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ABSTRACT


The focal mechanism of the Tokachi–Oki earthquake of 1968 ($M_s \sim 8.0$) and its aftershocks is studied on the basis of P-wave first motion, S-wave polarization angle, and long-period surface-wave data. The major objective is to understand the nature of the deformation of the oceanic lithosphere at a junction of two trenches. The main shock is interpreted as a low-angle thrust fault with a considerable strike-slip component, the oceanic side underthrusting beneath the continent. This type of faulting is common with other great earthquakes of the northwestern Pacific belt, and is considered to represent a major tectonic movement in this region. The largest aftershock ($M_s \sim 7.5$), that occurred about 10 hours after the main shock, suggests a faulting in which the slip direction is almost opposite to that of the main shock. Other aftershocks are grouped into either the main shock type or the largest aftershock type. A simple model is proposed to explain this unusual aftershock sequence. In this model a contortion of the underthrusting lithosphere at a junction of two trenches, the Kurile and the Japan trenches respectively, plays a key role. Because of this contortion of the lithosphere, the source region of the 1968 Tokachi–Oki earthquake interacts mechanically with a neighboring region where the 1952 Tokachi–Oki earthquake occurred. This interaction causes aftershocks whose faulting is in a direction opposite to that of the main shock. The source parameters of the main shock are as follows: plane $a$ (fault plane) dip angle $= 20^\circ$, dip direction $= S66^\circ W$; plane $b$ dip angle $= 78^\circ$, dip direction $= S60^\circ E$; seismic moment $= 2.8 \times 10^{24}$ dyne cm; slip dislocation $= 4.1$ m; stress drop $= 32$ bar; strain drop $= 0.71 \times 10^{-4}$; strain energy release (residual strain is assumed to be zero) $= 1.0 \times 10^{24}$ erg. In these calculations, the fault dimension and the rigidity are assumed to be $100 \times 150$ km$^2$ and $4.5 \times 10^{14}$ dyn/cm$^2$ respectively.

INTRODUCTION

A large earthquake ($M_s \sim 8.0$) occurred off the coast of Tokachi, Hokkaido, on May 16, 1968. The epicenter of this earthquake is located at $40.84^\circ N$ $143.22^\circ E$, and it is in the neighborhood of the junction of the Kurile and the Japan trenches. Therefore, elucidation of the focal mechanism of this large earthquake is of unique importance for understanding the mode of the deformation of oceanic lithospheres at such junctions. Although the deformation of oceanic lithospheres at trenches is usually pictured as a simple bending (e.g., Isacks et al., 1968), it is not at all clear how the oceanic-lithosphere deforms at a junction where two trenches meet.
This paper presents a detailed analysis of seismic data obtained for this particular earthquake in an attempt to obtain a most direct clue to the understanding of the nature of such deformation.

DATA

Actual-size copies of long-period seismograms at almost all the WWSSN* stations are used. Three earthquakes, the main shock and the two largest aftershocks that occurred within 24 hours after the occurrence of the main shock, are studied (see Table I). For the main shock, the first-motion data and multiple surface-wave data are used, and for the two aftershocks, the first-motion data and the S-wave polarization angles are used. The S-wave polarization angles are obtained from the initial half cycle of S waves. Since only stations at distances larger than 45° are used, no correction is made for the effect of the free surface on the polarization angle. The directions of the first motions and the polarization angles are shown in Fig. 1–3 on the Wulff grid. The lower half of the focal sphere is projected.

TABLE I
Earthquake data

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>Origin time</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Depth (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main shock</td>
<td>May 16, 1968</td>
<td>00h 48 55.4</td>
<td>143.22°E</td>
<td>40.84°N</td>
<td>7.1</td>
</tr>
<tr>
<td>Largest aftershock</td>
<td>May 16, 1968</td>
<td>10h 39 01.6</td>
<td>142.67°E</td>
<td>41.47°N</td>
<td>33</td>
</tr>
<tr>
<td>Second-largest aftershock</td>
<td>May 16, 1968</td>
<td>23h 04 54.7</td>
<td>143.08°E</td>
<td>39.83°N</td>
<td>37</td>
</tr>
</tbody>
</table>

For the analysis of surface waves, we mainly used multiple Love and Rayleigh waves, G3 and R3. In order to obtain as uniform an azimuthal coverage as possible, the data on G2, G4, R2 and R4 are added wherever possible. All the surface-wave trains are equalized to a uniform propagation distance of 5π/2 by the method described in Kanamori (1970a).

