatka between 5°N to 55°N assessed from the local seismicity data allows us to project most of the focal mechanisms on cross-section A-A' (Figure 3a and Table 1). These focal mechanisms show thrust faulting down to the depth of ~60 km, reflecting the seismogenic contact between the Pacific and North America plates. Below this depth, the focal mechanism solutions change to down-dip compression in the upper seismic plane (Figure 3a). A deeper sheet of seismicity, ranging in depth from ~50 km to about 180 km, shows focal mechanisms with down-dip tensional axis. At depths greater than 180 km, both seismic planes seem to merge into one, where the focal mechanisms show consistently down-dip compression (numbers 1, 3 and 37 in Table 1).

Table 1. Summary of Source Parameters

Event[1]	Date[2] YMD	Latitude[3] °N	Longitude[3] °E	Depth[4] km	Strike deg	Dip deg	Rake deg	M[5]
1^{m}	640318	52.43	153.79	437	47	84	-63	6.1
2^{m*}	711124	52.77	159.66	95	165	10	40	7.1
3^{m}	720527	54.87	156.48	418	23	78	-93	5.7
4^{m}	750823	54.53	160.35	151	122	30	1	5.8
5^{m}	770921	51.63	155.37	241	47	71	-89	6.1
7^{m}	800322	55.60	161.82	77	69	58	74	5.8
10^{m*}	821114	52.84	158.98	88	47	73	-91	5.3
11^{m}	830105	54.66	163.01	13	9	75	99	5.7
12^{m}	830404	52.95	160.02	57	23	56	101	5.7
13^{m*}	830724	53.77	158.62	168	217	81	103	6.0
18^{m}	850519	53.54	160.65	55	40	58	85	5.6
19^{m*}	850525	53.95	161.14	56	232	51	-105	5.6
21^{m}	860401	54.44	161.96	56	60	56	79	5.4
29^{f}	820417	55.71	161.27	165	7	90	90	5.3
31^{f}	831001	55.55	161.62	104	45	76	90	5.0
34^{f}	860423	56.12	160.83	179	37	79	-90	4.5
36^{h}	771106	53.50	159.96	60	36	18	109	5.1
37^{h}	791230	52.37	152.52	550	245	16	-41	5.4
38^{h}	811013	51.35	157.76	101	318	27	-117	5.3
39^{h}	820808	50.69	157.20	117	279	14	164	5.1
40^{h}	830415	53.30	160.64	30	184	38	47	5.8
41^{h}	840601	53.49	159.69	102	134	21	-176	5.2
42^{h}	870706	53.32	158.69	150	225	12	-93	5.2
43^{h}	880219	52.78	158.25	112	132	13	-175	5.2
44^{h}	880725	50.92	158.00	42	101	24	-9	5.6
45^{h}	880728	50.80	157.35	104	297	53	-160	5.1

[1] Identification number of events in Figure 2 and Figure 3. Indices mark the type of events: m - focal mechanism obtained from long-period wave form inversion; f - first arrivals; h - centroid moment tensor solutions of Harvard University (HCMTS) [*Dziewonski et al.*, 1981; *Dziewonski and Woodhouse*, 1983]; * - also analyzed by *Kao and Chen* (1994].

[2] Y: year; M: month: D: day.

[3] Estimates reported by the IVK.

[4] For modeled events the depths arc from analysis of long-period wave form inversion and for the rest of events the depth are assigned as reported by the IVK.

[5] Magnitude M_w for the modeled events and m_b for the rest of events.

