Sagami Bay is known as a seismogenic area occurring large earthquakes repeatedly with M > 7 at the boundary between the Philippine Sea plate and the overriding northeastern Japan with the Quaternary sediments. To investigate this area for understanding the mechanism of repeated large earthquakes, we carried out a high density single-channel seismic reflection survey around Sagami Bay in April - May, 2005 using R/V *Kaiyo* of Japan Agency for Marine-Earth Science and Technology (JAMSTEC). We propose new growth scenario of a unique reverse fault associated with the 1923 Kanto earthquake in the Sagami Trough in this paper as follows from units of sedimentary layers of the seismic profiles provided tectonics information studies of the clear sedimentary facies is indicated along the Sagami Trough. In particular, the fault with reverse sense displacement of ENE-WSW strike is recognized in the Sunosaki Canyon. This reverse fault is located on the asperity of the large aftershock epicenter (M7.3) in the 1923 Kanto earthquake. There is no active fault in the seafloor of sedimentary layers from this reverse sense displacement to onshore. Thus, this displacement would be developed with the subducting Philippine Sea plate. We propose the growth process of obtained reverse sense displacement in Sagami Trough.

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Sediment deformation in eastern Sagami Bay revealed by high-density seismic reflection survey

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Sagami Bay is known as a seismogenic area occurring large earthquakes repeatedly with M > 7 at the boundary between the Philippine Sea plate and the overriding northeastern Japan with the Quaternary sediments. To investigate this area for understanding the mechanism of repeated large earthquakes, we carried out a high density single-channel seismic reflection survey around Sagami Bay in April - May, 2005 using R/V *Kaiyo* of Japan Agency for Marine-Earth Science and Technology (JAMSTEC). We propose new growth scenario of a unique reverse fault associated with the 1923 Kanto earthquake in the Sagami Trough in this paper as follows from units of sedimentary layers of the seismic profiles provided tectonics information studies of the clear sedimentary facies is indicated along the Sagami Trough. In particular, the fault with reverse sense displacement of ENE-WSW strike is recognized in the Sunosaki Canyon. This reverse fault is located on the asperity of the large aftershock epicenter (M7.3) in the 1923 Kanto earthquake. There is no active fault in the seafloor of sedimentary layers from this reverse sense displacement to onshore. Thus, this displacement would be developed with the subducting Philippine Sea plate. We propose the growth process of obtained reverse sense displacement in Sagami Trough.

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**Original paper** —
1. Introduction and Regional setting in Sagami Bay

Japan is tectonically one of the most active areas with great earthquakes in the world. Figure 1 shows the tectonic map of Japanese Honshu arc convergence zone, in which Sagami Bay is a convergent margin where the Philippine Sea (PHS) plate is subducting beneath the North American plate and collided with the Izu-Bonin arc to the Japan Island arc during period of 0.5-1.0 Ma. The Izu peninsula has a collision to the Japanese Honshu arc in the Sagami Bay. Sagami Trough runs from north to south or NNW to SSE at the center of Sagami Bay. There are many monogenetic volcanoes associated with the collision of the Izu-Bonin arc in the southern part of the Sagami Bay. The recent volcanic activity have been reported in 1989 Teishi volcano eruption (e.g. Naka, 1994). Seismic source mechanisms as well as the configuration of the plates at depth (Fig. 1) have been approximately analyzed by Ishida 1992. She indicated that the configuration is consistent with the global motion data. The large disaster earthquakes (e.g. the 1923 Kanto earthquake [M=7.9]) have frequently occurred along a region estimated to be the convergent boundary between the Philippine Sea plate and the overriding the plate, the northeastern Japan. Recently, Kodaira et al. (2012) identified a deformation of the coseismic fault rupture due to the 2011 Tohoku-oki earthquake around the plate boundary using seismic reflection survey. Thus, it is a key to understanding on the coseismic deformation related to large earthquake along the Japan trenches and across the Sagami Trough being close to the focal region of the 1923 Kanto Earthquake occurred along the trough.

