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Deformation of the Manazuru Knoll in Sagami Bay, central Japan, associated with subduction of the Philippine Sea plate

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Abstract

In January 2010, we conducted a multichannel seismic (MCS) reflection survey in Sagami Bay. As a result of this study, the deformation of the Manazuru Knoll, which is located near the plate boundary, was obtained. The Manazuru Knoll was formed by an asymmetric anticline, and the knoll has a geometry that is bent in a shape similar to that of a crank. The anticlinal axis, which was confirmed by MCS data, lies along the anticlinal axis shown on the bathymetric map, and the axis is bent first to the southeast and then to the east. It is estimated that the easternmost part of Manazuru Knoll has reached the vicinity of Miura Canyon. The offset of the strike of the anticline axis is approximately 7 km. A reverse fault related to the formation of Manazuru Knoll was identified in the southwestern side of the knoll. It is hypothesized that this reverse fault formed as a result of shortening of the structure, which occurred when the relative motion of the Philippine Sea plate was acting in a perpendicular direction close to the Manazuru Knoll. Therefore, it is estimated that the relative motion of the Philippine Sea plate was almost oblique or parallel to the anticlinal axis of Manazuru Knoll and that the eastern end of Manazuru Knoll was bent into a crank shape by strike-slip motion. This suggests that a part of Manazuru Knoll, located to the west of the plate boundary, moved to the northwest. Finally, it is assumed that the sediments of Miura Canyon and Sagami Knoll have been overlapping on the eastern end of Manazuru Knoll.

Keywords: Manazuru Knoll; Multichannel seismic reflection survey; Sagami Bay; Sagami Knoll; Philippine Sea plate

Findings

Introduction

Sagami Bay is located along the boundary between the Philippine Sea plate and the Northeast Japan arc. Great earthquakes (e.g., the 1923 Great Kanto earthquake and the 1703 Genroku earthquake) have occurred frequently along the Sagami Trough, including the portion within Sagami Bay, and these earthquakes have caused a very strong motion, large tsunamis, and serious damage around the Kanto and Tokai areas. Imoto and Fujiwara (2012) discussed that the estimated probability of a magnitude 8 earthquake along the Sagami Trough within the next 30 years was 2.0% to 4.6%. Additionally, studies conducted during the last 25 years have contributed to crustal exploration of the Philippine Sea plate (e.g., Suyehiro et al. 1996; Kodaira et al. 2007). For example, Taylor (1992) found that the forearc in the Izu-Ogasawara arc includes a paleoarc formed during the Eocene and an island arc formed during the Oligocene. Thin crust distributed between these arcs was rifted during the Eocene and is overlapped by a thick layer of sediments (e.g., Takahashi et al. 2011). Because the Philippine Sea plate has these heterogeneous structures in the Izu-Ogasawara, it is important to understand how the plate affects the seismogenic zone around Sagami Bay.

The Manazuru Knoll and the Sagami Knoll are located in the central part of Sagami Bay (Figure 1). The depression between the two knolls is the narrowest in the northern Sagami Trough, and it is estimated that there is a plate boundary between the Northeastern Japan arc and the Philippine Sea plate in this area. Some geological studies, such as a study of a microfossil obtained by sampling an outcrop of the knolls using a remotely operated

