

EXPRESS LETTER

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The 2018 Hokkaido Eastern Iburi earthquake ($M_{JMA} = 6.7$) was triggered by a strike-slip faulting in a stepover segment: insights from the aftershock distribution and the focal mechanism solution of the main shock

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Abstract

The Hokkaido Eastern Iburi earthquake ($M_{JMA} = 6.7$) occurred on September 6, 2018, in the Hokkaido corner region where the Kurile and northeastern Japan island arcs meet. We relocated aftershocks of this intraplate earthquake immediately after the main shock by using data from a permanent local seismic network and found that aftershock depths were concentrated from 20 to 40 km, which is extraordinarily deep compared with other shallow intraplate earthquakes in the inland area of Honshu and Kyushu, Japan. Further, we found that the aftershock area consists of three segments. The first segment is located in the northern part of the aftershock area, the second segment lies in the southern part, and the third segment forms a stepover between the other two segments. The hypocenter of the main shock, from which the rupture initiated, is located on the stepover segment. The centroid moment tensor solution for the main shock indicates a reverse faulting, whereas the focal mechanism solution determined by using the first-motion polarity of the *P* wave indicates strike-slip faulting. To explain this discrepancy qualitatively, we present a model in which the rupture started as a small strike-slip fault in the stepover segment of the aftershock area, followed by two large reverse faulting ruptures in the northern and southern segments.

Keywords: The Hokkaido Eastern Iburi earthquake, Strike-slip fault, Reverse fault, Aftershock distribution, Focal mechanism solution, Local seismic network, Stepover segment

Introduction

The Hokkaido Eastern Iburi earthquake occurred on September 6, 2018, and the parameters of the hypocenter given by the Japan Meteorological Agency (JMA) are as follows: origin time = 03:07:59.3 JST,

epicenter = (42.691°N, 142.007°E), depth = 37.0 km, and $M_{JMA} = 6.7$. This earthquake is located in the Hokkaido corner region, where the northern Japan island arcs connect to the Kurile Islands. The Pacific plate subducts beneath Hokkaido Island on the North American or the Okhotsk Sea Plate in this region (e.g., Takahashi et al. 1999; Katsumata et al. 2002). In addition, the Kurile island arc is moving toward the southwest and colliding with the northeastern Japan arc (e.g., Kimura 1996). This region is called the arc–arc-type Hidaka

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collision zone (HCZ). The depth to the upper surface of the subducting Pacific plate is approximately 100 km around the focal area (Katsumata et al. 2003); therefore, this earthquake obviously occurred in the North American plate or the Okhotsk Sea plate, i.e., this earthquake was a shallow intraplate earthquake in the inland area of Japan.

The first purpose of this study is to re-evaluate the depth and distribution of the main shock and aftershocks accurately. The hypocenters of main shocks are usually shallower than 20 km for shallow intraplate earthquakes in the inland area of Japan (Omuralieva et al. 2012), whereas the depth of this sequence was obviously deeper than 20 km according to the preliminary report from the JMA. Therefore, we relocated the hypocenters of the main shock and aftershocks in this study by considering a local complex velocity structure of the crust.

The second purpose of this study is to investigate the reason for the mismatch between the centroid moment tensor (CMT) solution and the focal mechanism solution determined by using the first-motion polarities of P waves at individual stations. The CMT solutions of the main shock were reported by four groups: JMA (2018a), the National Research Institute for Earth Science and Disaster Resilience (NIED 2018a), the United States Geological Survey (USGS 2018), and the Global CMT project (Dziewonski et al. 1981; Ekström et al. 2012). All CMT solutions of this earthquake are consistent in showing that the earthquake resulted mainly from reverse faulting. However, the focal mechanism of this earthquake was mainly strike-slip faulting (JMA 2018b; NIED 2018b). We estimated the focal mechanism solution by adding data from seismic stations in the focal area and investigated a model to explain qualitatively the discrepancy between the CMT solutions and the focal mechanisms by referring to the relocated aftershock distribution.

