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Seismic structure of the source region of the 2007 Chuetsu-oki earthquake revealed by offshore-onshore seismic survey: Asperity zone of intraplate earthquake delimited by crustal inhomogeneity

Kazuo Nakahigashi [a,*], Masanao Shinohara [a], Eiji Kurashimo [a], Tomoaki Yamada [a], Aitaro Kato [a], Tetsuo Takanami [b,1], Kenji Uehira [c,2], Yoshihiro Ito [d], Takashi Iidaka [a], Toshihiro Igarashi [a], Hiroshi Sato [a], Ryota Hino [d], Koichiro Obana [e], Yoshiyuki Kaneda [e], Naoshi Hirata [a], Takaya Iwasaki [a], Toshihiko Kanazawa [a,2]

[a] Earthquake Research Institute, University of Tokyo, Tokyo 113-0032, Japan
[b] Institute of Seismology and Volcanology, Hokkaido University, Sapporo 060-0810, Japan
[c] Institute of Seismology and Volcanology, Kyushu University, Shimabara 855-0843, Japan
[d] Graduate School of Science, Tohoku University, Sendai 980-8578, Japan
[e] Japan Agency for Marine-Earth Science and Technology, Yokosuka 237-0061, Japan

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ABSTRACT

The 2007 Niigata-ken Chuetsu-oki earthquake occurred on July 16, 2007 with a magnitude of 6.8. Immediately after the mainshock, a dense network of ocean-bottom seismometers and temporary land seismic stations were deployed to obtain the accurate aftershock location. A seismic survey using ocean-bottom seismometers, land stations and controlled sources at sea and on land was also conducted along three profiles to estimate the detailed velocity structure of the source region. A thick sedimentary layer covers the crust, and this layer is thickest near the coast. The upper crust has a P-wave velocity of 6 km/s and a large lateral heterogeneity with respect to thickness and velocity. The lower crust, with P-wave velocity of 7 km/s, has a thickness of approximately 10 km. The thickness of the crust is estimated to be approximately 24 km. The precise aftershock distribution was obtained by using the high-resolution velocity structure. The aftershocks in the upper crust form a plane dipping to the southeast. Most of the aftershocks are located in the upper crust; in addition, a small number of aftershocks in the lower crust seem to be positioned on the same plane formed by the aftershocks in the upper crust. The mainshock fault estimated from the aftershock distribution is positioned in the high-velocity body of the upper crust. A large deformation of the sediments above the epicentral region is interpreted to be due to the repeated occurrence of large earthquakes. The lower crust immediately below the fault has low velocity. The source region of the 2007 event in the upper crust is sandwiched by a weakening structure. We suggest that the ductile deformation of both the sediments and the lower crust causes stress accumulation in the source region.

1. Introduction

The Niigata-ken Chuetsu-oki Earthquake (Mw 6.8) occurred on July 16, 2007 at a shallow depth near the central coast of Niigata Prefecture, Japan. The focal mechanism was estimated to be a pure reverse fault with a northeast strike using the first P-wave motions by the Japan Meteorological Agency (JMA). The regions of the Niigata and Nagano Prefectures were strongly shaken and were largely damaged by a maximum seismic intensity above 6 on the JMA scale. Many aftershocks occurred following the mainshock. The largest aftershock occurred on the same day as the mainshock, and the magnitude of the largest aftershock was 5.8. The source region of the Chuetsu-oki earthquake was estimated to lie mainly under an offshore region that stretches from a few kilometers up to 15 km off the coast of the Chuetsu region.

Global Positioning System (GPS) observations with a dense station distribution by the Geographical Survey Institute, Japan, revealed that the central coastal area of the Japan Sea, which is termed the Niigata-Kobe Tectonic Zone (NKTZ) (Sagiya et al., 2000), has large strain rate, after correcting for the short-term elastic response due to the subduction of the Pacific and Philippine Sea plates. Historically, large earthquakes

* Corresponding author at: Earthquake Research Institute, University of Tokyo, Yayoi, 1-1-1, Bunkyo-ku, Tokyo 113-0032, Japan. Tel.: +81 3 5841 1753; fax: +81 3 5841 8265.
E-mail address: kazuo@eri.u-tokyo.ac.jp (K. Nakahigashi).
[1] Now at: Earthquake Research Institute, University of Tokyo, Tokyo 113-0032, Japan.
[2] Now at: National Research Institute for Earth Science and Disaster Prevention, Tsukuba, 305-0006, Japan.

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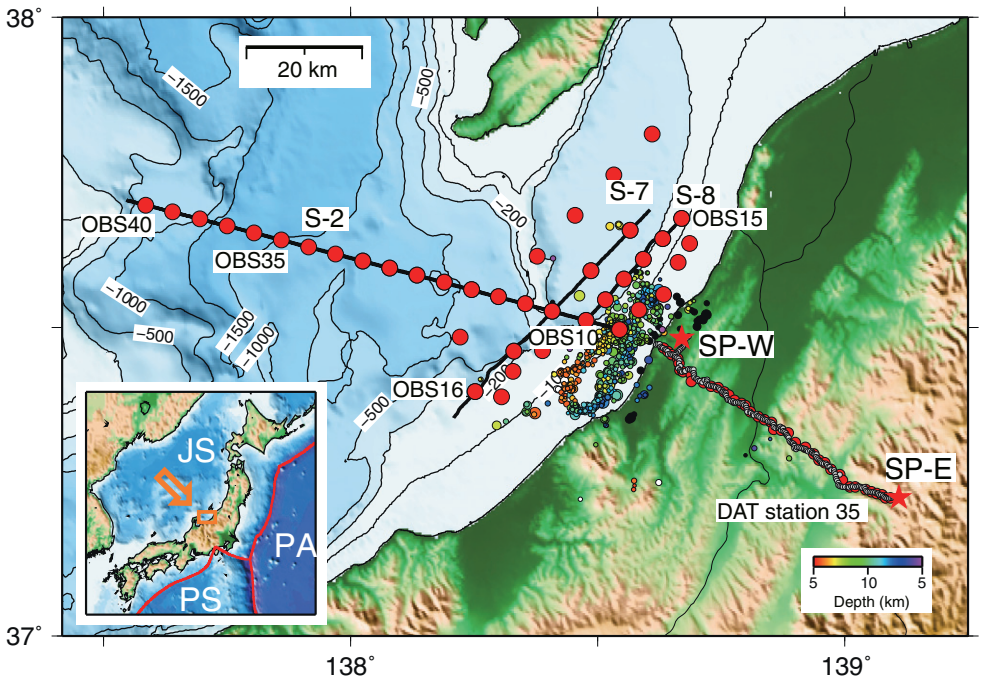

