北海道大学地球物理学研究報告
Geophysical Bulletin of Hokkaido University, Sapporo, Japan
No. 69, March 2006, pp. 23−39

The 29 November 2004 M7.1 Kushiro-oki earthquake: An event between the on-going seismic quiescence area and the asperity ruptured by the 1973 Nemuro-oki earthquake

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(Received December 12, 2005)

We have investigated the source process and the aftershock distribution of a large earthquake with M=7.1 occurred on 29 November 2004 off the coast of Kushiro (or Shiranuka) in the eastern Hokkaido, Japan. The source parameters are summarized as follows: the total seismic moment $M_0=3.4\times10^{19}$Nm, that is, $M_w=7.0$; (strike, dip, slip)=(238°, 33°, 117°); depth of the initial break point=48 km; and source duration time=10 sec. The aftershocks were relocated using the three-dimensional velocity structures of P- and S-waves, and we found that the aftershocks concentrated on a plane with the area of 30×15 km^2 dipping 22° toward the landside whose orientation agrees closely with that of the northwest-dipping nodal plane of the focal mechanism. The stress drop was estimated to be 89 bars. The aftershock area does not overlap with the asperity ruptured by the main shock, but outlined the asperity. These observations strongly suggest that the main shock itself is a very usual interplate event at depth of around 50 km in the Japan subduction zone. However, taking the tectonic circumstance into account, this is an outstanding event since the focal area was located between the five-years-lasting seismic quiescence area and the asperity ruptured by the 1973 Nemuro-Oki earthquake.

I. Introduction

At 3:32 on 29 November 2004 in Japan Standard Time, a large earthquake occurred off the coast of Kushiro (or Shiranuka) in the eastern Hokkaido, Japan (Fig. 1). Japan Meteorological Agency (JMA) determined the epicenter=(42.944°N, 145.280°E), the depth=48.2 km, and the magnitude (M)=7.1. Many aftershocks followed the main shock including two events larger than M=6.0: M=6.9 on 6 December 2004 and M=6.4 on 18 January 2005. This sequence of the main shock and aftershocks should be noteworthy since the focal area was located between the asperity ruptured by the 1973 Nemuro-Oki earthquake (Yamanaka and

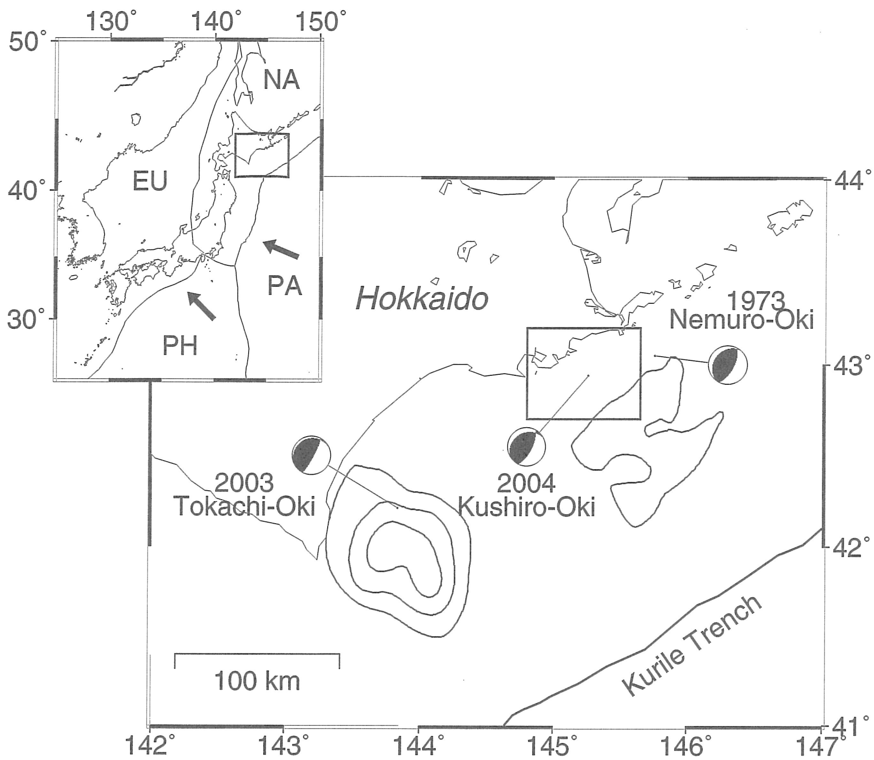

Fig. 1. Hokkaido subduction zone. Focal mechanisms are shown for the 2003 Tokachi-Oki earthquake ($M=8.3$), the 1973 Nemuro-Oki earthquake ($M=7.4$), and the 2004 Kushiro-Oki earthquake ($M=7.1$). Asperities are shown in contour every 1 m for the Tokachi-Oki and the Nemuro-Oki earthquakes (Yamanaka and Kikuchi, 2003). A rectangle indicates the area shown in the following figures 6, 7, 8, 9, and 11. Inset shows the area covered by the study area and the plate configuration. PA: Pacific plate, PH: Philippine Sea plate, EU: Eurasian plate, NA: North American plate. Arrows show the direction of plate motion relative to the Eurasian plate.

Kikuchi, 2002) and the on-going seismic quiescence area (Katsumata and Kasahara, 2004).

The Nemuro-Oki earthquake occurred on 17 June 1973, which was a low-angle -thrust-type reverse fault slip on the plate boundary in the Kurile subduction zone. The magnitude was estimated to be 7.4 by JMA, and the surface-wave magnitude was reported to be 8.3 by Tulsa and 7.7 by Berkeley. The total seismic moment was 6.7×10^{20} Nm ($M_w=7.8$) and the average fault slip was 1.6 m determined by Shimazaki (1974) using surface-wave data. Tada (1974) estimated that the average fault slip was 1.0 m using geodetic data.