Data

We used the arrival times of P and S waves from 35 permanent seismic stations maintained by Hokkaido University, JMA, and NIED (Fig. 1). Each station consists of a short-period seismograph with three components on the ground surface or in a vertical borehole. All waveform data are telemetered continuously in real time, and preliminary hypocenters are determined automatically. In total, 459 earthquakes were detected and located for ~ 2 days between 2018-09-06 03:00 and 2018-09-07 23:59, and we used the arrival times from these earthquakes in the following analyses. All waveform data were examined carefully by visual inspection, and all arrival times were read manually by a well-trained person. The

accuracies for most P and S arrival times are considered to be 0.05–0.1 s and 0.1–0.2 s, respectively. An electrical power loss occurred during this period, and the waveform data were not recorded for several hours at some stations. We deployed 25 temporary seismic stations in the focal area immediately after the main shock and observed aftershocks for approximately 2 months. Although we successfully recorded many earthquakes, we used no data from the temporary seismic stations in this study.

Analyses

To relocate hypocenters, we first determine hypocenters of earthquakes with an assumption of a 1-D velocity structure using the hypomh algorithm (Hirata and Matsu'ura 1987). We then used the hypocenters as the initial locations of earthquakes and carried out relative hypocenter relocation using double-difference tomography (tomoDD) (Zhang and Thurber 2003) with a fixed 3-D velocity structure. The initial locations of hypocenters were calculated with an assumption of a 1-D structure for the velocity of the P wave (V_p) based on Iwasaki et al. (2004) as shown in Fig. 1c: 3.2 km/s at 0.0 km depth, 4.8 km/s at 3.0 km, 5.78 km/s at 7.0 km, 4.65 km/s at 10.0 km, 6.95 km/s at 22.5 km, 7.2 km/s at 35.0 km, and 8.06 km/s at 50.0 km. The velocity of the S wave (V_s) was calculated at each depth as $V_p/1.73$ with the assumption that the V_p/V_s ratio is 1.73. Recently several authors presented a 3-D tomographic model of V_p and V_s in this region (Katsumata et al. 2006; Yoshida et al. 2007; Kita et al. 2012; Shiina et al. 2018); thus, we assumed a 3-D velocity structure as shown in Additional file 1. The study area was divided into grids every 10 km in both the longitude and latitude directions on each plane at depths of 0, 5, 10, 22.5, 35, and 50 km. Values of V_p and the V_p/V_s ratio at depths shallower than 10 km were based on Yoshida et al. (2007), and those at depths equal to and deeper than 10 km were based on Shiina et al. (2018).

To support the results obtained by the method described above, we determined the hypocenters by using a homogeneous station method. Seven seismic stations were selected among the 35 stations, and their epicentral distances from the main shock ranged from 14 to 38 km. Seventy aftershocks were relocated for the 4 h immediately after the main shock between 2018-09-06 03:15 and 07:18. The arrival times of both P and S waves were picked at all seven stations for all 70 aftershocks; thus, hypocenters have no variations due to differences in the combination of seismic stations. We used the hypomh program (Hirata and Matsu'ura 1987) to determine hypocenters, and the 1-D V_p structure was assumed to be as follows: 2.6 km/s at a depth