The Sagami Bay can be classified geomorphologically into three areas; western, central and eastern parts (Fujioka et al, 1989), according to structural variations of strongly folded and faulted Neogene to Quaternary strata, which characterize the subduction zone. The western part is located in the Philippine Sea plate covered with mostly Quaternary submarine volcanoes. The central part is mainly occupied by the axial deep water channel of the Sagami Trough runs from north to south or NNW to SSE. The Sagami Trough is filled with thick coarse-grained detritus derived from the Izu-Bonin arc as well as from the Japan Island arc. Kong et al. (1984) reported that this area is filled with Late Cenozoic sediments of more than 5 km thick. The eastern part is characterized...
by topographic high chains. According to Tokuyama et al. (1999), the direction of the Philippine Sea plate motion was the north in late Miocene, but the northeast in the Quaternary after the Sagami Trough was formed with the collision of the Izu-Bonin arc.

Various seismological investigations with single or multi-channel seismic reflection surveys and ocean bottom seismographs (OBSs) survey have been carried out around Sagami Bay (e.g. Iwabuchi et al., 1990, Nishizawa et al., 1996). The expanding spread profiles (ESPs) and the multi-channel reflection experiment are carried out at the northwestern part of Sagami Bay (Okino et al., 1994). Their ESPs shows clear first arrivals in the offset range over 15 km. However, there is no displacement of the trough sediments from their results despite of the shallow crustal structure could be divided into four layers. In the central part of Sagami Bay, P-wave velocity structure was estimated by Nishizawa et al. (1996). They obtained the velocity structure with four layers up to 10 km in depth in the northeastern part of the Sagami Trough by OBSs.

In this region, large-scale seismic reflection surveys were conducted in the special project for Earthquake Disaster Mitigation in Urban Areas in onshore. Sato et al. (2005) identify a megathrust fault from these deep seismic reflection profiles. They show the upper surface of the Philippine Sea plate that is shallower than previous estimates based on the distribution of seismicity. The depth of the Philippine Sea plate is located in 10 km at the Miura Peninsula and the coast of Sagami Bay from their reflection profile.

Thus, we conducted so far high density single channel seismic survey in the overall geologic architectures of Sagami Bay at every 4 km interval (Kinoshita et al., 2005). In order to investigate the active structure in the Sagami Bay, we consider the profiles along the trough axis and discuss the growth process of the active structure. This paper describes the detailed tectonic structure in Sagami Bay from the result of high density single-channel seismic survey.

2. Data acquisition and processing

High density single channel seismic (SCS) surveys were carried out by using R/V Kaiyo of Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in 2005: the cruise KY05-06. Figure 2 shows the survey lines of cruise KY05-06. The detailed report of the cruise KY05-06 has been published in Kinoshita et al. (2005) and Misawa et al. (2011). In order to obtain the shallow structure as well as deeper imagery, we deployed GI gun system (Generator 250 cu.in. / Injector 105 cu.in., streaming at 5 knots, 8 s shot interval and 50 m streamer length). We conducted 32 survey lines at 4 km spacing with the total length of ~ 850 km. Each seismic profile having enough quality to reflection image were obtained from this survey. The data processing contains noisy-trace editing, 14-180 Hz band-pass filtering and time migration (constant velocity Vp = 1500 m/s). In this paper, we introduce representative lines (line D, E, F, G, H and 12) as shown later.

3. Results

Obtained seismic profiles have good quality in this survey. The profiles imply thick sedimentary sequences in Sagami Bay. In this paper, we discuss the effect of plate subducting using the profile in the along (Line D, E, F, G and H) and across (Line 12) the trough axis.

Line D is located between Hatsushima Island and the southwestern margin of the Sagami Trough (Fig. 2). The profile of line D shows in Fig. 3. Thick and flat sediments under seafloor in the southern part of the Hatsushima Island. Thickness of the sediment layer does not change. Line E is located in southwestern margin of
Fig. 3. The profiles of line D. Upper: NW-SE seismic profiles by the high density single-channel survey during the cruise KY05-06. Vertical axis is a two-way travel time in second. Horizontal axis is the relative distance in km. Sedimentary features are clearly imaged along the trough axis. Lower: an interpreted section of the seismic reflection profile along NW-SE direction.

