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Large heterogeneous structure beneath the Atotsugawa Fault, central Japan, revealed by seismic refraction and reflection experiments

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ABSTRACT

A high-strain-rate zone termed the Niigata Kobe Tectonic Zone is located in central Japan and contains an active right-lateral fault called the Atotsugawa Fault. We present the results of an explosive-source seismic experiment that focused on identifying the formation mechanisms of the fault. The experiment used seven explosive sources and 1108 seismic stations, and was undertaken during October 2007 in the area of the Atotsugawa Fault. The seismic stations were set up on a survey line with a length of ~170 km, oriented orthogonal to the strike of the fault. The linear array was used to identify the seismic structure of the fault zone and the deeper parts of the crust in the study area, yielding fine details of the seismic structure of the crust along the profile line, including lateral variations in P-wave velocity and the configuration of layers in the crust. A relatively low P-wave velocity reflective zone was detected beneath the fault at depths of 15–25 km. This zone also has extremely low S-wave velocities, directly underlies three active faults, and contains three low-resistivity zones that underlie these faults. These reflective and low-resistivity zones are thought to represent fluid within the crust, and the data obtained during this study are consistent with a weak zone model for the formation of the active faults in the study area. This suggests that the reflective layer represents a weak zone in the lower crust that is responsible for the concentration of deformation within the upper crust. The presence of abundant fluids beneath the Atotsugawa Fault could also reduce the strength of the lower crust, again focusing deformation related to the regional stress regime in areas that overlie these fluid-containing zones. The results suggest that the reflective layer was an important factor in the formation of the Atotsugawa Fault.

1. Introduction

Very little is known about the cause of intraplate earthquakes, as such earthquakes have long recurrence cycles (from several hundred to several thousand years) that hamper our understanding of the processes that give rise to such events. However, these earthquakes can cause major disasters, primarily as their sources are close to population centers. As such, understanding the mechanisms that cause intraplate earthquakes is an important step in the mitigation of disasters, and it requires knowledge of the mechanisms of strain accumulation and stress concentration along the source faults of such events.

Previous research using a Global Positioning System (GPS) array with a high spatial density identified a high-strain-rate zone along the Japan Sea coastline of Japan (e.g., Sagiya et al., 2000; Fig. 1), termed the Niigata–Kobe Tectonic Zone (NKTZ). This zone has been the location of numerous historical large earthquake-related disasters, indicating that understanding the seismic structure of the NKTZ would be an important step in understanding the mechanisms of stress concentration and strain accumulation in and around Japan. The NKTZ has been studied previously (e.g., Hyodo and Hirahara, 2003; Iio et al., 2002; Shimazaki and Zhao, 2000; Yamasaki and Seno, 2005), leading to the proposal of various models for its origin. Quantitative investigations of observed horizontal displacement rates in the NKTZ led to the proposal of a detachment model (Hirahara et al., 1989), a collision model (Heki and Miyazaki, 2001; Miyazaki and Heki, 2001; Shimazaki and Zhao, 2000), and a back-slip model (Mazzotti et al., 2000), each with differing causal mechanisms and source depths, including within the upper crust and lower crust, and the uppermost mantle. However, the mechanisms that controlled the development of the NKTZ have yet to be identified. As such, determining the seismic structure of the crust and upper mantle in this area would be an important step in identifying the controls on the formation of the NKTZ.

The right-lateral Atotsugawa Fault is a large active fault within the NKTZ. This fault trends ENE–WSW (~060°), is subvertical (90° ± 10°)

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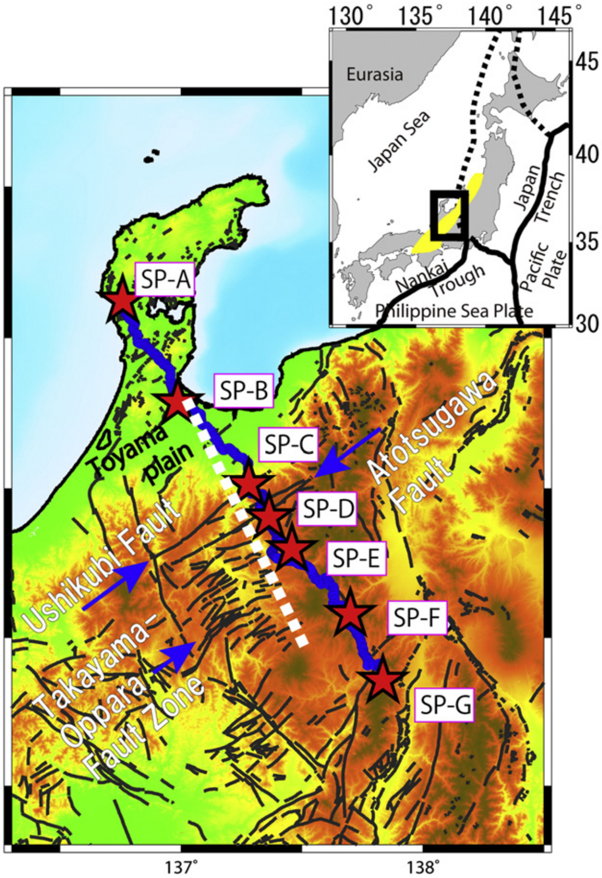