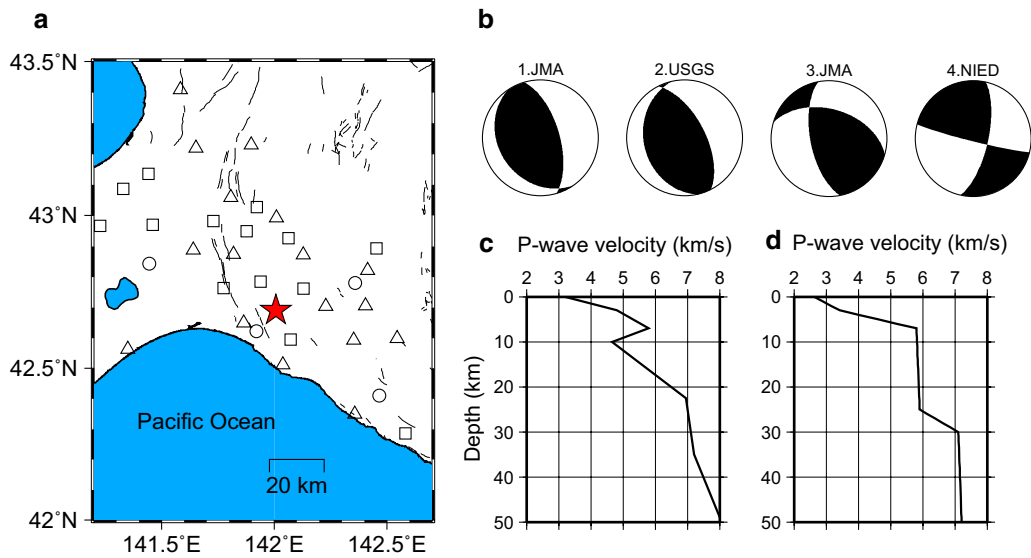


Fig. 1 **a** Seismic stations are used in this study. Squares and circles are stations maintained by Hokkaido University and JMA, respectively. Triangles are the Hi-net or F-net stations maintained by NIED. A red star marks the epicenter of the 2018 Hokkaido Eastern Iburi earthquake located by JMA. Thin lines indicate surface traces of active faults (Research Group for Active Faults in Japan 1991). **b** 1. JMA and 2. USGS are the CMT solutions of the main shock determined by JMA (2018a) and USGS (2018), respectively. 3. JMA and 4. NIED are the focal mechanism solutions of the main shock by using the first-motion polarities of the *P* wave determined by JMA (2018b) and NIED (2018b), respectively. **c** *P* wave velocity structure assumed for calculating the initial hypocenters before the hypocenter determination using a 3-D velocity structure. **d** Optimal *P* wave velocity structure obtained from the homogeneous station method

of 0 km, 3.4 km/s at a depth of 3 km, and 5.8 km/s at a depth of 7 km. These values are based on Iwasaki et al. (2004). The V_p structure at depths deeper than 7 km was assumed to be as follows: V_1 km/s at a depth of $(7+H)$ km, V_2 km/s at a depth of $(7+H)+5$ km, and 9.0 km/s at a depth of $(7+H)+5+370$ km. The four parameters, V_1 , V_2 , H , and the V_p/V_s ratio, were determined using a grid search technique. V_1 , V_2 , H , and the V_p/V_s ratio ranged from 5.9 to 7.9 km/s with every 0.1 km/s, from $V_1+0.1$ to 8.5 km/s with every 0.1 km/s, from 1 to 50 km with every 1 km, and from 1.60 to 1.80 with every 0.01, respectively. The optimal solution for the four parameters was determined under the condition that the residual of the 70 aftershocks reaches a minimum.

To determine the focal mechanism solution of the main shock, we used the HASH method (Hardebeck and Shearer 2002), which is a grid search program using the first-motion polarity of the *P* wave. *P* wave first-motion polarities were read manually by careful inspection at 53 seismic stations with epicentral distances from 9 to 114 km. No amplitude data were used.

Results

In total, 459 earthquakes were located for ~2 days between 2018-09-06 03:00 and 2018-09-07 23:59 (Fig. 2 and Additional file 2). We located the epicenter of the

main shock at (42.662°N, 142.011°E), and the depth was 40.5 km. We found that the aftershock area extended 25 km horizontally, approximately in the N–S direction, and that 95% of the hypocenters were distributed at depths from 20 to 40 km. The location errors were approximately 0.2 km in both the horizontal and vertical directions for the relocated main shock and aftershocks. These small errors indicated that the reading error depending on the ground noise level was very small and that the station coverage was very good. Zero, 14, 50, 387, and 8 hypocenters were located shallower than 10 km, 10 to 20 km, 20 to 30 km, 30 to 40 km, and 40 to 50 km, respectively. Therefore, the aftershocks of the 2018 Hokkaido Eastern Iburi earthquake occurred at the obviously greater depths than other intraplate earthquakes in the inland area of Honshu and Kyushu, Japan.

We also found that the aftershock area consists of three segments: the northern, the southern, and the stepover segments. Taking location errors into account, possible fault zones are shown in each vertical cross section in Fig. 3. The northern segment extends horizontally 15 km in the N–S direction and dips ~60° to the east. The southern segment extends horizontally 10 km in the NNE–SSW direction and dips ~65° to the ESE. The near-N–S horizontal trends and the dip angles of these two segments are consistent with one of the nodal planes of the CMT solutions, indicating that the main shock was