In this Nemuro-Oki area, Katsumata and Kasahara (2004) found that the microearthquake seismicity rate within the Pacific plate decreased 48 %, which started in June 2000 and has been lasting approximately five years. The seismic quiescence area is defined by a circle centered at (43.4°N, 145.0°E) with a radius of 46 km.

Before the 1973 Nemuro-Oki earthquake, the Tokachi-Oki earthquake ($M=8.1$) occurred in 1952, and the Kushiro-Oki earthquake ($M=7.2$) occurred in August 1961 that was followed by the largest aftershock ($M=6.9$) in November 1961. While on the other hand the Tokachi-Oki earthquake ($M=8.0$) occurred in 2003, which ruptured the same asperity as that of the 1952 Tokachi-Oki earthquake (Yamanaka and Kikuchi, 2003), and the Kushio-Oki earthquake ($M=7.1$) occurred in November 2004, which was followed by the largest aftershock ($M=6.9$) in December 2004. The sequence of these events is very similar to that after the 1952 Tokachi-Oki earthquake though the time intervals between the events are shorter.

There are two reasons why we believe that a large stress enough to produce a great earthquake has been accumulated in this area. First, the $M=7.4$ earthquake in 1973 released energy equal to only half of the $M=7.9$ earthquake in 1894, which was the previous event in Nemuro-Oki area (Shimazaki, 1974). Second, seismic coupling is almost 100 % in the region, as shown by geodetic data from the GPS network. Therefore the coseismic slip of 260 cm at least is expected 32 years after the 1973 earthquake since the relative plate motion is 8 cm/year based on NUVEL-1A model (DeMets et al., 1994). If the area of the seismic fault is 100×100 km^2, the moment magnitude will be $M_w \approx 8$.

The purpose of this study is to describe the 2004 Kushiro-Oki earthquake sequence in detail by determining the source process of the main shock and relocating aftershocks. To know the details on this sequence is very important because it might be a foreshock to a great earthquake in the Nemuro-Oki area in the near future.

II. Source Process of the Main Shock

1. Point Source Solution

We retrieved the broad-band seismograms archived by Data Management Center of IRIS (Incorporated Research Institutions for Seismology) and chose the stations at epicentral distances between 30° and 100° for the P wave, and the stations between 30° and 50° for the SH wave, as shown in Fig. 2. The azimuthal coverage is good. We selected sixteen vertical components of P wave data and two SH wave data. All the records were converted into ground motion displacement with a sampling rate of 1 Hz, and

Fig. 2. Seismographic stations used for the waveform inversion: FFC, KDAK, PFO, WRAB, COCO, DGAR, PALK, AAK, KURK, BRVK, KIV, OBN, GRFO, BFO, ESK, and BORG.

Table 1. Near-source structure used in this study.

V_P (km/s)	V_S (km/s)	ρ (10^3kg/m^3)	H (km)
1.50	0.00	1.00	2.0
6.50	3.74	2.87	20.0
7.80	4.40	3.30	–

V_P, V_S: P and S wave velocity, ρ: density, and H: thickness of layer.

band-pass filtered between 0.004 and 1 Hz.

Before estimating a space-time distribution of slip, we determined the focal mechanism and the depth of hypocenter for a single point source by using the method developed by Kikuchi and Kanamori (1991). Synthetic waveforms were calculated on the assumption that a near-source structure consisted of three layers as shown in Table 1, which is based on Iwasaki et al. (1989). We modeled a source time function by an isosceles triangle with duration of 8 sec.

We found that the calculated waveforms fitted the observations best if we assumed that the depth of hypocenter was 50 km and the focal mechanism was a reverse faulting on a shallow dipping plane: (strike, dip, slip) equal to (238°, 33°, 117°), rather than a steep dipping plane: (27°, 61°, 74°) (Fig. 3a). This result is consistent with solutions obtained by USGS, (239°, 29°, 120°), and by Harvard University, (242°, 26°, 122°).

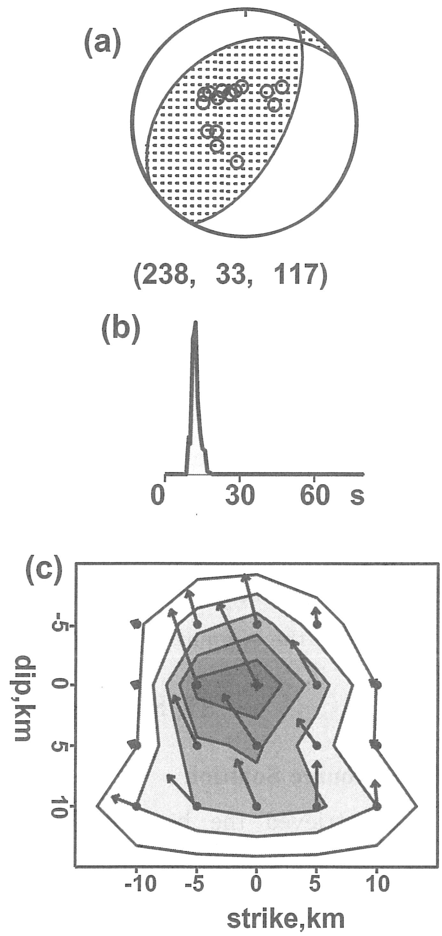

Fig. 3. (a) Focal mechanism, (b) source time function of the moment rate, and (c) slip distribution of the 29 November 2004 Kushiro-Oki earthquake. Contours in (c) are drawn from 0.3 to 2.7 m every 0.6 m. Arrows indicate slip vectors of the hanging wall at each grid point. Positive direction in the strike-axis points to the azimuth 238°, and positive direction in the dip-axis points to 33(downward from the horizon.