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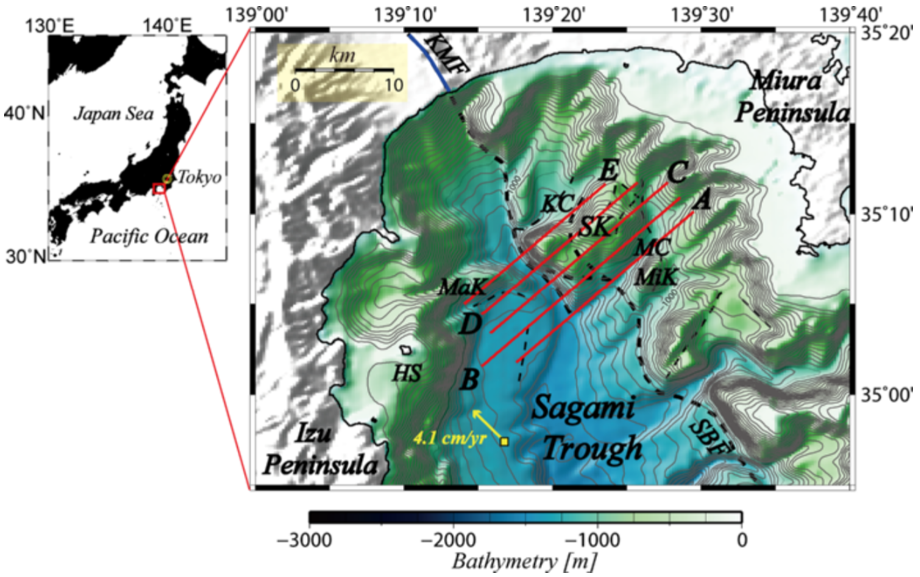

Figure 1 Location maps of the survey area. The solid red lines are the MCS lines of this survey. MaK, Manazuru Knoll; SK, Sagami Knoll; MC, Miura Canyon; MiK, Miura Knoll; KC, Katase Canyon; HS, Hatsu-shima; SBF, Sagami Bay Fault; KMF, Kozu-Matsuda Fault (blue line). Black broken lines indicate the traces of main active faults indicated by Ohkouchi (1990). The yellow arrow shows the crustal movement velocity relative to the stable part of the Eurasian plate at the seafloor reference point (Saito et al. 2008).

vehicle and research submersible, have been conducted in and around these knolls and have indicated that the Manazuru Knoll and Sagami Knoll have similar geological structures (Hattori et al. 1992; Yamazaki 1993; Hattori et al. 1995). From the results of these observations, Kanie et al. (1999) proposed that the Manazuru and Sagami Knolls were connected until recently and pointed out that there may have been deepening, similar to that in the Sagami Trough, between the knolls.

Many seismic reflection studies have been conducted to obtain a better understanding of the seismotectonics around Sagami Bay (e.g., Kato 1987; Iwabuchi et al. 1991; Kinoshita et al. 2005; Kinoshita et al. 2006). However, many of these surveys were conducted using short streamer cables and small seismic sources; therefore, it was difficult to image details of the deformation structures around the knolls due to the complex bathymetry associated with the structures. Recently, however, seismic acquisition technology for deep seismic imaging has improved rapidly. For example, Sato et al. (2005) and Sato et al. (2010) conducted an onshore-offshore seismic survey around Sagami Bay. As a result of these seismic data, the Philippine Sea plate has been traced to a depth of 11 km, suggesting that the Sagami Bay Fault and the extension of the Kozu-Matsuda Fault are splay faults caused by megathrusts in the Philippine Sea plate.

In this paper, we describe the relationship between the Manazuru and Sagami Knolls deduced from a multichannel seismic (MCS) reflection survey and bathymetric data. In particular, because we suppose the Manazuru Knoll to be one of the key structures for plate motion, the plate boundary, and the tectonic history of Sagami Bay, we emphasize the deformation structure of the Manazuru Knoll.

Data acquisition and processing

We conducted a MCS survey and bathymetric survey around the Sagami and Manazuru Knolls in Sagami Bay from January 4 to 8, 2010 (Figure 1). This survey was conducted as a part of the site survey for the Kanto Asperity Project (e.g., Kobayashi et al. 2010), which has been submitted to the Integrated Ocean Drilling Program. The MCS system used in the survey was on the deep-sea research vessel *KAIREI*, of the Japan Agency for Marine-Earth Science and Technology (Miura 2009). During the survey, the weather and sea conditions were normal, and the ocean current was weak; therefore, the data quality of this exploration was good. Bathymetric data were also recorded continuously during the survey.