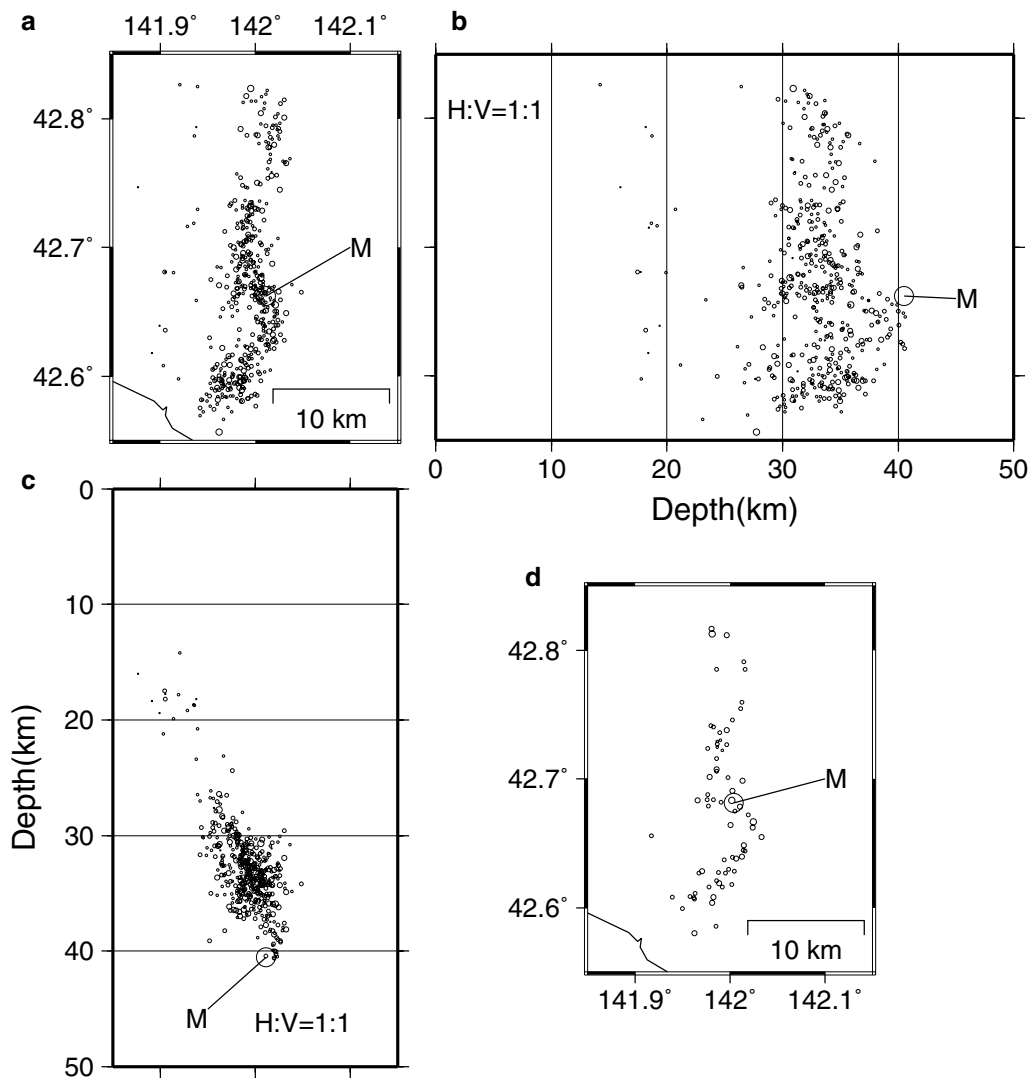
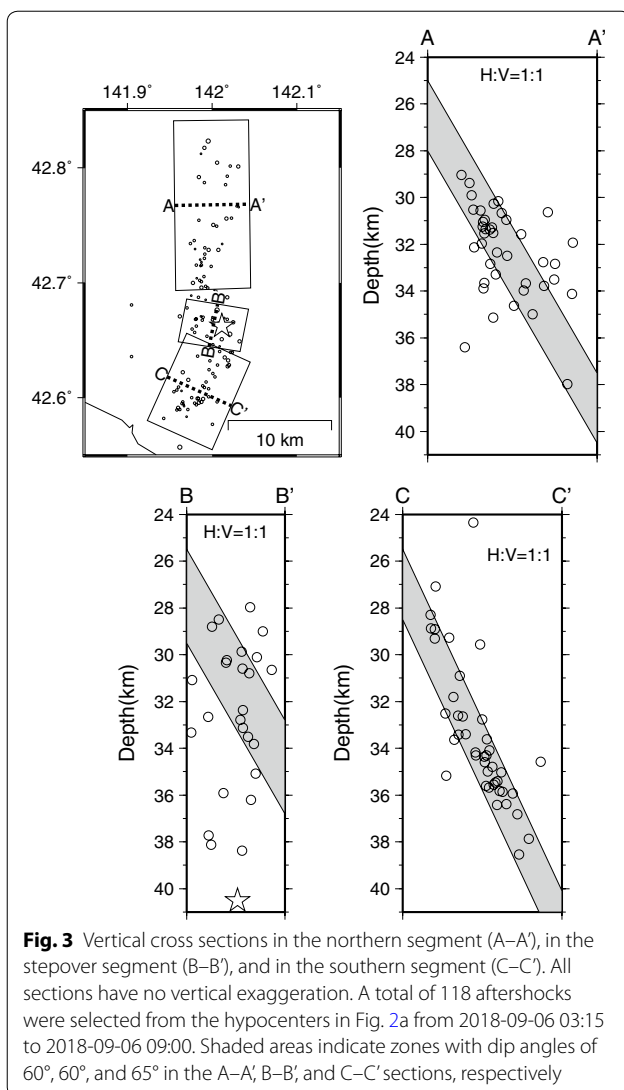


