Tectonophysics 472 (2009) 95–104

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Fine structure of P-wave velocity distribution along the Atotsugawa fault, central Japan

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ARTICLE INFO

Article history:
Received 6 March 2007
Received in revised form 24 May 2008
Accepted 9 June 2008
Available online 19 June 2008

Keywords:
Active fault
Crustal structure
Refraction study

ABSTRACT

A seismic experiment with five explosive sources and 396 seismic stations was conducted in August 2005 in the Atotsugawa fault area, central Japan. The 396 seismic stations were located on a survey line with a length of 47 km. The profile line was located along the Atotsugawa fault. The average spacing of the seismic stations was about 119 m. The spatially high-density linear-array was used to reveal the seismic structure of the fault zone. The fine structure along the Atotsugawa fault was obtained at depths shallower than 6 km. A large lateral variation of P-wave velocity, which was consistent with the geological structure, was found at the shallowest layer. The heterogeneous variation with a velocity range of 5.7 km/s–6.2 km/s was obtained at the second layer. The second layer was divided into three parts. The western part of the research area was determined to be high velocity. The low-velocity area was detected at the central part. At the east end of the profile line, the P-wave velocity was higher than that of the central part. The low-velocity area coincided with a low-seismicity area. The depth section of the reflection profile showed a boundary located at a depth of around 13 km. The boundary was roughly consistent with the cut-off depth of the seismicity of the microearthquakes. The high-seismic activity area was characterized to be reflective.

1. Introduction

A spatially high-density GPS array reveals the fine distribution of strain rates in Japan (e.g., Sagiya et al., 2000). A high strain rate zone, which is called the Niigata–Kobe Tectonic Zone (NKTZ), was found in central Japan. To identify the seismic structure of the NKTZ, it is important to understand the mechanism of strain accumulations in the Japanese Islands. Several models have been proposed for the origin of the NKTZ (e.g., Shimazaki and Zhao, 2000; Iio et al., 2002; Hyodo and Hirahara, 2003; Yamasaki and Seno, 2005). A large active fault, the Atotsugawa fault, is located inside the NKTZ. The Atotsugawa fault is a strike–slip fault with a right lateral displacement (Matsuda, 1966). The strike of the fault trace is approximately N60°E, and the fault plane is almost vertical (90°±10°) near the surface. From geological studies, activity at the Atotsugawa fault started in the Late Tertiary (Matsuda, 1966). There have been several large historical earthquakes along the Atotsugawa fault; one of the largest events was the 1858 Hietsu earthquake, which had a magnitude of about 7.0 (e.g., Mikumo et al., 1988). The seismicity map of microearthquakes suggests a clear lineation along the Atotsugawa fault. The area is one of the important fields for understanding the mechanism of inland earthquakes because a large right-lateral fault is located at the central part of the high strain rate zone.

The Atotsugawa fault, which is a right-lateral fault trending ENE–WSW with a length of 63 km, is easy to detect from topographic, geological, and seismological studies. Many studies have been done at the fault. Seismicity studies have found several characteristics of the fault (e.g., Mikumo et al., 1988; Ito and Wada, 2002). The Atotsugawa fault has the following characteristics. 1) There is remarkable micro-earthquake activity along the fault (Mikumo et al., 1988). 2) The cut-off depth of the upper crustal seismic activity is 15 km. 3) A creep zone was found at the central part of the Atotsugawa fault. The creep zone, with a rate of 1.0–1.5 mm/yr, was detected by repeated precise electronic distance measurements (EDM) on the short baseline across the fault (Geological Survey Institute (GSI), 1997). A surface fault creep has not been detected at any other active faults in Japan. 4) A large earthquake with a magnitude of around 7 was estimated to have occurred on this fault in 1858. A trenching survey in the western portion of the fault showed at least three events with a recurrence interval of 1100–2500 yr (Research Group for Active faults of Japan, 1983).

