Earthquake Generating Stresses in the Kuril-Kamchatka Seismic Region Derived from Superposition of P-Wave Initial Motions

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Earthquake Generating Stresses in the Kuril–Kamchatka Seismic Region Derived from Superposition of P–Wave Initial Motions

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Abstract: The earthquake generating stress field is studied in detail for the Kuril-Kamchatka seismic region by using the data of initial motions of P-waves from earthquakes which occurred during the period from January 1964 to March 1969. The present analysis is based on the method of composite mechanism solution. Earthquakes of reverse faulting are generally found at shallow depths with few exceptions of normal faulting. The stress type of down-dip compression is prevalent everywhere at deep depths, similarly to the results for other seismic zones in the world. The stress pattern is not so simple at intermediate depths. The composite mechanism solution indicates the stress type of down-dip extension in the northern part of the Kuril seismic region. In the southern part of the Kamchatka seismic region, however, it shows down-dip compression. The earthquake generating stress field seems to change its stress pattern rather abruptly beneath the southern edge of the Kamchatka peninsula. The stresses are opposite in sense between the southernmost and the northernmost parts of the Kuril-Kamchatka region. In the direction perpendicular to the motion direction of the Pacific plate relative to the Eurasian plate, the extensional force exists at the southernmost part and the compressional force does at the northernmost part of the region.

1. Introduction

Since the hypothesis of new global tectonics was proposed by Isacks *et al.* (1968), mechanisms of major earthquakes have been analyzed (Isacks *et al.*, 1969; Katsumata and Sykes, 1969; Isacks and Molnar, 1971; Ichikawa, 1971; Stauder, 1968, 1972) to investigate relations between the orientation of principal stress axis or the direction of slip vector on the fault and the plate motion expected for the hypothesis.

The major remaining problem in the hypothesis of new global tectonics is the driving mechanisms of the plate motion. Elsasser (1967) suggested that the motion of the plates themselves is not caused by viscous coupling with the mantle beneath, but that the cold slabs beneath island arcs sink and pull the rest of the plates with them.

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It seems reasonable (McKenzie, 1969) that the cold sinking slabs act as a stress guide.

Isacks and Molnar (1971) demonstrated the idea that the descending portions of lithosphere into the mantle play an important role in driving the lithosphere, from the analysis of focal mechanisms of 204 intermediate and deep earthquakes of which solutions are precisely determined with the data of the initial motions of P- and S-waves recorded by WWSSN. They further suggested that at a seismic zone where deep earthquakes are absent, the gravitational force of the cold sinking slab makes the tension axis in the sinking slab parallel to the dip of the zone at intermediate depths. At deep depths, say 300 km or deeper, the sinking slab is resisted to its downgoing motion by hard material of the mantle, leading to compressional stress parallel to the dip of the zone.

Our previous work (Koyama *et al.*, 1973) in the northeastern part of Japan indicated that the compressional stress parallel to the dip of the seismic zone is prevalent below the depth of about 80 km. Isacks *et al.* (1969) determined the mechanism solutions of the earthquakes which occurred in the Tonga-Kermadec seismic region and concluded that the compressional stress parallel to the dip of the seismic zone is predominant at depths between 80 km and 600 km. It does not seem plausible that the cold slab as short as 80 km is able to pull the rest of the lithosphere with it. It is very important to investigate precise fields of the earthquake generating stresses for various seismic zones.

In the Kuril-Kamchatka seismic region, 9 well determined mechanism solutions of deep and intermediate earthquakes are tabulated in the work of Isacks and Molnar (1971). Their results show that the mechanism solutions of intermediate earthquakes in the south Kamchatka and the middle part of the Kuril islands indicate the stress type of down-dip compression. On the contrary, the mechanism solutions of intermediate earthquakes are of down-dip extension type in other regions. It may be difficult to discuss in detail the earthquake generating stress field in the Kuril-Kamchatka region only from the 9 solutions.

Oike (1971) estimated for 51 active seismic zones over the world the earthquake generating stress fields at intermediate and deep depths from the smoothed radiation patterns of P-wave initial motions by the method developed by Aki (1966). All the earthquakes of intermediate and deep depths in the Kuril-Kamchatka seismic region are gathered into one group, and the smoothed radiation pattern obtained for this region shows down-dip compression between the depths of 100 km and 500 km.

This paper discusses details of earthquake generating stress fields in the Kuril-Kamchatka seismic region by using the data of initial motions of P-waves. The method of the analysis is similar to that in previous papers (Horiuchi *et al.*, 1972; Koyama *et al.*, 1973; Izutani *et al.*, 1975). The materials are taken from the bulletins of I.S.C. All the earthquakes that occurred in the Kuril-Kmachatka seismic region during the period from January 1964 to March 1969 are adopted as the data of analysis.