Fig. 2 Hypocenter distribution of the main shock and the aftershocks. **a** Distribution of epicenters determined by the tomoDD method from 2018-09-06 03:00 to 2018-09-07 23:59. A black line with “M” indicates the location of the main shock. The hypocenters are listed in Additional file 2. **b, c** Vertical cross sections of **a** in the N–S and E–W directions, respectively. **d** Distribution of epicenters determined by the homogeneous station method for 4 h immediately after the main shock from 2018-09-06 03:15 to 2018-09-06 07:18

mainly due to reverse thrust faulting. Both the horizontal lengths and the dip angles are almost the same for the northern and southern segments, whereas the horizontal direction of the southern segment is rotated slightly clockwise relative to the northern segment. Moreover, a clear horizontal offset or stepover of ~ 5 km is observed between the two segments. This stepover segment extends horizontally 5 km in the WNW–ESE direction and seems to connect the southern and northern segments. The hypocenter of the main shock, i.e., the initiation point of the rupture, is located in the stepover segment.

In the case of the homogeneous station method, the optimal solutions for the four parameters are as follows (Fig. 1d): $V_1 = 5.9$ km/s, $V_2 = 7.1$ km/s, $H = 18$ km, and $V_p/V_s = 1.70$. By using the optimal 1-D velocity structure, we located the epicenter of the main shock at (42.681°N , 142.004°E), and the depth was 34.3 km. The spatial patterns described above were also obtained in the homogeneous station method analysis, as shown in Fig. 2. The different analyses presented similar results. Therefore, the two noteworthy spatial patterns obtained in this study, i.e., (1) the deep distribution of aftershocks and (2) the aftershock area consisting of three segments, seemed to be reliable.



We obtained the focal mechanism solution of the main shock: nodal plane 1 (strike, dip, rake) = (177°, 73°, 143°) and nodal plane 2 (279°, 54°, 20°) (Fig. 4). As the station coverage was good and the misfit was small, the quality of solution was estimated to be A (good) by the HASH program. The solution in this study indicated strike-slip faulting with a small component of reverse faulting and did not match the CMT solutions. On the other hand, the strike of nodal plane 2 was estimated in the WNW-ESE direction, which was consistent with the direction of the aftershock distribution in the stepover segment.