Fig. 1. Location map of ocean-bottom seismometers and land seismic stations used in this study. Bathymetric contours indicate water depths of 100, 200, 500, 1000 and 1500 m. Large red circles indicate the positions of pop-up-type OBSs. Numerals indicate OBS and DAT number. Small red and gray circles denote the position of land seismic station used in this study. Small color-coded circles denote epicenters determined by Shinohara et al. (2008) from July 26 to August 24, 2007. Red stars indicate positions of the explosives on the land. Thick lines labeled S-2, S-7 and S-8 indicate the profiles of the seismic refraction/structural survey during the KR07-E01 research cruise. Inset indicates index map of the study area. PA, PS and JS indicate the Pacific plate, Philippine Sea plate and Japan Sea. The arrow and rectangle indicate the location of the study area.

have occurred in and around the NKTZ. Large strain rates have been estimated to induce the large earthquakes (Sagiya et al., 2000). In the coastal region of the central NKTZ, geological studies indicate that the thick sedimentary basin was formed by a rift structure with a normal fault system that developed during the extension stage of the Japan Sea (Sato, 1994). The normal fault system during the rifting stage has been reactivated as a reverse fault system by a change in the tectonic stress from extension to compression. This stress change is estimated to have been caused by a change in the dip angle of the subducting Pacific plate (Niitsuma, 1979).

Recently, there were two large earthquakes (The 2004 Chuetsu Earthquake and The 2007 Noto Hanto Earthquake) prior to the 2007 Chuetsu-oki earthquake in and around the NKTZ (e.g., Horikawa, 2008; Ozawa et al., 2008; Sakai et al., 2005a, 2008; Shibutani et al., 2005). To observe the aftershocks of the two earthquakes, spatially dense observations were performed using on-land and ocean-bottom seismometer (OBS) stations installed temporarily (Shinohara et al., 2008; Yamada et al., 2008). Therefore, the precise distributions of the aftershocks were estimated using the dense seismic network. Furthermore, the data were also used for tomographic studies to determine the crustal structure around the focal regions. Consequently, the focal regions of the recent two earthquakes are estimated to be positioned in the upper crust (Yamada et al., 2008) and are related to the heterogeneity in the crust (Kato et al., 2005, 2006; Okada et al., 2005).

Although permanent land seismic networks are operated by the National Research Institute for Earth Science and Disaster Prevention (NIED), JMA and universities near the source region of the 2007 Chuetsu-oki earthquake, the average spacing of these stations (approximately 30 km) is not sufficient for an accurate determination of the aftershock distributions in the source region. To obtain the accurate location of the aftershock distributions in and around the source region, a dense network of temporary seismic stations were deployed on land immediately after the 2007 Chuetsu-oki earthquake (Kato et al., 2008). However, it is difficult to estimate the exact focal plane geometry using aftershock distributions from only the land seismic networks because the source region of the Chuetsu-oki earthquake lies mainly under an offshore area. It is widely known that an OBS observation is essential to obtaining a high-resolution picture of the aftershock distribution associated with large earthquakes that occur in the marine environment (e.g., Sakai et al., 2005b; Shinohara et al., 2004; Yamada et al., 2005). In addition, spatially dense OBS observations are also necessary to precisely determine the aftershock distribution of earthquakes occurring near a coast line because a seismic network must cover the whole source region (Uehira et al., 2006; Yamada et al., 2008).

Previous studies of seismic velocity structure in the NKTZ suggest that the complex structures caused by crustal stretching at the opening of the Japan Sea have the potential to nucleate large earthquakes (Kato et al., 2006, 2008, 2009). To obtain a detailed picture of the seismic structure around the epicentral region of the 2007 Chuetsu-oki earthquake, it is important to study the seismogenic zone and crustal structure that may be linked to the opening of the Japan Sea. The precise velocity structure is also important in estimating the precise aftershock location. During the aftershock observation, controlled source seismic surveys were conducted in and around the source region of the 2007 Chuetsu-oki earthquake. A seismic survey using OBSs, land stations and active seismic sources off- and on-shore was conducted between August and September 2007 (Fig. 1). In this paper, we present the detailed P-wave seismic structure of the source region of the 2007 Chuetsu-oki earthquake and discuss possible links between the opening of the Japan Sea and the occurrence of the 2007 earthquake. We also present the precise aftershock distribution obtained from OBS and land-station data using the accurate velocity structure determined from the controlled-source seismic survey and discuss the relationship between the crustal structure and the earthquake rupture process.