In addition to this equalization, two kinds of filtering are applied to the seismograms, as follows: First, the seismograph response is modified from that for the actual 15 (pendulum period) — 100 (galvanometer period) system to that for a virtual 30 (pendulum period) — 100 (galvanometer period) system. Since the long-period seismographs used in the previous studies (Kanamori, 1970a, b) were of 30—100, it is more convenient to arrange the present results in conformity with the previous results. This modification is made numerically on the frequency domain. Second, shorter period components are removed by applying a filter \( S_3 S_5 \) (\( S_i \) denotes an operation of unweighted average over \( i \) points) to seismograms sampled at a 10 sec interval. This filter effectively removes components whose periods are shorter than 50 sec. The filtered and equalized seismograms thus obtained are shown in Fig. 4 and 5. These presentations can be compared directly with similar presentations given in Kanamori (1970a, b).

*World-Wide Standardized Seismograph Station Net.
Fig. 1. Stereographic projection (lower hemisphere) of the first-motion data of the main shock. The error-bars attached to the data for four stations nearest to the epicenter indicate the uncertainty in the focal depth.

Fig. 2. Stereographic projection (lower hemisphere) of the first-motion data and S-wave polarization angles obtained for the largest aftershock. The nodal planes are determined on the basis of the S-wave polarization angles. The error-bars attached to the data for four stations nearest to the epicenter indicate the uncertainty in the focal depth.

Fig. 3. Stereographic projection (lower hemisphere) of the first-motion data and S-wave polarization angles obtained for the second-largest aftershock. The nodal planes are determined on the basis of the S-wave polarization angles. The error-bars attached to the data for three stations nearest the epicenter indicate the uncertainty in the focal depth.

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Fig. 4. Rayleigh waves (R3) equalized to a propagation distance of $\Delta = 5\pi/2$. Tokachi–Oki earthquake, May 16, 1968. The vertical scale gives the trace amplitude on the standard 30–100 long-period seismograms with a magnification of 1500.

INTERPRETATION

The interpretation of the first-motion data and the polarization angles is straightforward. For the two aftershocks, we determine the nodal planes on the basis of the polarization angles. A double-couple model is assumed. For this purpose, a computer program developed by Hirasawa (1966) is used. For the second-largest aftershock (Fig. 3), the two nodal planes thus determined are perfectly consistent with the first-motion data, supporting the double-couple model. This solution represents an almost pure thrust faulting.

The solution for the largest aftershock (Fig. 2) based on the polarization angles is also consistent with the first-motion data. Comparing the first-motion data for the main shock with those for the two aftershocks, it is remarkable that the main shock and the second-largest aftershock are characterized by a similar thrust faulting, while the largest aftershock suggests a faulting characterized by a displacement in the opposite direction. This aftershock is by far the largest ($M_s = 7.5$) among all other aftershocks.