2. Source Process

By careful inspection of recorded waveforms, a phase due to the main rupture was clearly identified several seconds after the arrival time of the P wave. We modeled this phase with a waveform inversion method developed by Kikuchi and Kanamori (2003). We assumed a planar fault with a strike of 238° and a dip of 33°, which are same as those obtained in the previous section, and the area of 35×30 km². The fault plane was divided into 7×6 subfaults with an area of 5×5 km². Point sources placed at the center of each subfault for calculating synthetic waveforms. At all the point sources, the strike and the dip were fixed to be 238° and 33°, respectively, and the moment rate function and the slip direction were unknown parameters in the inversion.

We investigated the depth of the initial break point by a grid search method varying the depth by 1 km, and found that the best solution was obtained at a depth of 48 km. This depth corresponds to the upper boundary of the seismic plane associated with the subducting Pacific plate (Katsumata et al, 2003). We also investigated the rupture velocity by a grid search method, and found that it is 3.0 km/s.

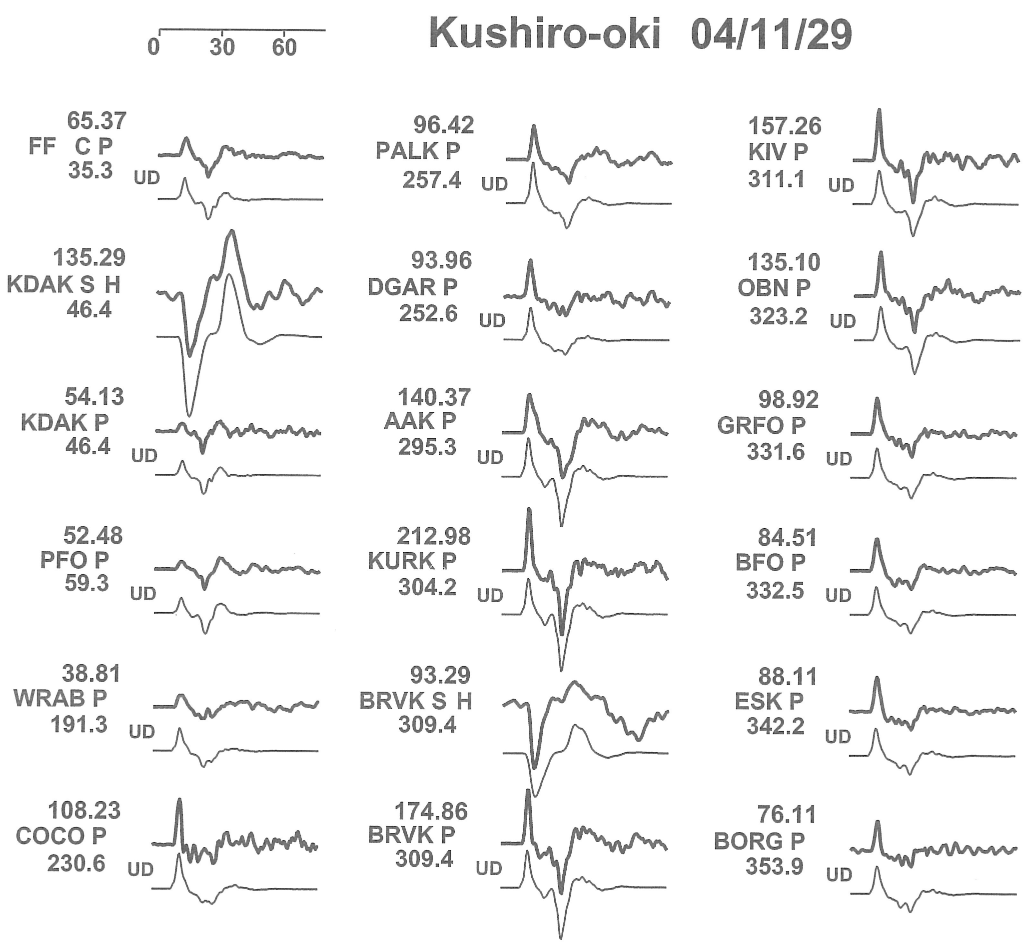

Fig. 4. Observed (upper bold lines) and synthetic (lower thin lines) waveforms at each seismic station. The numbers above the station codes are peak-to-peak amplitudes of the observed waveforms in microns, and numbers below are the azimuths of the station from the earthquake.

Fig. 3b shows a time history of a moment rate, dM_0/dt, and Fig. 4 shows the observed and the synthetic waveforms for the 29 November 2004 M7.1 Kushiro-Oki earthquake. The rupture duration time, that is, the rise time plus the rupture propagation time, was 10 sec. The total seismic moment was $M_0=3.4\times10^{19}$ Nm, that is, $M_w=7.0$, which is consistent with the CMT solutions obtained by USGS, $M_0=3.7\times10^{19}$ Nm, and by the Harvard University, $M_0=3.65\times10^{19}$ Nm. Fig. 3c shows a slip distribution on the assumed fault plane. At each grid point, we calculated the displacement, D, from the seismic moment, m_0, obtained by the waveform inversion, the area $A=5\times5$ km^2, and the rigidity $\mu=60$ GPa, using an equation, $m_0=\mu DA$. A large displacement is located around the initial break point, suggesting that the rupture propagated concentrically. The displacement was largest, amounting to 3.1 m, at a grid of the initial break point.

The final source parameters of the 29 November 2004 Kushiro-Oki earthquake are summarized as follows: the total seismic moment $M_0=3.4\times10^{19}$ Nm, that is, $M_w=7.0$; (strike, dip, slip)=(238, 33, 117); depth of the initial break point=48 km; source duration time=10 sec; and the maximum displacement=3.1 m. The stress drop averaged on the fault plane will be estimated in the following discussion.

III. Aftershock Sequence

1. Data

We used two data sets of arrival times of P and S waves, and relocated aftershocks. One was based on readings of the arrival times produced by a daily routine work at Institute of Seismology and Volcanology, Hokkaido University (ISV) (Data set 1), and another one was produced by the authors for ourselves (Data set 2).