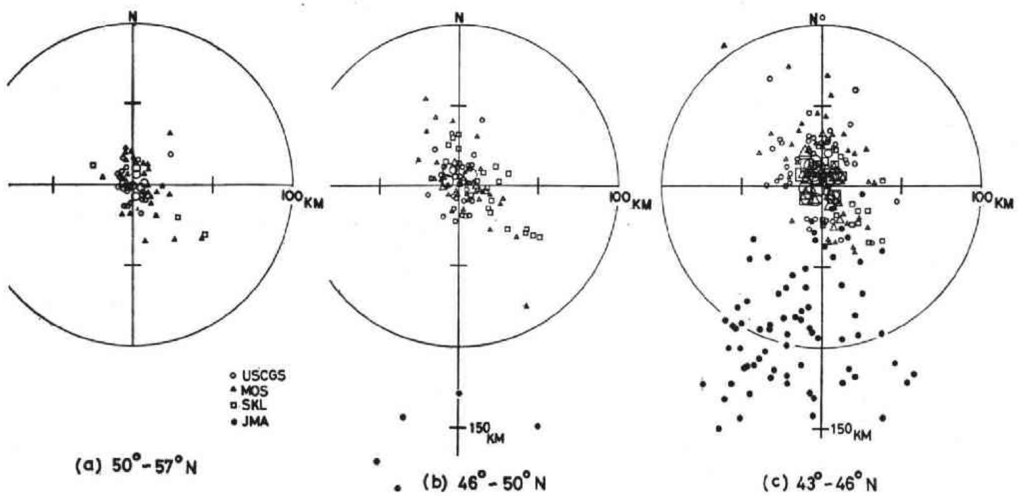


Fig. 1. Comparisons of the epicenter locations determined by I.S.C. with those by U.S.C.G.S., MOS, J.M.A., and S.K.L. The epicenters by I.S.C. are taken to be the origin of the coordinates for shallow earthquakes with magnitude greater than 5.0 in the period from 1964 to 1968. Symbol of small size; an epicenter for one shock. Symbol of medium size; epicenters for three shocks. Symbol of large size; epicenters for five shocks. Open circle; U.S.C.G.S. Solid circle; J.M.A. Triangle; MOS. Square; S.K.L.

2. Reliability of the Data

The reliability of determination of the epicenters by I.S.C. is checked by comparing them with those determined by U.S.C.G.S., MOS, J.M.A., and by S.K.L. Differences in the locations of epicenters determined by I.S.C. from those by other networks for the same earthquakes are plotted in Figs. 1 (a), (b), and (c).

The locations of the epicenters determined by J.M.A. are systematically shifted toward the Japan island by about 100 km on an average in comparison with those by other networks as seen in Fig. 1. It has been pointed out that the epicenters of earthquakes in this region are determined not so accurately by J.M.A., since most of the J.M.A. stations are situated far from this seismic region and the azimuthal distribution of the stations is limited to a narrow range. In addition, the cause of the discrepancies may be due to the existence of the high velocity zone which the seismic rays to Japanese stations pass through (Utsu, 1967).

Most of I.S.C. epicenters agree with those by U.S.C.G.S., MOS, and S.K.L. within 30 km in relative distance. It may be concluded that the error of the epicenter determination by I.S.C. is probably less than 30 km. We thus decide not to use the J.M.A. hypocenters but to use the I.S.C. hypocenters for our analysis.

The reliability of readings of the initial P-motion reported in the bulletins of I.S.C. is examined as follows: We numerically determine mechanism solutions individually for earthquakes in 1964 in the Kuril-Kamchatka seismic region, for which the number of P-wave data available is larger than 50. Figs. 2(a) and (b) show the relation of the score to the number of readings of the initial P-motion and the relation of the score to

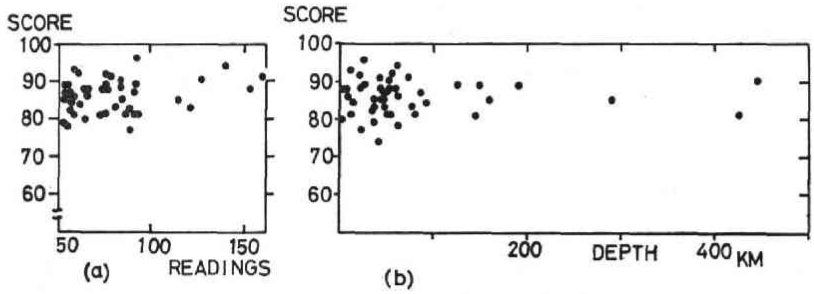


Fig. 2. The scores in the best fit solutions for individual earthquakes. The best fit solution is obtained for each earthquake for which the number of readings is more than 50.
(a): The score versus the number of P-wave data.
(b): The score versus the focal depth of earthquake.

the focal depth of earthquake, respectively, where the score is defined as

$$\mathrm{SCORE} = 100(1 - N_{inc}/N_{tot}) ,$$

N_{inc} being the number of inconsistent data in the best fit solution and N_{tot} the total number of the data. The results suggest that about 15% of the readings reported in the bulletins of I.S.C. are inconsistent, and that the score depends neither on the number of the readings nor on the focal depth of earthquake. It is concluded that the average score is about 85 even for a single earthquake regardless of its magnitude.

3. Method of Analysis

An analysis is made of all the earthquakes that occurred during the period from January 1964 to March 1969 in the Kuril-Kamchatka seismic region from 43°N to 57°N. This seismic region is divided into 50 sub-regions; 42 sub-regions for depths shallower than 80 km and 8 for intermediate and deep depths.

For depths shallower than 80 km, four ranges of the depth are adopted at an interval of 20 km. Then, for each depth range, the region is further divided into sub-regions by taking into consideration the epicenter distribution of the earthquakes. In doing this an attention is paid not to divide the aftershocks of a large event into two groups. Isolated earthquakes are omitted in the analysis.

For depths deeper than 80 km, initial P-motions from each earthquake for which the number of readings of initial P-motions is more than 25 are plotted on the focal sphere. Then, comparing the distributions of initial P-motions on focal spheres for the earthquakes with one another, the seismic region is divided into 8 sub-regions so that the earthquakes which show similar distributions of the initial P-motions may be grouped into one.