Heterogeneous seismic activity on the fault plane was reported (e.g., Ito and Wada, 2002). In the upper crust, at depths shallower than 15 km, seismic activity in the central part of the fault zone is low while

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doi:10.1016/j.tecto.2008.06.016

seismic activity at both sides of the fault zone is high. The creep zone, which was observed at the central part of the fault, is characterized as low seismic activity (GSI, 1997). A study with a GPS array across the Atotsugawa fault also suggested that the creep zone was located in the central part of the fault (Hirahara et al., 2003). Heterogeneous activity on the fault plane is important for identifying the concentration mechanisms of stress and strain. This area is considered to be an important seismic field for studying the mechanisms of inland earthquakes. The Japanese University Group of the Joint Seismic Observations at NKTZ has been conducting a five-year program of seismic observations since 2004 (Japanese University Group of the Joint Seismic Observations at NKTZ, 2005). Many groups have focused on this area as a good study field for inland earthquakes.

The heterogeneous resistivity structure of this area has been researched (Goto et al., 2005). Several seismic surveys with explosive sources have been done in the area (Watanabe and Fukui, 1980; Ito et al., 1993; Sakai et al., 1996; Iidaka et al., 2003; Ueno et al., 2005). A small number of tomography studies have been done around the Atotsugawa fault (e.g., Kato et al., 2006, 2007). The P and S wave velocity structures along the fault have been mapped by seismic tomography studies, and indicate that the P-wave structure along the fault zone is not uniform (Kato et al., 2007). The central part of the fault was found to have low velocity. Seismic velocity was found to be high on both sides of the low-velocity area. In seismic tomography studies, the resolution of the obtained seismic structure depends on the spatial density of seismic stations and earthquakes. However, the spatial distribution of seismic stations and earthquakes was not sufficient to reveal the fine structure along the fault. The resolution of seismic tomography in the shallowest layer was not good because the path coverage of the layer was not sufficient. A seismic tomography study using earthquakes is a good tool for learning about the seismic structure at deeper parts of the crust and uppermost mantle. The seismic structure at the shallower part has to be resolved to reveal the seismic structure at the deeper part. To obtain accurate seismic structures of the lower crust and uppermost mantle, the velocity structure at the shallower part has to be resolved. Lack of ray path coverage at the shallowest layer is a serious problem to reveal the seismic structure. The shallow ray path coverage for explosive sources is very well. Then, a seismic survey with explosive sources is important to accurately obtain the velocity structure at the shallower part along the fault.

We conducted a seismic experiment with explosive sources at the Atotsugawa fault zone in August 2005. Five explosive sources and spatially highly dense linear array were set up along the fault. The fine P-wave velocity structure was obtained along the fault zone.

2. Data

A seismic experiment with five explosive sources and 396 seismic stations was conducted in 2005 at the Atotsugawa fault zone, central Japan. The seismic experiment was performed on 24 and 25 August, 2005. We deployed a 47-km-long profile line in the E–W direction along the Atotsugawa fault, central Japan (Fig. 1). Five explosive sources with a charge size of 100 kg for S1, S2, S3, S4, and S5 were shot on the seismic survey line. We put 396 seismic stations along the survey line. The average interval of the seismic stations is 119 m. Two types of seismometer were used. Vertical-component sensors with a natural period of 2.0 Hz and 4.5 Hz were used at seismic stations of 176 and 220, respectively. Digital recorders with a sampling frequency of 200 Hz were used at the other seismic stations (Morita and Nishimura, 1993; Kurashimo et al., 2006).

3. Refraction analysis

We constructed a P-wave velocity model using the observed data according to the following process. 1) We picked up arrivals at each seismic record. 2) The line-up data, which are arrival time data very close to the shot points, are used to estimate the velocity structure of the shallowest layer. 3) The seismic structure is estimated by forward modeling using a ray-tracing method (Zelt and Smith, 1992). The record sections are shown with a reduction velocity of 6.0 km/s (Fig. 2). The amplitude of the waveforms is normalized by the maximum amplitude value of each trace.