Data set 1.

Seismographic stations that ISV used for hypocenter location are shown in Fig. 5a. Katsumata et al. (1995) and Katsumata et al. (2003) described on the daily routine work at ISV. From the seismic catalog compiled by ISV between 1 January 2002 and 29 January 2005, we selected earthquakes which filled the following six criteria: (1) error ellipse smaller than 1 km in the North-South and the East-West directions and 2 km in the depth direction, (2) root mean square (rms) of the residuals of P wave less than 0.5 s, (3) rms of the residual of S wave less than 1.0 s, (4) readings of 10 or more P wave arrival times, (5) readings of 5 or more S wave arrival times, and (6) $M=2.0$ or larger.

Data set 2.

We selected 37 seismographic stations near the aftershock area (Fig. 5b), and read the arrival times of P and S waves from 83 aftershocks with $M=3.5$ or larger. For each

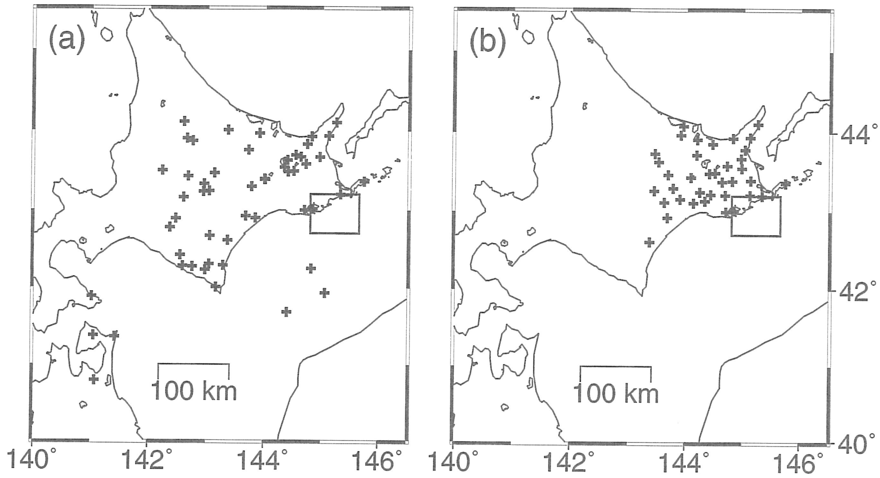

Fig. 5. Seismographic stations used for relocating aftershocks, (a) for Data set 1 and (b) for Data set 2. A rectangle indicates the study area shown in figures 6, 7, 8, 9, and 11.

earthquake we picked up both P and S waves at 14 stations without fail: HTU, AKK, NMR, AKSI, NKSB, RAUS, HNKH, BKEH, SCSH, BKWH, NSTH, STSH, TREH, and STNH, and only P wave at 23 stations without fail: NIT, TES, RUS, URH, ASYR, CHRI, JTKR, SCNH, TRSH, TRWH, ANSH, SYSH, ANNH, SNNH, KMZH, BHRH, HBTH, MMBH, RKBH, AYWH, SRMH, OKEH, and RBSH. The seismographic stations included in Hi-net (the high-sensitivity seismographic network) have a station code with four characters ending with "H". The Hi-net is maintained by the National Research Institute for Earth Science and Disaster Prevention (NIED). Since the arrival times are read from the 37 seismic stations in the fixed configuration, the relative position of hypocenter is expected to be more accurate than that from Data set 1.

2. Relocation of Hypocenters

Since the crust and the upper mantle beneath the Hokkaido Island have very complicated geological structures (e.g., Miyamachi et al., 1994; Moriya et al., 1998), it is not appropriate to use a simple one-dimensional layered velocity structure for the hypocenter calculation. Katsumata et al. (2002) determined three-dimensional (3–D) P and S wave velocity structures in and around the Hokkaido Island by applying a tomographic method developed by Zhao et al. (1992) to arrival time data from shallow and intermediate-depth earthquakes. In this study we assumed this 3–D velocity structure, and relocated the aftershocks included in Data sets 1 and 2. We used a hypocenter calculation method developed by Zhao et al. (1992).

3. Location Errors

We carried out a numerical simulation in order to estimate robustness and a relative error for the hypocenter relocation using Data set 2. The numerical simulation is a so-called bootstrap method. For an earthquake, we selected 37 seismographic stations randomly among the 37 stations described in the section III.1 with allowing to select the same station many times, and calculated a hypocenter. We repeated this procedure one hundred times. Then the robustness of hypocenter location was estimated by how the resulting hypocenters moved from the original location. We define an error as the standard deviation of one