The initial P-data from earthquakes occurring in each sub-region are superposed on a focal sphere and the best fit solution of focal mechanism is obtained, where the number of inconsistent stations in the best fit solution being expressed by N_{inc}^{o}. We seek a set of solutions that satisfy $N_{inc} \leqq (1+0.1)N_{inc}^{o}$, where N_{inc} is the number of inconsistent stations in a solution. The positions on the focal sphere of the pressure (tension) axis in these solutions cover some domain, which will be called the domain of pressure (tension) axis henceforth. The earthquake generating stress fields in the following discussions are estimated from these domains of the pressure and tension axes, and their reliabilities are graphically expressed by the areas of the domains.

The hypothesis of new global tectonics suggests that an oceanic lithosphere is sinking below island arcs from trenches. It is expected from the hypothesis that the fault plane for shallow earthquakes near the trench should be parallel to the trench axis. The nodal plane solutions for shallow earthquakes are re-calculated by assuming that one of the nodal planes of P-waves is parallel to the trench axis for the cases where the scores are greater than 80. It should be recalled that this assumption is not used for the estimation of earthquake generating stress field, as stated in the previous paragraph.

4. Results

Shallow earthquakes

The topographic feature of the Kuril-Kamchatka seismic region is shown in Fig. 3. The focal mechanism solution and the domains of the pressure and tension axes are numerically calculated from the superposed data of P-wave initial motions from earthquakes in each sub-region, and are shown in Figs. 5, 7, and 9. The calculated results are omitted for the sub-regions where the number of the superposed data is less than 50.

The epicenters of earthquakes with depths between 0 km and 80 km in the south Kuril region are shown in Figs. 4(a), (b), (c), and (d), where the abscissas are taken along the line CD in Fig. 3. The obtained results for the pressure and tension axes are exhibited in Figs. 5(a) and (b) for the depth ranges of 0 km to 40 km and of 40 km to

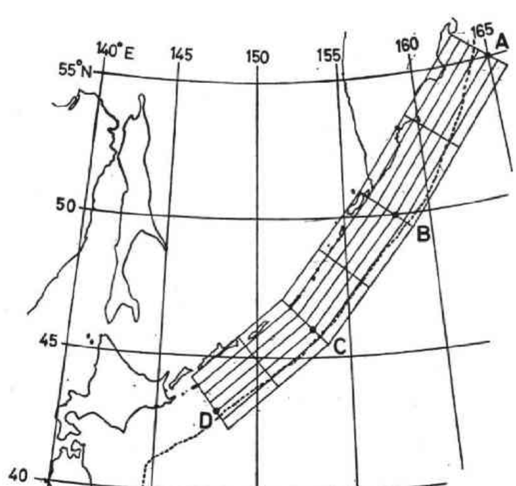


Fig. 3. Illustration for the division of the Kuril-Kamchatka seismic region. The trench axis is represented by dotted line. Lines parallel to the trench axis are drawn at an interval of 50 km simply for the reference sake. The lines AB, BC, and CD are referred to in Figs. 4, 6, 8, and 10.

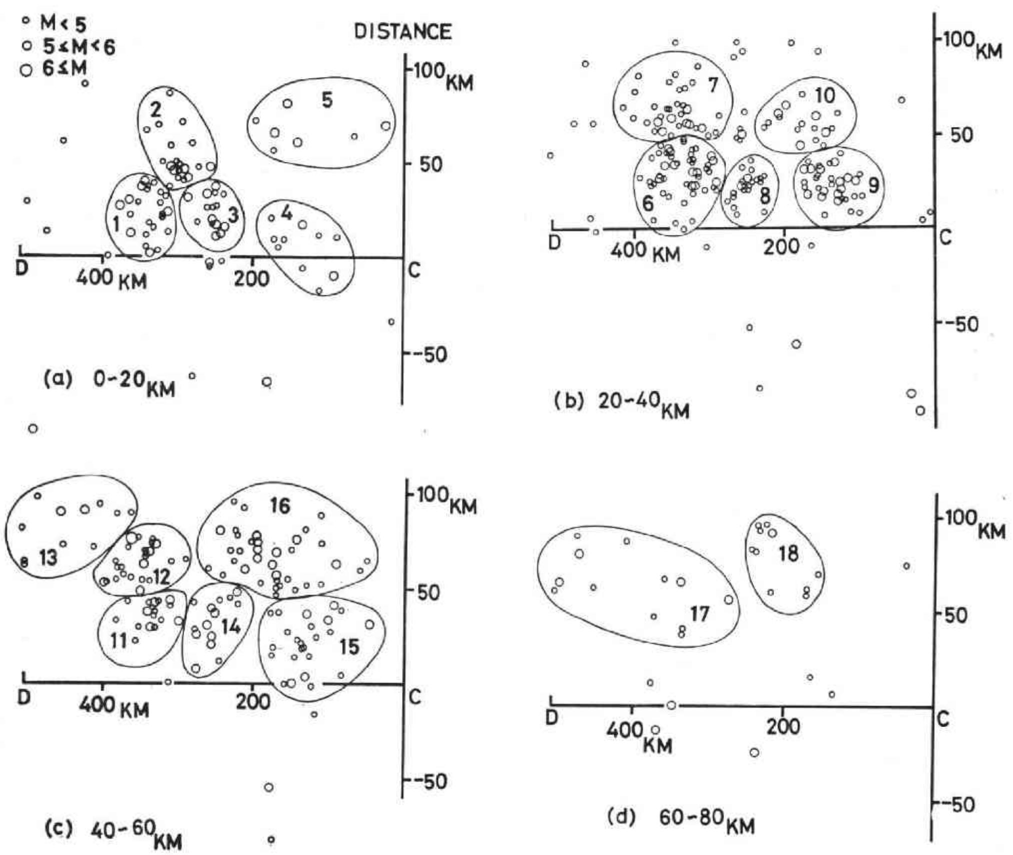
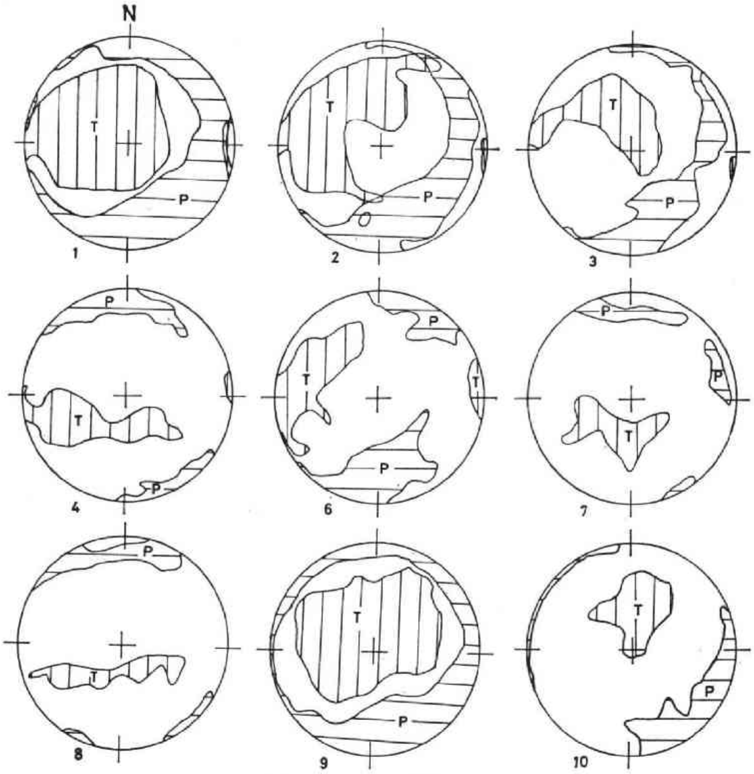