Fig. 1. Location map showing the profile line of the 2007 seismic experiment, oriented normal to the strike of the Atotsugawa Fault. Red stars denote shot points and blue circles indicate seismic stations. Active faults are shown as black lines. The white dotted line indicates the profile line of the resistivity structure shown in Fig. 7-(a) (Usui et al., 2011). The inset shows the location of the research area. The yellow shaded area within the inset is the NKTZ.

near the surface, has a length of 63 km, and is easy to detect in topographic, geological, and seismological data (Matsuda, 1966). The geology of the area suggests that activity along the Atotsugawa Fault started in the late Tertiary (Matsuda, 1966), and the fault has been associated with several large historical earthquakes. One of the largest events was the 1858 Hietsu earthquake, with an estimated magnitude of ~7.0 that was determined from the distribution of the seismic intensity (e.g., Mikumo et al., 1988). More than 200 people died during the Hietsu earthquake, with most of the damage located along the Atotsugawa Fault. In addition, microearthquake seismicity in this area defines a clear planar zone along the Atotsugawa Fault. The area is also suitable for research into the mechanisms that control intraplate earthquakes, as the central part of this high-strain-rate zone contains the Atotsugawa Fault, which is a large right-lateral fault. The Japanese University Group of the Joint Seismic Observations at NKTZ led the research project to undertake integrated geophysical observations in the NKTZ area for five years between 2004 and 2008 (The Japanese University Group of the Joint Seismic Observations at NKTZ, 2005).

The fine seismic structure of the Atotsugawa Fault has been the focus of previous research (Iidaka et al., 2009; Kato et al., 2006, 2007) that identified lateral variations in the P-wave velocity along the fault. The eastern and western parts of the fault contain high-velocity regions, with a seismic high-velocity zone in the western part of the fault associated with an area of low seismicity. The Hietsu earthquake was associated with a damage zone that varied laterally, with damage concentrated just above an aseismic high-velocity zone that was thought to be an asperity (Kato et al., 2007). It is generally thought that high-velocity zones represent more brittle and competent parts of the crust that are capable of sustaining seismogenic stress that can then be released from the high-velocity body by coseismic slip. This means that these high-velocity zones can define discrete asperities on fault planes that are often eventually associated with significant amounts of slip during earthquakes. The stress concentrated in the asperity is then released to the surroundings, often causing significant aftershock activity at the periphery of the asperity (i.e., the high-velocity body; Woessner et al., 2006). Detailed structural images of the Atotsugawa Fault have been obtained previously. However, understanding the mechanisms that cause the development of active intraplate faults and associated earthquakes, such as those associated with the Atotsugawa Fault, requires identification of the controls on strain accumulation and stress concentration within the source fault.

A dense seismic network, Hi-net, covers all of Japan at an average spacing of ~20 km (Okada et al., 2004); however, this spacing is too large to allow the detailed identification of structures associated with intraplate earthquakes and the processes involved in the formation of active faults. This led the Japanese University Group of the Joint Seismic Observations at NKTZ project to undertake temporary seismic observations within the NKTZ area using 73 seismic stations (The Japanese University Group of the Joint Seismic Observations at NKTZ, 2005). These seismic stations were located in a 100 × 100 km area surrounding the Atotsugawa Fault, thereby providing clear seismic images of P-wave and S-wave structures in this area using seismic tomography (Nakajima et al., 2010). Nakajima et al. (2010) outlined the P- and S-wave velocity structures beneath the Atotsugawa Fault using travel-time tomography of arrival-time data generated from a dense temporary seismograph network deployed by The Japanese University Group of the Joint Seismic Observations at NKTZ. This research identified a low-velocity zone just beneath the Atotsugawa Fault and suggested that this zone was caused by the presence of aqueous fluids.

One of the models that can explain intraplate earthquakes is the weak zone model (Iio et al., 2002), which describes a weak zone located in the lower crust that can deform easily, thereby concentrating stress within the upper crust just above the weak zone and leading to intraplate earthquakes. The low-velocity zone beneath the Atotsugawa Fault identified using seismic tomography by Nakajima et al. (2010) suggests that this fault may be related to a weak zone, in turn suggesting that the low-velocity zone beneath the Atotsugawa Fault may be the main cause of the active faulting in this area. However, the configuration, physical properties, and controls on the formation of this low-velocity zone need to be determined to fully identify the controls on faulting in this area. Detailed seismic images of the Atotsugawa Fault, integrated with other geophysical data, are required to better define the relationship between the low-velocity zone and the formation mechanism of the fault. The resolution of the low-velocity zone obtained from seismic tomography is not enough to deduce this relationship. Thus, a seismic study using artificial sources is necessary to clearly image the fault area at high resolution. Other geophysical data, such as resistivity measurements, can further assist in defining the overall structure and physical properties of the fault zone. Here, we present the results of a seismic experiment using artificial sources that was used to seismically image the low-velocity zone beneath the Atotsugawa Fault. These high-resolution seismic images will be discussed and integrated with other geophysical data to obtain a clear image of the fault.

2. Data

The artificial source seismic experiment near the Atotsugawa Fault used seven explosive sources and 1108 seismic stations, and was conducted in October 2007 (Fig. 1). The seismic stations were spaced along a NNW–SSE-oriented 170-km-long profile line that was perpendicular to the strike of the Atotsugawa Fault (Fig. 1). The explosive charge size was 500 kg for experiments SP-A and SP-G, and 300 kg for