For the main shock, the S-wave polarization angles cannot be determined because of too-large amplitudes. We therefore combine the first-motion data and the surface-wave data to obtain the fault plane solution. It has been shown (Kanamori, 1970a, b) that the long-period P-wave data and the surface-wave data can be combined without conflict to
obtain a fault plane solution. For this earthquake, the first-motion data can determine one nodal plane unambiguously as shown in Fig. 1 (dip direction $\phi = 120^\circ$; dip angle $\delta = 78^\circ$). We will determine, by the technique described in Kanamori (1970a), the other nodal plane on the basis of the surface-wave data given in Fig. 4 and 5. The Love-wave radiation pattern is four-lobed while the Rayleigh-wave radiation pattern is two-lobed. Although these radiation patterns are very similar to those obtained for the Kurile Islands earthquake (Kanamori, 1970a), and suggest a dip-slip faulting, one important difference should be noted: for the Kurile Islands earthquake the nodal directions of Rayleigh-wave, Love-wave and P-wave radiation patterns coincide with one another, while for the Tokachi–Oki earthquake, the nodal directions of the Love-wave radiation pattern are in the N–S and E–W directions, and they do not coincide with the strike of the P-wave nodal plane, N30$^\circ$E. This difference suggests that, unlike the Kurile Islands earthquake, the Tokachi–Oki earthquake has a considerable strike–slip component. A superposition of a strike–slip component rotates the nodal directions of surface-wave radiation patterns with respect to the strike of the P-wave nodal plane. Another important factor which controls the surface-wave radiation is the focal depth. We let a point source represent a finite fault, and regard the depth of the point source as the average depth of the fault. The depth of
the point source affects mainly the amplitude ratio of Love to Rayleigh waves. With these preliminary considerations, we compute synthetic seismograms of Love and Rayleigh waves for a variety of fault geometries and depths, with one P-wave nodal plane restrained. The method and the earth model are identical to those used in Kanamori (1970a). The same filterings as those applied to the equalized seismograms in Fig. 4 and 5 are applied. After trial and error, we find that a double-couple source whose P-wave nodal planes are shown in Fig. 1 can explain the observed radiation patterns of both Love and Rayleigh waves. As shown in Fig. 1, this solution is consistent with the first-motion data. The depth of the point source is varied from 16 to 53 km; a depth of 33 km is found to explain best the observed amplitude ratio of Love to Rayleigh waves. The synthetic seismograms calculated from this model at azimuths of each station are shown in Fig. 6 and 7 to be compared with the observed seismograms given in Fig. 4 and 5. The agreement is quite reasonable. From a direct comparison of amplitude between the observed and synthetic seismograms, a seismic moment of $2.8 \times 10^{28}$ dyn·cm is obtained for this earthquake; synthetic seismograms shown in Fig. 6 and 7 are computed for this moment. Note that this moment is about 1/3 of that for the Kurile Islands earthquake of 1963 ($M_s = 8.3$), and is about 1/30 of that for the Alaska earthquake of 1964 ($M_s = 8.5$).
Fig. 7. Synthetic Love waves (G3) at a propagation distance of $\Delta = 5\pi/2$ (see the caption for Fig. 6).

The focal depth of this earthquake has been determined only poorly on the basis of body-wave arrival times. The Japan Meteorological Agency (JMA) restrained it at 0 km, and the U.S. Coast and Geodetic Survey (USCGS) determined it at 7.1 km. Thus, it seems that the initial break occurred at a very shallow depth and the fault plane extends to a depth of 50 km or so, the average being 33 km. Since the azimuthal coverage of the surface-wave data is very dense and uniform, and one of the P-wave nodal planes is rigidly constrained, the solution given in Fig. 1 is constrained to a very narrow range, though the uniqueness of the solution cannot be completely guaranteed.

In Fig. 4 and 5, a slight asymmetry is observed for the radiation patterns of surface waves; for Rayleigh waves, the amplitude is slightly larger at northwestern stations, and for Love waves it is larger at northern stations. These asymmetries can be interpreted as due to the effect of rupture propagation over a finite distance. A similar but significantly larger asymmetry was observed for the Kurile Islands earthquake, and it was interpreted as a result of a rupture propagation over a distance of 250 km with a velocity of 3.5 km/sec. The smaller asymmetry observed for the Tokachi–Oki earthquake suggests a smaller rupture length or a bilateral rupture propagation. Although the present data cannot resolve the details of the rupture geometry, it can be shown that a unilateral rupture propagation over a distance of 150–200 km towards north to northwest can explain the observed asymmetry, the rupture velocity being assumed as 3.5 km/sec.

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Fig. 8. Aftershocks of the 1968 Tokachi-Oki earthquake within the 24 hours after the main shock.

The present result of the source geometry differs significantly from the preliminary results of Ichikawa (1969) who used the P-wave first motion data reported in various seismological bulletins. According to Ichikawa, the main shock is represented by a normal fault with a larger strike-slip component than that found in the present work. This difference may have resulted from a difference in the period of the P waves used in Ichikawa (1969) and the present work. Some of the first-motion data used by Ichikawa may have been read on relatively short-period records, while, in the present work, unambiguous readings made on the 15–100 long-period records are used. Since short-period waves represent the initial rupture and long-period waves the major rupture, the present solution is believed to represent the overall nature of the fault better.