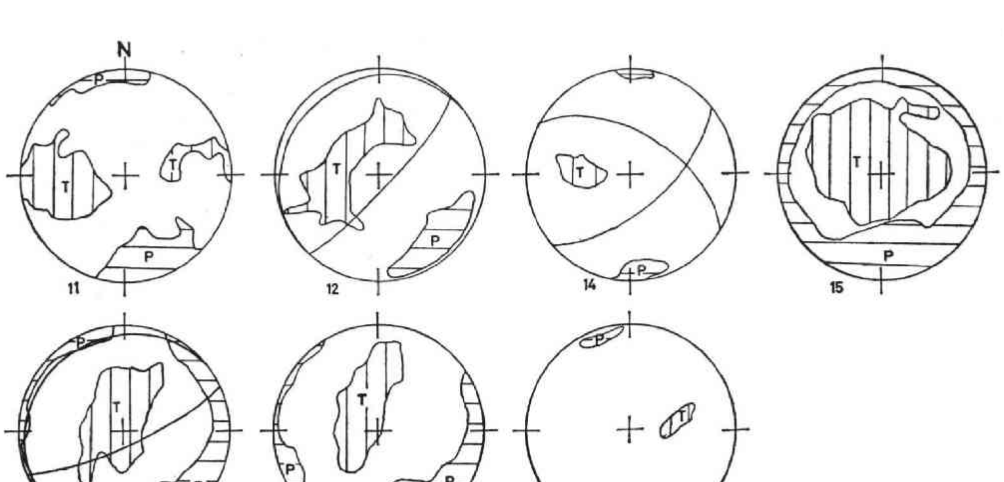
Fig. 4. Epicenter locations of earthquakes and divided sub-regions in the south Kuril seismic region along the line CD shown in Fig. 3. The sizes of circles indicate the earthquake magnitudes determined by I.S.C. Small size; Mag<5. Medium size; 5≤Mag<6. Large size; 6≤Mag. This convention is applied also to Figs. 6 and 8.

80 km, respectively. It is seen from these figures that the domains of both the axes are wide in area, and that the earthquake generating stress fields are not definitely determined. It is noticed, however, that we cannot find any stress type of normal faulting in which the pressure axis is in nearly vertical.

In spite that Sub-Region Nos. 6 and 8 are in neighbor to each other along the direction parallel to the trench axis, the focal mechanisms in the two sub-regions are quite different, as illustrated in Fig. 5(a). The focal mechanisms of reverse faulting are seen in Fig. 5(b) for both Nos. 12 and 16. If the plane nearly horizontal is taken as the fault plane, the fault motion is of underthrust type. This suggests that the oceanic lithosphere moves under the lithosphere of the islands, as generally found for earthquakes in various seismic zones in the island arcs. Sub-Region Nos. 11 and 14 are adjacent to each other along the direction parallel to the trench axis and are located between the trench and the sub-regions of Nos. 12 and 16. The mechanism solution for the sub-region of No. 14 is well determined, where the number of the superposed data is 589. The tension axis is nearly east to west plunging about 45° toward west.



(a) 0 km to 40 km.



(b) 40km to 80 km.

Fig. 5. Composite mechanisms for the sub-regions defined in Fig. 4. Closed curve enclosing P or T shows the domain of the pressure or tension axis. Numerals indicate Sub-Region Numbers in Fig. 4. The lower hemisphere of focal sphere is projected by the equal area projection.