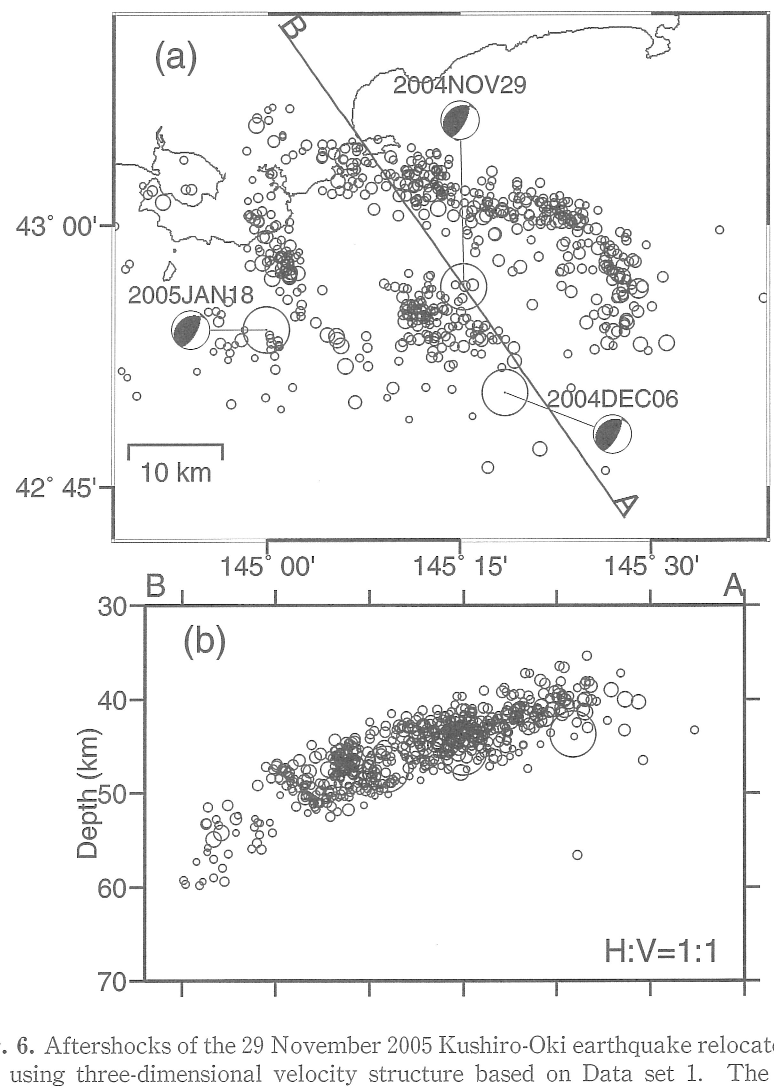

Fig. 6. Aftershocks of the 29 November 2005 Kushiro-Oki earthquake relocated by using three-dimensional velocity structure based on Data set 1. The time period is from 29 November 2004 to 29 January 2005, and the magnitude is 2.0 or larger. (a) Map view and (b) vertical cross section along the line A−B in (a). The focal mechanisms were determined by Harvard University, which are equal area projections of the lower hemisphere of the focal sphere.

hundred resulting hypocenters. The errors were approximately 1.5 km and 2.0 km for the East-West and North-South directions, respectively, and became larger slightly as a function of distance from the coast. This feature is seen more clearly in the depth direction. The error was constant to be approximately 1.2 km nearer than 30 km from the coast, and became larger than 2.0 km at distance farer than 40 km.

4. Results

Data set 1.

We relocated 582 aftershocks with $M=2.0$ or larger between 29 November 2004 and 29 January 2005 using Data set 1. From the calculated aftershock locations, we found that most of the aftershocks occurred within the rectangular area with 50 km in the East-West direction and 30 km in the North-South direction (Fig. 6). The outstanding feature is that the aftershocks are located in a cluster like a ring surrounding the main shock on 29 November. On a vertical cross section hypocenters are distributed between 35 and 55 km in depth and the depth appears to become deeper toward the landside. However we are not able to identify a fault plane clearly from the cross section.

The main shock on 29 November was followed by the two large aftershocks. We found that the focal areas ruptured by the three events did not overlap with each other (Fig. 7). The focal areas ruptured by the aftershocks on 6 December and on 18 January

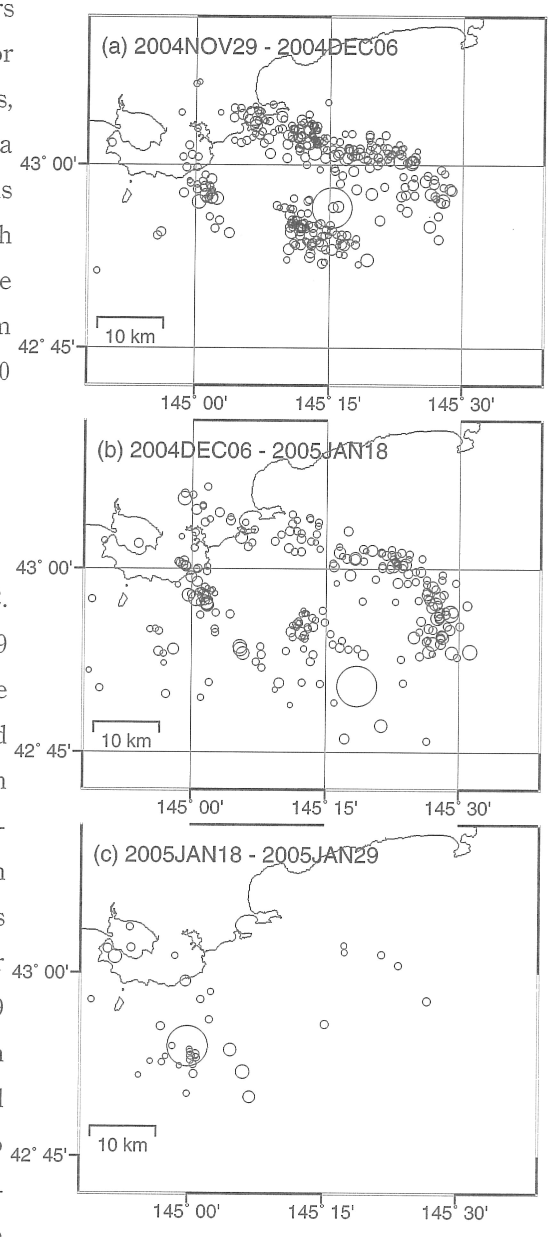

Fig. 7. Time slices of the aftershock activity following the 29 November 2005 Kushiro-Oki earthquake. (a) From the $M=7.1$ main shock to the occurrence of the $M=6.9$ aftershock on 6 December 2004, (b) from the $M=6.9$ aftershock to the occurrence of the $M=6.4$ aftershock on 18 January 2005, and (c) from the $M=6.4$ aftershock to 29 January 2005.