Fig. 4. The profiles of line E. Upper: NW-SE seismic profiles by the high density single-channel survey during the cruise KY05-06. Vertical axis is a two-way travel time in second. Horizontal axis is the relative distance in km. Sedimentary features are clearly imaged along the trough axis. Lower: An interpreted section of the seismic reflection profile along NW-SE direction. ATC: Atami Canyon, MZK: Manazuru Knoll.
Fig. 5. The profiles of line F. Upper: NW-SE seismic profiles of high density single-channel survey (KY05-06). Vertical axis is a two-way travel time in second. Horizontal axis is the relative distance in km. Sedimentary features are clearly imaged along the Trough axis.
Lower: Interpreted section of seismic reflection profile along NW-SE direction. ATC: Atami Canyon, MZK: Manazuru Knoll.

Fig. 6. The profiles of line G. Upper: NW-SE seismic profiles of high density single-channel survey (KY05-06). Vertical axis is a two-way travel time in second. Horizontal axis is the relative distance in km. Sedimentary features are clearly imaged along the Trough axis.
the Sagami Trough (Fig. 2). The profile of line E is shown in Fig. 4. This line is crosses the Atami Canyon (ATC) and the Manazuru Knoll (MZK). According to the previous study of submarine topography (Kato, 1999), the MZK is located in the boundary between the Philippine Sea plate and the overriding plate. Thick and slope sediments under the seafloor from the Sagami Trough to the MZK. Some deformation with no displacement is visible beneath the seafloor. Line F is located in the southwestern margin of the Sagami Trough (Fig. 2). The profile of line F is shown in Fig. 5. This line also crosses the ATC and the MZK. Thick and slope sediments with a small fold under the seafloor from the Sagami Trough to the MZK. There is no sediment of reflectors beneath the MZK. Line G is located in the northeastern margin of the Sagami Trough (Fig. 2). The profile of line G is shown in Fig. 6. A reverse fault with large throw is visible in Sunosaki Canyon (SSC). A few deformations with no displacement are indicated from the Sunosaki fault to onshore. Line H is located in the outside of northeastern margin of the Sagami Trough (Fig. 2). The profile of line H is shown in Fig. 7. This line is across the Sagami Knoll (SGK), Zyogasaki Canyon (ZGC), Misaki Knoll (MSK), Tokyo Canyon (TKC) and SSC with undulations. A reverse fault with a large throw is visible in the Sunosaki Canyon as well as Line G. Line 12 is located near the Izu-Oshima Island with NE-SW direction. The seismic survey has never been conducted around this line due to heavy of traffic. This line crosses the northern part of the Izu-Oshima Island, the Sagami Trough and the Sunosaki Canyon. The profile of line 12 is shown in Fig. 8. The reverse fault is recognized in the Sunosaki Canyon. Thick sediments are indicated in the Sagami Trough and Tokyo Canyon.

4. Discussion

Sagami Bay is known to be the high-speed accumulation and is covered with thick sediments (Fujioka et al., 1989). In general, any sediment sequences record the deformation in the recent history. The large disaster earthquakes have often occurred in the Sagami Bay. We extract the deformation record of the 1923 Kanto earthquake from our profiles.

There are two submarine channels, an axial channel of the Sagami Trough and the Tokyo canyon and a large amount of detritus is progressively transported to the Sagami and the So-o Troughs (Fujioka et al., 1989). Multi-channel seismic profiles suggest that the Sagami Trough fill sediments of 1.7 sec (two-way travel time) have been deposited since 2 Ma ago (Tokuyama et al., 1988). In Sagami Bay, it is characterized that many straight shaped knolls along NW-SE direction are developed on the NE side-slope of the trough axis. According to each obtained profile, the sedimentary layers that filling up the Sagami Trough show the folded and tilted structures, however the thickness of sedimentary layers have no difference in each profile. Therefore, these sedimentary layers were deformed by a compression of the horizontal direction in the Sagami Trough. The deformation is developed in the cross direction to the Sagami Trough in the profiles G and H. This phenomenon suggests that the island arc structure on the Philippine Sea plate subducts beneath the landward slope along the Sagami Trough.