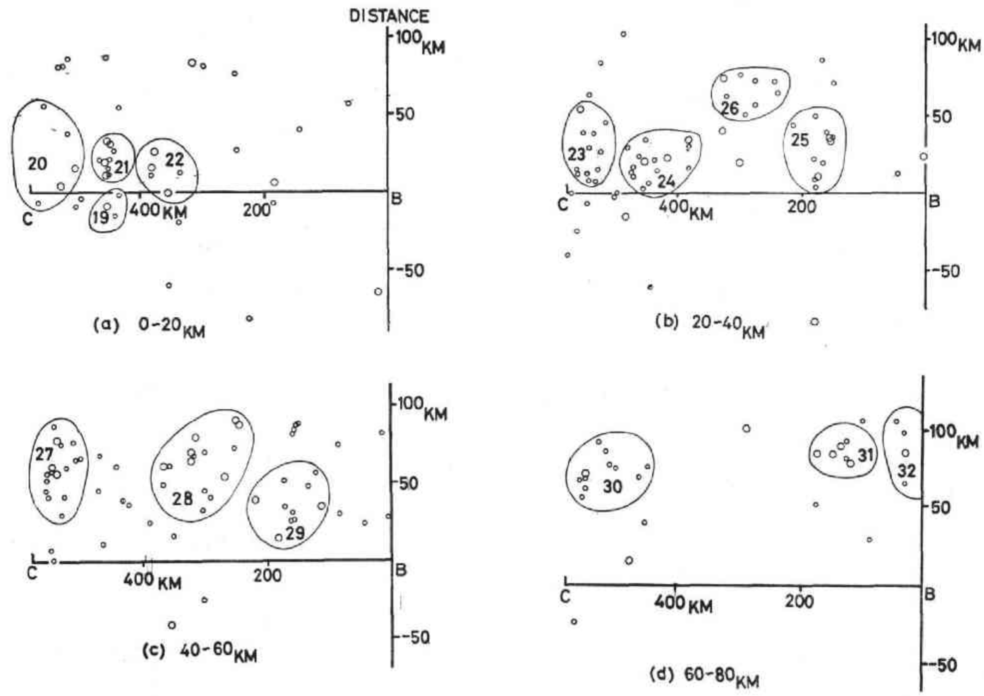


Fig. 6. Epicenter locations of earthquakes and divided sub-regions in the north Kuril seismic region along the line BC.

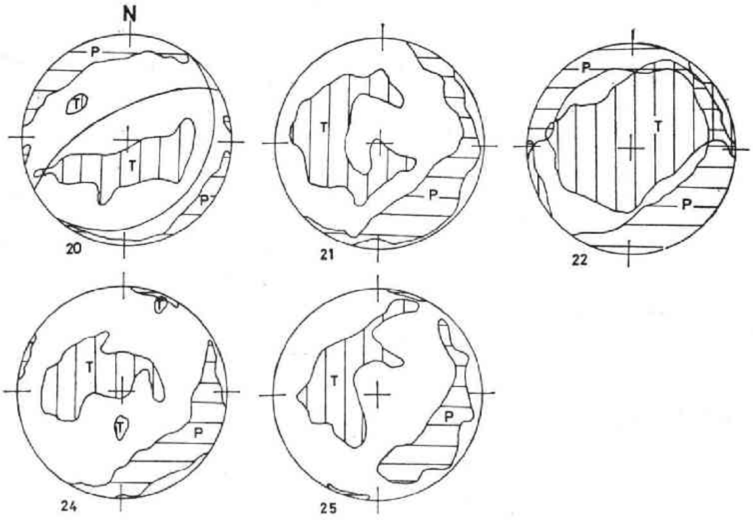
In other words, the focal mechanism for No. 14 is reverse-faulting type but not underthrusting type. The result for No. 11 is considered to be similar to that for No. 14.

Figs. 6(a), (b), (c), and (d) show the epicenters of earthquakes in the north Kuril region for the depth ranges of 0 km to 40 km and of 40 km to 80 km. The obtained results illustrated in Figs. 7(a) and (b) indicate that the tension axis is nearly vertical and the pressure axis is nearly horizontal, though the estimation of the focal mechanism solutions is not quite reliable. Particularly for the depth range between 40 km and 80 km, the focal mechanisms are similar to one another, as seen in Fig. 7(b). No indication is found for the existence of the stress type of normal faulting in the north Kuril region.

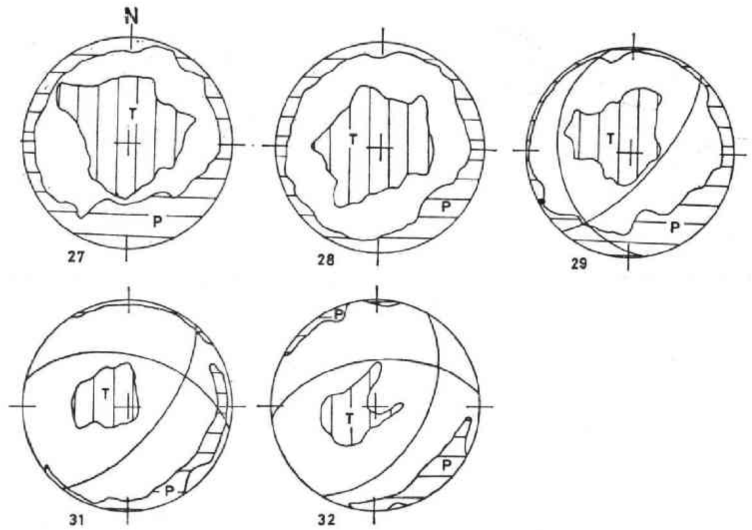
The epicentral distributions in the Kamchatka seismic region are illustrated in Figs. 8(a) and (b) for depths from 0 km to 40 km and in Figs. 8(c) and (d) for those from 40 km to 80 km. The focal mechanism of reverse faulting is evidently predominant as is found in Figs. 9(a) and (b).