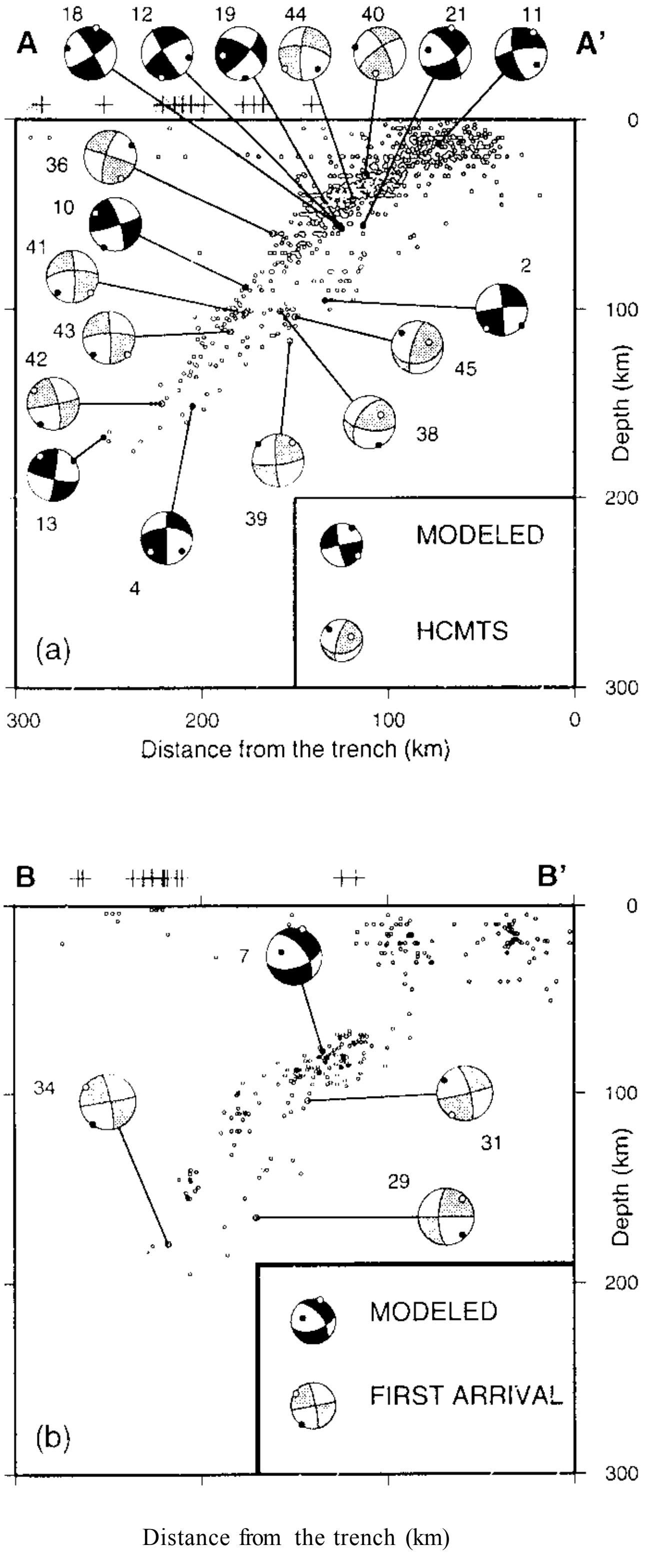

Figure 3. (a) Cross-section **A-A'**. All events recorded by the local seismic network within a band of 20 km on each side of the cross-section are selected, (b) Cross-section **B-B'**, All events within a band of 5 km on each side of the cross-section are selected. Focal mechanism solutions are shown on a side-looking lower hemispheric projection (symbols as in Figure 2). The black and white dots on the focal mechanisms are the locations of the P and T axes respectively. Numbers identify the events in Figure 2 and Table 1. Gray triangles are active volcanos. Crosses are seismic stations.

Two relatively shallow events in the upper part of the Wadati-Benioff zone (numbers 19 and 44 in Figure 3a and Table 1) show tensional mechanisms. Those tensional events are located at a depth of ~50 km, near the lower edge of the interplate contact.

Four focal mechanisms are presented on cross-section B-B' (Figure 3b). Although the distribution of the local seismicity does not reveal the double seismic zone as clearly as on cross-section **A-A'**, those four focal mechanisms certainly suggest a double-planed distribution of stresses (Figure 3b and Table 1). Unfortunately, a dearth of teleseismicaly recorded earthquakes and the diffuse distribution of local seismic stations give us no opportunity to study this area in more detail.

Discussion

It is interesting to compare the structure of the double seismic zone of Kamchatka obtained in this study with the results for other double seismic zones. The shape of the double seismic zone of Kamchatka is similar to that of Tohoku (Japan) in both the maximum depth and spatial separation of the two seismic bands *[Hcisegciwa et cil.,* 1978a, b]. Assuming that the thermoelastic stress regime of the subducting lithosphere, as defined by the subduction parameters, controls the existence and structure of double seismic zones *[Fujitci and Kanamori,* 1981*; Goto et al.*, 1985; *Kawakatsu,* 1986], this similarity is surprising considering that the subduction parameters: age **(A),** convergence velocity **(V),** and dip angle (a), are different in Tohoku (**A** = 130 m.a., **V** = 9.5 cm/yr, a = 33°) and in Kamchatka (**A** - 77 m.a., **V** = 7.7 cm/yr, a = 55") *[Cande et al.,y* 1989; *DeMets et al.*, 1990; *Hasegawa et al.*, 1978 a, b]. Probably each one of these parameters itself does not affect significantly the shape of the double seismic zones but somehow their combination might be of the same order of influence on both seismic zones that produces this similarity of shapes.

Kao and Chen | 1994] concluded that the double seismic zone in the central Kamchatka alters to a single seismic sheet of down-dip compression near 53°N. However our local seismicity data and focal mechanism solutions suggest that double seismic zone extends at 56°N. It is evident that the down-dip tensional events exist along the whole subduction zone of Kamchatka (Figure 2), in particular, the events numbered 4, 29 and 31 (Figure 2 and Table 1) lay to the north of 53°N and indicate the authenticity of the double seismic zone (Figure 3b).

A correlation between the changing in time coupling at the interplate thrust zone and the occurence of normal faulting earthquakes, immediately down-dip from the coupled interface was proposed by *Astiz et al.* [1988]. The location of tensional events numbered 19 and 44 in the upper plane of seismicity may be in favor of that model. However further study is required to understand the spatial and temporal variations in the stress regime of the Kamchatka subduction zone.

Conclusion

Our results show that a double-planed seismic zone with a dip angle of ~55° exists along most of the subduction of Kamchatka up to ~55°N, and probably 55°-56°N. The stress distribution within the Pacific plate descending beneath the Kamchatka peninsula is similar to that observed in the Tohoku (Japan) subduction zone farther south, where a sheet of tensional events lies beneath one showing down-dip compression, from ~50 km to ~200 km depth.

The maximum depth of seismogenic coupling is confirmed by the presence of thrust events down to a depth of ~60 km. Below this depth, the focal mechanisms show an abrupt change to down-dip compressional events in the upper sheet of seismicity. The lower seismic plane is represented by the down-dip tensional events at depths between ~50 km and ~180 km.

Two tensional events were discovered at the upper seismic plane, located just near the deeper edge of the interplate contact zone at a depth of -50 km. The origin of these events do not have a clear explanation and requires further detailed studies.

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