DISCUSSION

The selection of the actual fault plane out of the two P-wave nodal planes cannot be made on the basis of the mechanism diagram (Fig. 1) alone. However, the distribution of the aftershocks provides the key to the selection. Fig. 8 shows the epicenters of the aftershocks which occurred within 24 hours after the main shock. This map is based on the Earthquake Data Reports of USCGS, and is compiled by Tsumura (personal communication, 1970). If the steep nodal plane striking N30°E is the actual fault plane, one might
Fig. 9. Mechanism diagrams and slip vectors of the three earthquakes studied in this paper. Hatched part shows the compression field. The slip vectors show the direction of the motion of the foot-wall side with respect to the hanging wall side.

expect a distribution of aftershocks elongating in this direction; no indication of such distribution, however, is seen in Fig. 8. This leads to the selection of the gently dipping nodal plane striking N24°W for the fault plane. This selection is also favored by the north to northwest trending asymmetry found in the radiation patterns of Rayleigh and Love waves. Thus the Tokachi-Oki earthquake represents a low-angle thrust faulting with some strike-slip component, the oceanic side underthrusting beneath the continent; this type of faulting is common to other great earthquakes such as the Alaska earthquake of 1964, the Rat Island earthquake of 1965, and the Kurile Islands earthquake of 1963, and represents a major tectonic movement in the northwestern Pacific belt. For the major aftershocks, we assume that the fault geometry is, on the whole, similar to that of the main shock, and take the gently dipping nodal plane for the fault plane.

In Fig. 9 are shown the mechanism diagrams of the three earthquakes studied here. The slip vectors show the direction of the motion of the foot-wall side with respect to the hanging wall side. Note that the slip vector of the main shock is almost parallel to that of the Kurile Islands earthquake of 1963 (Kanamori, 1970a). Thus we may conclude that, despite the bend of the trench axis at the junction of the Kurile and the Japan trenches, the displacement of the Pacific lithosphere seems relatively uniform at least in this region.

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Fig. 10. Major earthquakes that are registered by a long-period seismograph at SHK within the 24 hours after the main shock. Closed circle denotes the compressional first motion and open circles, dilatational first motion. Crosses are the epicenters of aftershocks of the 1952 Tokachi–Oki earthquake within the 24 hours after the main shock.

The observation that the faulting of the largest aftershock is in a direction almost opposite to that of the main shock is most unusual and surprising. There is an indication that other earthquakes which occurred in the neighborhood of the largest aftershock have a mechanism similar to that of the largest aftershock. During the 24 hours after the main shock, the long-period seismogram obtained at SHK (Δ = 10.5°, azimuth = 236°) clearly registered, in addition to the two aftershocks studied here, three large aftershocks of which two show, unambiguously, dilatational first motion, and one, compressional first motion. At SHK, the main shock and the second largest aftershock registered compressional first motion while the largest aftershock registered dilatational first motion. As shown in Fig. 10, the earthquakes which show a dilatational first motion are located along a trough which branches off, towards northwest, from the junction of the Kurile and the Japan trenches. Thus we may conclude that a displacement in a direction opposite to that of the main shock prevailed along the NW–SE trending trough during the aftershock sequence. To the author’s knowledge, no well documented example of such unusual aftershock sequence has been reported. We suspect that this unusual phenomenon
Fig. 11. Schematic figure showing the contortion of the underthrusting oceanic lithosphere at the junction of the Kurile and the Japan trenches.

is related to the unique location, a junction at two trenches, of this earthquake. In the following, we will present a simple model which provides a mechanism of this unusual aftershock sequence. As suggested by the slip vectors of the Kurile Islands and the Tokachi–Oki earthquakes, the displacement of the Pacific lithosphere is uniform and perpendicular to the strike of the Kurile trench. Consequently when the lithosphere bends at the Kurile and the Japan trenches which meet at J with the apex pointing towards the continent, the sinking lithospheres on either side of AJ are pushed towards each other, and are forced to curve down to form a depression along AJ (Fig. 11). We consider that this depression manifests itself as the NW trending trough off the coast of Tokachi.