In the eastern part of Sagami Bay, the 1923 Kanto earthquake (including aftershocks) was only a recent disaster earthquake. The hypocenters with the shallow depth are restricted in the asperity of the 1923 Kanto earthquake. Based on these data, there should be deformation structures associated with the 1923 Kanto earthquake and its aftershock in Sagami Bay. The southeastern part of lines G and H shows the major reverse fault developing beneath the Sunosaki Canyon. The Sunosaki Canyon has a dip from ENE-WSW to WNW-ESE direction. The Zyogasaki Canyon also characterized by the deformation in the sedimentary layer. In previous study using sea bathymetry, active faults are proposed along the trough axis. There is a possibility that the boundary between the Philippine sea plate and the overriding plate existing the northern part. The ENE-WSW strike of the Sunosaki Canyon is corresponding to that of the Zenisu ridge (Takahashi et al., 2002). Four aftershocks (> M6.0) with the 1923 Kanto earthquake occurred in the eastern Sagami Bay area (the earthquake catalog reported by Japan Meteorological Agency). These hypocenters become deeper to onshore. Figure 9 shows the relationship between the fault beneath the Sunosaki Canyon and these aftershock epicenters. The Sunosaki Canyon is nearly situated on the epicenter of the aftershock M7.3. This supports that the reverse fault beneath the Sunosaki Canyon would be generated with that aftershock.

Yamazaki (1992) indicates that the active faults in the onshore Izu collision zone are imbricated in association with accretion processes, as branched fault from the concealed boundary fault of plates. We estimate the process of tectonics from the SCS profiles for three steps in Fig. 10 as follows:

Stage 1: faults with reverse sense displacement are formed beneath the seafloor by the subducting the Philippine Sea plate.

Stage 2: The faults with reverse sense displacement are growing with the subduction.

Stage 3: A new displacement is formed beneath the seafloor more inside the trough.

The deformation of the seafloor at Stage 1 is indicated...
Fig. 7. The profiles of line H. Upper: NW-SE seismic profiles of high density single-channel survey (KY05-06). Vertical axis is a two-way travel time in second. Horizontal axis is the relative distance in km. Sedimentary features are clearly imaged along the Trough axis.
Fig. 8. The profiles of line 12. Upper: NE-SW seismic profiles of high density single-channel survey (KY05-06). Vertical axis is a two-way travel time in second. Horizontal axis is the relative distance in km. Sedimentary features are clearly imaged across the trough axis. Lower: Interpreted section of seismic reflection profile along NE-SW direction. TKC: Tokyo Canyon, OKY: Oki-no-yama, SSC: Sunosaki Canyon, OS: extended part of Izu-Oshima.
in the profiles E, F and G. The reverse sense fault growth of Stage 2 is corresponding to the fault beneath the Sunosaki Canyon in the profiles G, H and 12.

Figure 9 shows the resultant slip distribution, which calculated by Kobayashi and Koketsu (2005) from jointly inversion between the historical geodetic and teleseismic data of the 1923 Kanto earthquake. Their result indicates two asperities, being an area of large slips, in this region. The slip direction changes from predominantly right-lateral strike slip around the hypocenter to fairly the dip slip in the eastern asperity. The fault with reverse sense displacement obtained from our study is located near the boundary of the eastern asperity as a dip-slip area. It is consistent with the reverse sense displacement beneath the Sunosaki Canyon.

5. Conclusions

As mentioned above, the high density SCS survey was conducted by using R/V Kaiyo on May 2005. We described and interpreted the SCS profiles around the Sunosaki Canyon in detail. A general interpretation of the seismic profiles provided tectonics information in the sedimentary sequences. The fault with reverse sense displacement of NE-SW strike is observed in the Sunosaki Canyon from the obtained seismic profiles (Fig. 9). The location of this displacement is close to the location of aftershock hypocenter (M7.3) in the 1923 Kanto earthquake. This displacement should play an important role in the 1923 Kanto earthquake and also in such large earthquake events.

Fig. 9. Topographic fault distribution determined beneath the Sunosaki Canyon by this study. The dashed contour with interval of 2 m shows the resultant slip distribution of 1923 Kanto earthquake (Kobayashi and Koketsu, 2005). The black line with triangles show the strikes of faults confirmed in this study. The gray lines show the seismic lines in this study. The circle indicates the aftershock epicenter of the 1923 Kanto earthquake as each magnitude obtained by Japan Meteorological Agency. The black star shows the cold seep location (e.g. Hattori et al., 1996).

Fig. 10. The cyclic process in the shallow depths associated with the collision of the Izu-Bonin arc in the Sagami Bay area. The arrow shows the motion direction of the subducting Philippine Sea plate.
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