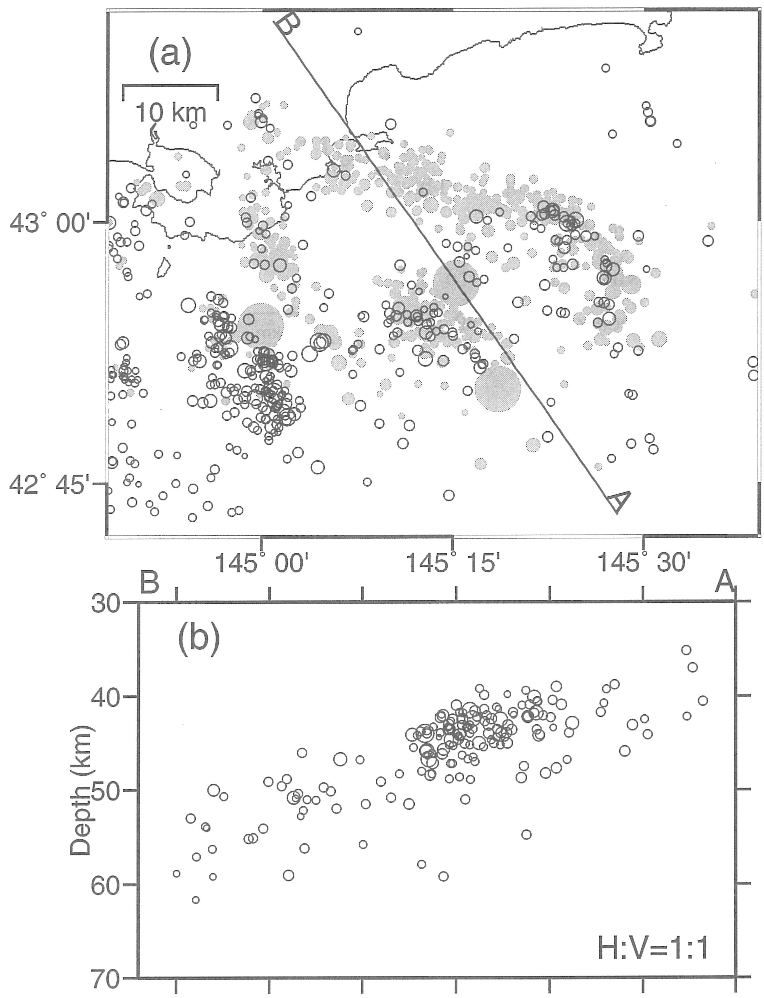

Fig. 8. Background seismicity from 1 January 2002 to 28 November 2004 (open circles) and the aftershocks of the 29 November 2004 Kushiro-Oki earthquake (gray circles). (a) Map view and (b) vertical cross section along the line A-B in (a). Note that the aftershocks were not plotted on (b).

were located on the southeastern and the southwestern boundaries of the focal area ruptured by the main shock, respectively.

The background seismicity between 1 January 2002 and 29 November 2004 was active in some earthquake clusters in the focal area. We identified three active clusters centered on (42.8°N, 145.0°E), (42.8°N, 145.3°E), and (42.9°N, 145.4°E), and found that lots of the aftershocks occurred in the three active clusters (Fig. 8).

Data set 2.

We were not able to identify the fault plane clearly on the vertical cross section based on the relocated aftershocks using Data set 1. To obtain more accurate image we relocated 83 aftershocks with $M=3.5$ or larger between 29 November 2004 and 29 January 2005 using Data set 2. The aftershock distribution is generally same as the results obtained by Data set 1 (Fig. 9). The errors defined in the section III.3 were presented on Fig. 9c-e. On the vertical cross section, the hypocenters are located on a plane dipping 22° toward the land-side whose orientation agrees closely with that of the northwest-dipping nodal plane of the focal mechanism. Moreover, the aftershocks occurred on the upper plane of the double seismic zone presented by Katsumata et al. (2003) (Fig. 10).

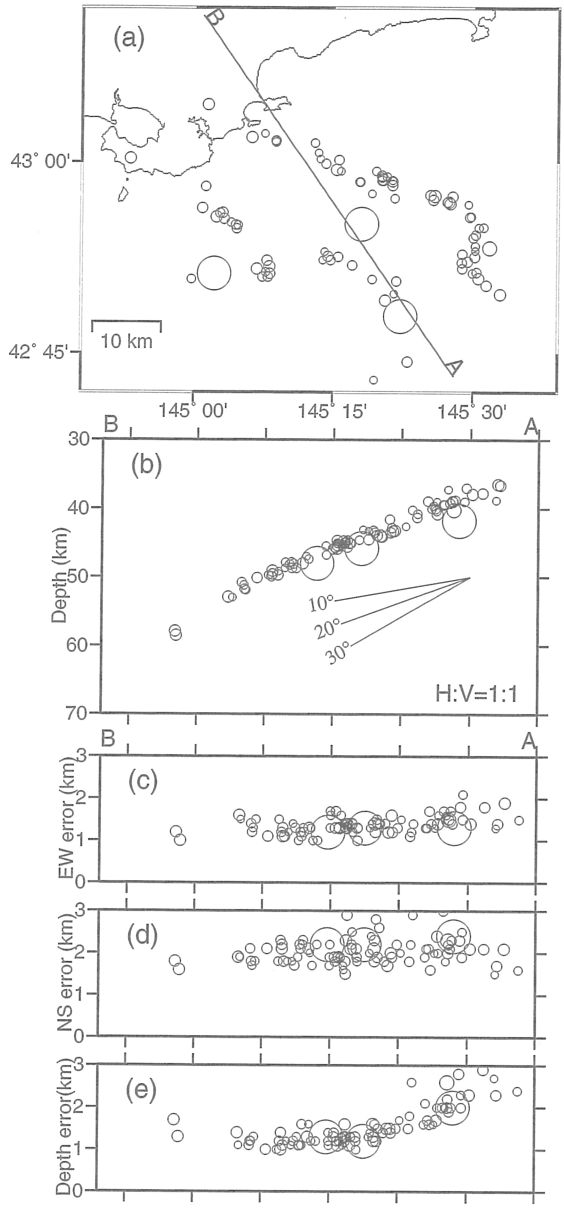

Fig. 9. Aftershocks of the 29 November 2005 Kushiro-Oki earthquake relocated by using three-dimensional velocity structure based on Data set 2. The time period is from 29 November 2004 to 29 January 2005, and the magnitude is 3.5 or larger. (a) Map view and (b) vertical cross section along the line A-B in (a). (c)-(e) The location errors defined in the section 3.3 in this paper.