To obtain high-quality MCS data, we shot an air gun array at a spacing of 37.5 m, which corresponds to a spacing of 20 to 30 s depending on the vessel speed (average of 4 kn). The tuned air gun array had a maximum capacity of 7,800 in.^{3} (approximately 130 l) and consisted of 32 air guns. The standard air pressure was 2,000 psi (approximately 14 MPa). During the experiment, the air gun array depth was maintained at 6 m below the sea surface. During shooting, we towed a 360-channel hydrophone streamer cable with a group interval of 12.5 m. The lengths of the total active section and lead-in cable were 4,500 and

110 m, respectively. The towing depth of the streamer cable was maintained at 10 m below the sea surface by depth controllers. The sampling rate and record length were 2 ms and 15 s, respectively.

Data processing was conducted in the conventional processing sequence, which includes trace header edit, trace edit, common midpoint (CMP) binning with an interval of 6.25 m, minimum phase conversion, bandpass filter, datum correction, amplitude recovery, predictivedeconvolution, velocity analysis, normal moveout correction, demultiple processing, mute, CMP stack, F-X deconvolution, bandpass filter, and Kirchhoff time migration.

Results and discussion

Interpretation of results

Figures 2 and 3 show the time migration and interpreted sections of the processed MCS data. We divided the study area into three parts, the Manazuru Knoll, the Sagami Knoll, and the Sagami Trough, based on tectonic features.

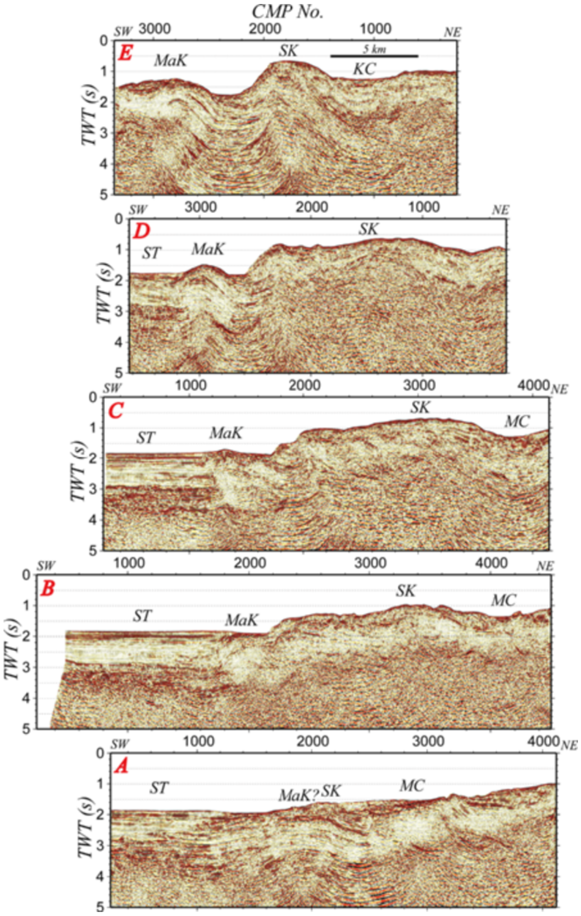

Figure 2 Time-migrated sections obtained from MCS data of lines A-E. MaK, Manazuru Knoll; SK, Sagami Knoll; MC, Miura Canyon; KC, Katase Canyon; ST, Sagami Trough.

