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Aftershock distribution of the October 4, 1994 Mw8.3 Kurile islands earthquake determined by a local seismic network in Hokkaido, Japan

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Abstract. On October 4, 1994, an earthquake with magnitude Mw8.3 occurred in the western part of Kurile Islands at 43.42°N, 146.81°E and 33 km in depth. The hypocenter parameters were determined by Hokkaido University in Japan. Aftershocks following this remarkable event were located using data from a local seismic network operated by Hokkaido University. We found that most of the aftershocks occurred (1) on the fault plane of the mainshock, (2) in the subducting plate around the fault plane of the mainshock, and (3) in the focal area of the largest aftershock, which occurred on October 9 with Mw7.3. Both (2) and (3) were not active immediately after the mainshock. Considering the time sequence of the aftershock activity, we identified one of the nodal planes of the Harvard quick CMT solutions as the fault plane of the mainshock; the strike is almost parallel to the trench axis and the dip angle is near vertical. It is obvious that this event is different from a low-angle thrust-type interplate earthquake. The distribution of aftershocks strongly suggests that it is an intraplate event.

Introduction

A great earthquake (Mw=8.3) occurred on October 4, 1994 in the Kurile Islands. This event was named the "1994 Hokkaido Toho-Oki earthquake" by the Japan Meteorological Agency. The hypocenter located by Hokkaido University in Japan was 43.42°N and 146.81°E at a depth of 33 km. This epicenter was approximately 50km landward of the trench axis (Fig. 1). The aftershock distribution provides us with the valuable information about the rupture area of this event. Although large aftershocks (M>5.5) can be located by the worldwide seismic networks, the detailed aftershock activity of smaller events cannot be determined. Japan is covered by a dense network of short-period seismographic stations for the purpose of earthquake monitoring and earthquake prediction research. In this study we present a map of the locations of aftershocks larger than M=3.0 determined by the network operated by the Research Center for Earthquake Prediction (RCEP) at Hokkaido University. We show that the October 4, 1994 Kurile Islands earthquake is not an interplate but an intraplate event.

Data and analysis

The RCEP network consists of 32 short-period seismic stations. All waveform data are sent via exclusive telephone lines to RCEP, converted to digital data with 100Hz, and stored on both magneto-optical disks and 8mm video tapes. The waveform data are stored on magneto-optical disks only when an event has been detected by the automated event-detection system. All waveform data from all channels are recorded continuously on the 8mm video tapes whether an earthquake is detected or not; therefore, we can be sure that we never fail to record any event.

We selected 9 stations, i.e., NMR, RUS, TES, AKK, KNP, AIB, HRK, URH and MYR, to use in locating the aftershocks of the October 4, 1994 Kurile Islands earthquake (Fig.1). The crustal structure in the western part of Hokkaido differs from that in the eastern part; therefore, we did not use stations in the western part. HRK has vertical and North-South components, the other stations have vertical, North-South and East-West components. Two short period horizontal components at NMR were available after October 16. The three components from the Streckeisen broadband seismometer 1 (STS1) at NMR were used to read the *S*-wave arrival times of the mainshock and the largest aftershock because the short-period channels were saturated. RUS was installed on October 8 to improve azimuthal coverage.

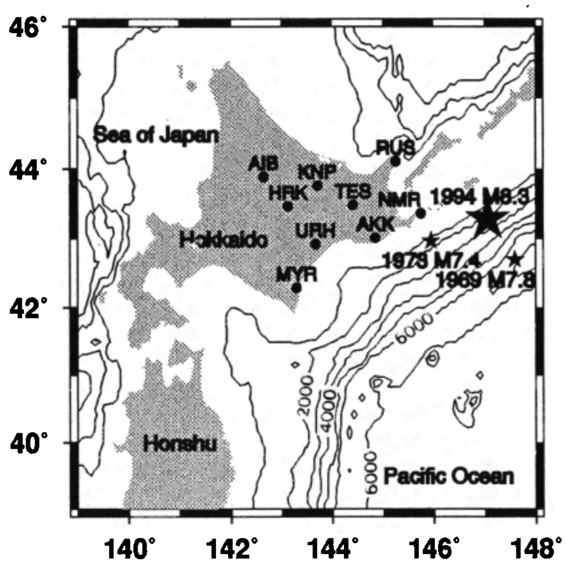

Figure 1. Location of seismic station in Hokkaido. The nine stations labeled were used to locate the aftershocks of the 1994 Kurile Islands earthquake, indicated by a large star. Locations of the great 1969 Kurile Islands earthquake (M=7.8) and the 1973 Nemuro Hanto-Oki earthquake (M=7.4) are also indicated by small stars. Contour lines indicate the water depth in meters.