Discussion

Extraordinarily deep aftershock distribution

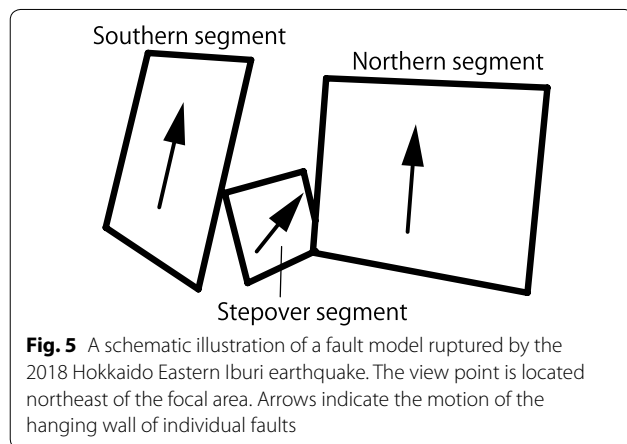
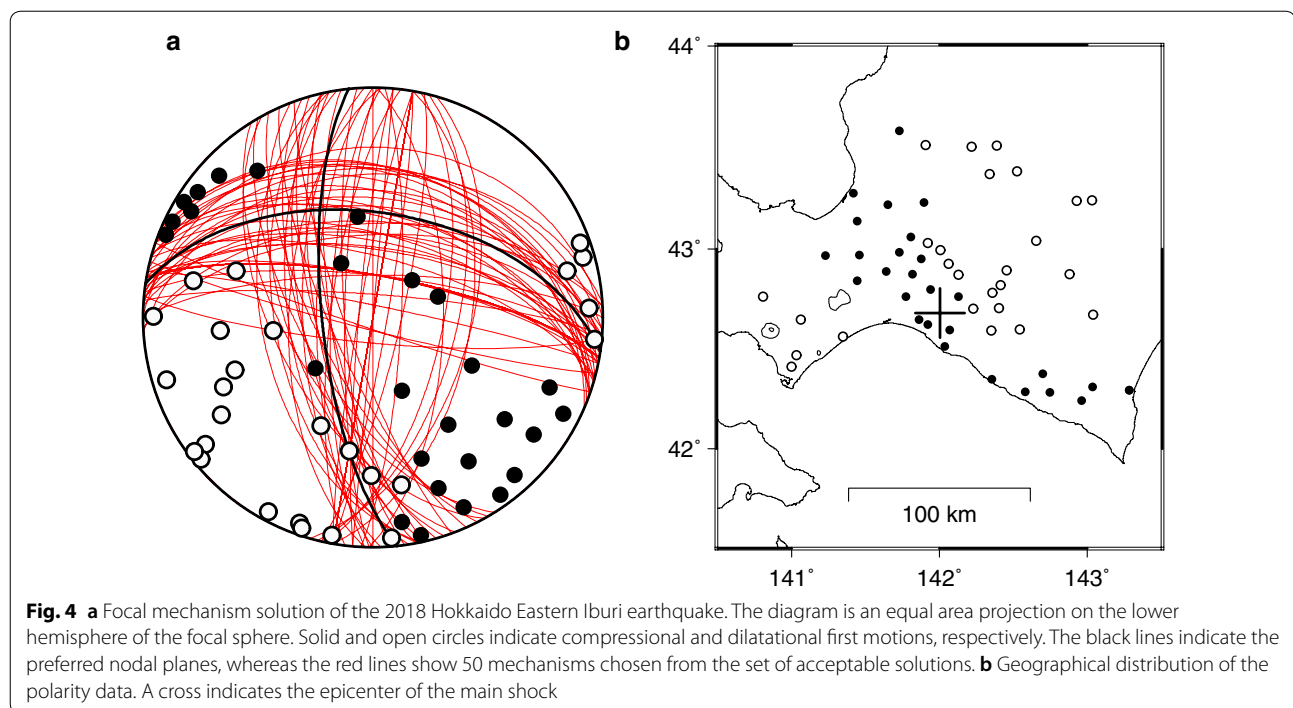
In this study, we relocated the main shock and the aftershocks of the 2018 Hokkaido Eastern Iburi earthquake

and found that almost all earthquakes were concentrated at depths from 20 to 40 km. This range is extraordinarily deeper than other intraplate earthquakes in the inland area of Honshu and Kyushu, Japan. Table S1 in Additional file 3 shows that in the case of the 1995 Hyogo-ken–Nanbu earthquake (M_{JMA} 7.2), the depth range of the aftershock area is from 0 to 20 km (Hirata et al. 1996); the 2000 Western Tottori (M_{JMA} 7.3), 2–13 km (Shibutani et al. 2005); the 2004 mid-Niigata (M_{JMA} 6.8), 2–13 km (Okada et al. 2005); the 2005 West Off Fukuoka (M_{JMA} 7.0), 2–16 km (Shimizu et al. 2006); the 2007 Chuetsu-oki (M_{JMA} 6.8), 5–22 km (Nakahigashi et al. 2012); the 2007 Noto Hanto (M_{JMA} 6.9), 1–13 km (Sakai et al. 2008); the 2008 Iwate-Miyagi Nairiku (M_{JMA} 7.2), 2–8 km (Okada et al. 2012); the 2011 Iwaki (M_{JMA} 7.0), 2–15 km (Kato et al. 2013); the 2016 Kumamoto (M_{JMA} 7.3), 2–18 km (Shito et al. 2017); and the 2016 Tottori (M_{JMA} 6.6), 5–15 km (Ross et al. 2018). On the other hand, the aftershock area is deep in and around the HCZ, Hokkaido. For example, in the cases of the 1970 M_{JMA} = 6.7 Hidaka earthquake and the 1982 M_{JMA} = 7.1 Urakawa-oki earthquake, the aftershocks were located at depths from 20 to 30 km and from 18 to 35 km, respectively (Moriya 1972; Moriya et al. 1983). The 2018 Hokkaido Eastern Iburi earthquake is also located in the HCZ and its deep distribution of aftershocks is very similar to those of previous earthquakes in this region.