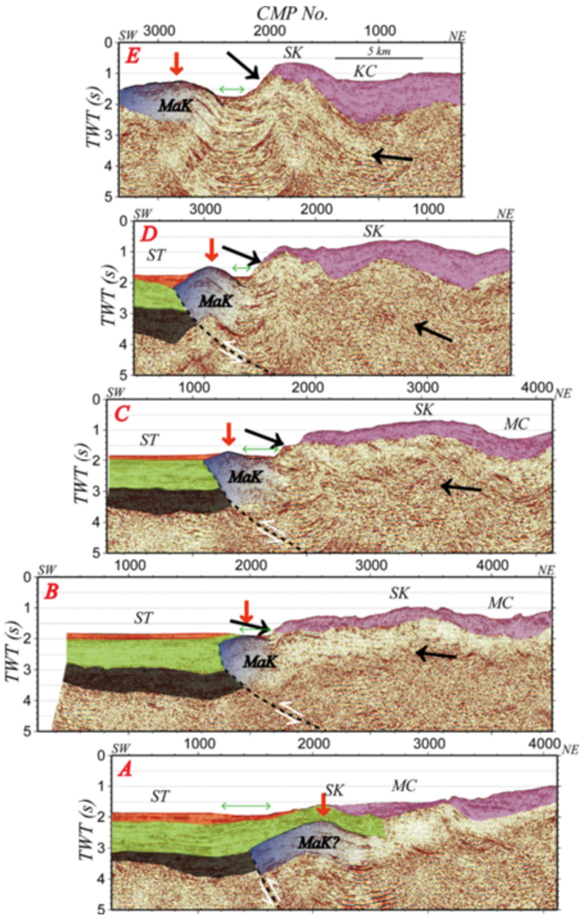

Figure 3 Interpreted time sections of lines A-E. Blue areas show the Manazuru Knoll. Purple areas show the sedimentary layer on the Sagami Knoll. Orange, green, and black areas show the sedimentary layer of the Sagami Trough. Black broken lines indicate the reverse fault related to the Manazuru Knoll. Red arrows indicate the anticlinal axis of the Manazuru Knoll. Black arrows represent the east-dipping reflector in the Sagami Knoll. Green arrows show the erosional area in the Sagami Trough. MaK, Manazuru Knoll; SK, Sagami Knoll; MC, Miura Canyon; KC, Katase Canyon; ST, Sagami Trough.

The data confirmed that the Manazuru Knoll was formed by an asymmetric anticline, shown in survey lines C-E. Because line E was set to be as parallel as possible with the strike of the anticline, the width of the anticline appears larger in line E than in the other lines. In contrast, because lines D and C gradually intersected the strike of the anticline, the width of the anticline appeared to be gradually decreased. Although the anticline did not appear on the seafloor at lines A and B, the anticline was obtained beneath the seafloor from the MCS data. As the coherence of reflectors in the anticline was not good, the reflector of the basement separating the upper crust and sedimentary layers was not identified. Based on the forms of the anticlines and the seismic characters of lines A-D, we suppose that the reverse fault is located to the south of Manazuru Knoll (represented by the black dotted line in Figure 3).

The Sagami Knoll is covered with a thinner layer of sediments than other areas, and the coherence of the sedimentary layer is not good overall. Because the knoll has a very complex shape, topography, and structure, the seismic characteristics and thickness of the sedimentary layer vary greatly with location. The approximate maximum thickness of the sedimentary layer of the knoll in each line is as follows: 0.8 s for line A, 0.9 s for line B, 0.4 s for line C, 0.4 s for line D, and 0.1 s for line E. The sedimentary layer tends to be thicker in the northern seismic lines (A and B) than in the southern seismic lines (C, D, and E). In addition, we found that the east-dipping reflector in the knoll has a gradually higher angle toward the northern line (represented by the black arrows in Figure 3).