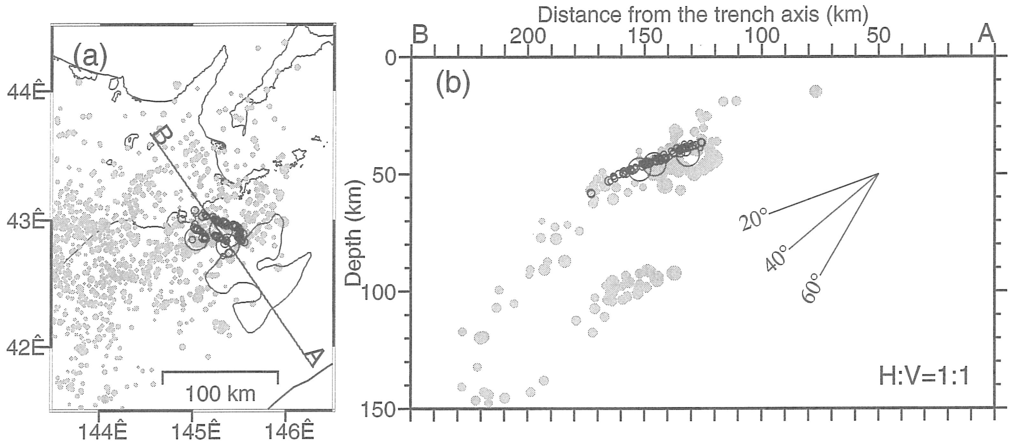

Fig. 10. Regional background seismicity from July 1999 to July 2001 presented by Katsumata et al. (2003) (gray circles), and the aftershocks of the 29 November 2004 Kushiro-Oki earthquake (open circles), which were relocated using Data set 2. (a) Map view with a contour of 1 m indicating the asperity ruptured by the 1973 Nemuro-Oki earthquake determined by Yamanaka and Kikuchi (2002), (b) vertical cross section along the line A-B in (a).

IV. Discussions

1. Source Process and Aftershock Distribution

Comparing with the source process of the main shock and the aftershock distribution, we found that the aftershocks outlined the asperity ruptured by the main shock (Fig. 11). Yagi et al. (1999) reported that aftershocks of the Hyuga-nada earthquake in 1996 occurred in the area not ruptured by the main shock, and they suggested that in the aftershock area there were barriers that stopped the rupture extent during the main shock. Taking the similar aftershock distribution into account, our plausible interpretation is that many aftershocks of the Kushirro-Oki earthquake concentrated on the regions that played a role of barriers to dynamic rupture in the main shock. We found the three clusters in the aftershock area with high seismicity, which were very active even before the main shock. This activity is apparently caused by the strong mechanical coupling on the plate boundary, and it is possible to play a role of barriers.

2. Average Stress Drop

We calculated the stress drop, $\Delta\sigma$, averaged on the fault plane from $\Delta\sigma=2.5M_0/S^{1.5}$, where M_0 and S are the seismic moment and the fault area, respectively. We estimated the fault area ruptured by the main shock on 29 November from the extent of the aftershock zone after one day, resulting that the area is $S=30\times15$ km^2 (Fig. 11). The total seismic moment was $M_0=3.4\times10^{19}$ Nm obtained by the present study. Thus we obtain that the average stress drop was $\Delta\sigma=8.9$ MPa, that is, 89 bars.

From the statistical point of view the $M7.1$ Kushiro-Oki earthquake on 29 November 2004 was a usual event. Bilek and Lay (1998) found that the average stress drop of the interplate event gets larger as the depth of hypocenter gets deeper in the Japan subduction zone (Fig. 12). According to their analysis, the average stress drop is approximately 100 bars around 50 km in depth. For the Kushiro-Oki earthquake we obtained that the depth of hypocenter is 48 km and the average stress drop is 89 bars, which is very consistent with the results obtained by Bilek and Lay (1998).

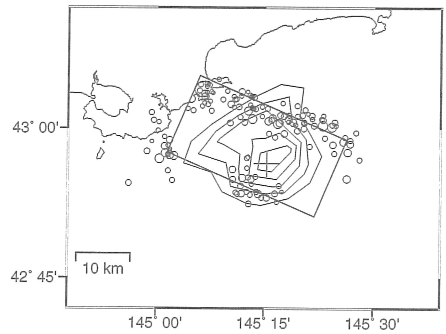

Fig. 11. Aftershock area of the 29 November 2004 Kushiro-Oki earthquake after one-day and the slip distribution. The cross and open circles indicate the epicenter of the main shock and aftershocks, respectively. A rectangle represents the area ruptured by the main shock, which was used for calculating the stress drop. Contours are drawn from 0.3 to 2.7 m every 0.6 m.

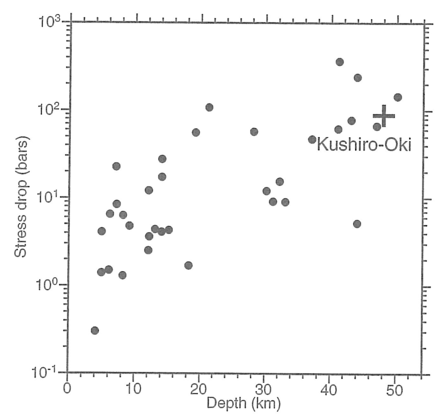

Fig. 12. Stress drop as a function of depth of hypocenter in the Japan trench after Bilek and Lay (1998) (closed circles). A cross indicates the stress drop and the depth for the 29 November 2004 Kushirro-Oki earthquake determined in this study.