Intermediate and deep earthquakes

Figs. 10(a), (b), and (c) show the epicentral distributions of intermediate and deep earthquakes with focal depths deeper than 80 km in the sub-regions of Nos. 43 to 50, where the abscissas are taken along the lines AB, BC, and CD in Fig. 3. The calculated results for the pressure and tension axes for the above sub-regions are



(a) 0 km to 40 km.



(b) 40 km to 80 km.

Fig. 7. Composite mechanisms for the sub-regions defined in Fig. 6.

exhibited in Fig. 11.

Sub-Region Nos. 43 and 44 are located in the southern part of the Kuril seismic region and their depth ranges are from 80 km to 140 km and from 140 km to 200 km, respectively. There is a distinct difference, as indicated in Fig. 11, in stress type between the two sub-regions, though the domains of both the pressure and the tension axes are wide in area. The calculated result for No. 45 with the depth range of 80 km to 200 km, located at the northeast of the sub-regions of Nos. 43 and 44, shows that the tension axis is nearly horizontal in the north to the south.

The tension axis beneath the east Hokkaido is directed also in the north to the

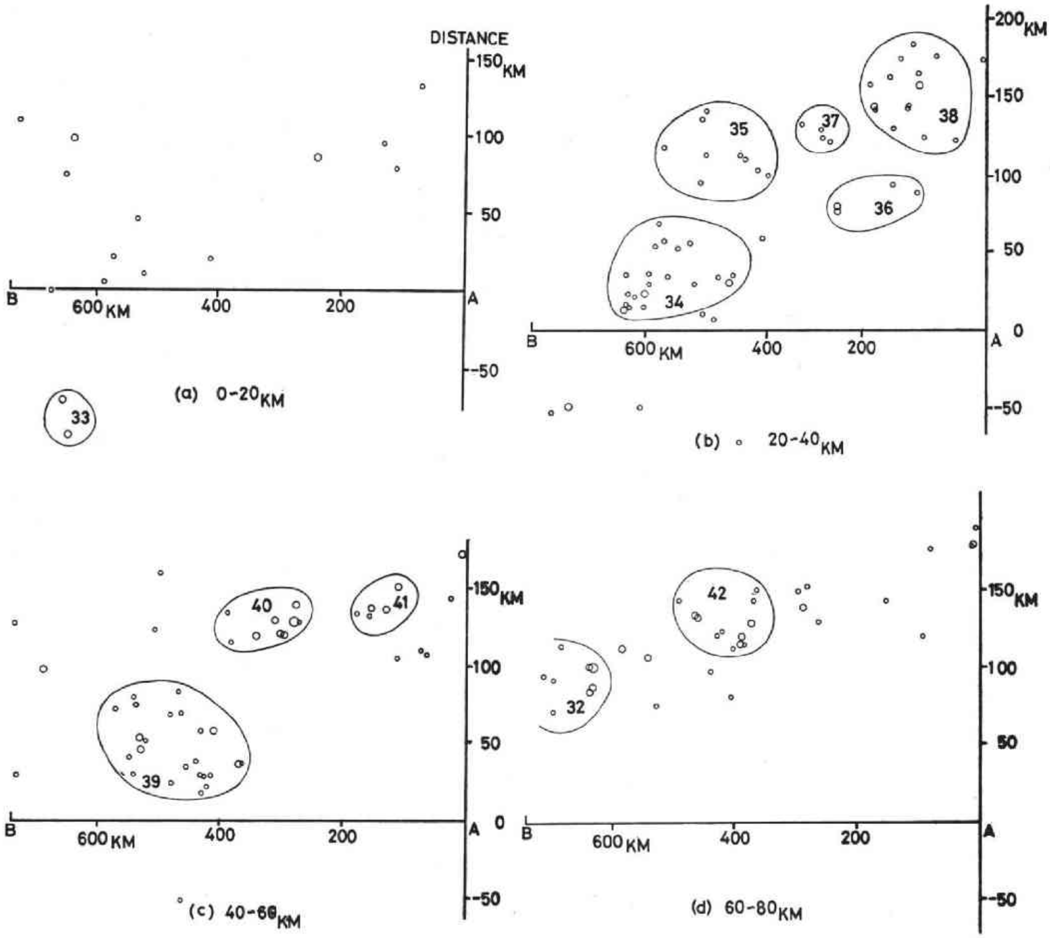
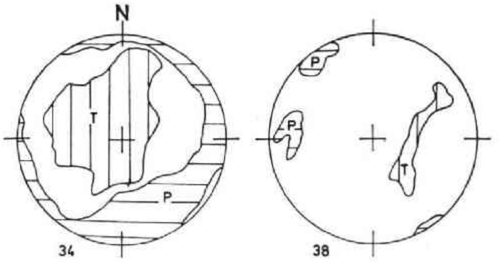


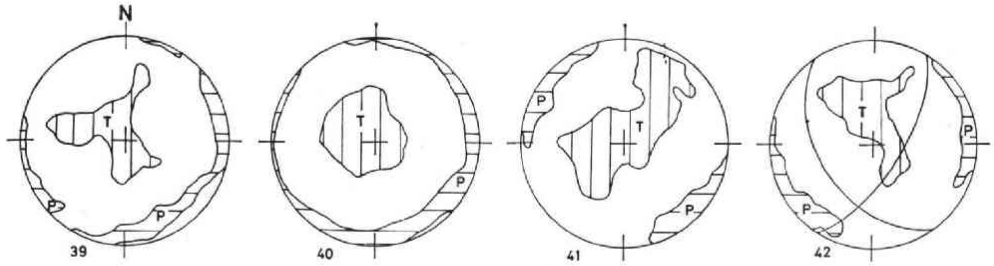
Fig. 8. Epicenter locations of earthquakes and divided sub-regions in the Kamchatka seismic region along the line AB.

south in the mechanism solutions of individual intermediate earthquakes obtained by Isacks and Molnar (Nos. 123 to 127 in their paper). There is a difference in orientation, however, between the pressure axis for the east Hokkaido and that for Sub-Region No. 45 near the middle part of the Kuril region. Although the earthquake generating stress fields among the east Hokkaido region and the sub-regions of Nos. 43, 44, and 45 are different from one another, the tension axis tends to align in the direction from the north to the south in the southern part of the Kuril seismic region including the east Hokkaido region.