The Sagami Trough has the thickest sedimentary layer, maximum of approximately 2.0 s in the study area. Based on the amplitude and coherence of the reflectors in the

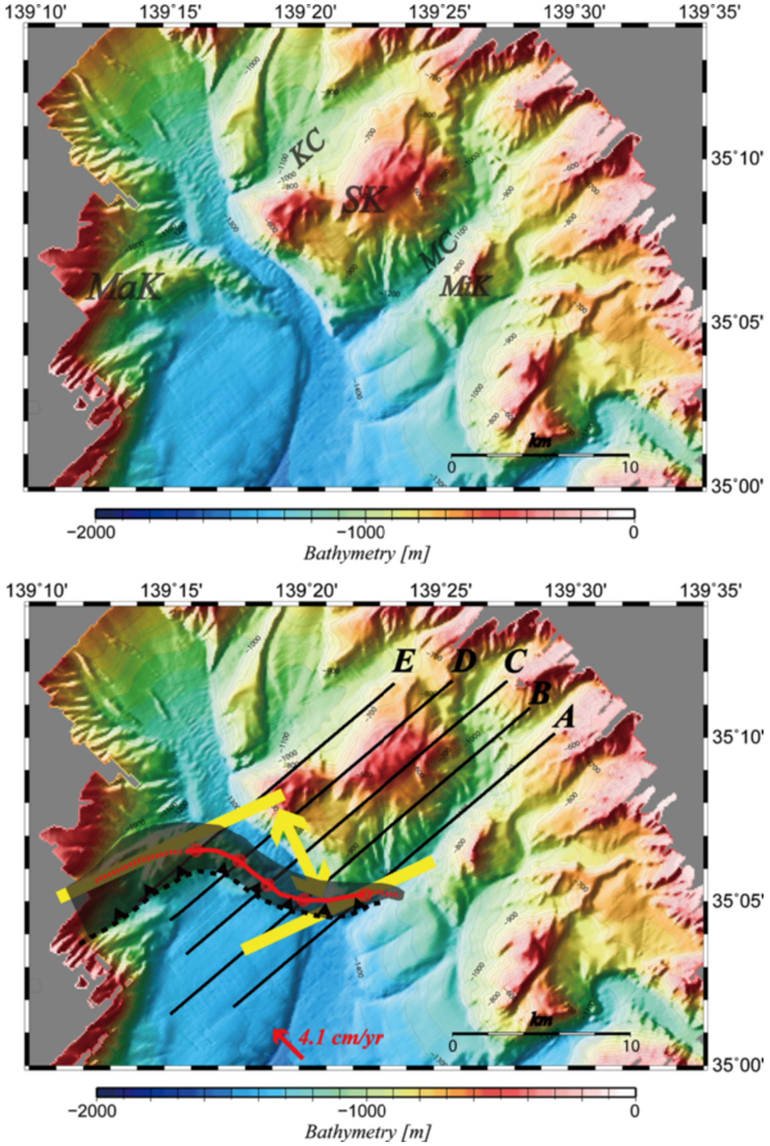

Figure 4 Multibeam bathymetric map around the study area and interpreted map illustrating the formation of the Manazuru Knoll. (Top) Multibeam bathymetric map around the study area. MaK, Manazuru Knoll; KC, Katase Canyon; SK, Sagami Knoll; MC, Miura Canyon; MiK, Miura Knoll. (Bottom) Interpreted map illustrating the formation of the Manazuru Knoll. Black solid lines are the seismic lines of this study. The black area shows the Manazuru Knoll, as estimated by MCS and bathymetric data. Red circles and the red solid line show the anticlinal axis of the Manazuru Knoll obtained by MCS data. The red dotted lines are the anticlinal axis of the Manazuru Knoll estimated by bathymetric data. The yellow lines and yellow arrow show the strike offset of the anticline axis, which is bent. The black broken line indicates the reverse fault. The red arrow represents the crustal movement velocity in Sagami Bay detected by seafloor geodetic observation (Saito et al. 2008).

sedimentary layers of the Sagami Trough, we divided the sedimentary layers into three units. The uppermost unit (orange area in Figure 3) has a thickness of 0.2 to 0.4 s. The eastern side of this unit becomes relatively thinner because of erosion (represented by the green arrows in Figure 3). The unit is in contact with the top of the Manazuru Knoll in lines C and D and thickens toward the knoll. The middle unit (green area in Figure 3) has a thickness of 0.5 to 1.2 s. The coherence of reflectors is good in this unit, although their amplitude is small. Lines B-D show onlap of this unit to the Manazuru Knoll, and line A shows that the unit is located at the top of the Sagami Knoll. The bottom unit has a maximum thickness of approximately 1.0 s. In this unit, reflector coherence is not good, but the amplitude of reflectors is relatively large.