3. Seismic Quiescence Area and the Asperity Ruptured by the 1973 Nemuro-Oki Earthquake

In the Nemuro-Oki area, Katsumata and Kasahara (2004) found that the microearthquake seismicity rate within the Pacific plate decreased 48 %, which started in June 2000 and has been lasting approximately five years. The seismic quiescence area is defined by a circle centered at (43.4°N, 145.0°E) with a radius of 46 km, which referred to Area 4. Fig. 13 shows that the 2004 Kushiro-Oki earthquake is located between the seismic quiescence area and the asperity ruptured by the 1973 Nemro-Oki earthquake. These areas do not overlap each other.

Murakami (2005) reported at a regular meeting of the Coordinating Committee for Earthquake Prediction on 21 February 2005 that a slow slip with a velocity of 10 cm/year started in mid 2004 on the plate boundary in Area 4, based on data from GEONET, which is a dense GPS network in Japan.

A qualitative hypothesis to describe what is going on in this region is as follows: (1) an aseismic slow slip started in June 2000 on the plate boundary in Area 4, (2) a shear stress was partly released and the seismicity decreased in Area 4, (3) the aseismic slow slip loaded a shear stress on the focal area of the Kushiro-Oki earthquake, and (4) the Kushiro-Oki earthquake occurred on 29 November 2004.

The aseismic slow slip was possibly very small in displacement at the beginning, and the stress drop was relatively large. This is a reason why the aseismic slow slip was not detected by the GPS network until mid 2004 while the seismicity rate had decreased clearly since 2000. We suppose that the aseismic slow slip was accelerated in mid 2004, and was detected by the GPS network.

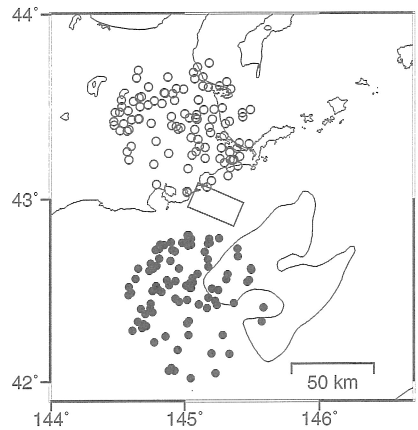

Fig. 13. Aftershock area, asperity, and change in seismicity rate. Earthquakes within the Pacific plate has been suffered from the seismic quiescence (open circles) and the seismic activation (closed circles) since May 2000 (Katsumata and Kasahara, 2004). A rectangle indicates the area ruptured by the main shock on 29 November 2004, which is same as that in Fig. 11. A contour of 1 m represents the asperity ruptured by the 1973 Nemuro-Oki earthquake determined by Yamanaka and Kikuchi (2002).

V. Concluding Remarks

We investigated the source process and the aftershock distribution of the 29 November 2004 Kushiro-Oki earthquake, and found that this event is a large underthrusting earthquake rupturing the plate boundary between the subducting Pacific plate and the overriding North American plate. The main shock was a very usual event around 50 km in depth from the points of view including the extent of the aftershock zone and the average stress drop. However, taking the location of the focal area into account, this is an outstanding event, which was located between the region suffering from the five-years-lasting seismic quiescence and the asperity ruptured by the 1973 Nemuro-Oki earthquake. Moreover, an aseismic slow slip has been observed since mid 2004 in the seismic quiescence area. The important points to consider are whether the aseismic slow slip has loaded the shear stress on the asperity ruptured by the 1973 Nemuro-Oki earthquake, and whether a great earthquake rupturing this asperity will be induced in the near future.

Acknowledgements We thank four engineers at ISV for maintaining the seismographic network: M. Ichiyanagi, M. Okayama, M. Takada, and T. Yamaguchi. We thank D. Zhao at Ehime University for providing computer software for the 3−D hypocenter determination. We used waveforms from seismic stations belonging to IRIS for analyzing the source process, and belonging to ISV, Hirosaki University, Tohoku University, Sapporo City, JMA, and NIED for relocating the aftershocks. GMT (Wessel and Simith, 1991) was used to make figures.

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地震活動静穏化域と 1973 年根室半島沖地震震源域との間で発生した 2004 年 11 月 29 日釧路沖地震($M7.1$)

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(2005 年 12 月 12 日受理)

2004 年 11 月 29 日に釧路沖（または白糠沖）で発生した$M7.1$の地震の震源過程と余震分布を調査した．本研究で決定された震源パラメータは以下の通りである．地震モーメント$M_0=3.4\times 10^{19}$ Nm（モーメントマグニチュード$M_w=7.0$）；（断層面の strike, dip, slip)=(238°, 33°, 117°)； 破壊開始点の深さ 48 km; 破壊継続時間 10 秒．また，3 次元P波・S波速度構造を用いて余震の震源を再決定したところ，余震域は面積が 30×15 km² で陸側に向かって 22°の角度で傾斜していることが分かった．この角度は震源メカニズム解の 2 つの節面の内，北西方向に傾斜した面と調和的である．本研究で決定した地震モーメントと余震域の面積を用いて計算した応力降下量は 89 バールであった．余震は本震で破壊したアスペリティ内部にはほとんど発生しておらず，アスペリティを取り囲むように分布していた．11 月 29 日の釧路沖地震は太平洋プレート上面付近で発生した典型的な低角逆断層型の地震であったと考えられる．しかし現在継続中の地震活動の静穏化域と 1973 年根室半島沖地震の震源域との中間地点で発生した地震であるため，今後の推移を注意深く見守る必要があろう．