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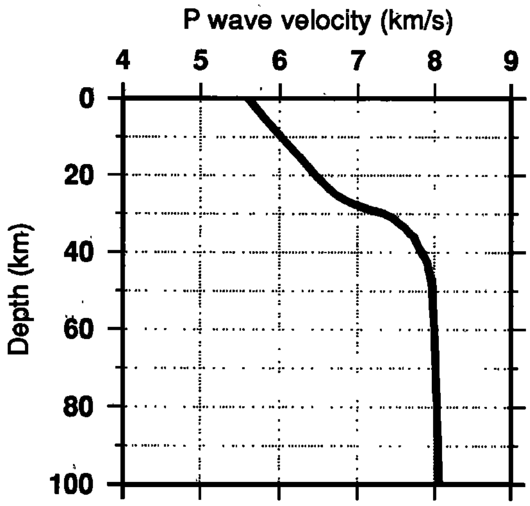

Figure 2. *P*-wave velocity model. Poisson's ratio is assumed to be 0.25.

The arrival times of *P*- and *S*-waves were picked manually from careful inspection of the vertical and horizontal seismograms. The hypocenter locations were determined [*Hirata and Matsu'ura*, 1987] and plotted using the "win" program [*Urabe*, 1990], which is a helpful tool for displaying waveform on a workstation. The *P*-wave velocity structure of the eastern Hokkaido region shown in Figure 2 is assumed in this study [*Iwasaki et al.* ,1989; *Ozel*, 1993]. The Poisson's ratio was assumed to be 0.25 in each layer.

The station corrections were added to the observed arrival time data, which were (station code, a correction for *P*-wave, a correction for *S*-wave) = (NMR, -0.02s, -0.05s), (AKK, 0.36, 0.19), (TES, 0.33, 0.37), (KNP, -0.53, -1.15), (URH, 0.06, -0.01), (HRK, 0.06, -0.94), (MYR, -0.80, -0.57), (AIB, -0.78, -0.76) and (RUS, 0.10, -0.54). These are the mean residuals calculated by averaging the residuals of the aftershocks at each station.

1990 hypocenters with more than five *P*-wave arrivals, in which NMR was always included because NMR was the nearest station to the focal area, and more than two *S*-wave arrivals were determined from October 4 to November 19, 1994. From these hypocenters, we selected 597 events which have (1) error ellipses smaller than 20 km in the North-South and the East-West directions and 30 km in the depth direction, (2) rms of the residuals of both *P*- and *S*-waves less than 1.0 s, and (3) depths deeper than 0 km.

Aftershock distributions

The focal area of the Kurile Islands earthquake was far outside of the RCEP network; therefore we must pay careful attention to the location of the aftershocks. Although the absolute locations are systematically biased, we emphasize that the relative locations and geometry of the aftershock zone are well-determined.

In Figure 3, events which occurred within 26 hours of the mainshock are plotted to estimate the rupture area and fault plane of the mainshock. The hypocenter is also plotted at the location determined using the eight *P*-wave arrivals at the stations listed above and one *S*-wave arrival read on a East-West component of the STS1 seismograph at NMR. The plot shows a clear lineation in the NE-SW direction which is almost parallel to the trench axis. Moreover, the hypocenters are aligned almost vertically, as can be seen in the cross-section perpendicular to the trench axis. Therefore, we adopted the nodal plane with strike=52° and dip=77° obtained by Harvard University as the rupture plane of the mainshock. We are confident of this selection even though location errors and uncertainties of the velocity structure must be taken into account. Although the focal area is outside of the RCEP network in Hokkaido, the alignment of the aftershocks in the NE-SW direction cannot be deformed into the NW-SE direction, even if slight changes are made to the velocity structure or another combination of seismic stations is used in the hypocenter calculation.

In Figure 4, events from October 4 to November 19 are shown. We found that the aftershocks in this period occurred (1) on the fault plane of the mainshock (Type 1), (2) in the subducting plate around the fault plane of the mainshock (Type 2), and (3) in the focal area of the largest aftershock which occurred on October 9 with Mw=7.3 near the NE end of the main fault (Type 3). The lineation of epicenters parallel to the trench axis is clear, and it is obvious that the hypocenters are aligned into an almost vertical plane. Figure 5 schematically explains the geometry of these areas in the N60E cross section in Figure 4.