Discussion

Some features revealed by the MCS data around the Manazuru Knoll are very important for the study of the plate boundary along the northern Sagami Trough. Figure 4 is a plot of the anticlinal axis of the Manazuru Knoll, as identified in Figures 2 and 3. The anticlinal axis, which was confirmed by MCS data of lines C-E, is along the anticlinal axis shown on the bathymetric map, and the axis is bent in the southeast direction. The anticlinal axis of the Manazuru Knoll in lines A and B gradually bends to the west. As a result, the geometry of the eastern end of the Manazuru Knoll is bent in a shape similar to that of a crank. Based on the past seismic reflection data in Sagami Bay obtained by Kinoshita et al. (2005), Kinoshita et al. (2006), and Yamashita et al. (2013), it is estimated that the easternmost part of Manazuru Knoll extends to the vicinity of Miura Canyon. The offset of the strike of the anticline axis, which has a crank shape, is approximately 7 km (indicated by the yellow arrow in Figure 4).

According to the results of seafloor geodetic observations in Sagami Bay, the seafloor of western Sagami Bay is moving northwest at a velocity of approximately 4.1 cm/year (Saito et al. 2008). On the other hand, relative motion along the Sagami Trough (as indicated by GPS data) was estimated to be 23 to 28 mm/year in the direction of N 25° W (Nishimura 2011). The direction of relative plate motion according to these geodetic results is almost consistent with the bending direction of the anticlinal axis of the Manazuru Knoll obtained by this study.

A reverse fault, which is related to the formation of Manazuru Knoll, is clearly developed to the southwest of the knoll in lines A to D. Ohkouchi (1990) interpreted that a reverse fault formed from east to west at the southern margin of the Manazuru Knoll. We suppose that this reverse fault on the southwestern margin of Manazuru Knoll was formed by structural shortening when the relative motion of the Philippine Sea plate was acting in a perpendicular direction near Manazuru Knoll. Therefore, it is estimated that the relative motion of the Philippine Sea plate was almost oblique or parallel to the anticlinal axis of Manazuru Knoll and that the eastern end of Manazuru Knoll was bent into a crank shape by right-lateral strike-slip motion. As a result, it is estimated that most of Manazuru Knoll, which was located to the west of the plate boundary, has been moving to the northwest. In addition, because the development of the crank-shaped deformation by right-lateral strike-slip motion corresponds with the present plate motion, we suppose that the development of the crank-shaped deformation occurred later than the formation of the anticline and reverse fault by shortening motion. Accordingly, the relationship between a structure of the Manazuru Knoll formed by shortening and the crank-shaped bend structure formed by the right-lateral strike-slip motion indicates the history of the plate boundary in the northern Sagami Trough. Furthermore, according to a previous study of calcareous nannofossil ages in and around the Sagami Knoll, the geological age of the southern outcrop is older than that of the northern outcrop (Kanie et al. 1999). Comparing this study with the previous study, we suggest that the base of the outcrop of the southern Sagami Knoll is the same as that of the Manazuru Knoll.