The hypocenter of the 2018 earthquake is located near the bottom of the aftershock area. This fact is consistent with a model in which the stress accumulates on a seismic fault in the upper crust due to a weak zone in the lower crust (Iio et al. 2002). The P and S wave velocities, the resistivity, and the pore pressure in and around the aftershock area provide clues for further discussion.

A model of the fault ruptures during the main shock

Here, we first summarize the results: (1) the hypocenter of the main shock was located in the stepover segment in the central part of the aftershock area and (2) the focal mechanism solution of the main shock is consistent with the aftershock distribution in the stepover segment. Based on these results, we present a model in which the fault rupture during the main shock started at the stepover segment in a small area, possibly 5×5 km² and $M \sim 5$, with left-lateral strike-slip faulting, and immediately afterward, large ruptures, possibly with fault areas of 10×10 km² and $M \sim 6.4$ each, were triggered in the northern and southern segments with reverse faulting (Fig. 5). Nodal plane 2 of the focal mechanism obtained in this study probably corresponds to the first strike-slip faulting, which dips toward the NNE; thus, the hanging wall of this fault plane moved westward and upward.



Qualitatively, these motions possibly promoted reverse faulting in the northern and southern segments. To test the fault model, the Coulomb failure stress change (ΔCFS) in and around the focal area was calculated (see Additional file 4). In the case of the 2007 Noto Hanto earthquake, Sakai et al. (2008) also proposed a model in which small strike-slip faulting occurred first, and 0.6 s later, the main rupture with reverse faulting was triggered by the small strike-slip faulting. The model presented in this study should be supported by other data and analyses, including far-field body waves, near-field strong motion records, global

navigation satellite system (GNSS), and interferometric synthetic aperture radar (InSAR).

The rupture process including a stepover segment is well known in the case of strike-slip faulting, e.g., the 1992 M_w 7.3 Landers earthquake (Sieh et al. 1993) and the 2016 M_w 7.8 Kaikoura, New Zealand earthquake (Hamling et al. 2017). Many numerical simulations and theoretical studies on the physical mechanism of rupture propagation consider a stepover segment between strike-slip faults (e.g., Bai and Ampuero 2017). However, little is known about the rupture process with a stepover segment in the case of reverse thrust faulting. In this sense, the 2018 Hokkaido Eastern Iburi earthquake is an unusual earthquake.

Conclusions

We relocated hypocenters of the main shock and aftershocks immediately after the 2018 Hokkaido Eastern Iburi earthquake ($M_{JMA}=6.7$) by using two different methods: the hypoDD method with an assumed 3-D velocity structure and a homogeneous station method. As a result, we found that the main shock was located obviously deeper than 30 km, and almost all aftershocks were located at depths between 20 and 40 km. These depths are extraordinarily deeper than those for other intraplate earthquakes in the inland area of Japan. The CMT solution of the main shock is inconsistent with the focal mechanism solution determined by the first-motion polarities of the P wave. This discrepancy is probably

explained by the model proposed in this study in which the rupture started as a small left-lateral strike-slip fault in the stepover segment, and afterward, two large reverse faults were triggered in the northern and southern segments.

Additional files

Additional file 1. 3D *P* wave velocity structure.

Additional file 2. List of hypocenters in Fig. 2a, b, and c.

Additional file 3: Table S1. Depth range of aftershock area.

Additional file 4. A calculation of the Coulomb stress change.

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Authors' contributions

MI read all arrival times of *P* and *S* waves and determined hypocenters using the tomoDD method. KK performed the homogeneous station method analysis, the HASH analysis and was a major contributor in writing the manuscript. MO, HA, RT, MT, TY, KO, and HT are the technical staff members who maintain the seismic stations of Hokkaido University. SS, SM, TO, TM, SH, TT, SH, MK, HK, YI, AN, NT, TU, and members of the Group for the Aftershock Observations are the assistant staff to maintain the seismic stations. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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