Type 2 activity was not active immediately after the mainshock, and a large number of events occurred later. The area of Type 2 activity dips approximately 30° landward. This is one of the most noteworthy features of the aftershock activity. This area is not included on the mainshock rupture plane and no subevents of the main shock was detected in this region [*Kikuchi and Kanamori*, 1994] ; therefore, we interpreted Type 2 events as induced events after the mainshock that occurred in the Pacific plate subducting beneath the Kurile Islands.

The hypocenter of the largest aftershock on October 9, which was at 43.64°N, 147.06°E at a depth of 8 km as located by RCEP, was included in the area of Type 3 activity (Fig 6). Moreover, this activity began immediately after the largest aftershock. Therefore Type 3 activity are aftershocks of the largest aftershock.

To estimate the effect of the lateral velocity variation on hypocenter determination, we relocated the hypocenters with a three-dimensional structure [*Miyamachi*, 1994]. The structure had two velocity discontinuities, i.e., the Moho and the upper boundary of the Pacific plate [*Miyamachi et al.*, 1994] (Fig. 7). The *P*-wave velocity $V(r)$ at a point with a distance r from the center of the earth is expressed as,

$$V(r) = V_0\left(\frac{r}{R-H}\right)^{K},$$

where V_0 is the velocity of the uppermost depth of the layer, R is the radius of the earth, H is the depth of the boundary measured from the center of the earth and k is an arbitrary coefficient. We applied (V_0, k) = (5.8 km/s, -30) in the crust, (7.4 km/s, -4) in the mantle and (8.1 km/s, -4) in the Pacific plate. Poisson's ratio was assumed to be 0.25 at any point. We found that although the hypocenters were changed, the

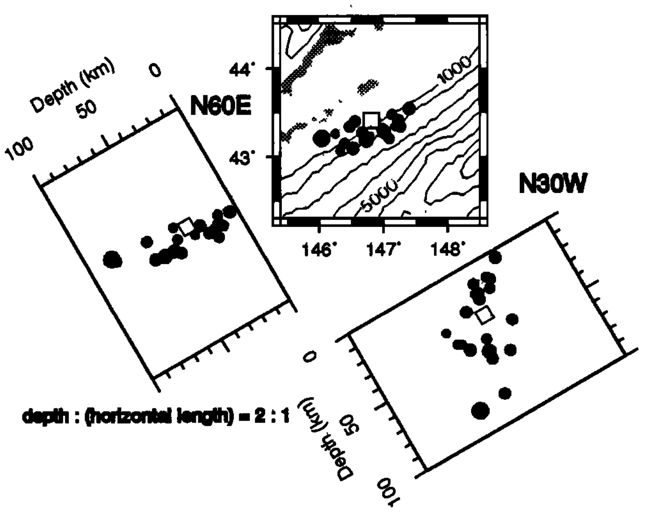

Figure 3. Aftershocks of the 1994 Kurile Islands earthquake which occurred within 26 hours of the mainshock. The depth to length ratio is 2. N60E and N30W are cross-sections perpendicular and parallel to the trench axis, respectively. Contour lines indicate water depth in meters.