A clear reflector dipping to the northeast (indicated by the black arrow in Figure 3) was identified below the basement of the Sagami Knoll. By comparison with the onshore-offshore seismic survey across the Kozu-Matsuda Fault and Sagami Trough (Sato et al. 2005; Sato et al. 2010), this reflector is suggested to correspond to the splay fault from the plate boundary located in the extension of the Kozu-Matsuda Fault. This suggestion corresponds with the tectonic maps of Ohkouchi (1990) and Ogawa et al. (2008). Their maps showed that the southernmost extension of the Kozu-Matsuda Fault is located around Manazuru Knoll. On the other hand, according to their maps, the positions of many active faults in the northern Sagami Trough are related to the positions of the knolls. As described above, Manazuru Knoll, which was formed by the anticline and reverse fault due to the shortening movement and was deformed by right-lateral movement, has been strongly influenced by the plate motion in Sagami Bay. Therefore, we suggest that there is a possibility that the end of the southern extension of the Kozu-Matsuda Fault was constrained by Manazuru Knoll.

Conclusions

The results of this study are summarized as follows:

- Manazuru Knoll was formed by an asymmetric anticline, and the knoll geometry is bent into a crank-like shape. It is estimated that the easternmost part of Manazuru Knoll has reached the vicinity of Sagami Knoll and Miura Canyon.

- The reverse fault of the southwestern margin of Manazuru Knoll formed by shortening of the structure when the relative motion of the Philippine Sea plate was acting in a perpendicular direction near Manazuru Knoll. Therefore, it is estimated that the relative motion of the Philippine Sea plate was almost oblique or parallel to the anticlinal axis of Manazuru Knoll and that the eastern end of Manazuru Knoll was bent in a crank-like shape by right-lateral strike-slip motion.
- A clear reflector dipping to the northeast below the basement of the Sagami Knoll is believed to correspond to the splay fault from the plate boundary, which is located in the extension of the Kozu-Matsuda Fault.

Abbreviations

CMP: common midpoint; GPS: global positioning system; MCS: multichannel seismic reflection.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TN designed the survey, processed and interpreted the data, and drafted the manuscript. NT participated in the data acquisition and interpretation. SM and MY participated in the data acquisition. YK participated in the data acquisition and editing of the bathymetric data. SK organized the data acquisition cruises and research. All authors read and approved the final manuscript.

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References

Hattori M, Kanie Y, Okada H, Arima M (1992) Geology of Sagami Knoll Okinoyama Bank Chain, Sagami Bay central Japan. Proc JAMSTEC Symp Deep Sea Res 8:185–192 (in Japanese with English abstract)

Hattori M, Iwaki C, Okada H, Kanie Y, Akimoto K (1995) Nannoflora and biostratigraphy of the tertiary and quaternary sequences of Sagami Bay and Okinoyama Bank Chain. JAMSTEC J Deep Sea Res 11:269–278 (in Japanese with English abstract)

Imoto M, Fujiwara H (2012) Long term probability of a magnitude 8 Kanto earthquake along the Sagami Trough, central Japan. Earth Planets Space 64:e17–e20. doi:10.5047/eps.2012.06.005

Iwabuchi Y, Kato Y, Hashimoto F, Kondo T, Shinbayashi K (1991) Multi-channel seismic reflection survey of Sagami Bay. J Jpn Soc Mar Surv Tech 3:39–51 (in Japanese)

Kanie Y, Hirata D, Imanaga I (1999) Geology and microfossil age of the formations composing the Oiso Hill and Okinoyama Bank Chain, south-central Japan. Res Rep Kanagawa Prefect Mus Nat Hist 9:95–110 (in Japanese with English abstract)

Kato S (1987) Multi-channel seismic reflection survey in the Nankai, Suruga, and Sagami troughs. Mar Geod 11(4):251–268

Kinoshita M, Yamashita M, Okano T, Shimizu S, Hashimoto Y, Kasaya T, KY05–06 Leg 2 Shipboard Scientific Party (2005) High-density single-channel seismic profiles obtained during KY05-06 cruise in the Sagami Bay, Japan. JAMSTEC Rep Res Dev 2:41–56

Kinoshita M, Yamashita M, Okano T, Nakasone T, Yamamoto F, Shimizu S (2006) High quality multi-frequency seismic profiles obtained during KY06-01 cruise in the Sagami Bay, Japan. JAMSTEC Rep Res Dev 4:41–54