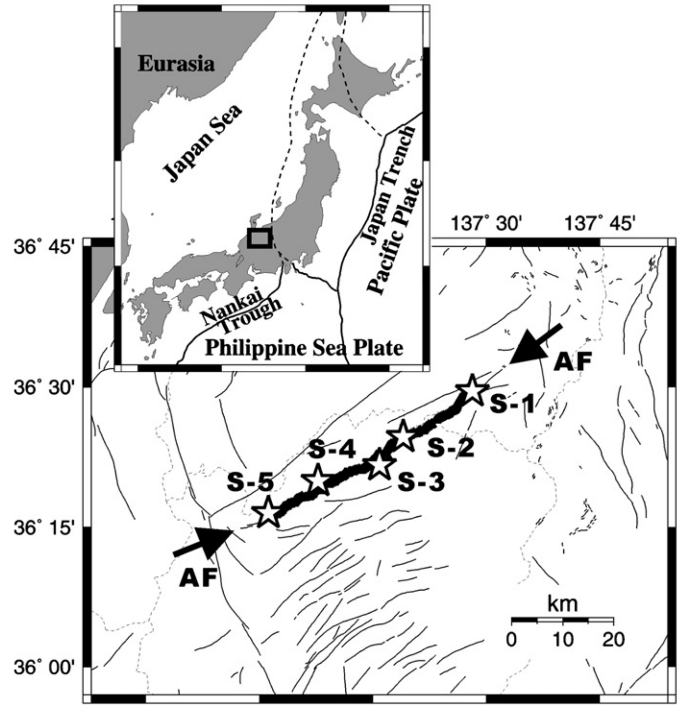

Fig. 1. Location map of the profile line of the 2005 experiment. The profile line is located along the Atotsugawa fault. The open stars denote shots. The seismic stations are shown by circles. The research area is shown in the inset. The active faults are shown by lines. AF denotes the Atotsugawa fault.

The ray diagram and velocity model obtained are shown in Figs. 3, 4, and 5, respectively. The root mean square travel time residual in the final model obtained is 0.073. The seismic velocity at the shallowest layer is recognized to be heterogeneous (Fig. 5). The P-wave velocity varies from 2.5 km/s to 4.0 km/s along the profile line. The low velocity of 2.5 km/s is obtained at the shot point of S-5, which is consistent with the line-up data. The velocity near the shot point S-3 was also found to be 2.5 km/s. The low velocity is required to explain the observed data at a distance range around 25 km on the record section of S-1, S-2, S-4, and S-5 (Fig. 3).

The P-wave velocities of the second layer vary from 5.7 km/s to 6.2 km/s (Fig. 5). The thickness of the shallowest layer decreases at the central part of the profile line, which is just below shot point S-3. The P-wave velocity in the second layer of the area was found to be high. The velocity of 6.2 km/s is higher than those of both sides. The P-wave velocity at the second layer in the distance range of 30 km–40 km is characterized to be low with a velocity of about 5.7 km/s. The area in the distance range of 25 km–35 km is estimated to be a creep zone (GSI, 1997). The creep zone was detected by repeated precise EDM measurements on a short baseline across the fault. The zone is estimated to have a low seismic velocity at the depth range of 2 km–8 km according to seismic tomography studies. The tomography study indicates that the low-velocity area is located at the depth range of 3 km–8 km beneath the creep zone (e.g., Kato et al., 2007). We found the low-velocity area in the depth range shallower than 4 km. It is well resolved at the shallower part in this refraction study. Based on these two studies, the velocity of the area is recognized to be low at depths from surface to 8 km.

The third layer with a velocity of 6.2 km/s is required to explain the arrival time data at the distance range of 0 km–10 km on the record