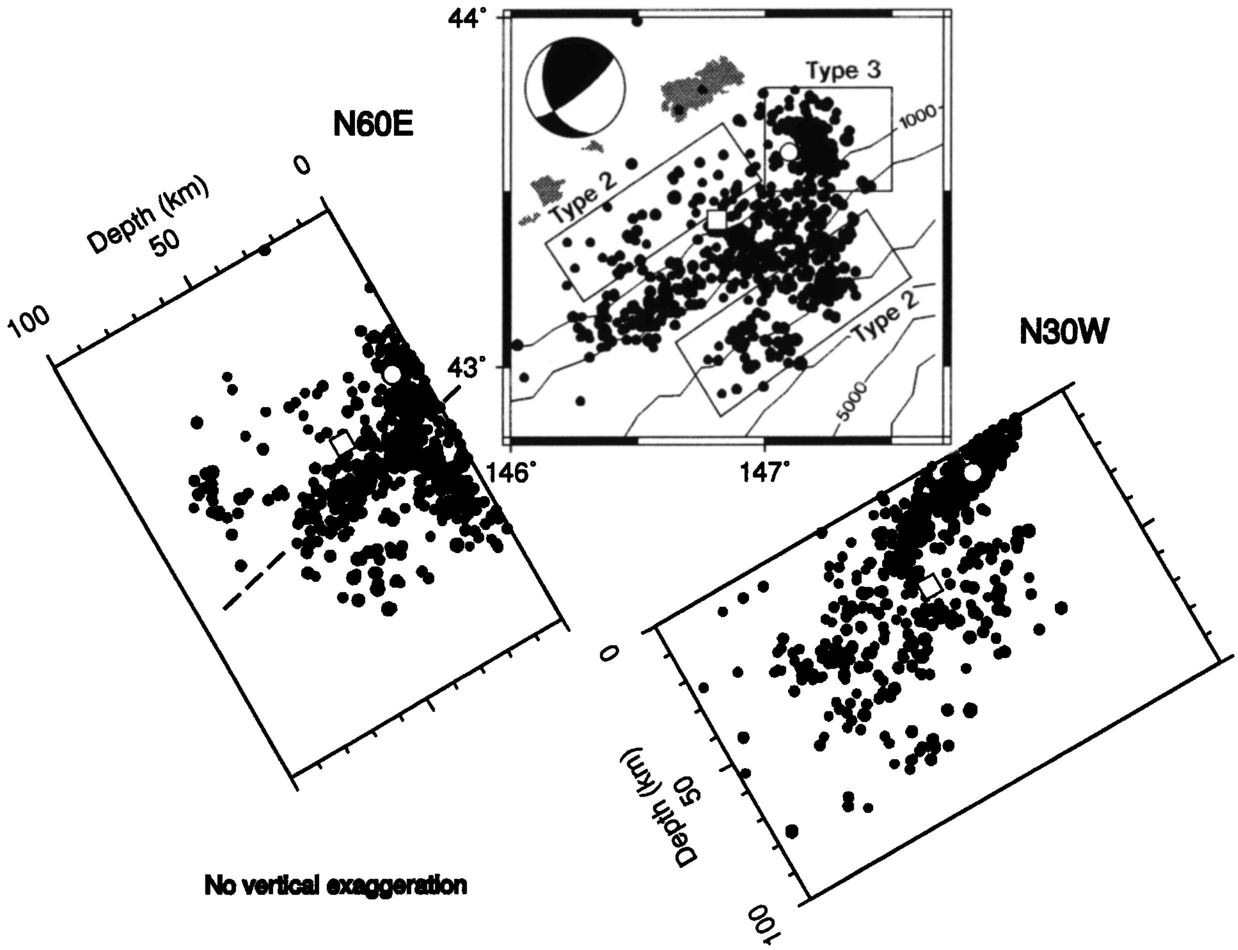

Figure 4. Aftershocks which occurred from October 4 to November 19, 1994. There is no vertical exaggeration. The open square and open circle are location of the mainshock and the largest aftershock, respectively, as determined by Hokkaido University. The cross-sections are as in Fig. 3. Contour lines indicate water depth in meters. The Harvard quick CMT solution of the mainshock is also shown, the nodal planes of which are (strike, dip, rake) = NP1(158°,40°, 21°) and NP2(52°, 77°, 128°). The broken line in the N60E cross-section has a dip of 77° corresponding to NP2. Three boxes labeled indicate the regions of Type 2 and Type 3 activities. See text for explanation.

geometries of Type 1, Type 2 and Type 3 were almost same as in Figure 4 (Fig. 8). For instance a clear lineation of the epicenters in the NE-SW direction can be seen and the N60E cross-section in Figure 8 can be interpreted as shown in Figure 5. Therefore in this case the

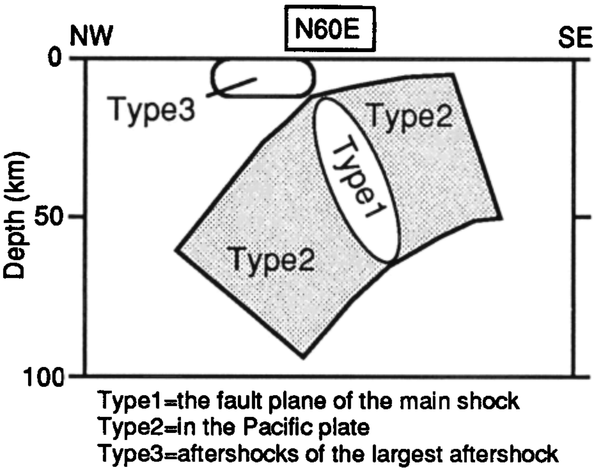

Figure 5. Schematic explanation on the geometries of the aftershock activities. This is corresponding to N60E cross-section in Figure 4.