Kobayashi R, Yamamoto Y, Sato T, Shishikura M, Ito H, Shinohara M, Kawamura K (2010) Kanto Asperity Project—background and future prospects. JpGU Meeting 2010:SSS023-01

Kodaira S, Sato T, Takahashi N, Miura S, Tamura Y, Tatsumi Y, Kaneda Y (2007) New seismological constraints on growth of continental crust in the Izu-Bonin intra-oceanic arc. Geology 35:1031–1034. doi:10.1130G23901A

Miura S (2009) A history of JAMSTEC seismic data acquisition system. JAMSTEC-R IFREE Spec Issue. pp 81–88 (in Japanese with English abstract)

Nishimura T (2011) Back-arc spreading of the northern Izu–Ogasawara (Bonin) Islands arc clarified by GPS data. Tectonophysics 512:60–67. doi:10.1016/j.tecto.2011.09.022

Ogawa Y, Takami Y, Takazawa S (2008) Oblique subduction in an island arc collision setting: unique sedimentation, accretion, and deformation processes in the Boso TTT-type triple junction area, NW Pacific. In: Draut AE, Clift PD, Scholl DW (ed) Formation and applications of the sedimentary record in arc collision zones. Geological Society of America Special Paper, vol 436. pp 155–170

Ohkouchi N (1990) Active geological structures and tectonics in Sagami Bay area. J Geogr (Chigaku Zasshi) 99(5):458–470 (in Japanese with English abstract)

Saito H, Sato M, Matsumoto Y (2008) The crustal movement velocity at the seafloor reference point "Sagami Bay" detected by seafloor geodetic observation. Tech Bull Hydrography Oceanography 26:23–27 (in Japanese)

Sato H, Hirata N, Koketsu K, Okaya D, Abe S, Kobayashi R, Matsubara M, Iwasaki T, Ito T, Ikawa T, Kawanaka T, Kasahara K, Harder S (2005) Earthquake source fault beneath Tokyo. Science 309:462–464

Sato H, Iwasaki T, Ishiyama T (2010) Long-term evaluation of active fault branching from the plate boundary—deep seismic profiling across the Sagami Trough. Kagaku 80:825–831 (in Japanese)

Suyehiro K, Takahashi N, Ariie Y, Yokoi Y, Hino R, Shinohara M, Kanazawa T, Hirata N, Tokuyama H, Taira A (1996) Continental crust, crustal underplating, and low-Q upper mantle beneath an oceanic island arc. Science 272:390–392

Takahashi N, Yamashita M, Kodaira S, Miura S, Sato T, No T, Takizawa K, Tatsumi Y, Kaneda Y (2011) Rifting structure of central Izu-Ogasawara (Bonin) arc crust: results of seismic crustal imaging. In: Ogawa Y et al. (ed) Accretionary prisms and convergent Margin tectonics in the northwest pacific basin. Modern Approaches in Solid Earth Sciences 8. pp 75–95. doi 10.1007/978-90-481-8885-7_4

Taylor B (1992) Rifting and the volcanic-tectonic evolution of the Izu-Bonin-Mariana arc. In: Taylor B, Fujioka K, et al. (ed) Proc. ODP, Sci. Results, 126. Ocean Drilling Program, College Station, TX, pp 627–651. doi:10.2973/odp.proc.sr.126.163.1992

Wessel P, Smith WHF (1991) Free software helps map and display data. Eos Trans AGU 72:441

Yamashita M, Kinoshita M, Kasaya T, Takahashi N, Kaneda Y (2013) Sediment deformation in eastern Sagami Bay revealed by high-density seismic reflection survey. JAMSTEC Rep Res Dev 17:1–10

Yamazaki H (1993) Geological and geomorphological survey on the northwestern edge of Sagami Knoll by the DSRV Shinkai 2000. Proc JAMSTEC Symp Deep Sea Res 9:191–203 (in Japanese with English abstract)

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