The stress type at intermediate depths in the north Kuril region, namely No. 47, is of down-dip extension. It is noticed that deep earthquakes below 300 km hardly occur in this region. On the contrary to the result for No. 47, the earthquake generating stress is the type of down-dip compression for No. 48 in the south Kamchatka seismic region. This result for No. 48 is consistent with the focal mechanism of No.

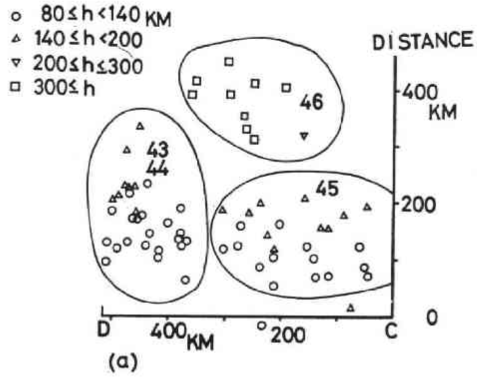


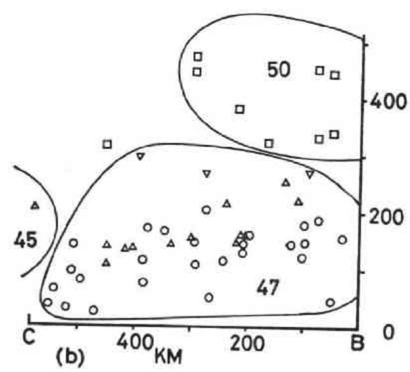
(a) 0 km to 40 km.



(b) 40 km to 80 km.

Fig. 9. Composite mechanisms for the sub-regions defined in Fig. 8.





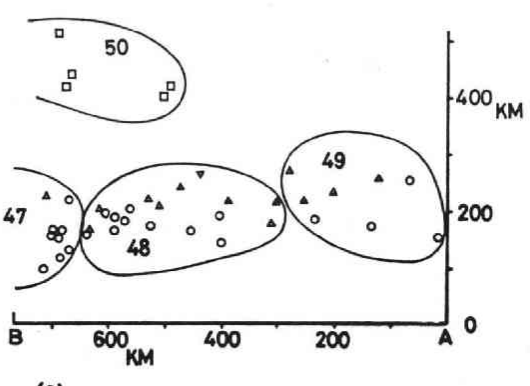


Fig. 10. Epicenter locations of the intermediate and deep earthquakes and divided sub-regions in the Kuril-Kamchatka seismic region. Open circles; 80 km to 140 km. Upward-pointing triangles; 140 km to 200 km. Downward-pointing triangles; 200 km to 300 km. Squares; below 300 km.

(a): Sub-regions in the south Kuril seismic region along the line CD in Fig. 3.

(b): Sub-regions in the north Kuril seismic region along the line BC.

(c): Sub-regions in the Kamchatka seismic region along the line AB.