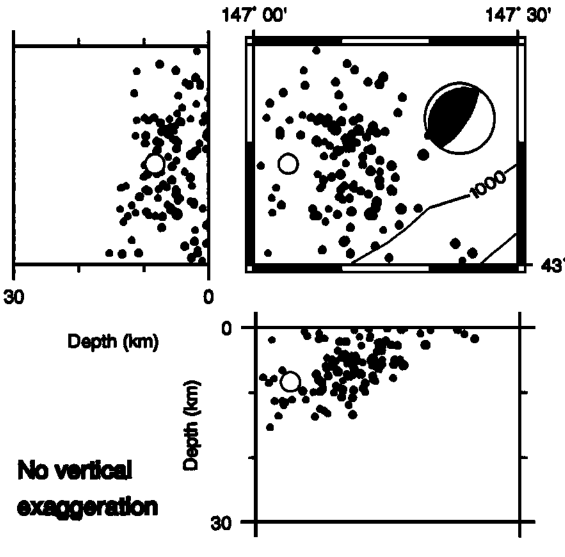

Figure 6. Detailed aftershock distribution of the events around the largest aftershock (Type 3). The open circle is the largest aftershock. The quick CMT solution of Harvard University is also shown. Contour lines indicate water depth in meters.

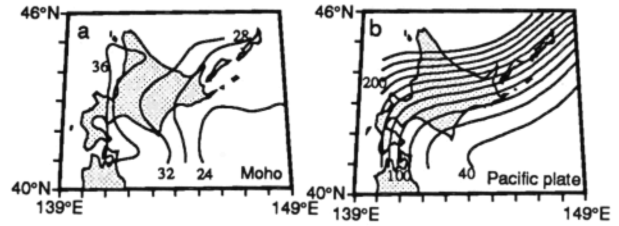

Figure 7. Three-dimensional structures of (a) the Moho and (b) the upper boundary of the Pacific plate. Contour lines indicate the boudary depth in kilometers.

lateral velocity variation does not affect our interpretation of the aftershock activity. Almost the same conclusion was obtained by *Iwasaki et al.* [1991].

Discussion

In this study we found that the aftershocks of the 1994 Kurile Islands (Hokkaido Toho-Oki) earthquake occurred on a plane with strike parallel to the trench axis and dip angle near vertical. Therefore, we identified the steep fault plane of the Harvard CMT solution as the fault plane of the mainshock. This agrees with the sequence of subevents of the mainshock determined by *Kikuchi and Kanamori* [1995] using broadband seismograms recorded by the IRIS network. They found that the steep fault model provided a better waveform match than the shallow-dip fault model. This aftershock distribution strongly suggests that the October 4, 1994 Kurile Islands earthquake was not an interplate event like the great 1969 Kurile Islands earthquake [*Abe*, 1973] but an intraplate event.

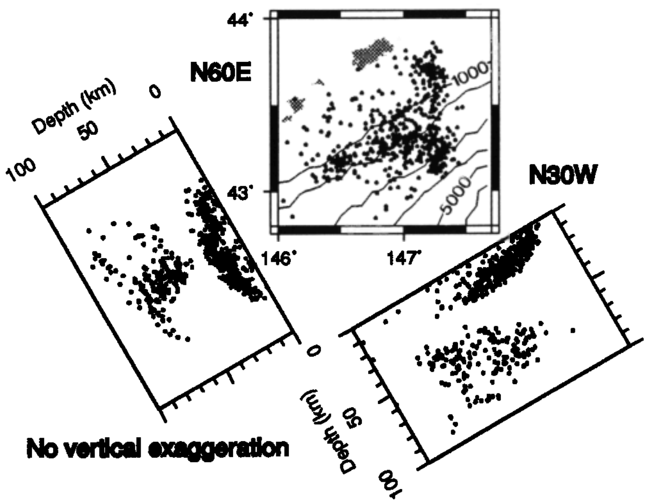

Figure 8. Hypocenters relocated by using the three-dimensional structure. The area and time period are the same as Figure 4. There is no vertical exaggeration. Contour lines indicate the water depth in meters.

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