From the distribution of the aftershocks, it is obvious that the Tokachi–Oki earthquake of 1968 occurred as a result of an interaction between the sinking lithosphere and the continental lithosphere south of AJ (see Fig. 8). In contrast, the aftershocks of the major Tokachi–Oki earthquake of 1952 ($M_8 = 8.1$) are distributed in a region north of AJ (see Fig. 10). Thus the distribution of the strain in this region just before the 1968 event may be schematically shown by Fig. 12a. In the region north of AJ (Region I), the lithosphere is more or less unstrained, the strain having been released by the 1952 event. On the other hand, in the region south of AJ (Region II), the continental lithosphere is highly strained because of the frictional drag exerted by the underthrusting oceanic lithosphere. We consider that, for this gradual process of strain accumulation, two regions, Region I and Region II, are mechanically decoupled, and behave more or less independently. At the time of the 1968 event, the restitutive stress in Region II exceeded the frictional drag and Region II rebounded to a more or less unstrained state. This rebound took place as a major low-angle thrust faulting as given by Fig. 1. The direction of the displacement of the continental lithosphere is schematically shown by an open arrow in Fig. 12b. Because, in the present model, Region I and Region II are pushed towards each other in a direction perpendicular to AJ, it is possible that, for such a sudden rebound, Region I is
Fig. 12. The distribution of the strain before (a) and after (b) the 1968 Tokachi–Oki earthquake. The open arrow indicates the direction of the motion of the continental lithosphere, with respect to the oceanic lithosphere, at the time of the 1968 event. The closed arrow indicates the direction of the motion of the continental lithosphere in the hatched region during the aftershock sequence.

mechanically coupled, to some extent, to Region II. The coupling between the Region I and II is assumed to be a viscous coupling which may be modeled by a “dash-pot” connecting the two regions; for a slow movement no interaction takes place, but for a sudden motion the two regions are coupled rigidly. As a result of this coupling, a part (hatched part in Fig. 12b) of Region I along AJ is dragged by Region II, and becomes strained as shown in Fig. 12b. Intermittent release of this strain during the subsequent stage represents the aftershock sequence along AJ. The displacement of the continental lithosphere (shown by a closed arrow in Fig. 12b) associated with this strain release is evidently in a direction more or less opposite to that associated with the main shock. Essential to the above mechanism is a mechanical coupling between Region I and Region II for a sudden displacement. This coupling is caused by the contortion of the lithosphere along AJ at the junction of the Kurile and the Japan trenches. It therefore follows that this unusual aftershock sequence is a phenomenon characteristic of major earthquakes occurring at a junction where two trenches meet. It is hoped that future investigations of major earthquakes at similar localities will provide more detailed pictures of such deformation of lithosphere.

CONCLUSION

The Tokachi–Oki earthquake of 1968 is represented by a low-angle thrust faulting with a considerable strike–slip component, the oceanic side underthrusting beneath the continent. The seismic moment is estimated as $2.8 \times 10^{28}$ dyn·cm. Although the dimension of the fault plane cannot be determined directly, a value of $150 \times 100$ km$^2$ may be estimated on the basis of the aftershock area. If this value is correct, the slip displacement on the fault plane and the stress drop are estimated as 4.1 m and 32 bar respectively, the ri-
gidity being assumed as $4.5 \times 10^{11}$ dyn/cm². If the residual stress (the stress after the fault is formed) is assumed to be zero, the total released strain energy is estimated as $1.0 \times 10^{24}$ erg. The direction of the slip vector is almost parallel to that of the Kurile Islands earthquake of 1963 ($M_s = 8.3$) indicating that the motion of the Pacific plate is uniform in this region. The largest aftershock ($M_s = 7.5$) suggests, rather surprisingly, a faulting whose displacement is almost opposite to that of the main shock. This peculiar aftershock occurrence can be explained, though not uniquely, in terms of an interaction between two independent continental lithospheric blocks bounded by a trough which branches off from the junction.

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REFERENCES