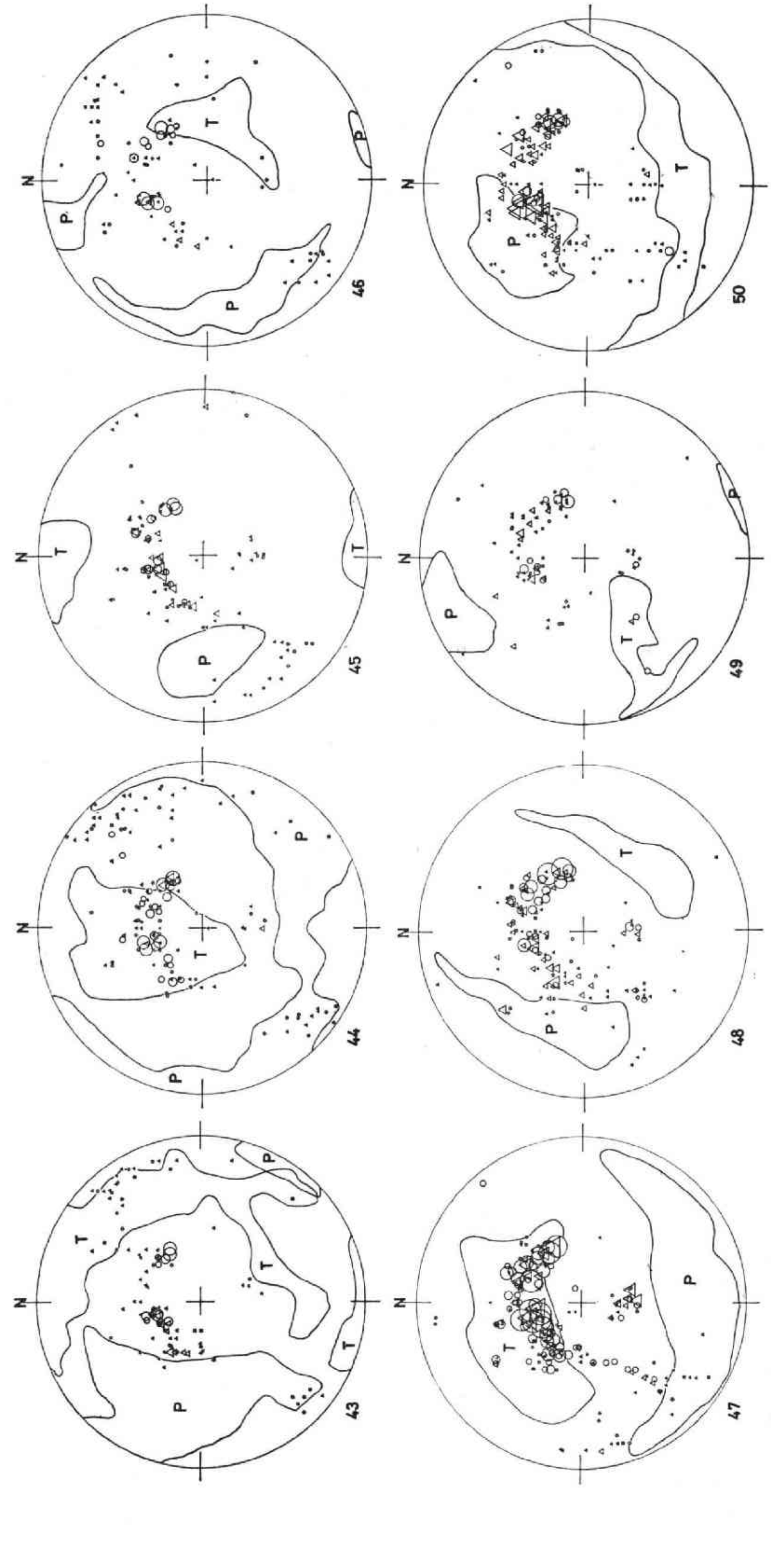


Fig. 11. Composite mechanisms for the sub-regions at intermediate and deep depths defined in Fig. 10. Compressions or dilatations of initial P-motions are represented by circles or triangles. The sizes of the symbols indicate the numbers of readings, that is, 1, 3, 5, and 10 readings.

117 in Isacks and Molnar's paper.

The calculated result for Sub-Region No. 49, at intermediate depths in the north Kamchatka seismic region, shows that the solution is fairly well determined. The pressure axis is directed from southwest to northeast plunging toward southwest. The earthquake generating stress field is not classified as a down-dip compression or not as a down-dip extension either. This is similar to the result for Sub-Region No. 45 in particular at intermediate depths in the south Kuril seismic region, but the senses of the stresses in the two sub-regions are opposite to each other. It is interesting to compare the result for No. 45 with that for shallow earthquakes in the sub-region of No. 14 which is located just above the sub-region of No. 45. The comparison shows that the earthquake generating stresses are opposite in sense between the two sub-regions (*cf.* Fig. 5(b)).

The calculated results for Nos. 46 and 47, at deep depths in the Kuril and the Kamchatka regions, respectively, indicate that the type of the stress fields is down-dip compression, similarly to the results in other seismic zones in the world. Further, the composite mechanism solution for No. 46 is consistent with the mechanism solution obtained by Isacks and Molnar for an earthquake (No. 116 in their paper) in this sub-region. It is interesting that the homogeneous stress field at deep depths throughout the Kuril-Kamchatka seismic region is markedly contrasted with the complicated one at intermediate depths.

5. Conclusion

The earthquake generating stress fields in the Kuril-Kamchatka seismic region are studied in details from the initial motions of P-waves by the method of composite mechanism solution. The main results are briefly summarized as follows.

Earthquakes of reverse faulting are generally found at shallow depths throughout the seismic region. The focal mechanism of normal faulting is not obtained for shallow depths in the present study. This result is similar to that for the region off the coast of Fukushima Prefecture, the northeastern part of Japan. It is different, however, from the result obtained by Koyama *et al.* (1973) for the region off the coast of Iwate Prefecture, north of the region stated above, and that by Stauder (1968, 1972) for the Aleutian islands, in which the earthquakes of normal faulting are widely found below the axis of the trench.

The earthquake generating stress fields are quite complicated at intermediate depths. In the north Kuril region where deep earthquakes below 250 km hardly occur, the stress type is of down-dip extension. In the south Kamchatka region, on the other hand, down-dip compression is prevalent below the depth of 80 km. In addition, no apparent aseismic zone between the two seismic regions is found from the hypocentral distribution of intermediate earthquakes. These suggest that the earthquake generating stress field abruptly changes its stress pattern beneath the southern edge of the Kamchatka peninsula. This complexity of the stress field in this region may not be accounted for only by the simple idea that the gravitational force of the cold sinking slab makes the tension axis parallel to the dip of the seismic zone at intermediate depths. In the northernmost part of the Kuril-Kamchatka seismic region, a predominant compressional-force seems to exist in the horizontal direction perpendicular to such a relative motion between the Pacific and the Eurasian plates as suggested by Le Pichon (1968), Chase (1972), and by Minster *et al.* (1974). In the southernmost part of the Kuril-Kamchatka region and in the east Hokkaido seismic region, however, a predominant extensional-force exists in the same horizontal direction as stated above.

The composite mechanism solutions indicate the stress type of down-dip compression everywhere at deep depths throughout the Kuril-Kamchatka region. This result is consistent with those obtained for other deep seismic zones over the world by, *e.g.*, Isacks and Molnar (1971) and Oike (1971).

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